Draining the Swamp: Wetlands, Flooding, and the Clean Water Act*

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Abstract

In June 2020, the Environmental Protection Agency and the Army Corps of Engineers narrowed the definition of 'Waters of the United States' (WOTUS), significantly limiting wetland protection under the Clean Water Act. Current policy debates and litigation center on the uncertainty around wetland benefits, especially concerning damages from flooding, the most costly and frequent natural disaster. Our study estimates the value of wetlands for flood mitigation across the entire US using detailed flood claim and land use data. Employing three different identification strategies, we find that a hectare of wetland provides $2,300 in annual flood mitigation value when accounting for spatial spillovers. Our results indicate that wetland loss between 2001 and 2016 increases flood claims by $535 million (or 19%) annually. The spatial heterogeneity we document in wetland benefits has implications for the WOTUS rule change affecting the 50% of 'isolated' wetlands.

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1 Introduction

The Clean Water Act (CWA) is among the most important, wide-reaching, and costly pieces of environmental legislation in the United States. A primary component of the CWA is the regulation of wetlands under Section 404, which requires a permit in order to dredge or fill wetlands for real estate or infrastructure development, water resource projects, or mining activities. In June 2020, the Navigable Waters Protection Rule (NWPR) came into effect narrowing the extent of 'waters of the United States' (WOTUS) that fall under CWA jurisdiction. As a result, an estimated 50% of wetland area will no longer be protected under Section 404 (Sullivan et al. 2019). The matter is being litigated in federal court and is likely to proceed to the Supreme Court.

Underlying this debate is the highly controversial nature of wetland regulation, which pits the protection of productive ecosystems against the rights of private landowners. Wetlands provide a multitude of public goods in the form of ecosystem services, including flood mitigation, water quality improvement, and wildlife habitat. Many of these services provide off-site benefits, which the resource owner is unable to capture (Turner et al. 2000). There is limited financial incentive to preserve wetlands since the private benefits derived by the landowner do not reflect the full benefits of wetlands to society (Heimlich 1998).

Wetland regulation is intended to correct this market failure. While the costs of regulation are well documented, the benefits are more difficult to quantify, making benefit-cost analysis challenging (Georgiou and Turner 2012). A common concern is that policy-makers might undervalue resources that are not quantified, impeding proper management (Costanza et al. 2014). This issue is central to the debate over the recent NWPR, which excludes the value of ecosystem services provided by wetlands from its benefit-cost analysis, citing a lack of credible empirical evidence on the economic value of wetlands for flood mitigation and other ecosystem services.

This study estimates the value of wetlands for flood mitigation in the US. Although flood mitigation is only one of many ecosystem services provided by wetlands, rich data on flood damages allows for a uniquely tractable empirical evaluation of the contribution of wetlands to human well-being. We conduct a large-scale analysis across the entire continental US linking zip code-level data on FEMA's National Flood Insurance Program (NFIP) claims with high-resolution data on wetland area from 2001 to 2016.

To our knowledge, we are the first to estimate the causal effect of wetlands on flood damages. There is limited empirical evidence on the economic value of these ecosystems for flood mitigation, particularly for freshwater wetlands, which represent 95% of total wetland area in the US (Brander et al. 2006; Barbier 2013; Dahl 2011). Analyzing 34 hurricanes, Costanza et al. 2008 find that a hectare of coastal wetland is associated with an average $8,000 reduction in annual storm damage in the US, a general finding supported by recent papers (Narayan et al. 2017; Sun and Carson 2020). However, these studies do not explicitly assert or test causal mechanisms. Importantly, prior work focuses primarily on coastal wetlands and damages from hurricanes, and may not be representative of the vast majority of US wetlands, which are located inland, or more typical flood events, which, unlike hurricanes, are not accompanied by storm force winds.

The empirical challenge is that wetland spatial extent is associated with other factors that drive flood damage dynamics. For example, locations with wetter climates are more likely to experience flood events and also have more wetlands. Additionally, locations experiencing rapid population growth are likely to see both reductions in wetland area due to urban expansion into natural areas and higher flood claims due to an increase in the housing stock. Such omitted variables may confound estimates of the economic value of wetlands for flood mitigation. To address this challenge, we employ three different identification strategies—long differences, panel analysis, and upstream-downstream differences-in-differences—which rely on different assumptions and identifying variation to establish a causal effect. These methods yield quantitatively similar results, providing plausible bounds for the causal effect of wetlands on flood damages.

We estimate that one hectare of wetland loss increases NFIP claims by $2,300 per year when accounting for spatial spillovers. To put this value into context, we use high-resolution land price data (Nolte 2020) to estimate the value of private lands that are classified as wetlands. We find that the mean market value across all wetlands in the continental US is $12,700, while wetlands that were lost between 2001 and 2016 have an estimated value of $31,600. Using this range, the societal benefits from reduced flooding outweigh the cost of conserving wetlands (based on land price) within 5 to 17 years, on average. One interpretation of our results is that lifting federal protections for wetlands represents a transfer from taxpayers, who fund the NFIP, to private landowners, who profit from converting wetlands to other uses. We note that our estimates are a lower bound on the overall value of wetlands that exclude their benefits related to recreation, habitat, water quality, and the fishing industry.

Our results have several important policy implications: first, we find no effect of *increases* in wetland area on flood insurance claims, calling into question the extent to which wetland restoration can offset the adverse impacts of wetland loss. Second, we find substantial spatial spillovers in the benefits of wetlands, supporting the oft-cited theory that regulation may be required to achieve the optimal provision of wetlands due to the presence of positive downstream externalities. Third, we evaluate wetland location relative to the surface water network and find that the most valuable wetlands for flood mitigation are those located 500 meters to 750 meters from the nearest stream or river. This finding is at odds with the new WOTUS rule change that eliminates federal protections for the estimated 50% of 'isolated' wetlands that lack a surface water connection.

We also document significant heterogeneity in the impact of wetlands on flood damages. Geographically, we find the greatest benefits in the eastern half of the US. We observe heterogeneity by ecoregion and type of land use conversion, which aligns with the fact that wetlands and their functions vary greatly by type, location, and position—suggesting that a more decentralized implementation of the CWA may be appropriate for wetland regulation. Finally, we find the flood mitigation benefits of wetlands to be greatest during anomalously high precipitation events, which are projected to become more frequent with climate change.

The remainder of the paper proceeds as follows: Section 2 provides background information on the relationship between wetlands and flooding, wetland regulation under the Clean Water Act, and the National Flood Insurance Program. Sections 3 and 4 outline our data and identification strategies. Section 5 presents our empirical estimates of the effect of wetlands on flood damages, along with several extensions. Section 6 is a discussion of the implications of our findings.

2 Background

2.1 Wetlands and flooding

Examples of recent extreme flooding in the US Midwest (2019), Houston (2017), Puerto Rico (2017), and Baton Rouge (2016) have underscored the human and economic cost of floods. The most common disaster globally, flooding is responsible for half of all natural disaster deaths. Floods were responsible for 6.8 million deaths in the 20th century (Doocy et al. 2013) and impose a significant public health burden (Alderman et al. 2012). In 2019 floods caused $82 billion in global economic losses, and cumulative losses since 2000 are estimated to be $1 trillion (AON 2019). In the US, the Congressional Budget Office estimates that flooding causes $20 billion in annualized economic losses.

Flood risk is expected to increase in the coming years with rising sea levels and more frequent and extreme precipitation events (Knutson et al. 2010). Consequently, there is increased demand for flood mitigation strategies that are physically sound, cost-effective, and politically feasible (Woodruff et al. 2013). There is a lack of agreement on the best way to mitigate flood damages. While one effective approach is to relocate people and capital away from flood-prone areas, this option is often politically infeasible. The most common approach is environmental engineering (i.e., levees) but such practices generally displace the destructive force of floodwaters elsewhere.

An alternative strategy is nature-based solutions that utilize ecosystem functions of wetlands to reduce flood risk (Spalding et al. 2014). Wetlands are transitional lands between terrestrial and aquatic ecosystems that are water-saturated enough to support hydrophytic vegetation and hydric soils. Wetlands mitigate flooding by acting as "natural sponges" that absorb and hold floodwaters until they are able to infiltrate the ground or slowly release into nearby streams. Wetland vegetation, such as trees and root mats, help reduce the speed of floodwaters moving across floodplains. In combination, these two properties of wetlands have been shown to influence the peak flows, volume, timing, and duration of floods (Acreman and Holden 2013; Thomas and Nisbet 2007).

2.2 Wetland regulation under the Clean Water Act

The Clean Water Act was passed in 1972 with a stated purpose 'to restore and maintain the chemical, physical, and biological integrity of the Nation's waters.' A primary component of the CWA is Section 404, which prohibits any activity involving the discharge of dredged or fill material into 'waters of the United States' (WOTUS) unless a permit is issued by the US Army Corps of Engineers (EPA 2020c) in cooperation with the Environmental Protection Agency. Such regulated waters include wetlands, a land form encompassing over 5% of the continental US (Dahl 2011). The law thus affects many segments of the economy: real estate development, infrastructure (i.e., highways, ports, airports), water resources (i.e., dams, levees), industrial development, agriculture, and mining.

Over the last several decades, the national policy goal has been one of "no net loss" of wetland area, prompting the development of Compensatory Mitigation requirements under CWA Section 404 (EPA 2020a). This program requires that when adverse impacts of wetlands are unavoidable, developers must offset the reduction in wetland functions by restoring, creating, or enhancing other wetlands in the watershed.

CWA Section 404 imposes financial and administrative burdens on many segments of the economy. The costs of the program are well documented: the EPA estimates that Section

404 costs developers between $20 million and $53 million per year in permit applications and compensatory mitigation costs (2013). In addition, the program carries administrative costs for the federal government estimated at $7 to $11 million annually, as well as opportunity costs associated with delays in project implementation (2013; Sunding and Zilberman 2002). In contrast, the benefits of wetland regulation, in the form of ecosystem services, are more difficult to quantify because they are not captured in the market and many of the benefits accrue to off-site users.

Legal debates over the CWA focus on the definition of WOTUS, which determines which areas receive federal protection under the legislation. WOTUS has been subject to several Supreme Court decisions over the decades.[1] Following an Executive Order from President Trump in 2017, the EPA and the Army Corps implemented the NWPR in June 2020, redefining WOTUS to exclude wetlands considered 'isolated' from navigable waters (EPA & Army Corps 2020). Specifically, wetlands lacking surface water connections to intermittent or perennial streams are no longer protected. Although it is unclear how this rule will be applied in practice, a 2017 analysis by EPA and the Army Corps estimates that over 50% of the nation's wetlands will no longer be under federal jurisdiction (Sullivan et al. 2019).

Several lawsuits have been filed recently in federal court challenging the new WOTUS rule. Plaintiffs include environmental groups like National Wildlife Federation and Natural Resources Defense Council,[2] as well as 17 states, Washington DC, and New York City.[3] The legal debate centers on the extent to which WOTUS extends beyond an original narrow definition of navigable waters that encompassed tributaries (perennial, intermittent, and ephemeral) and other connected waters. Of particular concern is WOTUS's treatment of non-adjacent, or 'isolated', wetlands.[4]

The previous definition of WOTUS, established in 2015, relied on Justice Kennedy's Ra-

[1] United States v. Riverside Bayview Homes (1985) upheld that wetlands adjacent to navigable waters were 'inseparably bound' and to be included in the definition of WOTUS; Solid Waste Agency of Northern Cook County v. U.S. Army Corps of Engineers (2001) found that isolated non-navigable intrastate ponds utilized by migratory birds did not constitute a sufficient basis; Rapanos v. United States (2006) concluded that WOTUS encompassed some waters not navigable in the traditional sense. Justice Kennedy stated that to be covered by the CWA "a water or wetland must possess a 'significant nexus' to waters that are or were navigable in fact or that could reasonably be so made." Significant nexus is achieved if the wetlands "either alone or in combination with similarly situated [wet]lands in the region, significantly affect the chemical, physical, and biological integrity of other covered waters more readily understood as 'navigable'."

[2] Available: https://www.southernenvironment.org/uploads/words_docs/2019.10.23_-_Final_Repeal_Rule_Complaint.pdf

[3] Available: https://oag.ca.gov/system/files/attachments/press-docs/WOTUS%20Complaint%20Filed_05012020.pdf

[4] While the term 'isolated' lacks a consistent definition in policy documents, the scientific literature defines 'geographically isolated wetlands' as those surrounded by uplands.

panos criteria of 'significant nexus' to determine what constitutes jurisdictional waters. In applying this guidance, the EPA and the Army Corps estimated a value of wetlands ranging from $129,000 to $292,000 per acre based on their combined fishing, hunting, fur trapping, recreation, water filtration, flood control, aesthetic, and habitat value (EPA 2013). Acknowledging potential bias due to double counting, non-representative wetlands, and lack of empirical strategies to assert causal inference, the agencies opted to rely on household surveys of willingness to pay (WTP) for wetlands in the benefit-cost analysis.

The WTP-derived benefits, which primarily came from flood protection values, were then allocated to non-adjacent or 'isolated' wetlands. Such wetlands were estimated to comprise over half of all wetlands and over 20% of total wetland area (Tiner 2003; Cohen et al. 2016). The EPA and Army Corps report concluded that wetland benefits vary by region, ranging from $26,000 to $287,000 per acre. A concurrent scientific review supported the 2015 rule's treatment of isolated wetlands, finding that such wetlands generally are "physically, chemically, and biologically integrated with rivers" and that they provide many downstream benefits including storage of floodwater (EPA 2015).

In contrast, the 2020 NWPR rejects the 'significant nexus' criteria and draws on a new EPA and Army Corps impact assessment that largely excludes wetland benefits, citing a lack of credible recent research (2018; Howard and Shrader 2019).[5] Since wetlands comprised the largest benefit category in the 2015 assessment, the costs of the 2015 rule were determined to significantly outweigh the benefits. EPA's Science Advisory Board opposed the new rule, stating it "lacks a scientific justification" in relation to the exclusion of wetlands without a direct surface connection to navigable water (Science Advisory Board 2020). Boyle et al. 2017 discuss the implications of this agency-level inconsistency in their approach to benefit-cost analysis. Thus, a rigorous analysis of the value of wetlands at a nation-wide scale is needed to inform this policy debate.

2.3 National Flood Insurance Program

The National Flood Insurance Program (NFIP) was created in 1968 by the federal government to provide affordable flood insurance to property owners. Currently, the program is the dominant flood insurer in the US, with more than 5.1 million policies covering more

[5] Excerpt from the 2018 report (EPA 2018): "Many components of the 2015 analysis do not satisfy these requirements. No national level studies concerning WTP for the expansion or preservation of wetland acreage are currently available for the U.S., and the U.S. freshwater (non-coastal) wetlands valuation literature is relatively thin. While there are several wetlands valuation studies in the literature, many are context-dependent and not suitable or appropriate for transfer in this analysis."

than \$1.3 trillion of property as of 2018 (FEMA 2020b). To simplify the rate-setting process, flood insurance premiums are based on average historical losses in stratified flood risk zones. The program has come under criticism for failing to charge actuarially fair rates (GAO 2017). More than 20% of the policies are heavily subsidized, charging less than half of full risk levels (CBO 2014). It is also debatable whether the remaining "full risk" policies are actuarially priced since they do not include a "loading charge" to build up reserves for especially costly years. As a result, the NFIP owes \$20.5 billion to the US Treasury (Congressional Research Service 2021).

The structure of the NFIP has two important implications for wetland regulation. First, since flood risk is subsidized by the federal government, the financial incentive of private landowners to conserve flood mitigating-wetlands is not aligned with that of society. Second, if reductions in wetland area causes increases in NFIP claims, any change to wetland regulation that removes barriers to development on wetlands could represent a transfer from taxpayers to property owners and developers.

3 Data

We derive our data on the spatial extent of wetlands from the National Land Cover Database (NLCD). The NLCD is a remotely-sensed product that provides nationwide data on land cover at 30-meter resolution from 2001 to 2016 (Homer et al. 2020). The latest generation of NLCD, released in 2019, is harmonized across years so that individual years can be compared, facilitating land cover change detection. The NLCD indicates the spatial extent of wetlands was approximately 47.1 million hectares (5.8 percent of the conterminous US) in both 2001 and 2016. Over the 15-year study period, the nation lost approximately 340,000 hectares of wetland area, but these losses were offset by a comparable amount of wetlands gains—thus achieving at a national level the long-standing federal objective of "no net loss" of wetlands. Figure 1 maps the data on wetland extent from the NLCD. Panel A shows the percentage of area covered by wetlands (blue scale). Areas with gains and losses in wetlands over the 2001 to 2016 study period are indicated in green and red, respectively. These changes constitute the primary source of variation used in our identification strategy.

We complement the data on wetland extent with geospatial information on the US water drainage network from the National Hydrography Dataset (NHD) (Buto and Anderson 2020), which is used by the EPA and the Army Corps for CWA jurisdictional determinations. We employ the NHD in two distinct ways. First, we classify wetlands as upstream

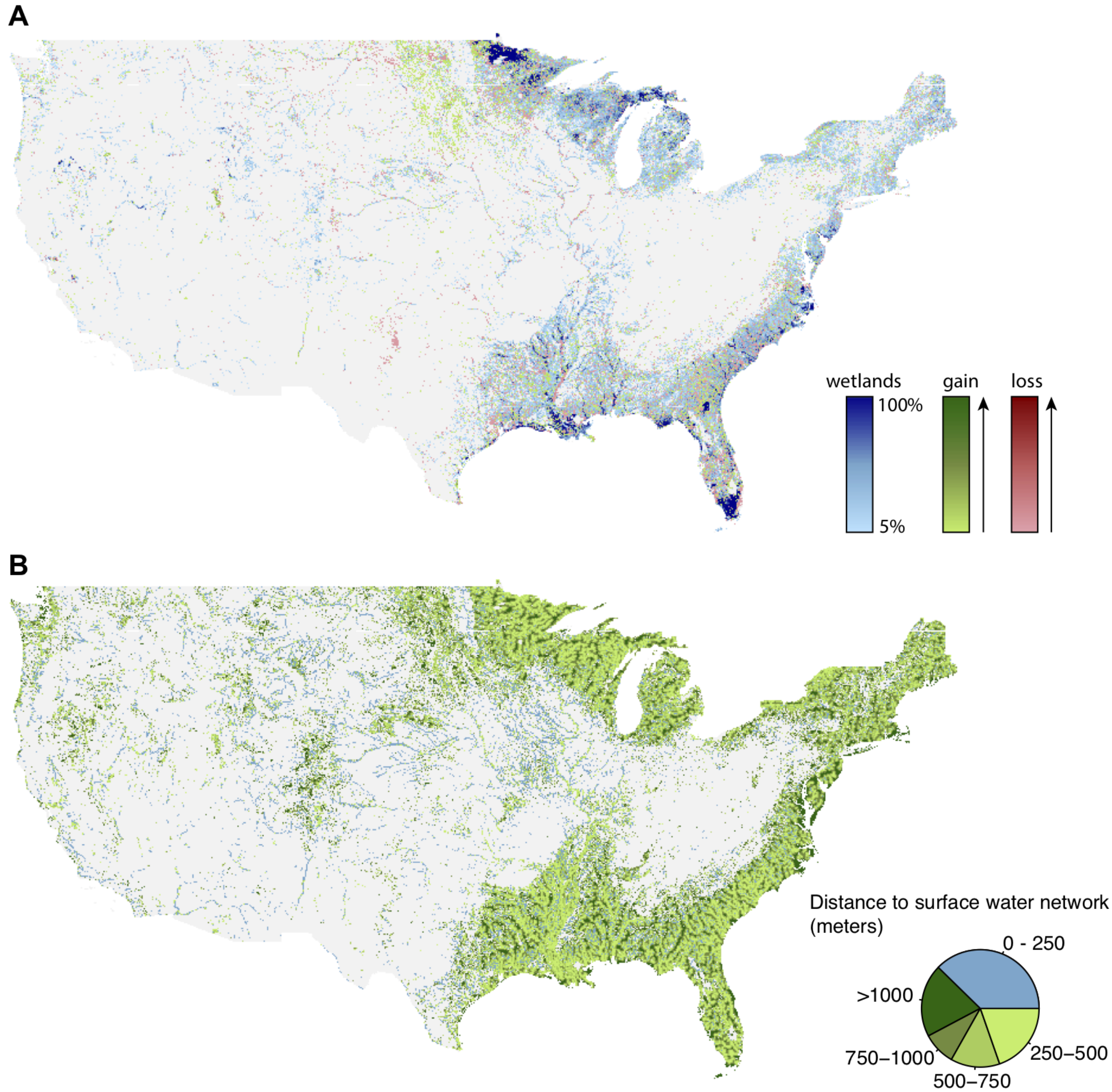

Figure 1: **Wetlands in the United States.** (A) Shows percentage of area covered by wetlands (blue scale). Areas with increases and decreases in wetlands over the 2001 to 2016 study period are indicated in green and red, respectively. (B) Maps the most prevalent type of wetland, separated into riparian (blue) and isolated (green) wetlands. Since no formal definition for isolated wetlands exists, we show isolated wetlands using multiple distance cutoffs. Grid cells are classified as containing wetlands if at least 5% of the 3km × 3km area is classified as wetland. Data are from the National Land Cover Dataset (NLCD) for the years 2001 and 2016.

or downstream of each zip code in our sample using the flow direction in NHD's Watershed Boundary Dataset (WBD), enabling our upstream versus downstream difference-in-differences analysis. Second, we compute the distance of all wetland areas in our sample from the NHD surface water network, enabling our evaluation of the relative contribution of 'isolated' wetlands to flood mitigation. Panel B of Figure 1 maps the area of wetlands by distance from the surface water network. Wetlands shown in blue represent those within 250 meters of the nearest stream or river. Green areas represent wetlands that are further removed from the surface water network, with the darker shades representing larger distances.

Data on our dependent variable, flood insurance claims, come from the FEMA's National Flood Insurance Program (NFIP) Redacted Claims Dataset (FEMA 2020a). This dataset comprises the NFIP's full claim history and represents more than 2 million transactions. Due to privacy concerns, the NFIP does not provide address-level data; we identify the location of each claims transaction by the property zip code. To control for differences in flood insurance uptake, we also obtain zip-code level data on population, income, number of housing units, and median home values from the US Census and American Community Survey, changes in developed land from the NLCD (area categorized as either Low, Medium, or High Intensity Developed where impervious surfaces account for over 20% of cover), and local governance as measured by participation in the NFIP's Community Rating System.

To construct our dataset, we aggregate the measures of wetland area from the NLCD to the zip code-level for the years 2001, 2006, 2011, and 2016. We then average NFIP claims over the 5-year periods surrounding these dates (i.e., 1999 to 2003 for 2001) and merge the two data sources. We elect to use five-year averages because the amount in NFIP loss dollars paid is highly variable across individual years due to the infrequent nature of flood events.[6]

4 Empirical Strategy

The goal of our empirical estimation is to capture the causal effect of wetlands on flood insurance claims. The primary challenge is that wetland extent is correlated with other factors that drive flood damages. For example, communities with wetter climates and more frequent flooding tend to have more wetlands. Indeed, we find a positive correlation

[6] We show the sensitivity of our results to using alternative time windows in Appendix B.

between wetland extent and flood damage. This relationship should not be interpreted as wetlands causing flooding since confounding factors (including precipitation) could be driving the correlation. Similarly, flood damages and real estate development are positively correlated, further raising concerns about omitted variables.

To overcome this challenge, we employ three different identification strategies—long differences, panel analysis, and upstream-downstream differences-in-differences—which rely on different assumptions and identifying variation to establish a causal effect.

4.1 Long differences

In our base specification, we adopt a long differences approach to model changes in flood insurance claims over time as a function of changes in wetland area, accounting for time-invariant unobservables at the local level and time-trending unobservables at the state-level. We estimate the LD model:

$$\Delta F_{is} = \beta \Delta W_{is} + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{is} \tag{1}$$

where ΔF_{is} is the change in NFIP claims in zip code i and state s between the years 2001 and 2016. The treatment variable ΔW_{is} represents the change in the spatial extent of wetlands in zip code i over the same period. The vector of covariates, $\mathbf{X}$, includes changes in population, income, the number of housing units, average housing value, and local governance (as measured by participation in the NFIP's Community Rating System) to control for changes in NFIP uptake. We also control for changes in built-up land (i.e., impervious surfaces) over time to account for the fact that urban expansion is correlated with both wetland loss and an increase in flood damages as people and capital move into flood plains. Finally, we include state fixed effects, α_s, to control for any unobserved state-level trends.

These controls were selected in consultation with the existing literature on empirical determinants of NFIP uptake and claims (Kriesel and Landry 2004; Kousky and Michel-Kerjan 2017; Wagner 2019). We cluster standard errors at the state level to control for correlation in the error term over both time and space.

We also estimate an alternative specification that allows flood damages to respond differently to gains and losses in wetlands. This model is identical to equation (1) except that we model changes in NFIP claims as a simple piecewise linear function of changes in wetland area:

$$\Delta F_{is} = \beta_1 \Delta W_{is}^{GAIN} + \beta_2 \Delta W_{is}^{LOSS} + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{is} \tag{2}$$

where W_{is}^{GAIN} describes an increase in the spatial extent of wetlands in zip code i over the period 2001 to 2016 and W_{is}^{LOSS} describes a decrease in wetland area. That is, $W_{is}^{GAIN} = \Delta W_{is}$ for localities with $\Delta W_{is} \geq 0$, and $W_{is}^{LOSS} = \Delta W_{is}$ for localities with $\Delta W_{is} < 0$.

4.2 Panel analysis

We alternatively estimate a panel fixed effects model that relies on shorter-term changes in wetland area to identify the effect of wetlands on flood damages. Specifically, we estimate the model

$$F_{ist} = \beta W_{ist} + \theta \mathbf{X}_{ist} + \alpha_i + \delta_{st} + \epsilon_{ist} \tag{3}$$

where all variables are defined as in equation (1) and the panel contains four observations per zip code corresponding to the four years with wetland measures available from the NLCD: 2001, 2006, 2011, and 2016. The identification relies on 5-year deviations from average wetland area to identify the coefficient of interest. This approach controls for unobservable heterogeneity at the zip code-level as well as state-level time trends in NFIP flood claims. We continue to include time-varying controls including zip code-level population, per capita income, built up land, and participation in the CRS.

The panel approach allows us to include all years in the NLCD in our analysis; however, this comes at the cost of potentially introducing more measurement error into our data. The NLCD is a remotely-sensed product, and although the dataset is designed to be comparable across years, any misclassification of wetlands in a given year will appear as land use change in our data. One general concern with fixed effects estimates is attenuation bias caused by measurement error in the treatment variables. Further, given the sticky nature of land use, it is improbable that a pixel will categorically change its land use in a five-year period, and even less likely that it will change its land use more than once over the 15-year period. Therefore we believe that longer-term variation better describes the land use change process and we use the long difference model as our primary specification. And we utilize the panel estimates as a check on the robustness of our results to using alternative identifying variation.

4.3 Upstream-downstream difference-in-differences

We also estimate the effect of wetlands on flood damages using a difference-in-differences (DID) framework. This approach takes advantage of the fact that for non-coastal areas, flood risk should be affected by changes in upstream wetland area but not by changes in downstream wetland area. Figure 2 illustrates this dynamic.

Figure 2: **Wetlands and flooding schematic.** *Left*: city under non-flood conditions with both upstream and downstream wetlands. *Center*: city under flood conditions with both upstream and downstream wetlands, in which case the upstream wetlands mitigate flooding, while downstream wetlands do not. *Right*: city under flood conditions with only downstream wetlands, in which case the wetlands do not mitigate flooding.

Given the nature of water flow, we can utilize changes in downstream wetland area as a natural counterfactual for changes in upstream wetland area. The difference-in-differences model is estimated using the equation:

$$\Delta F_{is} = \beta \Delta W_{is}^{UP} + \lambda \Delta W_{is}^{ALL} + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{is} \tag{4}$$

where ΔW_{is}^{UP} denotes changes in wetland area upstream of zip code i and ΔW_{is}^{ALL} denotes changes in wetland area both upstream and downstream of the zip code. The spatial extent of upstream versus downstream wetland area was computed using National Hydrography Dataset flow direction over the geographic extent of the watershed (see Appendix

A for details). The coefficient of interest, β, represents the differential effect of upstream wetlands on flood insurance claims.

The DID framework leverages different identifying variation than the LD approach by using downstream changes in wetland area to effectively control for time-varying factors unrelated to flooding that drive both changes in overall wetland extent and changes in NFIP claims. Consider real estate development, for example: wetlands are lost to urban expansion in places with high population growth, which in turn experience higher flood damages due to the larger housing stock. As a result, wetland loss could be misidentified as causing NFIP claims. The DID framework addresses this concern under the assumption that real estate development is not systematically biased toward either upstream or downstream areas relative to a given zip code. To provide a partial test on this identifying assumption, we empirically assess whether real estate development favors upstream or downstream areas using the "developed" land cover class from the NLCD. Reassuringly, we find no significant difference.[7]

5 Results

5.1 Main results

We first establish that wetland loss significantly increases property damages from flooding. Table 1 shows the estimated effect of changes in wetland area on NFIP claims using the three different identification strategies. Columns 1-3 specify the response as linear as in equation (1), while columns 4-6 allow for differential responses to gains versus losses in wetland area as in equation (3). Our results suggest that flood damages respond differently to gains versus losses in wetland area, indicating that the piecewise specification better describes the shape of the response function.

Across all specifications, we find that wetland loss significantly increases NFIP claims. We estimate that one hectare of wetland loss is associated with an increase in zip code-level NFIP claims ranging from \$415 under the long differences approach (column 4) to \$726 using the upstream-downstream difference-in-differences (column 6) approach. These results are robust to specifying the outcome variable as claims per policy, limiting our results to locations that experienced flooding over the study period, using alternative time

[7] The difference in means for change the proportion of area developed between 2001 and 2016 (upstream less downstream) is -0.0003 (95% CI = -0.0017 to 0.0012).

	Dependent variable: Zip code-level NFIP claims					
	Diffs	Panel	DID	Diffs	Panel	DID
Wetland change	−173.4**	−206.3***	−479.6*			
	(84.7)	(76.0)	(275.3)			
Wetland gain				−6.0	139.4	−22.0
				(62.2)	(225.6)	(82.5)
Wetland loss				−414.8**	−461.3*	−726.1*
				(195.2)	(272.2)	(436.3)
Developed area	414.5***	2,286.0**	124.3	395.8***	3,005.8	114.9
	(132.6)	(1,064.4)	(102.9)	(128.3)	(2,257.9)	(97.7)
Median income	−0.8	0.5*	0.1	−0.8	1.1	0.1
	(0.7)	(1.1)	(0.5)	(0.7)	(2.4)	(0.5)
Population	15.4	−114.5	28.4**	15.8	−181.1	28.4**
	(10.8)	(92.8)	(11.9)	(10.9)	(183.1)	(11.8)
Housing units	−14.4	160.1*	87.7***	−14.8	391.2*	87.2***
	(23.2)	(96.8)	(28.4)	(23.2)	(215.2)	(28.2)
Median home value	0.2	0.8**	0.4	0.2	0.7	0.3
	(0.2)	(0.4)	(0.4)	(0.2)	(0.5)	(0.5)
CRS discount	486,914***	67,014**	6,079	486,904***	94,920**	6,540
	(63,702)	(26,532)	(21,052)	(63,715)	(39,,889)	(20,748)
Fixed effects	State	Zip, Year	State	State	Zip, Year	State
Observations	27,292	116,202	25,969	27,292	87,315	25,969

Table 1: **The effect of wetlands on flood damages.** We estimate the effect of wetlands on NFIP claims at the zip code-level using three different identification strategies: long differences (Diffs), panel fixed-effects (Panel), and upstream-downstream differences-in-differences (DID). We specify the response of flood damages to changes in wetland area as linear in columns (1-3) and allow for differential responses to gains and losses in wetland area in columns (4-6). Covariates include developed area, median income, population, number of housing units, median home value, and the mean Community Rating System discount rate across all NFIP policies in the zip code. Standard errors are clustered by county. Asterisks indicate statistical significance at the 10% (*), 5% (**) and 1% (***) levels.

windows to calculate flood damages, withholding regional blocks of data, and aggregating to the county level rather than zip code (Appendix B). Interestingly, we do not find compelling evidence that wetland gains are associated with decreased flood insurance claims. The estimated effect of wetland gain is small in magnitude and never significantly different from zero.

To illustrate the benefit of using three different identification strategies to establish a causal effect, Figure 3 shows variation used by each estimator and the resulting point estimates. In panel A, we use Alabama as an example to plot the variation used by each estimator, with green indicating administrative units with wetland gain and red indicating units with wetland loss. We can see that the long differences, panel, and upstream-downstream difference-in-differences estimators exploit different sources of variation in the treatment variable. Panel B returns to the national-level analysis and shows that the estimated response functions are overlapping, despite relying on different assumptions and sources of identifying variation.

5.2 Spatial extensions

We next explore how the flood-reducing benefits of wetlands depend on their location. This is motivated by the fact that the cumulative influence of individual wetlands within watersheds can strongly affect the spatial scale, magnitude, frequency, and duration of water flows (EPA 2015). First, we test for the presence of positive spatial externalities (i.e., whether wetlands produce measurable off-site benefits). Then we evaluate how the location of wetlands with respect to the surface water network impacts their value for flood mitigation—a highly relevant matter for WOTUS rulemaking and the Clean Water Act.

5.2.1 Spatial lag model

We test for the presence of spatial spillovers using a spatial lag model (Cressie and Wikle 2015), where zip code i's damages from flooding are affected by i's wetland extent, plus the wetland extent of all *upstream* neighbors j whose centroids fall within concentric rings around i's centroid with 10km widths (see Figure 4 Panel A). The estimating equation is:

$$\Delta F_{is} = \sum_{d=1}^{6} (\beta_{d1} W_{dis}^{GAIN} + \beta_{d2} W_{dis}^{LOSS}) + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{dis} \qquad (5)$$

where W_{dis}^{GAIN} and W_{dis}^{LOSS} denote the wetland gain and loss, respectively, in distance band

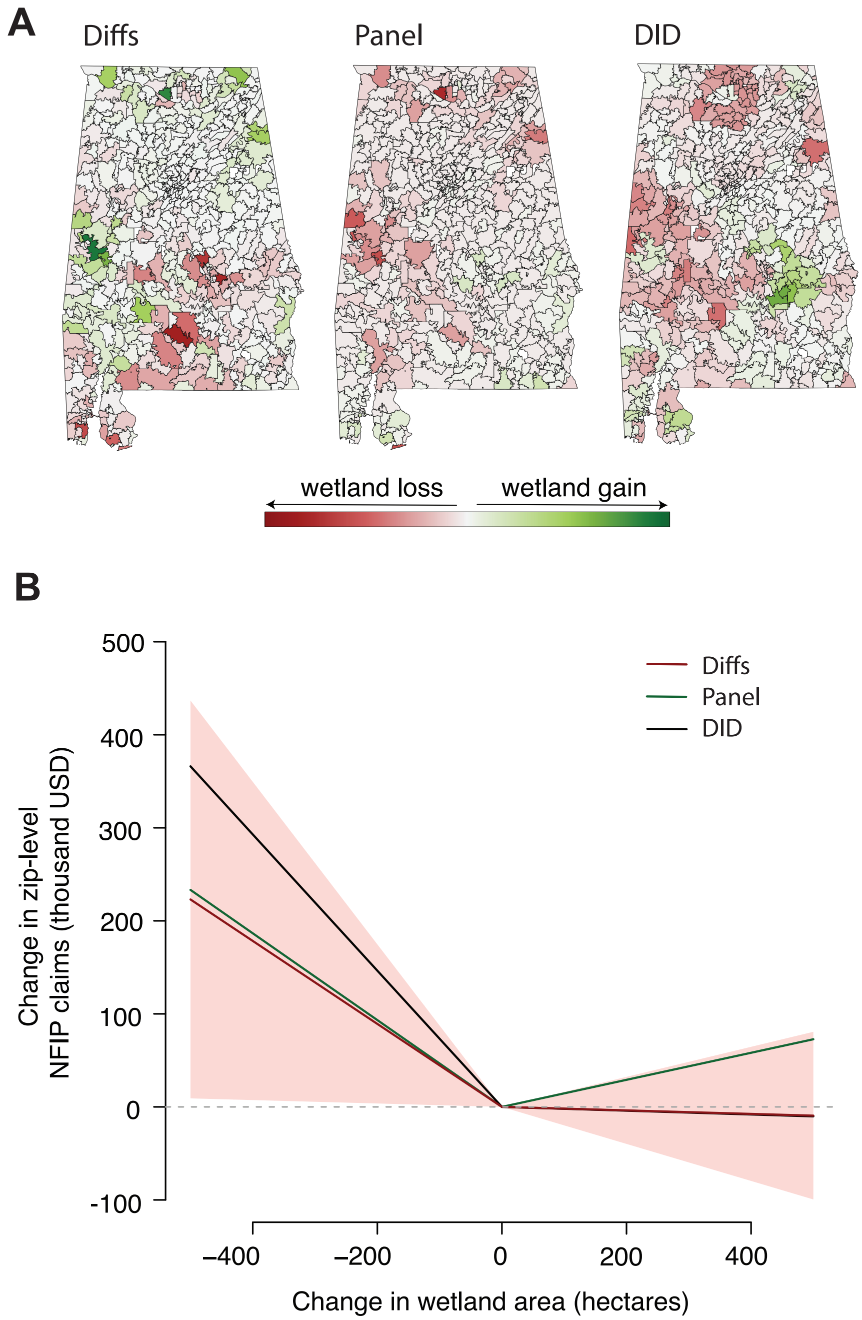

Figure 3: **Estimates of the effect of wetlands on NFIP claims using different identification strategies.** (A) Shows the variation used by each estimator in Alabama. Green indicates zip codes with wetland gain over the period 2001 to 2016, and red indicates zip codes with wetland loss. The long difference (Diffs) estimator exploits the change in wetland area over the 15-year period. The panel fixed effects (Panel) estimator relies on short-term deviations from average wetland changes to identify coefficients. We plot these deviations for the year 2016. The differences-in-differences (DID) estimator compares the differential effect of a change in wetland upstream versus downstream. We illustrate this concept by plotting upstream change in wetland area less downstream change in wetland area. (B) Compares the estimated effect of wetlands on NFIP claims using the Diffs, Panel, and DID estimators. Shaded polygons show 90% confidence intervals.

d (e.g. 10 to 20km away from zip code i). The parameters of interest are the β_{d2}, which represent the change in zip code i's NFIP claims caused by a one hectare decrease in the spatial extent of wetlands that are located a given distance (e.g., 10 to 20km) away from zip code i.

Panel A of Figure 4 plots the spatial lags estimated using this model. Despite some statistical uncertainty, our results suggest that there are spatial spillovers in the benefits of wetlands such that wetlands have a substantially larger value to society than that which accrues to local property owners. To calculate the total estimated damages resulting from changes in wetland area, we take the linear combination of coefficients from the spatial lag model, accounting for the fact that not all zip codes have upstream wetlands.[8] We find that each hectare of wetland loss increases NFIP claims by \$2,295 (90% CI = \$396 to \$4,194).[9] Thus the flood mitigation value of wetlands to local property owners (in the same zip code) amounts to less than 20% of the benefits of wetlands to all users within 100 kilometers.

5.2.2 Distance to surface water

Next, we evaluate how wetland location with respect to the surface water network affects flood mitigation value. This analysis is motivated by the recent NWPR rule change to the definition of WOTUS that eliminates federal protections under the CWA for 'isolated' wetlands (i.e. those without a surface water connection to streams or rivers). We first calculate how far each wetland area is from the nearest surface water connection using the detailed mapping of the US water drainage network contained in the National Hydrography Dataset. We then bin these distances in increments of 250 meters and jointly estimate the effect of wetlands in each distance bin using the equation:

$$\Delta F_{is} = \sum_{k}^{5}(\beta_{1k} W_{kis}^{GAIN} + \beta_{2k} W_{kis}^{LOSS}) + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{is} \tag{6}$$

where k denotes the discrete distance bins (e.g. 0 to 250 meters from the nearest surface water connection). All other variables are defined as in equation (3).

[8] For example, since only 50% of zip codes have upstream wetlands in the 10-20km band, the point estimate for the 10-20km distance bin is multiplied by 0.5 when taking the linear combination of coefficients.

[9] As a robustness check, we also estimate the effect of wetland change on NFIP claims at the county-level. Results are shown in Appendix B. When data is aggregated to the county-level, we find a size consistent with the model that accounts for spatial lags.

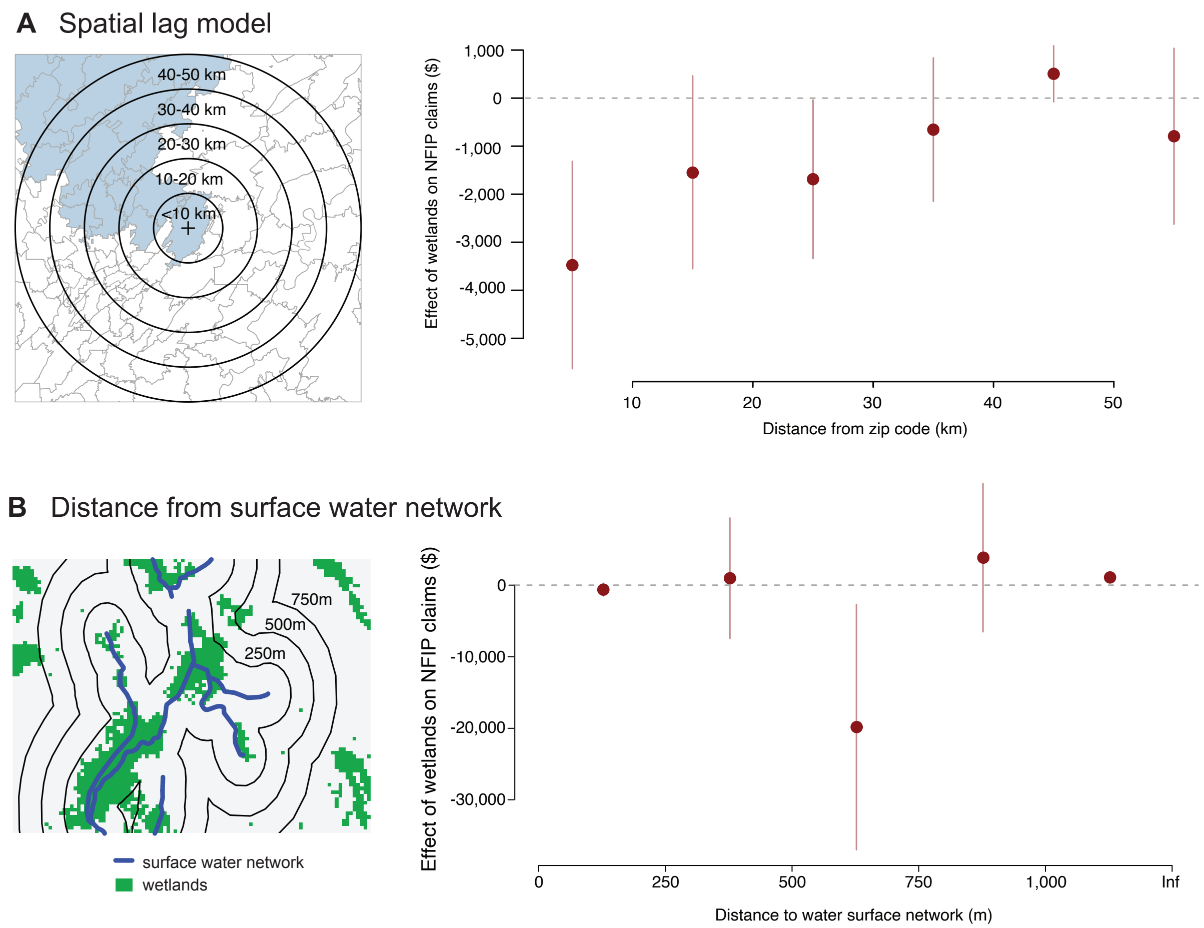

Figure 4: **Spatial analyses of the value of wetlands for flood mitigation.** (A) Spatial lag model. Left shows an example of the annuli used to construct spatial lags, with upstream zip codes highlighted in blue. Right plots the coefficients on the spatial lags for the effect of wetland loss on zip-code level NFIP claims. (B) Analysis of how distance from the surface water network affects the flood mitigation benefits of wetlands. Left shows an example of how the distance from the surface water network is calculated. Right plots the estimated effect for each distance bin. Whiskers show 90% confidence intervals.

Panel C of Figure 4 displays the results. We find that wetlands located 500 to 750 meters from the nearest stream or river provide economically large and statistically significant flood mitigation benefits. We do not find evidence of flood mitigation benefits for wetlands located less than 500 meters or greater than 750 meters from the nearest surface water connection. We contend that this finding is consistent with the hydrological concept that wetlands reduce flood damages by 'acting like a sponge'. Intuitively, wetlands that are directly adjacent to a stream or river may already be fully saturated and not have excess capacity to absorb floodwater, while wetlands that are far from the nearest surface water connection are less likely to intercept floodwaters before causing damage. Indeed, we find that the most valuable wetlands for flood mitigation are those at an intermediate distance, ones which would have excess capacity to absorb floodwater but still likely to be located between floodwaters and residential properties.

5.3 Heterogeneity

5.3.1 Regional heterogeneity

We now explore regional heterogeneity across the US in the flood mitigating effects of wetlands. It is worth noting the complexity of floods: they occur through several hydrological mechanisms including high tidal levels (i.e., coastal flooding), direct precipitation (i.e., pluvial flooding), high groundwater levels (i.e., groundwater flooding) or high river flows (i.e., fluvial flooding). The impacts of floods are also highly influenced by civil infrastructure like levees and canals. Further, given the variety of wetlands types, which can encompass forestland, grassland, salt marshes, and peat bogs, the hydrology literature is often hesitant to generalize flood reduction properties across all wetlands (Acreman and Holden 2013; Bullock and Acreman 2003).

To address these concerns, we assess whether the impact of wetlands on flood damages differs by geographic region. Specifically, we examine the differential effect of wetlands on either side of the 100° meridian, a boundary long thought to separate the humid eastern US and the arid Western plains (Powell et al. 1879). We also evaluate the effect of wetlands in nine broad ecoregions: Eastern Temperate Forests (ETF), Northern Forests (NF), Tropical Wet Forests (TWF), the Great Plains (GP), North American Deserts (NAD), Southern Highlands (SH), Northern Forested Mountains (NFM), Marine West Coast (MWC), and Mediterranean California (MC).[10] Ecoregions were derived by Omernik 1987 in collabora-

[10] We combine Southern Semi-Arid Highlands and Temperate Sierras into Southern Highlands (SH) due

tion with the EPA to highlight areas generally similar in their ecosystems and environmental resources and to serve as a spatial framework for ecosystem research and management (EPA 2020b). A map of ecoregions in the US can be found in Appendix Figure A2.

Figure 5 shows our estimates for the effect of wetlands on NFIP claims in each region. We find significant regional heterogeneity, with the largest benefits east of the 100° meridian, as well as in the Great Plains, Eastern Temperate Forests, and Tropical Wet Forests. For example, we estimate that a hectare of wetlands east of the 100° meridian reduces NFIP claims by $3,537, but find no discernible effect west of the 100° meridian where we estimate a precise zero. It is worth noting that 90% of wetlands in the US are located east of the 100° meridian, as seen in Figure 1. Wetlands in the Great Plains have the highest estimated flood mitigation potential, with a value of $5,374 per hectare, followed by those in Eastern Temperate Forests ($2,194 per hectare) and Tropical Wet Forests ($1,312 per hectare). These results are robust to subsetting our sample to only include zip codes with considerable wetland area (greater than 10 hectares) or only including zip codes where some flooding occurs, as indicated by positive flood insurance claims over the study period (see Appendix B).

5.3.2 Heterogeneity by type of land use change

The type of land use conversion may influence the consequences of wetland loss. There is likely a differential impact of wetlands converted to an impervious surface (i.e., a parking lot) versus wetlands drained for agriculture given that cropland maintains some water-holding capacity. To address this, we categorize all areas that transition from wetland in 2001 to non-wetland in 2016 by the land use class they are replaced by.[11] Excluding open water, we find that development accounted for 35% of wetland loss and 0% of wetland gain, which matches our intuition that developed land is unlikely to revert back to wetlands. Cropland and pasture accounted for 35% of wetland loss, and 58% of wetland gain. Other natural land uses (forest, grassland, shrubland, open areas, and barren land) accounted for 30% of wetland loss and 42% of wetland gain.

to the small number of observations in each of these neighboring regions. If estimated separately, the estimates are still not significantly different from zero but are less precise.

[11] Over 50% of both wetland gains and losses involve a transition from or to open water. Such a high and consistent proportion for wetland loss and gain can be expected given that wetlands often border surface water bodies and the fact that there is a natural gradient between wetland and water. While wetlands can become open water as a result of sea level rise and land subsidence, it appears that much of the conversion to/from open water is due to natural processes and the classification of these transitional land classes (Homer et al. 2020).

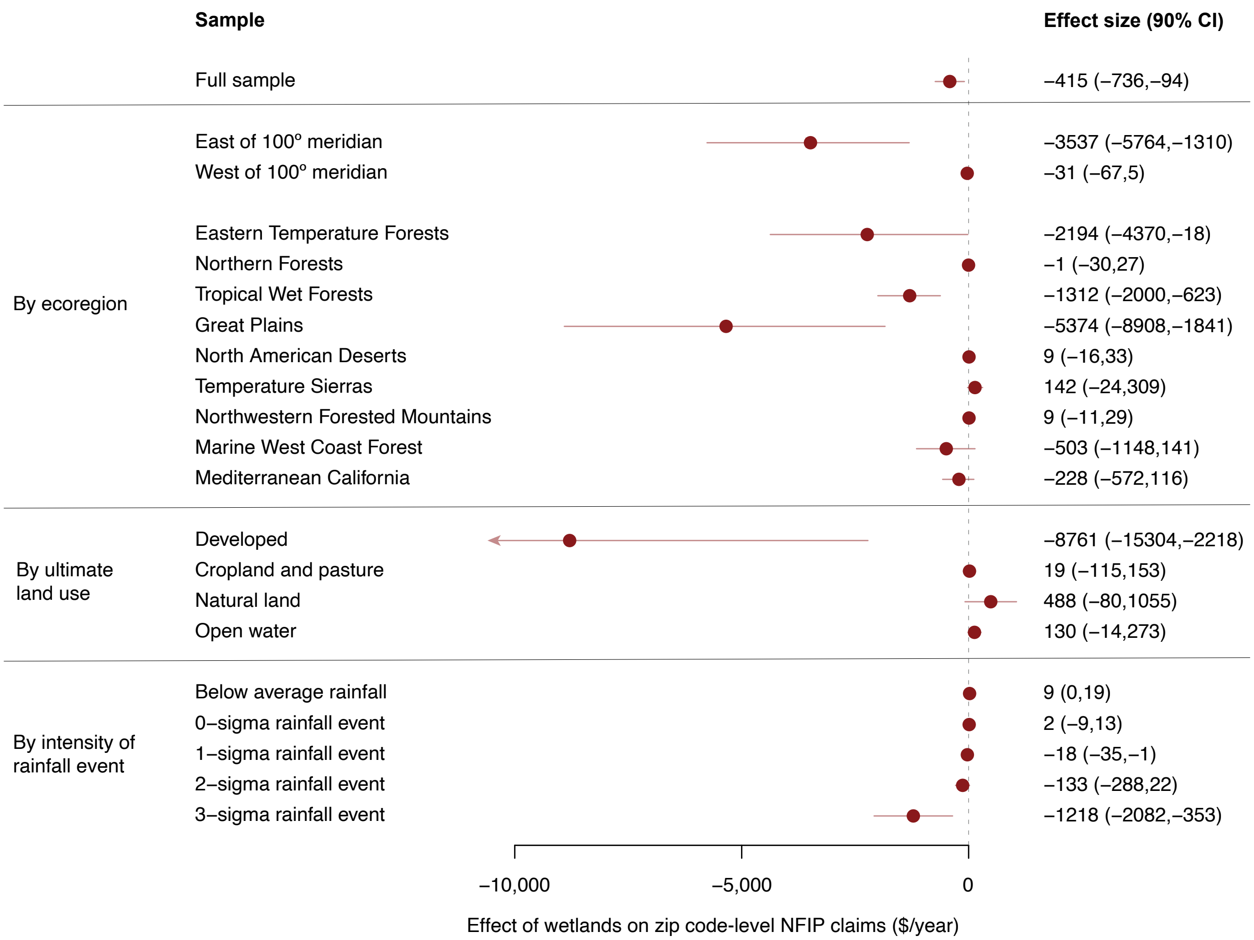

Figure 5: **Heterogeneous effects of wetland loss on flood damages.** Dots are point estimates and lines are 90% confidence intervals. We show heterogeneity by region, ultimate land use (the land use class that wetlands were replaced by), and intensity of rainfall events in the month for which NFIP claims are observed. See text for descriptions.

To test for differential flood mitigation impacts by land use, we run our primary long difference model separating out area of wetland loss by the land use class the wetlands were replaced by. Our results are shown in Figure 5. We find that the loss of wetlands only increases flood damages in the event that wetlands are converted to developed land (defined by the NLCD as areas for which impervious surface covers at least 20% of total cover). For each hectare of wetlands converted to developed area, zip code-level NFIP claims increase by \$8,761. We find little detectable effect of conversion to other land uses.

5.3.3 Effect of wetland loss conditional on precipitation

Finally, we test whether wetlands have differential impacts on NFIP claims conditional on flood intensity. In other words, we assess whether wetlands are more effective at mitigating floods during low, medium or high levels of rainfall. This is an important question given that extreme precipitation events are expected to become more frequent with climate change (Donat et al. 2016).

To understand how the effect of wetland loss depends on the intensity of flooding, we take advantage of the fact that we can observe both NFIP claims and rainfall events at high temporal frequency. We model monthly zip code-level NFIP claims as a function of wetland area changes, conditional on monthly precipitation using the equation

$$\Delta F_{imt} = f(\Delta W_i^{GAIN} | P_{imt}) + h(\Delta W_i^{LOSS} | P_{imt}) + \theta \Delta \mathbf{X}_i + \alpha_i + \delta_{mt} + \epsilon_{imt} \tag{7}$$

where P_{imt} are monthly precipitation levels and all other variables are defined as in equation 3. The functional forms of $f(\cdot)$ and $h(\cdot)$ exploit linear interactions between wetland area changes and monthly precipitation binned by their standard deviation from the location-specific monthly mean. Specifically, we include four precipitation bins: below average precipitation, 0-sigma precipitation events (precipitation between 0 and 1 standard deviation above the mean), 1-sigma precipitation events, 2-sigma precipitation events, and 3-sigma precipitation events. Because the distribution of monthly rainfall within a location is approximately normal, 1-sigma, 2-sigma, and 3-sigma events have probabilities of 13.6%, 2.1%, and 0.1%, respectively.

Our results are shown in Figure 5. We find that wetland loss only increases NFIP claims in months with 3-sigma precipitation events. In these months, we estimate that one hectare of wetland loss is associated with a \$1,218 increase in zip-code level NFIP claims. This finding is consistent with the intuition that wetland loss should only affect NFIP claims when flooding occurs (i.e. there is an extreme precipitation event).

5.4 Comparison of flood mitigation benefits to conservation costs

Both the flood mitigation value of wetlands and the cost of conserving these natural landscapes depend on local development levels. More developed areas have more exposed capital and thus greater potential for wetlands to reduce flood damages to buildings and other assets. At the same time, land values tend to be higher in more populated areas, increasing the cost of conserving wetlands. Taking these opposing factors into consideration, this section provides guidance on targeting conservation efforts towards high-benefit, low-cost wetlands.

First, we re-estimate the effect of wetland area changes on flood damages, this time allowing the response to vary based on local levels of development. To implement this approach, we compute the percent of developed area for each zip code. Then we capture heterogeneous patterns of wetland benefits via the model:

$$\Delta F_{is} = g(\Delta W_{is}^{GAIN} | D_{is}) + l(\Delta W_{is}^{LOSS} | D_{is}) + \theta \Delta \mathbf{X}_{is} + \alpha_s + \epsilon_{is} \tag{8}$$

where D_{is} is the sample-period average percent developed area in zip code i and other variables are defined as in equation (3). The functional forms of $g(\cdot)$ and $l(\cdot)$ are modeled as linear interactions between wetland area changes and each quintile of D_{is}. This approach allows us to estimate the differential effect of wetland losses in areas with lower versus higher levels of development. Indeed, we find that wetlands in the top quintile zip code of development (>38% developed) reduce NFIP claims by \$12,773 (95% CI = $-2,404$ to $-23,142$) per hectare, while wetlands in the first two quintiles of developed area ($<$ 2.5% developed) have no detectable effect on NFIP claims.

We approximate conservation costs using high-resolution maps of the value of private lands from Nolte 2020. This dataset was produced by training an ensemble of machine learning models on 6 million land sales across the contiguous US with the purpose of assessing trade-offs between public and private benefits from land use decisions.

The benefit of wetlands, in terms of avoided flood damages, are estimated in annual flows. The conservation cost is a one-time, upfront investment to purchase the land and ensure it will not be developed. In order to compare the costs and benefits of wetland conserva-

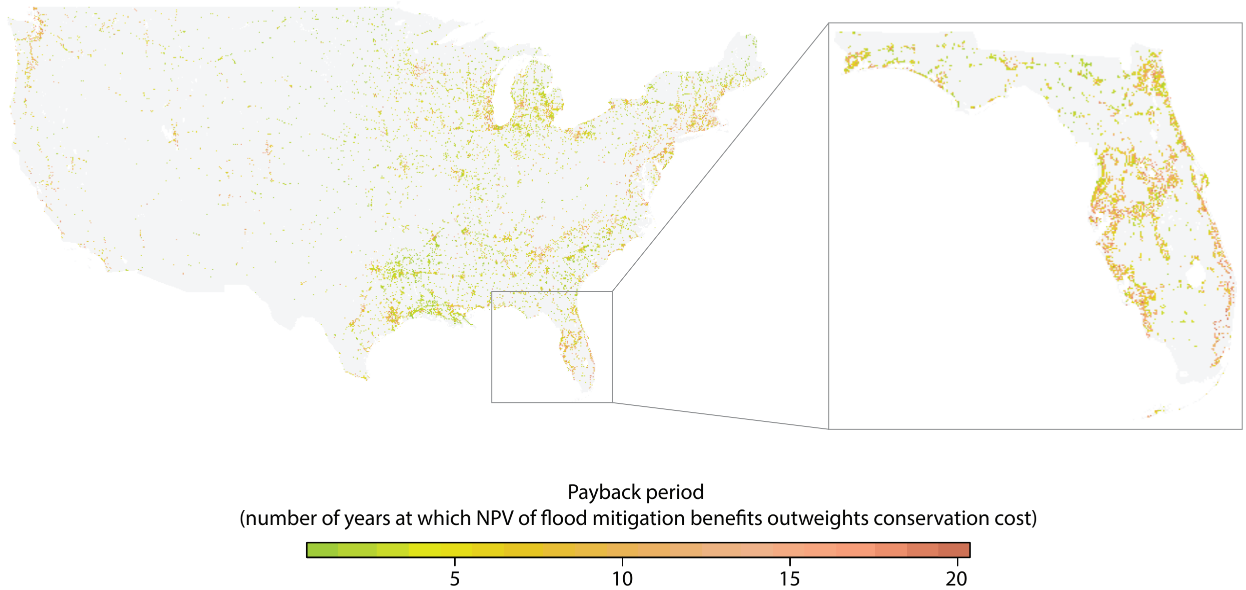

Figure 6: **Spatially-resolved comparison of wetland benefits and conservation costs.** We plot the payback period for conserving wetland areas, defined as the number of years in the future at which the expected value of annual benefits from wetland conservation exceed the initial investment in purchasing the land. Wetland benefits mapped here only include flood mitigation value, and differ across space according to local levels of development (see equation 8). The net present value of annualized flood mitigation values is computed using a discount rate of 3%. Conservation costs are approximated as the market value of private land from Nolte 2020.

tion, we compute the "payback period" for US wetlands. The payback period is simply the number of years in the future at which the expected value of annual benefits from wetland conservation exceed the initial investment in purchasing the land. For the mean hectare of wetlands in the continental US, we find that the societal benefits from reduced flooding outweigh the cost of conserving the wetland ($12,700 per hectare) within 5 years. Wetlands lost between 2001 and 2016 have a higher market value than the national average at $31,600. For these wetlands, we compute an average payback period of 17 years.[12] However, such national averages mask significant heterogeneity in the net benefits of wetlands across space. Figure 6 plots spatially-resolved estimates of the payback period for all US wetlands. These estimates can be used to identify high-benefit, low-cost areas to prioritize wetland conservation. To facilitate such efforts, we make our estimates of conservation costs, benefits, and approximate payback periods publicly available to researchers and decision-makers.[13]

[12] To calculate the net present value of annualized flood mitigation benefits, we use a discount rate of 3%.
[13] Authors to include link

6 Discussion

Flooding is by far the most costly and frequently-occurring natural disaster, and flood events are expected to intensify with climate change (Donat et al. 2016). This paper undertakes a large-scale analysis across the continental US to estimate the value of wetlands for flood mitigation. To our knowledge, we are the first to estimate the causal effect of wetlands on flood damages. Our main results suggest that each hectare of wetland loss increases NFIP claims by approximately $2,300 annually when accounting for spatial spillovers. These results are robust across three identification strategies utilizing different sources of temporal and spatial variation. To put our estimates in context, we calculate the amount of NFIP claims that can be expected in response to wetland loss over the 2001 to 2016 study period. We estimate that the 340,000 hectares of wetlands lost over this period are will increase annual NFIP claims by $535 million per year, which amounts to 19% of average annual total NFIP payouts between 2001 and 2016 ($2.66 billion annually).

Interestingly, we find no discernible effect of increases in wetland area on flood insurance claims, calling into question whether the Compensatory Mitigation requirements under the CWA are achieving their intended objective of offsetting the adverse impacts of wetland loss. If wetland gains do not offset the reduction in ecosystem services occurring as a result of wetland losses, policy ought to emphasize conservation of existing wetlands. However, we emphasize that our study design does not specifically investigate wetland areas created, restored, or enhanced under Compensatory Mitigation. CWA requirements only account for a portion of overall wetland gain—other drivers can include abandonment of tiled/drained agricultural lands, storm surges, and land subsistence, and conservation-oriented wetland restoration. Nevertheless, we believe research into the efficacy of the Compensatory Mitigation is warranted. On one hand, it possible that human-made wetlands provide less flood mitigation potential than mature, naturally-occurring ecosystems. Conversely, prior research has found that human-made wetlands can have a higher economic value because they are constructed with the specific purpose of providing services for human use (Ghermandi et al. 2010). Net water holding capacity of wetland gain versus wetland loss may also vary: as explained in the heterogeneity analysis by type of land use change, lost wetlands are far more likely to become developed lands, while wetlands gained are almost never from developed land.

Additionally, we conduct a number of extensions that exploit the geo-spatial nature of our data to inform the design of wetlands policy. First, we document spatial spillovers in the flood mitigation benefits of wetlands up to 50 km away. Hydrological connections between wetlands and downstream waters often span long distances: in Prairie Pothole Region, lakes can expand up to 40 km to form a direct surface-water connection with 'isolated' wetlands (Vanderhoof and Alexander 2016). Non-floodplain wetlands can be directly connected to the river network over long distances through subsurface or groundwater flows (EPA 2015; Cohen et al. 2016). Our result provides new empirical evidence for the oft-cited theory that regulation may be required to achieve the optimal provision of wetlands due to the presence of positive externalities.

Second, we evaluate how the location of wetland relative to the surface water network affects their value. We find that the most valuable wetlands for flood mitigation are those located 500 to 750 meters from the nearest stream or river. Such relatively isolated wetlands can act as a 'sink' for excess water, sediment, and pollutants, preventing their export to downstream waters (EPA 2015). Our result is at odds with the 2020 WOTUS rule that eliminates federal protections for the nearly half of wetlands lacking a direct surface water connection. Our results better align with the thresholds of 1,500 feet (460 meters) and 4,000 feet (1,220 meters) referenced in the 2015 WOTUS rule regarding varying conditions to determine adjacency to navigable waters.

We also show that considerable regional heterogeneity exists in the benefits of wetlands, with large benefits in the eastern US and little to no benefits in the western US. We note that the vast majority of wetlands (90%) are located east of the 100° meridian. However, the variation we see across ecoregions suggests that a decentralized implementation of federal policy may be more appropriate for wetland regulation.

Finally, we find the flood mitigation benefits of wetlands to be greatest during anomalously high precipitation events. Since the magnitude and frequency of such extreme events are projected to increase over time, wetlands may play an important role in climate change adaptation strategy *vis-a-vis* their ability to reduce future flood damages.

There are several important limitations to our study. For one, converting wetlands into developed areas can increase flood damages in two ways. Prior research suggests that wetlands mitigate flooding by absorbing and holding floodwaters (Acreman and Holden 2013). Converting these 'natural sponges' to impervious surfaces increases the severity of flood events by increasing peak discharges and water depths during rainfall events—an effect shown in our heterogeneity analysis by type of land use change. At the same time, real estate development along transitional terrestrial-aquatic zones results in additional capital being exposed to flooding, and by extension, higher potential damages (Kousky et al. 2013). Our paper does not distinguish between these two pathways. However, we note that the significant effects of upstream wetlands, while controlling for changes in local wetland area, suggest that the benefits of wetlands are in part driven by altering hydrological processes.

Second, we estimate the effect of all wetlands on flood damages; however, we recognize that the term 'wetlands' describes a diverse set of ecosystems with different levels of flood mitigation potential. Our estimates can be interpreted as the average treatment effect of wetlands, but future research should investigate the contribution of wetland by land cover (e.g., herbaceous vs. forested) and type (e.g., swamps, marshes, bogs). Indeed, the regional heterogeneity we see in flood-reducing benefits of wetlands suggests that not all wetlands function in the same way.

A third limitation of our study is that there may be selection into what types of wetlands are converted to other land uses. For example, landowners have a higher incentive to build on wetlands in more developed areas because they tend to have higher property values. Since we find that wetlands in more developed areas have higher flood mitigation potential, this type of selection would suggest that we overestimate the value of the average hectare of wetlands in the US. On the other hand, selection into wetland loss may be biased in the opposite direction due to the strict regulations surrounding the filling or dredging of wetlands under Section 404 of the CWA. Indeed, since it is more difficult to obtain a permit to develop wetlands that the EPA and Army Corps regard as providing more ecosystem services, development may favor wetlands with lower than average flood mitigation value. This type of selection would suggest that our estimates underestimate the value of the average hectare of wetlands in the US.

Finally, our estimates likely represent a lower bound on the flood mitigation value of wetlands because our dependent variable, NFIP claims, only captures one component of property damages from flooding. While the NFIP is the dominant insurer for flooding in the US, less than 15% of American homeowners participate in the program and the CBO estimates that NFIP claim payments represent just 16% of annual flood damages to the residential sector (Congressional Budget Office 2019). It is difficult to extrapolate without knowing the spatial distribution of NFIP policyholders, but if one takes this proportion as given, our estimates would suggest that each hectare of wetland loss increases residential flood damages by approximately $14,400. Still, this estimate does not capture damages to non-residential property like commercial and governmental properties, as well as farms and crop yields.

Further, we focus our analysis on flood mitigation alone and do not contemplate the value of wetlands in relation to other ecosystem services. Wetland restoration, for example, limits the amount of nitrogen discharged into the Gulf of Mexico, thereby reducing hypoxia extent and coastal deadzones (Mitsch et al. 2005). As such, it is not surprising that our per hectare valuation falls well below previous EPA estimates of the value of wetlands derived from willingness to pay surveys, which take into account not only their value for flood control, but also for fishing, hunting, fur trapping, recreation, water filtration, aesthetics and wildlife habitat (EPA 2013).

Nonetheless, as lower bounds, our estimates represent the cost to US taxpayers of converting wetlands to other uses—and thus have policy implications for the highly-subsidized National Flood Insurance Program as well as the jurisdictional debates around wetland protection under the Clean Water Act. As flood events intensify with climate change, efficient flood mitigation policy that properly accounts for wetland-related public good provision becomes increasingly important.

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Appendix

A Data

A.1 National Land Cover Database

We derive our data on the spatial extent of wetlands from the The National Land Cover Database (NLCD). The NLCD provides gridded data on land cover and land cover change in the US at 30 meter spatial resolution. The product is remotely sensed using data from Landsat Thematic Mapper (TM), and includes 21 classes of land cover. The NLCD defines wetlands following Cowardin and Golet 1995 as "areas where the soil or substrate is periodically saturated with or covered by water." It maps both woody wetlands ("areas where forest or shrubland vegetation accounts for 25-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water") and emergent herbaceous wetlands ("areas where perennial herbaceous vegetation accounts for 75-100 percent of the cover and the soil or substrate is periodically saturated with or covered with water"). Because wetlands classes are difficult to identify from Landsat TM spectral information alone, the NLCD uses of ancillary information such as National Wetlands Inventory (NWI) to provide the most accurate mapping (Homer et al. 2020).

We use Google Earth Engine to access the NLCD and derive our zip code-level data on wetland area. We classify land use codes 91 (woody wetlands) and 92 (emergent herbaceous wetlands) as wetlands, and do not distinguish between these two wetland types. We aggregate the data to the zip code level by intersecting the NLCD raster with zip code shapefiles, and then summing the total wetland area in each polygon. Summary statistics are provided in Table A1. Between 2001 and 2016, the nation lost approximately 340,000 hectares of wetland area, but these losses were offset by 386,000 hectares of wetlands gains—thus achieving at a national level the long-standing federal objective of "no net loss" of wetlands.

A.2 National Hydrography Dataset

We use geospatial data on the US surface water network and hydrologic drainage areas from the National Hydrography Dataset (NHD). [14] The NHD is vector-based data that maps the Nation's rivers, streams, canals, lakes, ponds, and related features. It also includes the Watershed Boundary Dataset (WBD), which represents the Nation's drainage areas as nested levels of hydrologic units. According to the USGS, the NHD and WBD

[14] https://www.usgs.gov/core-science-systems/ngp/national-hydrography/access-national-hydrography-products

are the most up-to-date and geographically inclusive hydrography datasets for US. We use the NHD in two distinct ways: (i) to calculate the upstream and downstream wetland area for each zip code and (ii) to compute the distance of all wetland areas in our sample from the surface water network, enabling our evaluation of the relative contribution of 'isolated' wetlands to flood mitigation.

(i) Calculating upstream and downstream wetland area for each zip code

The WBD provides a map of hydrologic units (HU), which represent the area of the landscape that drains to a portion of the stream network.[15] To construct our data, we use 12-digit hydrologic units (HUC12), which are the most spatially granular data available for the complete US. We calculate the spatial extent of wetlands upstream and downstream of each zip code out to a maximum distance of 50km[16] using the following steps:

1. Intersect the WBD with the NLCD to determine the spatial extent of wetlands within each HUC12.
2. Construct a HUC12-HUC12 flow matrix that identifies which HUC12s are upstream and downstream of every other HUC12 in the watershed. This matrix is constructed using the *ToHUC* attribute, which identifies which HUC12 is immediately downstream from another HUC12 unit.
3. Intersect the HUC12 flow matrix with a shapefile of zip code boundaries to generate a zip-HUC12 flow matrix that identifies which HUC12s are upstream, downstream, and inside of each zip code.
4. Use the zip-HUC12 matrix in combination with the data on wetland area within each HUC12 to calculate the spatial extent of wetlands upstream and downstream of each zip code. Notably, we exclude wetland area that lies within the focal zip code because we cannot discern whether these wetlands are located upstream or downstream of the NFIP claims we observe in that zip code.
5. Calculate the amount wetland area upstream and downstream of each zip code out to a maximum distance of 50km.

(ii) Computing the distance of wetland areas to the surface water network

We use three sets of features from the NHD to construct the water surface network for the continental US: NHDFlowline, NHDArea, and NHDWaterBody. With the aim of gen-

[15] https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset?qt-science_support_page_related_con=4qt-science_support_page_related_con
[16] We choose the 50km cutoff based on the results of the spatial lag model.

erating policy-relevant estimates, we subset the line and polygon features in the NHD to include only those that are included in the 2020 definition of WOTUS.[17] Specifically, we include features with the following FCodes:

NHDFlowline: 55800 (Artificial paths), 33600-33603 (Canals), 56600 (Coastline), 46000-46006 (Streams and rivers, excluding ephemeral).

NHDArea: 31200 (Bay/Inlet), 33600-33603 (Canals), 46000-46006 (Streams and rivers, excluding ephemeral), 46100 (Submerged stream).

NHDWaterbody: 49300 (Estuaries), 39000-39012 (Lake/pond), 36100 (Playa).

Note that NHDFlowline and NHDArea have some overlapping FCodes. NHDFlowline are line features, and thus do not accurately represent the spatial extent of large streams, rivers, and canals. Features with a widths greater than 50 feet are represented as polygons in the NHDArea dataset.

Next, we calculate the distance of all wetland areas in our sample from the water surface network in distance bands of 250 meters out to a maximum distance of 1000 meters. We do so by creating consecutive buffers around the NHD shapefile and intersecting these buffers with the data on wetland extent from the NLCD. This processes is depicted in Panel B of Figure 4. Note that these distance bands are comparable to the thresholds of 1,500 feet (460 meters) and 4,000 feet (1,220 meters) from the high water mark used in the 2015 WOTUS rule (EPA & Army Corps 2015) to determine which waters are adjacent to navigable waters.

A.3 NFIP Redacted Policies Dataset

Data on our dependent variable, flood insurance claims, come from the National Flood Insurance Program (NFIP) Redacted Policies Dataset (FEMA 2020a). This dataset comprises the NFIP's full claim history and represents more than 2 million transactions. We construct the dependent variable as sum of claims payments for property damage to buildings and contents. We identify the time and location of flood damages using the $yearofloss$ and *reportedzipcode* variables. Due to privacy concerns, the NFIP does not provide address-level data.

To match data on NFIP claims with the years in which we observe wetland extent (2001 and 2016), we average NFIP claims over the 5-year periods surrounding these dates (1999

[17] https://www.epa.gov/sites/production/files/2020-01/documents/navigable_waters_protection_rule_prepbulication.pdf

to 2003 and 2014 to 2018). We elect to use five-year averages because the amount in NFIP loss dollars paid is highly variable across individual years due to the infrequent nature of flood events. We show the sensitivity of our main results to using alternative time windows in Appendix D.1.

Summary statistics are provided in Table A1 and a map of claims is in Figure A1.

	Mean	Std. Dev.	Min.	Max.
Zip code-level (N=33,716)				
Wetland area, 2001 (ha)	1,349.0	4,808.2	0.0	260,164.8
Wetland area, 2016 (ha)	1,348.9	4,810.2	0.0	260,063.7
Wetland change, 2001 to 2016 (ha)	−0.1	105.0	−3,805.2	4,540.2
Wetland gain, 2001 to 2016 (ha)	10.7	79.7	0.0	4,540.2
Wetland loss, 2001 to 2016 (ha)	−10.8	66.7	−3,805.2	0.0
Average annual NFIP claims, 2001 ($1000)	20.4	236.3	0.0	18,289.5
Average annual NFIP claims, 2016 ($1000)	107.9	1,606.6	0.0	122,001.6
Change in NFIP claims, 2001 to 2016 ($1000)	87.5	1,536.7	−9,169.4	112,977.7

Table A1: **Summary statistics.** Data on the spatial extent of wetlands is from the National Land Cover Database (NLCD) and is reported at a resolution of 30 meters for the years 2001 and 2016. We aggregate these data to the zip code level and calculate the change in the spatial extent of wetlands over time, differentiating between wetland gains and losses. Data on NFIP claims are from the NFIP Redcated Policies Dataset and are reported at the transition level. We aggregate these transitions to the annual level for all counties and zip codes, and calculate the claims for 2001 and 2016 as the average for the 5-year windows surrounding these dates. We include claims payouts for property damage to both buildings and contents.

A.4 Ecoregions

We assess whether the impact of wetlands on flood damages differs by geographic region (results shown in main text). Specifically, we examine the differential effect of wetlands on either side of the 100° meridian, a boundary long thought to separate the humid eastern US and the arid Western plains (Powell et al. 1879). We also evaluate the effect of wetlands in nine broad ecoregions. Ecoregions were derived by Omernik 1987 in collaboration with the EPA to highlight areas generally similar in their ecosystems and environmental resources and to serve as a spatial framework for ecosystem research and management (EPA 2020b). A map of US ecoregions is shown in Figure A2.

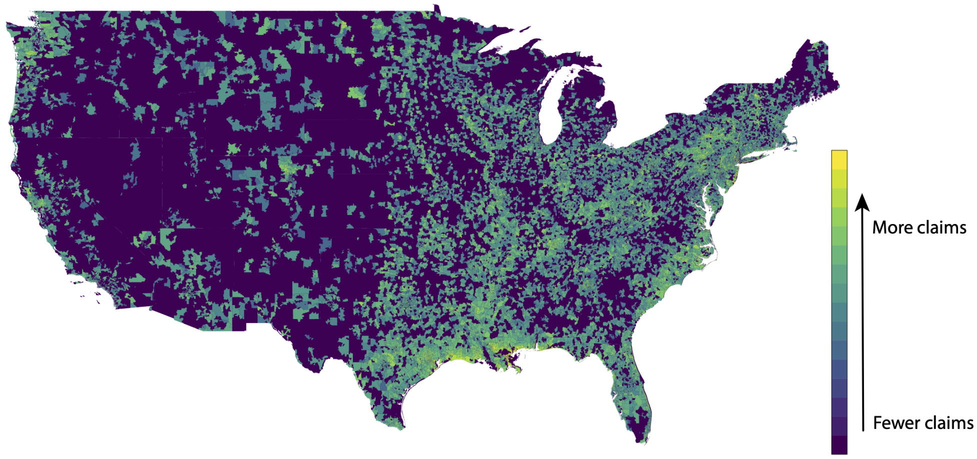

Figure A1: **NFIP flood insurance claims.** Plots zip-code level NFIP claims for the period 2001 to 2016. Data are from the NFIP Redacted Claims Dataset and claims are calculted as the sum of payments for buildings and contents.

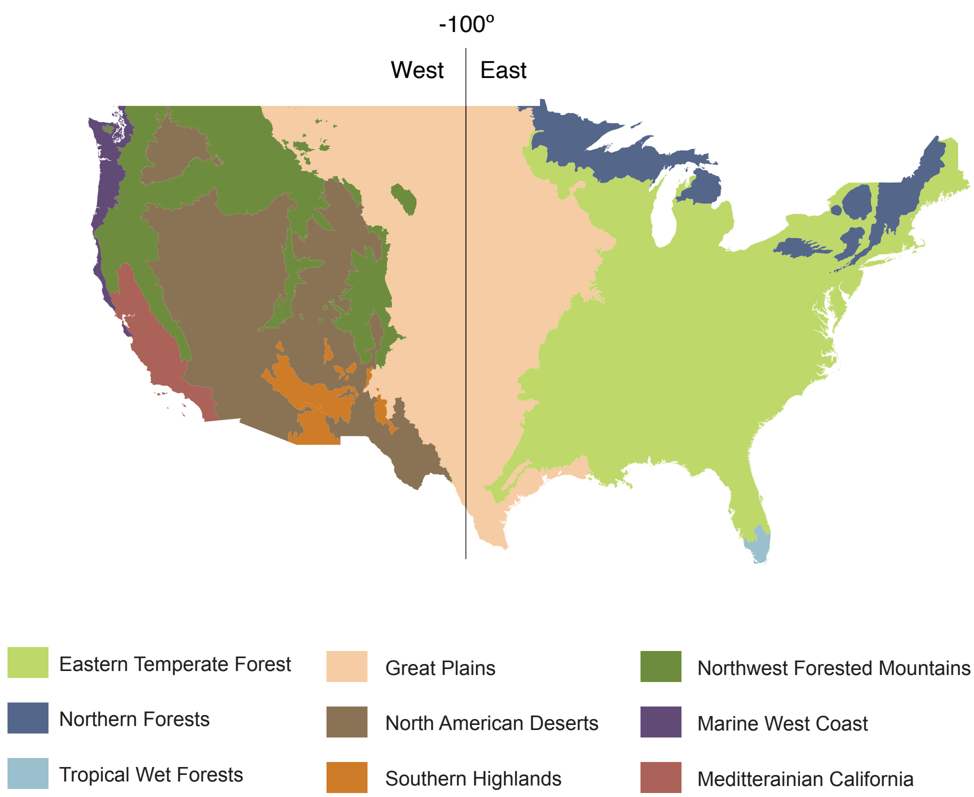

Figure A2: **Map of level-1 ecoregions of the US.** We use ecoregions as the subsamples in our regional heterogeneity analysis.

B Additional Robustness Checks

B.1 Sensitivity of main results

Alternative temporal aggregation of NFIP claims. We only observe the spatial extent of wetlands for two time periods, but we observe NFIP claims on an annual basis. In order to conduct our analysis, we must decide how to match NFIP claims with the two periods (2001 and 2016) in which we observe wetlands. Because the amount in NFIP loss dollars paid is highly variable across individual years due to the infrequent nature of flood events, we elect to average NFIP claims over the 5-year periods surrounding these dates (1999 to 2003 and 2014 to 2018) in the main analysis. In Table A2, we show how the results differ when we instead use 3-year periods (Column 2) and 7-year periods (Column 3). Across all three methods, our main findings — that wetland loss significantly increases NFIP claims but wetland gain has no identifiable effect — holds. However, the magnitude of the estimates is somewhat sensitive, with larger effect sizes when we use a 3-year window and smaller effect sizes when we use a 7-year window. It is not surprising that the effect size differs when we include different years in the sample given how variable NFIP claims paid are over time.

	(1)	(2)	(3)	(4)	(5)
Wetland gain	−6.0	1.5	−9.2	−77.7	-1.9
(ΔW^{GAIN})	(62.2)	(101.4)	(46.3)	(239)	(156.1)
Wetland loss	−414.8	−618.0	−298.3	−946.2	-4.1
(ΔW^{LOSS})	(195.2)	(309.9)	(141.8)	(440.4)	(2.0)
Observations	27,292	27,292	27,292	11,602	27,292

Table A2: **Sensitivity of the main results to different specifications of flood damages.** Column (1) shows the main results, as reported in Table 1 column 5, for the long differences model that includes state fixed effects and controls for built-up area. Columns (2) and (3) show the estimated effects for the same regression, but calculating the NFIP claims paid as averages over 3 year and 7 year windows, respectively, rather than over a 5 year window as in the main results. Column (4) shows the results when the sample is limited to localities in which there was flooding over the sample period, as indicated by positive NFIP claims. Column (5) is an alternative outcome variable: claims per policy. Standard errors are clustered by county.

Limiting the sample to flooded locations. We also examine how our results differ when we limit our sample to only include locations that experienced flooding over the study period (as indicated by having positive NFIP claims). In the main analysis, we include all localities in the US in our sample in order to estimate the average treatment effect of US wetlands. However, because flooding is an infrequent event, it is possible that large wetland losses are not associated with changes in NFIP claims in our data simply because no flood event occurred in those locations during the sample period. In column 4 of Table A2 we show that, as expected, the estimated effects are larger in magnitude when we limit our sample to only including localities with flooding. Again, we see that that wetland loss significantly increases NFIP claims but wetland gain has no identifiable effect.

Specifying the outcome as claims per policy. One threat to identification is if NFIP uptake is correlated with changes in wetland area. To address this concern, we control for the primary drivers of NFIP uptake – including population, income, number of housing units, housing values, and local governance (as measured by participation in the NFIP Community Rating System) – in our baseline specification. An alternative way to control for uptake is to specify the outcome variable as NFIP claims per policy. Unfortunately, this approach is difficult in our setting because while data on NFIP claims are available going back to before 2000, data on NFIP policys are only available from 2009 onwards.

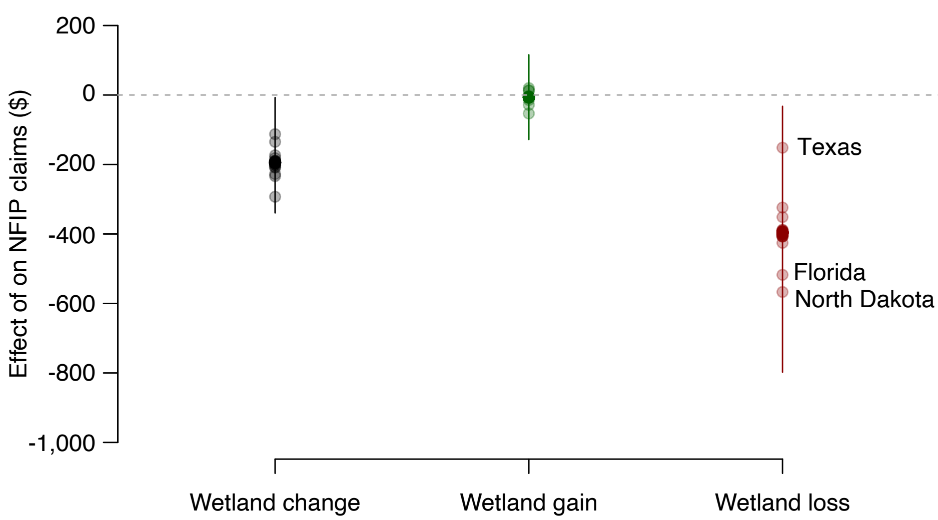

Figure A3: **Leave-one-out sensitivity analysis.** This test re-runs zip code-level LD model 49 times, each time dropping one state (or Washington D.C.) from the sample. Circles plot the range of effects estimated for each coefficient of interest using this procedure. Whiskers show 95% confidence intervals for our main results, using the full sample of data. States with an outsized influence on the point estimates are labelled for reference.

Therefore, we cannot simply specify our outcome as the difference in claims per policy between 2001 and 2016. However, as a robustness check, we approximate this approach by interpolating the number of policies backwards to 2001. That is, we use information on zip code level changes in policies from 2009 to 2016 to approximate the number of policies in force in each location in 2001. We truncate approximated values between 0 (i.e. do not allow for negative policies) and the maximum number of policies in 2016. Our results are shown in column 5 of table A2. We estimate that each hectare of wetland loss is associated with a $4.1 increase in NFIP claims per policy. Thus our main result, that wetland loss significantly increases damages from flooding, holds when considering claims relative to NFIP policies.

Leave-one-out sensitivity analysis. We test whether our main results are driven by a particular state using a "leave-one-out" sensitivity test. This test re-runs the long differences model 49 times, each time dropping one state (or Washington D.C.) from the sample. Figure A3 plots the range of effects estimated using this procedure. The results imply that there is no one state that is fully responsible for the estimated effect of wetlands on flood damages. While some states, such as Texas, are do influence to the magnitude of our point estimates, this is to be expected given that flooding is an infrequent event that does not affect all localities in all years.

B.2 Sensitivity of regional effects

We check that the regional heterogeneity we identify in the effect of wetlands on NFIP claims is not simply an artifact of where wetlands are located or where flooding occurs. To do so, we limit our sample to only include zip codes in which there was flooding over the sample periods (as indicated by positive NFIP claims) and zip codes in which there are at least 10 hectares (25 acres) of wetlands. The results are shown in Figure A4. The point estimates are highly consistent across the there samples except in two regions when we limit the sample to only include zip codes with flooding. In the Great Plains, wetlands provide greater flood-mitigating benefits in the restricted sample, and in the Southern Highlands, wetlands appear to actually increase flood damages in the restricted sample.

B.3 County-level estimates

As a robustness check, we also estimate the long differences model at the county-level. Estimating the model at a higher level of spatial aggregation allows us to capture spatial

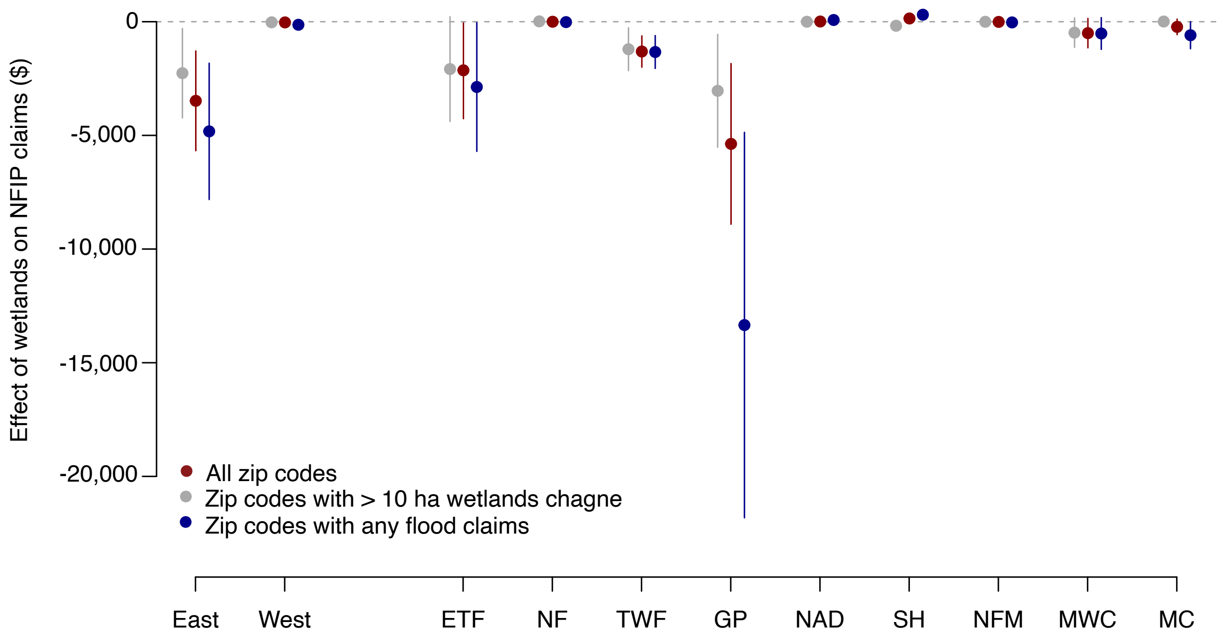

Figure A4: **Robustness of regional effects.** We estimate the effect of wetland loss on NFIP claims in the eastern and western US, as well as nine level-1 ecoregions: Eastern Temperate Forests (ETF), Northern Forests(NF), Tropical Wet Forests (TWF), the Great Plains (GP), North American Deserts (NAD), Southern Highlands (SH), Northern Forested Mountains (NFM), Marine West Coast (MWC), and Mediterranean California (MC). The coefficient estimates using the full sample are shown in red, with whiskers indicating 95% confidence intervals. As a robustness check, we also estimate these effects limiting our sample to zip codes in which flooding occurred over the sample period (blue) and zip codes with at least 10 hectares of wetland area (grey).

spillovers without including spatial lags in the regression model. To see this, suppose that wetlands in zip code j not only reduce NFIP claims in j but also in neighboring zip code i. Further assume that both zip codes are located in county c. If we do not include spatial lags in the zip code-level model, we underestimate wetland value because we will only associate the wetlands in zip code j with the NFIP claims in zip code j and with not the claims in i. But if we conduct our analysis at the county-level, we will associate the NFIP claims in both zip codes j and i with the wetlands in zip code j even in the absence of spatial lags.

At the county-level, we estimate the same regression models as in equations (1) and (3) with one notable exception. Because information on the number of NFIP policies in force and total coverage is available for the years 2001 and 2016 at the county-level, we now include these two additional controls in the model. The results are shown in Table A3. We estimate that one hectare of wetland loss is associated with an increase of $3,235$ in county-level NFIP claims. We find no significant effect of gains in wetland area on NFIP claims. These estimates are broadly consistent with the zip code-level estimates that account for spatial spillovers in the benefits of wetlands.

	Dependent variable: NFIP claims paid			
	(1)	(2)	(3)	(4)
Wetland change	$-1,582.8^{**}$		-872.9^{**}	
	(682.9)		(383.3)	
Wetland gain		-683.0		248.8
		(417.0)		(301.8)
Wetland loss		$-2,295.4^{**}$		$-3,235.9^{**}$
		(1154.3)		(1561.0)
Observations	26,334	26,334	3,100	3,100

Table A3: **Sensitivity of the main results to estimation at the county-level.** Columns (1-2) shows the zip code-level estimates for the effect of wetland changes on NFIP using the model that accounts for spatial lags, as reported in the main text. Column (3-4) shows the county-level estimates. Standard errors are clustered by state. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) levels.