Using Markets for Environmental Offsetting: Evaluation of Wetland Area Gains and Losses under the US Clean Water Act

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Abstract

Mitigating the impacts of economic development on biodiversity is an urgent global priority. Offsetting policies reconcile development and conservation objectives by allowing environmental losses in some locations, given that the losses are compensated with equivalent gains elsewhere. In this paper, we quantify net losses of wetland area under the US Clean Water Act compensatory mitigation program, which is the most extensive and longest-running environmental offsetting program in the world. A unique feature of the program is how most of the compensation is financed through a market mechanism where permittees purchase compensation credits that specialized firms have generated from wetland conservation activities. We measure wetland area gains at 400 compensation sites over 1995–2020 using high-resolution satellite imagery and land cover change data. Comparing realized compensation projects to planned but withdrawn projects in a difference-in-differences framework, we find that the majority of the gains would not have occurred without dedicated conservation activities. We also find that the market mechanism allocates the type and location of conservation activities according to the opportunity cost of land use. Nonetheless, the wetland area gains appear insufficient to compensate for the wetland area losses regulated within the program. This makes it unlikely that the program will achieve its environmental goals in the long term.

1 Introduction

The current rate of biodiversity loss is unprecedented in history and will have potentially catastrophic consequences. Humanity depends on the diversity of nature to sustain the quality of air, water, and soil; regulate the climate; reduce the impact of natural hazards; and produce food, through pollination and pest control (Brondizio et al., 2019). Impairments to the productivity, stability, and resilience of natural ecosystems in providing these services adversely affect human well-being and economic growth, with a disproportionate impact on individuals whose livelihoods depend directly on ecosystem services (Dasgupta, 2021). Although national governments widely recognize the need for ambitious conservation policies, progress on policy implementation has not been sufficient to reduce the global rate of biodiversity loss. The main political obstacle is the prioritization of – and unwillingness to compromise on – short-term economic development goals (Johnson et al., 2017; OECD, 2017).

Biodiversity offsetting has emerged as a policy tool for reconciling development and conservation objectives. These policies balance biodiversity losses in one location with an equivalent biodiversity gain elsewhere (Bull and Milner-Gulland, 2020). Offsetting policies typically aim to achieve *no net loss* of the impacted environmental asset. However, there is a lack of empirical evidence regarding the environmental performance of these policies, largely owing to the unavailability of transparent monitoring data that would allow large-scale evaluations (zu Ermgassen et al., 2019).

In this paper, we quantify net losses of wetland area under the US Clean Water Act (CWA) compensatory mitigation program, which is the most extensive and longest-running biodiversity offsetting program in the world (OECD, 2016). Since the early 1990s, the CWA Section 404 compensatory mitigation program has had an overarching goal of "no net loss of wetland area and functions" (Corps and EPA, 1990). A unique feature of the program is how offsetting is financed through a market mechanism. Private firms can establish *mitigation banks* – conservation sites that establish wetland areas or improve the functions of existing wetlands – to provide an advance supply of offsets to meet the compensation needs of future projects. In turn, developers can buy these offsets to comply with their obligation to compensate for the impacts they are causing to wetlands.

To assess whether the market-based offsetting scheme under the CWA is achieving its no-net-loss target, we collect novel data to quantify wetland area gains at the mitigation bank sites within the program. We analyze satellite imagery to identify and delineate the extent of wetland area gains at 400 mitigation banks established between 2001 and 2020. We combine our own data collection with land cover change detection data, enabling us to assess the timing and causality of the wetland area increases. In a difference-in-differences framework, we compare outcomes at the mitigation bank sites against 141 planned mitigation banks that had withdrawn their permit applications. To our knowledge, our study is the first of its kind in two respects: we estimate the causal impact of offsetting projects on environmental outcomes, and we use these estimates to provide a program-wide evaluation of a no-net-loss target.

Mitigation banking currently generates compensation for the majority of authorized impacts under Section 404 of the CWA, with compensation credits awarded for over 100,000 acres of wetlands conserved over the course of the program (Corps, 2022). Despite the apparent benefits, several studies have argued that mitigation banking is falling short of achieving the no-net-loss target. Reasons include unsuccessful compensation projects, mismatches between the compensation and impact type, and questionable causal impact of the compensation projects. Likewise, existing empirical evidence falls short of enabling a comprehensive assessment of net losses. The lack of monitoring data is a major impediment, and most existing studies on mitigation banks have limited sample size and temporal scope (Griffin and Dahl, 2016; Levrel et al., 2017; Tillman et al., 2022).

Our analysis improves on previous studies in several respects. First, our novel data collection enables us to estimate wetland area gains within the mitigation banking program across all jurisdictional areas of the program. Second, unlike previous studies that typically compare outcomes against a reference target, we contrast the observed outcomes against a counterfactual to allow for a causal interpretation of the wetland area gains. Third, we track outcomes over a long time period, 1995–2020, to allow for temporal variability of the success of restoration activities.

Our results indicate that the majority of the observed gains in wetland area would not have taken place without dedicated conservation activities. However, contrasting the gain estimates to the wetland losses that the program is designed to compensate, we find that the program likely results in a net loss of wetland area. Importantly, our estimates are a lower bound on the wetland area net losses. A limitation of our method is that we cannot assess the hydrological and ecological quality of the newly created wetland areas, and, in our calculations, we assume they are equivalent in functionality to the lost wetland areas. This assumption is unlikely to hold (Tillman et al., 2022), rendering the implications of our results even less favorable.

There is considerable heterogeneity in our wetland gain estimates across administrative regions. Such variability is associated with the opportunity cost of land use. Wetland area gains are the highest in regions with an abundance of low-cost agricultural land that can be converted to wetlands. In contrast, in regions with less available agricultural land for conversion, firms choose to earn compensation credits by improving the functions of existing wetlands instead of establishing new wetland areas. While this pattern may appear beneficial from the perspective of efficient land use allocation, it may have adverse implications for ecosystem services in regions where wetland area losses are high.

Evaluating whether the US mitigation banking program is achieving its target of no net loss of wetlands provides insights into the effectiveness of offsetting policies more generally. This knowledge is particularly important considering that biodiversity offsets have now been introduced in a number of countries, despite the lack of knowledge about their environmental performance (OECD, 2016). Our study contributes to improving the evidence base around the effects of one of the most widely used policies for addressing the environmental impacts of development projects.

The remainder of the paper is organized as follows: Section 2 discusses the paper in relation to the existing literature, while Section 3 describes mitigation banking under the US Clean Water Act. In Section 4 we describe the data. In Section 5 we describe the empirical strategy in estimating wetland area gains, and in Section 6 we describe the estimation results. Section 7 discusses the implications of our estimates on whether the program is achieving its no-net-loss target. Section 8 concludes.

2 Relation to Literature

Wetlands are among the most biodiverse and economically valuable ecosystems in the world. They provide a range of critical ecosystem services, including carbon storage, water purification, flood control, and habitat to animal and plant populations (Mitsch and Gosselink, 2000; Moreno-Mateos et al., 2012). Since many of these services are public goods and the private benefits of wetlands to landowners do not reflect the total benefits to society, there are limited financial incentives for conservation (Heimlich, 1998; Turner et al., 2000). The purpose of regulating the use and conservation of wetlands is to correct this market failure. Recent evaluations report large benefits to society from wetland protection. For instance, Taylor and Druckenmiller (2022) estimate that US wetlands provide up to $2.9 trillion in flood mitigation value alone.

Our paper contributes to the literature investigating the outcomes of ecological offsetting. Previous empirical literature falls short of providing a robust evaluation of offsetting policies and in particular whether they achieve no-net-loss goals. There is a clear gap between the increasing global implementation of offsets and the evidence for their effectiveness (zu Ermgassen et al., 2019). Existing studies suffer from a series of limitations. For instance, studies conducting detailed ecological on-site assessments have small sample sizes and focus on a specific region, which reduces the generality of the findings due to potential selection biases (Tillman et al., 2022). Moreover, studies that measure outcomes at a single point in time face a potential performance bias, since it takes at least four years for a mitigation bank to reach its ecological potential, and this period can be even longer for some specific ecological functions (Moreno-Mateos et al., 2012). Finally, these studies are characterized by a lack of comparability between the analyzed outcomes. Some studies focus on diverse definitions of ecological performance, while other studies focus on administrative performance (i.e., compliance rates) (Tillman et al., 2022).

The results in previous studies are mixed (see reviews in Levrel et al. 2017; Tillman et al. 2022) but provide insights on the factors affecting the success of mitigation banking. Some studies point out mismatches between the permitted adverse impact and the compensation, as well as declining compliance with regulatory standards over time, as factors undermining the performance of mitigation banking.

Concerning mismatches between impact type and offset type, offset projects have primarily focused on the rehabilitation, enhancement, or preservation of existing wetland areas, instead of creating new ecosystems by establishing new wetland areas or re-establishing former wetland areas. Qualitative improvements to existing wetlands are a poor match to compensate for losses in wetland area extent. Still, the use of qualitative improvements as the compensation type has increased over time, while the use of establishment and re-establishment has decreased (Theis and Poesch, 2022). We analyze the spatial and temporal variation in different compensation types to assess the equivalence between impact and compensation at a national scale.

Concerning compliance, the mandatory monitoring period for a mitigation bank is typically only five years, which is not long enough to guarantee successful restoration in the long term (Tillman et al., 2022). Previous research has primarily examined outcomes within or at the end of the monitoring period (Levrel et al., 2017). Multiple environmental stressors (i.e., increased input of nutrients and pollutants and pressure from invasive species) may affect the performance of a compensation site beyond this time frame and possibly compromise the success of the project (Van den Bosch and Matthews, 2017). We evaluate outcomes up to 19 years after bank establishment to evaluate the temporal variability of the success of restoration activities.

Methodologically, our study also relates to recent literature using remotely sensed land cover data products to measure changes in environmental outcomes (Sonter et al., 2019; Taylor and Druckenmiller, 2022). Although land cover data enable low-cost environmental monitoring at a considerable spatial and temporal resolution and scale, these data can suffer from high error rates in detecting land cover change in specific applications (Stehman and

Wickham, 2020; Stehman et al., 2021; Wickham et al., 2021). Mapping and monitoring wetlands with algorithm-based data products are particularly challenging and an active research area in the remote sensing literature (Mahdavi et al., 2018). To overcome these caveats, we delineate newly created wetland areas through visual interpretation of high-resolution satellite imagery (Griffin and Dahl, 2016). Combining our own data collection with land cover change detection data provides a reliable measure of the *extent* and *timing* of wetland area gains.

3 Policy Background

3.1 No net loss and compensatory mitigation

The conterminous United States has lost over half of its original wetlands, mostly due to drainage for agriculture, forestry, and urban expansion (Dahl, 1990). As the understanding of wetlands and the importance of their ecological functions improved, in the 1970s, regulatory efforts began to reverse the trend of losses. Currently, US wetlands and streams are protected under Section 404 of the 1972 Clean Water Act (CWA), which provides the US Army Corps of Engineers (Corps) and the US Environmental Protection Agency (EPA) with the authority to regulate threats to the "physical, chemical, and biological integrity" of water bodies in the US.[1] Under Section 404, any development activity that causes adverse impacts to wetlands and streams must secure a permit from the Corps.

In 1990, the Corps and the EPA adopted a goal requiring *no net loss* of wetlands as a guiding principle for evaluating Section 404 permit applications (Corps and EPA, 1990).[2] Since then, under both federal and state regulations, developers are required to follow a sequence of mitigation steps if a project will impact aquatic resources: (1) reconfigure development sites to avoid impacts, (2) minimize unavoidable impacts, and (3) provide compensation for unavoidable impacts in the form of restoration, establishment, enhancement, or preservation of alternate wetlands and streams.[3]

The last step in the mitigation process has led to the development of three compensation methods, in which *offsets* are provided by (1) mitigation banks, or entrepreneurial firms

[1] 33 US Code § 1251 (101)(a).

[2] Early policy documents formulated the goal as "no overall net loss of wetlands functions and values". Later, the language evolved to "no net loss of wetland acreage and function". See Corps and EPA (1990, 2008).

[3] 33 US Code § 332.2 defines the different compensation types as follows: (i) Restoration: returning natural/historic functions to a former or degraded aquatic resource. (ii) Establishment: developing an aquatic resource that did not previously exist at an upland site. (iii) Enhancement: improving the functions of an existing aquatic resource. (iv) Preservation: the removal of threat to or preventing the decline of an aquatic resource.

that invest in restoration projects and sell offsets to permittees, (2) government agencies or nonprofits who collect and pool fees for impacts through in-lieu fee (ILF) programs that later fund restoration projects, or (3) the permittees themselves, a process known as permittee-responsible mitigation (PRM).

In this study, we focus on evaluating the performance of mitigation banking, since it is currently the most widely used implementation method.[4] Several reports have determined that onsite PRM has not been effective in terms of ecological outcomes and have highlighted the high rate of non-compliance (Government Accountability Office, 2005; National Research Council, 2001). In contrast, mitigation banking was deemed to improve the efficacy of wetlands offsets, because (1) it reduces the number of stakeholders responsible for the success of compensatory measures, and (2) it increases the probability of success of compensatory mitigation by promoting large-scale ecological restorations and ensuring that ecological gains occur prior to impacts (thus reducing the risk of temporal losses of wetlands).

Changes in regulatory support for third-party mitigation were promulgated in the 2008 Final Compensatory Mitigation Rule (2008 Rule, Corps and EPA 2008). The 2008 Rule explicitly names mitigation banking as the preferred method of compensatory mitigation, while maintaining a proximity criterion whereby mitigation should occur within the boundaries of the watershed of the impacted wetland. Federal guidelines then signaled a shift toward mitigation performed by third parties at off-site locations, where the biophysical characteristics may be more suitable for the protection of high-quality wetlands.

3.2 Mitigation banking

Mitigation banking was first introduced as a method for compensatory mitigation in the 1990s, following the release of the 1995 Banking Guidance (Corps and EPA, 1995). Mitigation banks have four distinct components: (1) a bank site (the property where wetlands are restored, established, enhanced, or preserved), (2) a bank instrument (the formal agreement between the bank owners and regulators, which establishes liability, performance standards, monitoring requirements, and the terms of bank credit approval), (3) an Interagency Review Team (consisting of all state and federal agencies that provide approval and oversight of the bank, with the Corps as lead), and (4) a service area (the geographic area/watershed or political boundaries in which permitted impacts can be compensated for at a given bank).

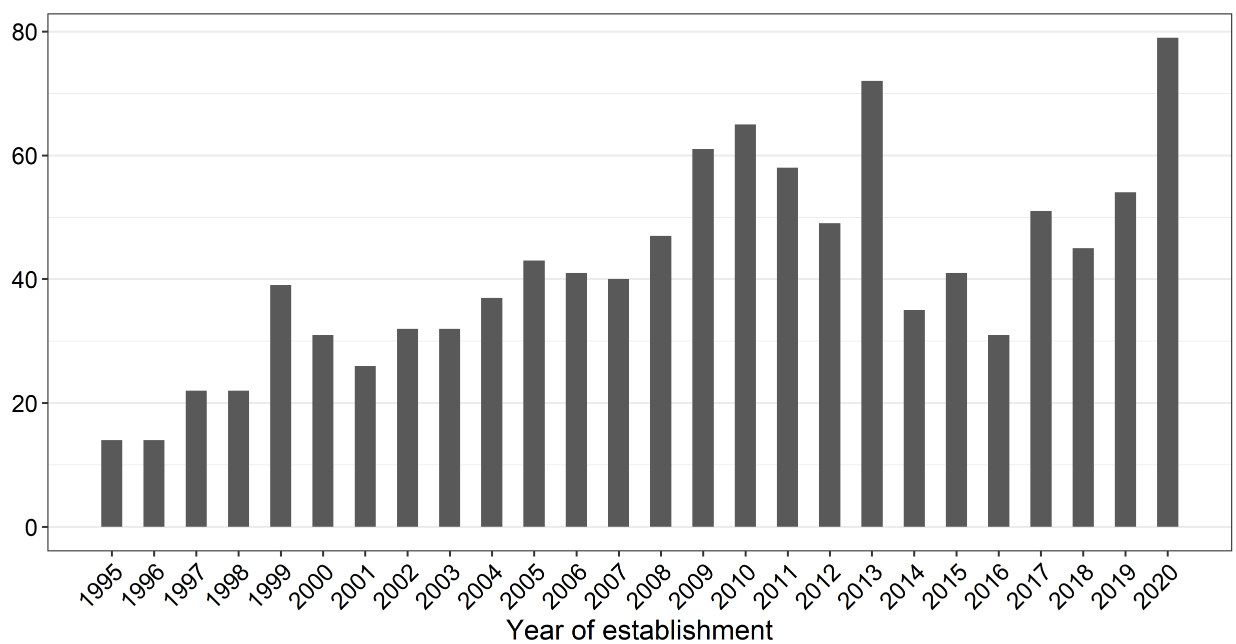
The bank instrument identifies the number of credits available for sale. This determination is based on the ecological value of the compensation project. Once a bank successfully meets its performance standards and monitoring requirements, it receives the specified cred-

[4]Between 2015 and 2020, mitigation banking was mandated for 51%, ILF for 16%, and PRM for the remaining 33% of required mitigation actions (Corps, 2020).

its and can sell them to developers. In turn, the developers use the credits to satisfy their compensation obligations.

Since mitigation banking involves the transfer of liability from developer to banker in the face of uncertainty regarding the demand and success of compensatory measures, creating a mitigation bank is a risky venture that requires a high level of specialized expertise. Bankers often need the help of qualified and experienced consultants to navigate the multi-step process. It usually takes from two to five years to secure the initial documentation and approval, and about ten years to complete development (BenDor and Riggsbee, 2011; Levrel et al., 2017). Nevertheless, following a series of institutional responses that supported mitigation banking and reduced some of its economic risks, banking is now the most important mitigation mechanism. Whereas permittee-responsible mitigation represented about 60% of all compensatory measures permitted by the Corps in 2008 (Institute for Water Resources, 2015), it represented only 33% over 2015–2020. By contrast, mitigation banking now represents 51% of all mitigation methods (Corps, 2020).[5]

Figure 1: Annual counts of established wetland mitigation banks



Data source: RIBITS, Corps (2022)

This increase in banking as a mitigation method has been accompanied by a significant development of the banking industry over the years. Figure 1 plots the counts of established

[5]Data on all mitigation methods permitted by the Corps in 2020 were obtained from the Operation and Maintenance Business Information Link, Regulatory Module (ORM), which is the Corps database for tracking Section 404 permitting data. ORM data was obtained through Freedom of Information Act requests.

banks over 1995–2020. In 2007, a total of 403 banks with Section 404 wetland credits had been approved, and the rate of approvals averaged about 30 banks per year following the release of the 1995 Banking Guidance (1995–2007). In the 12 years since the 2008 Rule, the rate of approvals has averaged about 53 banks per year (2008–2020), which corresponds to a more than 70% increase relative to the period before. As of December 2020, there were 1091 banks selling wetland credits, and 214 more pending approval.

Different states have adopted mitigation banking to varying degrees. For example, in the Northeastern US, state authorities have chosen not to endorse private for-profit mitigation banking and instead rely on non-profit in-lieu fee banking and permittee-responsible mitigation. Conversely, in states such as Louisiana and Minnesota, regulators have endorsed private mitigation banking, with over 94% of impacts permitted over 2012–2020 requiring compensation from mitigation banks (source: Corps 2020). In the following section, we describe the distribution of mitigation banks across the US and our estimation sample.

4 Data

4.1 Wetland mitigation banks

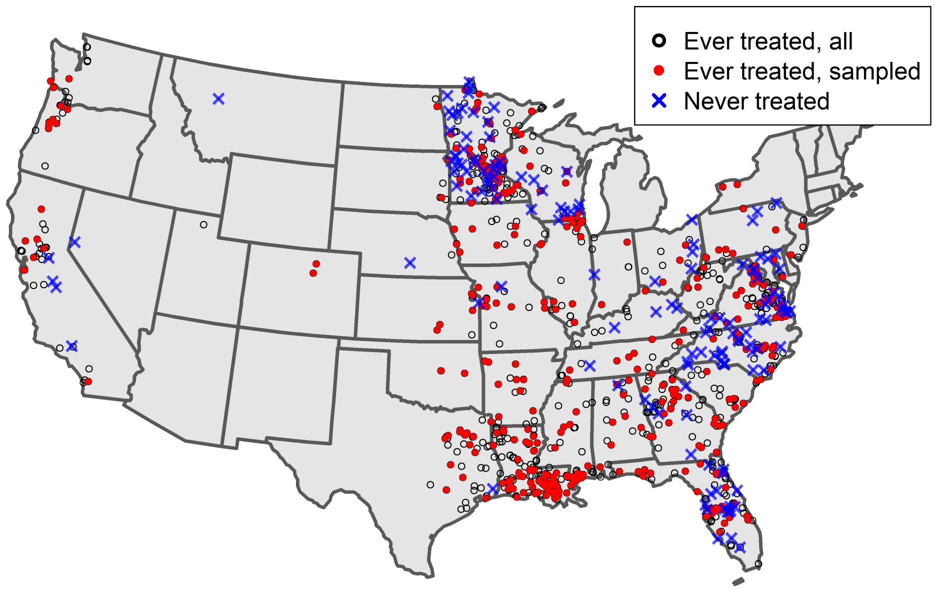
We obtain information on mitigation banks from the Regulatory In-lieu fee and Bank Information Tracking System (RIBITS, Corps 2022). The RIBITS database tracks information on all mitigation banks, including their location, the type and number of credits supplied, and their credit transaction ledger.

We collect data for a sample of 400 banks out of 952 private wetland mitigation banks that were established between 2001 and 2020. Additionally, we collect data for 141 candidate private mitigation bank sites, which constitute a never-treated control group in our analysis. These sites first entered the permitting process to allow operation as a mitigation bank but eventually withdrew from the process before obtaining a permit. Typical reasons for project withdrawals include property ownership disputes and substantial required revisions to the project design due to potential effects on neighboring properties or adjoining water resources.[6] Figure 2 displays the geographic distribution of the wetland mitigation banks included in our estimation sample.

For the purpose of measuring outcomes at the mitigation bank sites, we observe the site polygon for 428 banks. For the remaining 113 banks, we only observe the site centroid coordinates. For these sites, we approximate the site area with a circular buffer around the site centroid such that the buffer area corresponds to the bank area as stated in RIBITS.

[6] Information on reasons for project withdrawals is available in bank documentation in RIBITS.

Figure 2: Estimation sample



Ever treated, all:	Private wetland mitigation banks established between 2001 and 2020 (N = 952)
Ever treated, sampled:	Random sample where outcome data collected (N = 400)
Never treated:	Candidate mitigation banks that withdrew their application during the permitting process (N = 141)

Data source: Corps (2022)

4.2 Wetland area

We combine two data sources to measure changes in the extent of wetlands at mitigation bank sites. As a first step, we collect novel data by interpreting high-resolution satellite and aerial imagery to delineate newly established wetland areas. As a second step, within the delineated wetland areas, we use land cover change detection data (USGS, 2022) to accurately assess the timing of conversion from cropland to wetland. This process is illustrated in Figure 3 and explained in detail below.

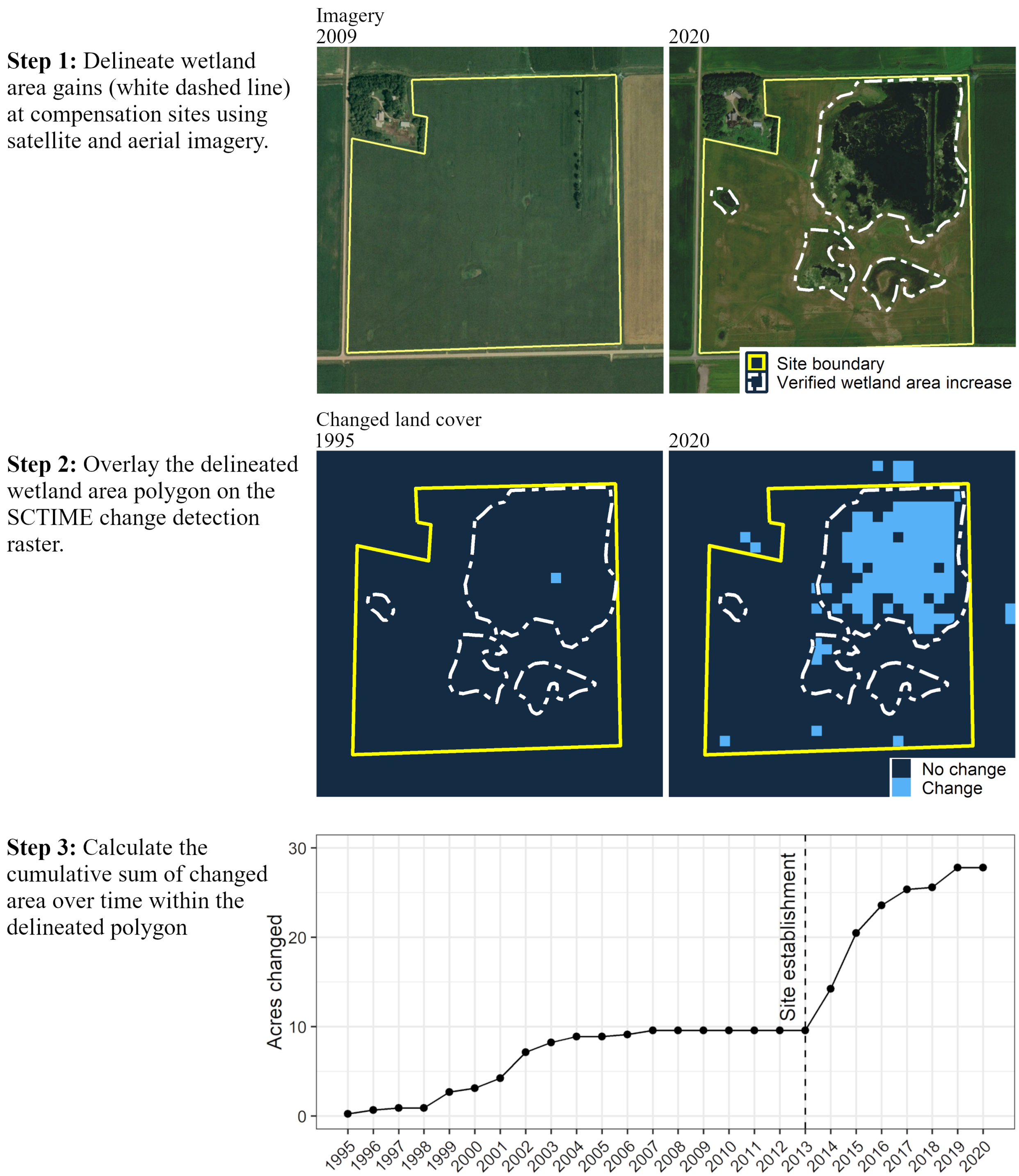
4.2.1 Imagery interpretation

We interpret historical satellite and aerial imagery to delineate the extent of conversion of agricultural land to wetlands within the mitigation bank sites. The analysis relies primarily on observable physical changes that are evident in the imagery and secondarily on the mitigation bank documentation, which provides contextual information such as elevation and soil maps and a description of the permitted conservation project.

Figure 3 provides example imagery of a mitigation bank that was established in 2013. The first image shows how the entire site was in agricultural use in 2009. By 2020, 29% of the site area was converted to wetland, visible in the image as flooding and vegetation change around the flooded areas. To record this change, we draw a polygon around the newly restored wetland plot and calculate its area. We also record the years between which the change is observed. Importantly, for all mitigation bank sites, we confirm that the created or restored wetland area remained intact until the endline year 2020.

Visual interpretation provides an accurate measurement of wetland area at the treated sites at the endline year. In most cases, it is also straightforward to observe that the site was in agricultural use until conversion to a mitigation bank and that the gains do not merely reflect a change in the surrounding landscape, e.g., due to a larger restoration project outside the CWA compensatory mitigation program. However, especially for the sites that were established in the first years in our sample, imagery availability and quality impose constraints on determining the exact timing of the change. First, for over 48% of the examined sites, comparable imagery before and after the treatment year were over five years apart. This causes uncertainty in assessing the exact timing, and thus the additionality, of the changes. Another source of uncertainty is low image quality. Major re-wetting, as visible in Figure 3, is easy to delineate. However, the timing of vegetation change in the absence of visible flooding (30% of examined sites) is difficult to assess without high-resolution imagery. To address these shortcomings, we employ land cover change detection data. These data enable us to measure the timing of change within the recorded wetland polygons at annual intervals.

Figure 3: Wetland gain measurement



Data sources: Google Earth (USDA/FPAC/GEO and CNES/Airbus); USGS (2022)

4.2.2 Land cover change detection

We combine the delineated wetland gain polygons with land cover change detection data to construct an annual time series of wetland gains. To this end, we use the Time of Spectral Change (SCTIME) layer in the LCMAP data suite (USGS, 2022). The SCTIME layer maps land cover change in the continental United States at 30-meter resolution and at annual intervals from 1985 to 2020. Identification of land cover change is based on an algorithm that fits a time series model for the surface reflectance of individual pixels in Landsat satellite imagery. Abrupt and systematic changes in surface reflectance will manifest as a model break, which in turn is identified as land cover change (Dwyer et al., 2018; Xian et al., 2022; Zhu and Woodcock, 2014).

Comparing the imagery and land cover change data in Figure 3 provides an example. The altered surface reflectance of the flooded areas is recorded as land cover change in SCTIME.[7] This example also demonstrates the suitability of SCTIME in our application where we measure wetland area gains on agricultural parcels. Agricultural land, typically monoculture, produces a stable time series of surface reflectance. Conversion to wetland alters the vegetation and may partially inundate the area. The resulting changes in the surface reflectance time series are likely identified as a model break.

Used independently, a major limitation of SCTIME is that it does not identify the type of change or whether the change is permanent. For example, major natural flooding events may be recorded as change although no permanent land cover change took place. Using SCTIME together with the wetland gain polygons resolves this caveat. Within these polygons, we know the land cover type before and after change (cropland and wetland), and SCTIME is a reliable indicator of the timing of the change.

We construct our primary measure of wetland gains as follows:

$$\text{Wetland gain}_{it} = \frac{\text{SCTIME}_{it}}{\sum_t \text{SCTIME}_{it}} \times \text{Verified wetland area}_{i,\ t=2020} \tag{1}$$

where SCTIME_{it} is the recorded cumulative change (acres) within verified wetland polygons at site i in year t. The term Verified wetland area$_{i,\ t=2020}$ is the area of the polygon that was delineated using imagery. The scaling of SCTIME_{it} corrects for the fact that the extent of the detected change in SCTIME is typically smaller than the extent of the wetland area

[7] Within the largest delineated polygon, SCTIME records change in approximately 69% of the area over 1995–2020, while approximately 45% of the area changed after site establishment. Vegetation change and flooding within the three smaller polygons remain mostly undetected. This is likely due to the area of changed land cover being too small in comparison to the mapping unit of 30-meter pixels. Alternatively, the changes in the surface reflectance time series may be too small in magnitude in comparison to pre-treatment patterns. The pre-treatment pattern may have been similar, e.g., due to seasonal flooding.

gains we observe in imagery. This feature is visible in Figure 3. In the SCTIME data from 2020, the area of recorded change (light pixels) is less than the area of delineated wetland gains (white dashed line). In the example, SCTIME succeeds best in detecting a large patch of visible flooding. By contrast, subtle changes in vegetation, as well as changes that are small in comparison to the minimum mapping unit (30-by-30 meter pixel), are less likely to be detected.

To enforce equality between Wetland gain_{it} and the delineated wetland area gain polygon, we divide SCTIME_{it} by the total detected change and multiply by the total verified wetland area. As a result, in the scaled measure it will hold that

$$\text{Wetland gain}_{i,\ t=2020} = \text{Verified wetland area}_{i,\ t=2020}$$

For two sites, no change was recorded in SCTIME over the entire time frame of the analysis, and the denominator in eq. 1 becomes zero. For these sites, we set the gains to zero.

4.2.3 Other data sources

We use county-level data on GDP, population (US Bureau of Economic Analysis) and agricultural land value (US Department of Agriculture) as covariates in regression analysis. We also control for precipitation, available as annual mean in a 1-kilometer resolution grid (Thornton et al., 2020). To describe the landscape characteristics of our estimation sample, we support the analysis with the Primary Land Cover (LCPRI) product in the LCMAP data suite. LCPRI classifies land cover in the continental United States into eight thematic classes. We aggregate these classifications into five categories of interest: wetland, other natural (grass/shrub, tree cover), cropland, developed (artificial land cover such as roads and buildings), and open water. The LCPRI data are available at a 30-meter resolution at annual intervals between 1985 and 2020.

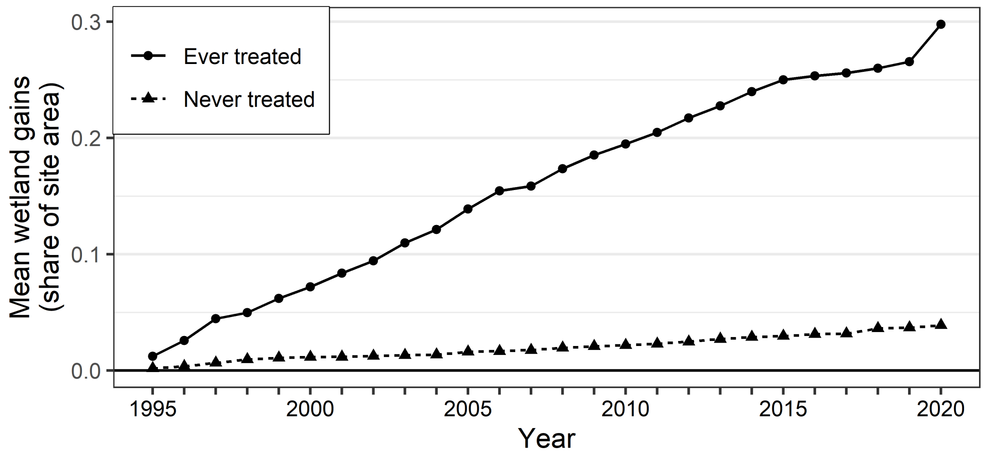
4.3 Data description

Figure 4 depicts the trends of wetland gains over time at the ever-treated and never-treated sites in our estimation sample. The wetland area gains are steady in both groups, although the gains are only about four percent of site area for the never-treated units. Figure 4b shows the average gains in treated units relative to permit approval year, normalized to zero in the year preceding approval. The graph shows a distinct increase in the wetland area starting approximately ten years before permit approval and continuing as a steady increase throughout the depicted time period.

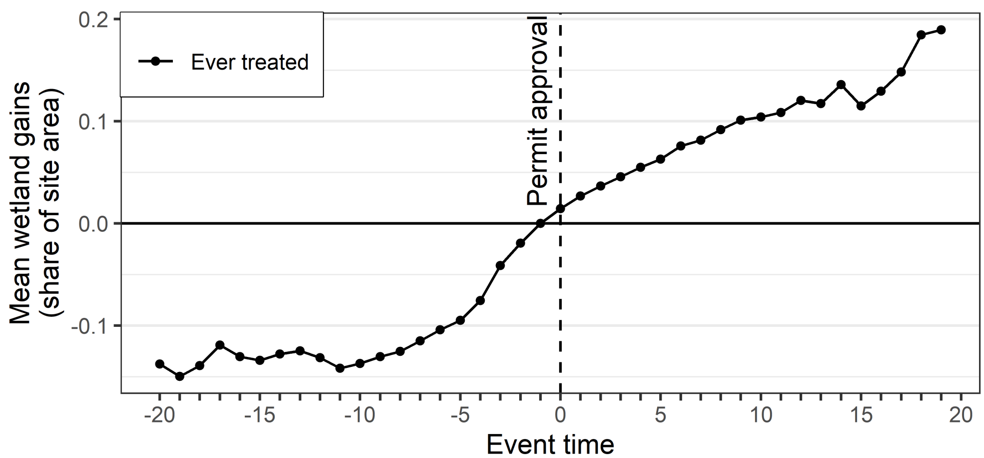
It is important to assess whether the pre-approval changes in the outcome represent an anticipatory treatment effect or whether they would have occurred in the absence of the permit process. As discussed in Section 3.2, the permit process typically takes 2–5 years, and realizing the compensation project can take up to 10 years (BenDor and Riggsbee, 2011; Levrel et al., 2017). Landowners who anticipate a positive permit decision may start preparatory work prior to permit approval in order to expedite the completion of the project and the subsequent acquisition of compensation credits. Anticipatory behavior has implications for estimation, as it runs counter to the identifying assumptions in standard difference-in-differences models. We discuss the issue in more detail in Section 5, and we account for possible anticipation in the estimation.

Figure 4: Outcome trends.

(a) Wetland area gains in estimation sample over 1995–2020.



(b) Wetland area gains at ever-treated sites relative to permit approval year.



Panel (a): Wetland area gains at ever-treated and never-treated sites in estimation sample over 1995–2020. Wetland gains are defined as in eq. (1), and normalized by mitigation bank site area.

Panel (b): Wetland area gains as in (a) in ever-treated units with time period normalized to zero in the permit approval year and level normalized to zero in the year preceding approval.

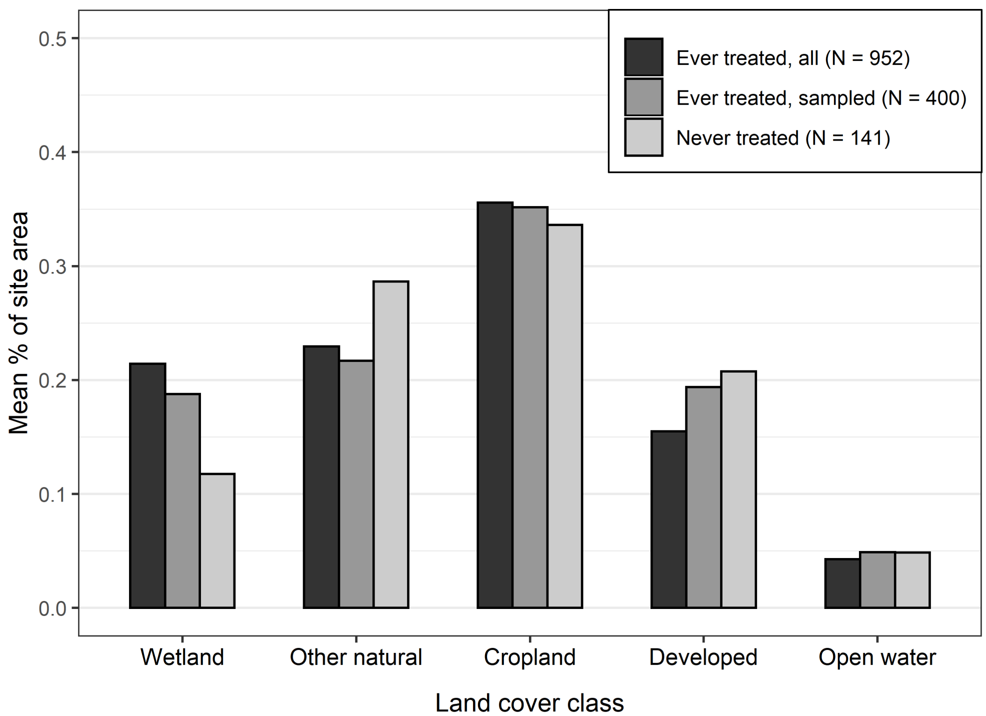
Ever treated: Sampled private commercial wetland mitigation banks established during 2001–2020 (N = 400). Never treated: Candidate mitigation banks that withdrew their application during the permitting process (N = 141).

Data sources: Own data collection, Corps (2022); USGS (2022).

Figure 5 describes the landscape characteristics of our estimation sample using the LCPRI land cover classification map measured in 2000 (USGS, 2022). The full population of wetland mitigation banks and the banks in our estimation sample closely resemble each other in their land cover class distribution. As for the never-treated sites (withdrawn candidate sites), the only distinctive differences are in the shares of wetlands and other natural areas. The never-treated sites had on average 7 percentage points less wetland area than the sampled ever-treated sites, although the combined average share of wetlands and other natural areas is almost exactly equal at 40%.

Differences in geographical distribution between the two groups explain the pattern (see Figure 2). For example, none of the never-treated sites are located in Louisiana, which is abundant in wetlands. Another explanation relates to the different types of conservation activities. Most wetland creation and re-establishment take place on agricultural land, whereas wetland enhancement, by definition, takes place on existing wetlands. Since wetland creation and re-establishment are generally more costly than enhancement, these projects are more likely to be withdrawn during the permitting process. Regardless, for the purposes of using the withdrawn candidate sites as a never-treated control group, it is important that they have comparable potential for wetland creation and re-establishment. This potential is best reflected in the baseline cropland area, which is roughly equal across groups.

Figure 5: Landscape characteristics of mitigation banks



Land cover class measured in 2000.

Data sources: Corps (2022); USGS (2022).

Table 1 shows descriptive statistics of the covariates used in the analysis. Note that the covariates are measured at an aggregate level: land value, GDP per capita, and population density are recorded at the county level, whereas precipitation is measured within a 1-kilometer grid cell. Overall, the counties where the mitigation bank sites are situated resemble each other across groups.

Table 1: Descriptive statistics

	Group		
Variable	Ever treated, all	Ever treated, sampled	Never treated
Ag. land value (USD / acre)			
Mean	2138.9	2066.2	2031.9
Std. dev.	1771.3	1326.3	1198.9
GDP per capita (1000 USD)			
Mean	37.8	37.8	34.9
Std. dev.	21.2	19.7	13.7
Population/km^2			
Mean	92.2	95.4	87.0
Std. dev.	154.8	155.9	147.5
Precipitation (mm/year)			
Mean	1035.5	1007.5	957.6
Std. dev.	253.6	247.6	242.6
N	952	400	141

Summary statistics of covariates used in the analysis. Agricultural land value, GDP per capita, and population density measured at the county level. Precipitation measured within a 1-kilometer grid cell. Variables are measured in the year 2000, except land value, which is measured in 1997.

Data sources: US Bureau of Economic Analysis, US Department of Agriculture, and Thornton et al. (2020).

5 Empirical strategy

We model the effect of mitigation bank establishment on wetland area as follows:

$$y_{it} = \tau D_{it} + X_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{2}$$

where y_{it} is the wetland area gained (see definition in eq. 1) at site i in year t, measured as a share of the total site area. D_{it} is an indicator equal to one if site i had a mitigation banking permit in year t. The terms α_i and γ_t are site and year fixed effects. X_{it} is a vector of control variables that include GDP, population, land value, and precipitation. Treatment timing is staggered over t. Treated units do not change their status back to untreated.

We also estimate the dynamic path of treatment effects and treatment effects specific to treatment cohorts according to the following models:

$$y_{it} = \sum_{s \in \mathcal{S}} \tau_s D_{its} + X_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{3}$$

$$y_{it} = \sum_{g \in \mathcal{G}} \tau_g D_{itg} + X_{it}\beta + \alpha_i + \gamma_t + \varepsilon_{it} \tag{4}$$

where, in equation (3), D_{its} is an indicator equal to one if year t is s years after site i was first treated and, in equation (4), D_{itg} is an indicator equal to one if site i belongs to treatment cohort g (was first treated in year g) and was treated in year t.

Recent literature has shown that OLS is unsuitable for estimating treatment effect parameters in two-way fixed effects models, such as in equation (2), when treatment adoption is staggered and treatment effects are heterogeneous over time or treatment cohorts (Borusyak et al., 2021; Callaway and Sant'Anna, 2021; De Chaisemartin and d'Haultfoeuille, 2020; Gardner, 2022; Goodman-Bacon, 2021; Roth and Sant'Anna, 2021; Sun and Abraham, 2021). As regulatory practices have evolved considerably over the last two decades, this type of heterogeneity is likely in our setting. Accordingly, we report estimates from various alternative estimators suggested in the literature.

The identification of treatment effect parameters in equations (2)–(4) requires treatment assignment to be mean-independent of variables that affect changes in the outcome (*parallel trends*). As a never-treated control group, we use candidate mitigation bank sites that entered the permitting process but eventually withdrew their applications. As discussed in Section 4.3, these candidate sites are similar to our treated sites in terms of their suitability for conversion to wetland and the opportunity costs of different land uses. Their outcome trends arguably reflect the counterfactual outcome trends of the treated sites.

A second identifying assumption requires that there is no treatment effect in pre-treatment periods (*no anticipation*). As depicted in Figure 4b, the wetland area gains at the treated sites are largest during the five years immediately before permit approval. It is important to distinguish whether this pattern should be interpreted as treatment anticipation or endogeneity.

Anticipation is a reasonable interpretation if the economic agents in question have information on future treatment and if there is a benefit to acting before treatment (Malani and Reif, 2015). Both of these characterizations are applicable in the context of our study. Submitting a permit application amounts to information on future treatment, although permit approval is not always a certainty. If a bank owner perceives the probability of permit approval as sufficiently high, they have an incentive to start the restoration activities at the bank site. This will give the owner earlier opportunities to secure compensation credits and earn revenue from selling them. Therefore, anticipatory behavior is a likely explanation for the observed changes prior to permit approval.

To ensure that treatment anticipation does not confound our estimates, we follow Butts and Gardner (2021); Rambachan and Roth (2019) in their suggestion to adjust the treatment date back in time such that anticipatory effects do not occur before the *adjusted* treatment date. As discussed in Section 3.2, securing a permit for a mitigation bank site typically takes up to five years (BenDor and Riggsbee, 2011; Levrel et al., 2017). Accordingly, we adjust the treatment date back five years and assume that no treatment anticipation existed before that. We also report estimates from alternative adjustments.

6 Results

Table 2 presents estimates of τ in eq. (2) across different model specifications and estimators. The first model indicates that, on average, the share of wetland area at a site increased by 0.15 (95% CI: 0.13–0.17), or 15 percentage points, due to mitigation bank establishment. Including covariates does not modify the estimate, but including a state-specific trend slightly decreases the estimate. The results vary slightly between estimators; the highest point estimate is 0.17 (Gardner 2022, column (7)) and the lowest is 0.10 (TWFE, column (5)). We discuss our preferred estimate and effect magnitude together with the event study estimates that are presented in the following.

Table 2: The effect of mitigation bank establishment on wetland area

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\widehat{\tau}$	0.15	0.15	0.15	0.13	0.10	0.14	0.17
Std. error	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Covariates							
Precipitation		✓	✓	✓	✓	✓	✓
Population density			✓	✓	✓	✓	✓
GDP			✓	✓	✓	✓	✓
Land value			✓	✓	✓	✓	✓
State × trend				✓			
Estimator							
Sun and Abraham (2021)	✓	✓	✓	✓			
TWFE					✓		
Callaway and Sant'Anna (2021)						✓	
Gardner (2022)							✓
N	14066	14066	14066	14066	14066	14066	14066
N clusters	29	29	29	29	29	29	29

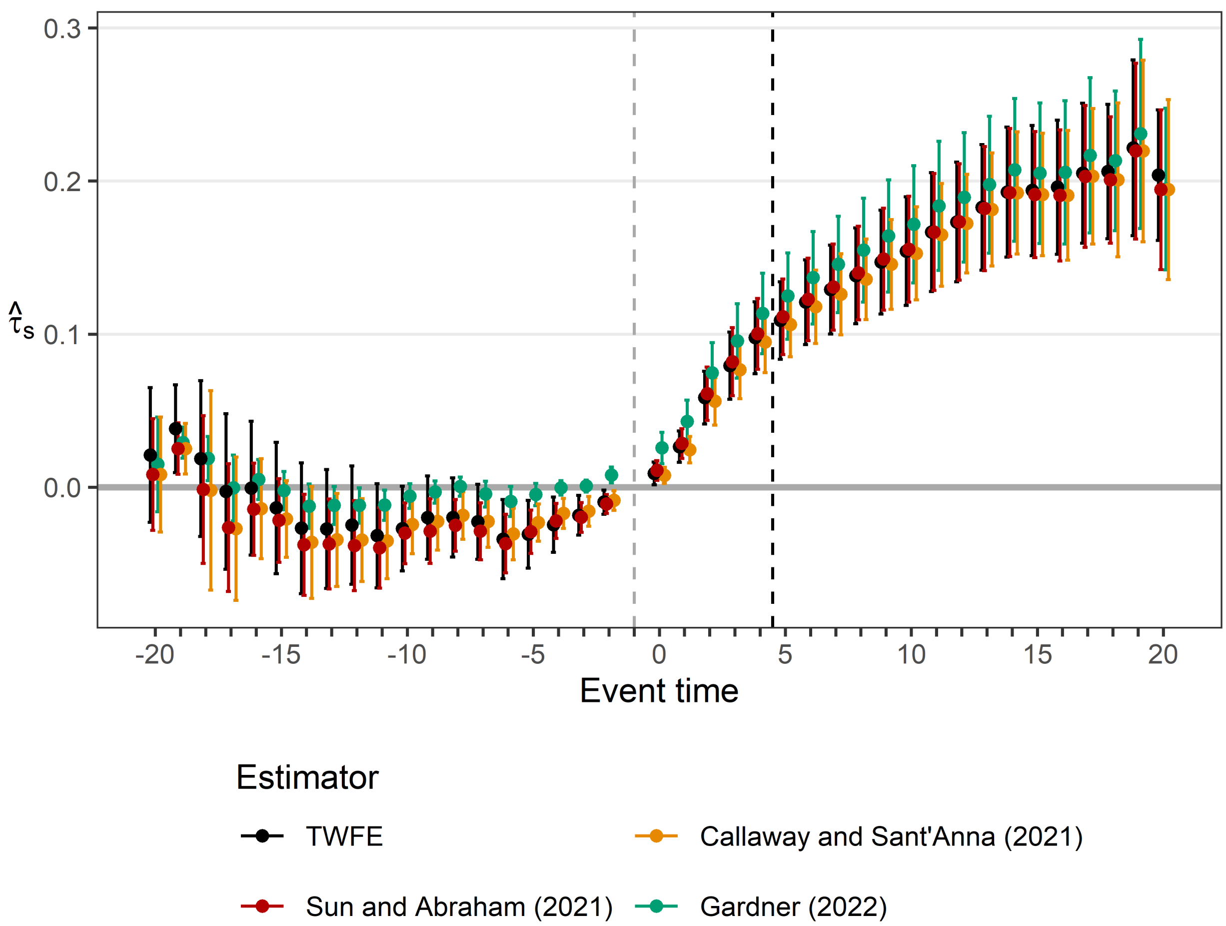
Standard errors clustered by state. Due to possible treatment anticipation, treatment year is adjusted five years back in estimation.

Dependent variable:	Wetland area gains (share of site area)
Treatment:	Mitigation bank establishment
Ever treated units:	Private wetland mitigation banks established in 2001–2020 (N = 400)
Never treated units:	Candidate private wetland mitigation bank sites (N = 141)
Data sources:	USGS (2022), Corps (2022)

Dynamic estimates. Figure 6 presents the estimates of τ_s in equation (3), estimated without including covariates. Note that, to prevent treatment anticipation from confounding the estimates, we have adjusted the treatment date back five years; the period enumeration follows the *adjusted* relative years. The adjusted relative period 5 is the date of permit acquisition as stated in the administrative data, and the adjusted relative period 0 is the first treatment year in the estimation.

The dynamic pattern is similar across estimators. The pre-treatment estimates using Gardner (2022) are close to zero and are precisely estimated. In turn, for TWFE, Sun and Abraham (2021) and Callaway and Sant'Anna (2021), the pre-treatment estimates average approximately −0.04 and there is a monotonic increase from relative period −6 to treatment onset. The patterns in post-treatment estimates are also similar across estimators. Estimates for the relative periods 0 to 4 can be interpreted as anticipation effects, reaching approximately 0.1 before treatment onset. A gradual increase in the point estimates contin-

Figure 6: The effect of mitigation bank establishment on wetland area. Dynamic estimates.



Point estimates of τ_s in eq. (3) and 95% pointwise confidence intervals. Standard errors clustered by state.

Dependent variable:	Wetland area gains (share of site area)
Treated units:	Private wetland mitigation bank sites (N = 400)
Control units:	Candidate private wetland mitigation bank sites (N = 141)
Dashed line, black:	The relative period 5 in the graph is the permit approval year as stated in the administrative data. Due to possible treatment anticipation, treatment year is adjusted five years back in the estimation.
Dashed line, grey:	Reference period and the last untreated period in estimation.

ues, with the estimates reaching approximately 0.20 in the last relative periods. Overall, the pattern in the dynamic estimates strongly suggests that the estimated post-treatment gains would not have occurred in the absence of treatment.

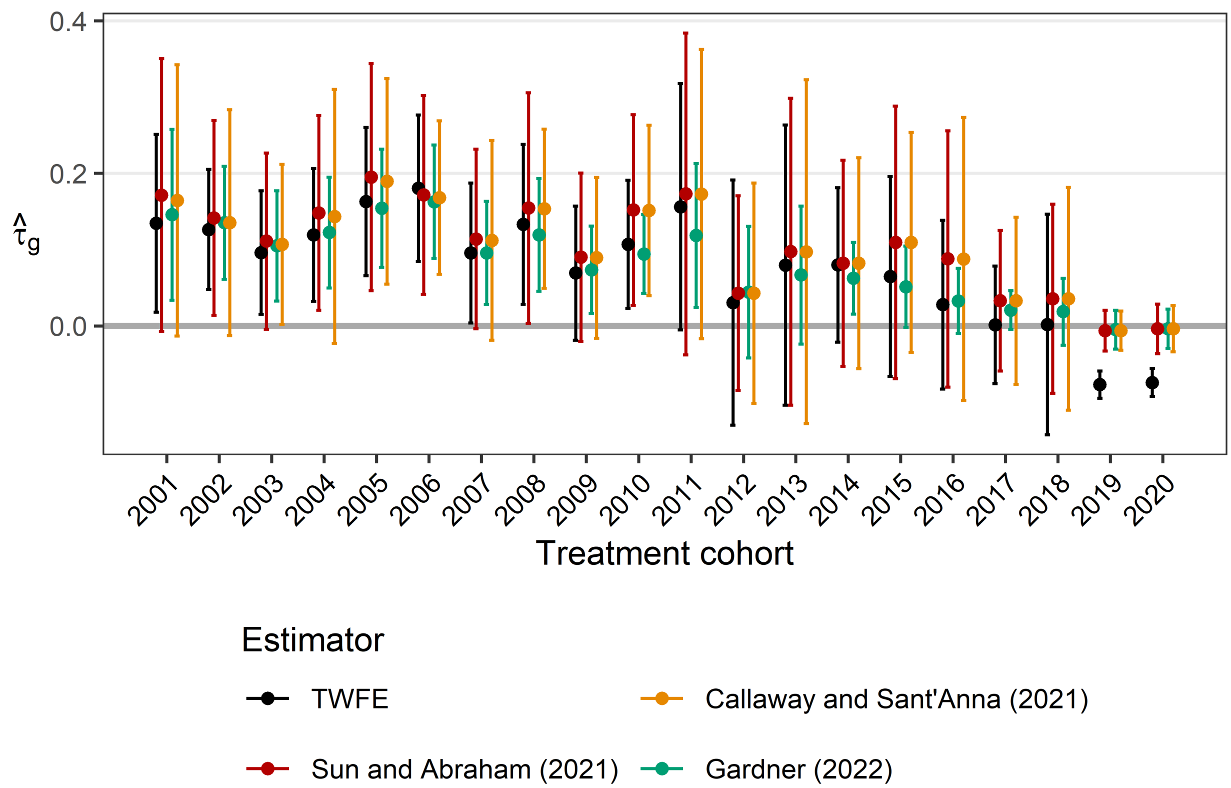
The dynamic estimates show that the gains in wetland area have been gradual. Thus, when ascertaining the magnitude of the effect, it is sensible to consider the dynamic estimates only for the last periods. Aggregating the estimates from Sun and Abraham (2021) for the last five relative periods provides a point estimate of 0.20 (95% CI: 0.16–0.24). This corresponds to a 20 percentage point increase in the share of wetland area at a site due to mitigation bank establishment. In total area gains, this estimate translates to 15,900 acres (95% CI: 12,900–18,900) of wetlands at the ever-treated sites summed over the estimation sample. We interpret these gains as the causal effect of conservation activities. The estimated causal effect is less than the 18,000 acres of wetland area gains that we identified directly in imagery, although the direct observation is within the 95% confidence interval of the causal estimate.

The estimation results are generally not sensitive to the choice of estimator or the inclusion of covariates (see Table 2). We provide further sensitivity analysis in Section A in the Appendix where we present the dynamic estimates from using different adjustments to the treatment year.

Cohort estimates. Figure 7 presents treatment effect estimates by treatment cohort (τ_g in equation 4). Again, the estimates are very similar across estimators, with the exception of the TWFE estimates for the cohorts 2019–2020. For these cohorts, no increases in wetland area were recorded, although some sites showed signs of conversion activity taking place. This is because any wetland gains are unlikely to be visible in imagery only few years after treatment.

The higher estimates for the earlier cohorts may indicate greater availability of agricultural land with low cost of conversion to wetland. These types of locations will be picked first in the early years of the program. In later years, as locations with low-cost conversion potential become more scarce, mitigation firms increasingly start to generate credits from other types of compensation activities.

Figure 7: The effect of mitigation bank establishment on wetland area. Cohort estimates.

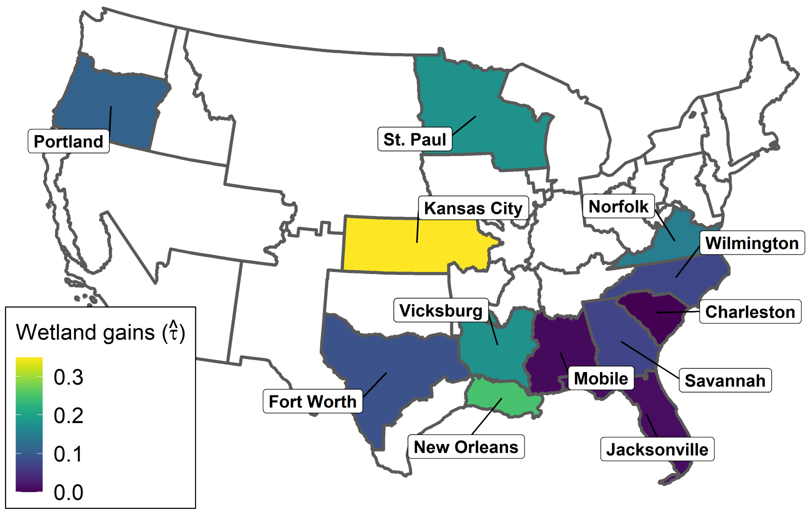


Point estimates and pointwise 95% confidence intervals of τ_g in eq. (4) by treatment cohort. See the notes in Table 2 for details on estimation.

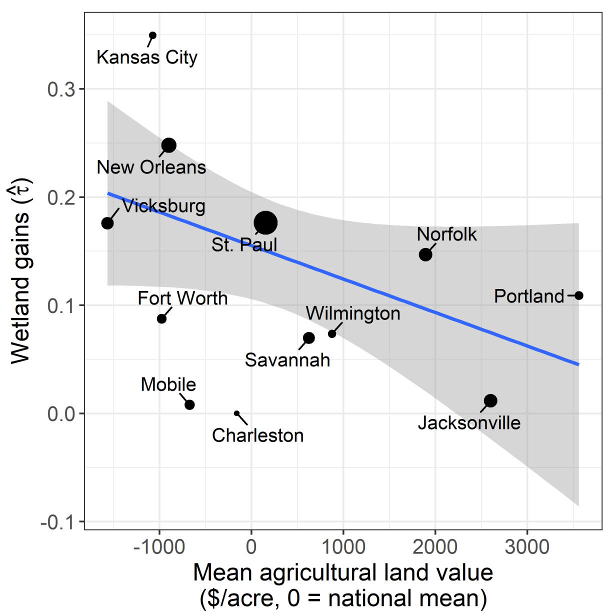
Heterogeneity by region. Figure 8 presents the point estimates of treatment effects by the administrative districts of the US Army Corps of Engineers. We produce the estimates only for districts with five or more ever-treated sites in the full estimation sample. The estimates display heterogeneity, ranging from zero or close to zero estimated gains in some districts (Charleston, Jacksonville and Mobile) up to 0.35 (Kansas City). Panel (b) in Figure 8 shows how the heterogeneity is associated with the opportunity cost of land use. The estimates are generally higher in regions where low-cost agricultural land was available. Further heterogeneity analysis in Appendix C corroborates this finding, indicating that wetland area gains have occurred mostly in agricultural landscapes.

Figure 8: Heterogeneity by region

(a) Heterogeneity of wetland area gains by the administrative districts of the US Army Corps of Engineers



(b) Land value and heterogeneity of wetland area gains



Panel (a): Treatment effect estimates by region (estimates of τ in eq. (2)). Each estimate is obtained from a regression that includes the ever-treated sites belonging to one region and all never-treated sites. Only regions with five or more ever-treated sites are included in this estimation sample.

Panel (b): Treatment effect estimates are as shown in panel (a). Agricultural land value is measured in the county of the mitigation bank site, in the year of site permit approval, and demeaned against the national mean in that year. The fitted line and 95% CI are based on a weighted linear regression, where the weights (point sizes) correspond to the number of ever-treated sites in the full estimation sample.

7 Policy implications

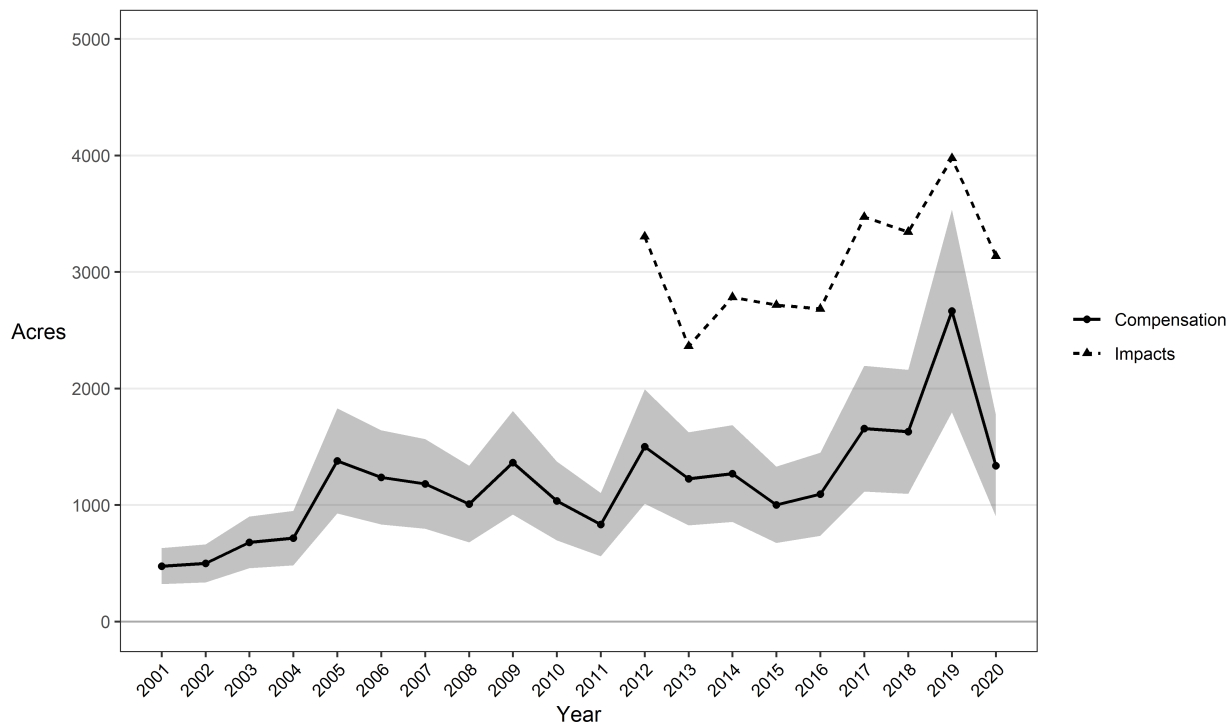
Given our estimates of wetland area gains, we can assess whether the compensatory mitigation program is achieving no net loss of wetland area. Recall that compensation credits are awarded both for wetland area gains and for improving the functions of existing wetland areas. Using the estimates of wetland area gains, we can estimate the average share of wetland area gains out of the total wetland area that was used for compensating losses. In turn, this quantity allows us to assess whether the compensatory program as a whole is succeeding in offsetting wetland area losses with gains. The details of this calculation are given in Appendix B. For the purposes of the calculation, we consider our preferred estimate of the wetland area gains, which we obtain by aggregating the last five dynamic estimates reported in Figure 6. Using the estimator from Sun and Abraham (2021), this estimate becomes 0.20 (95% CI: 0.16–0.24).

In Figure 9, the resulting estimated wetland area gains embedded in compensation transactions are depicted together with the wetland area losses they were supposed to compensate. Even the upper bound of the gain estimates stays well below the total impacts, indicating net loss of wetland area. Over 2012–2020, the estimated net loss is on average 1600 acres per year (confidence bounds according to the 95% CI of $\widehat{\tau}$: 1115–2085). Heterogeneity in the estimated net losses is depicted in Figure D.1 in the Appendix, showing how gains are driven by available agricultural area for mitigation and losses are driven by wetland areas.

A net loss of wetland area does not directly imply a net loss of ecological or hydrological functions of wetlands. Instead, the area net loss estimates can be interpreted as a *quality gap*: To achieve no net loss of wetland functions, the area net losses must be offset with qualitative improvements. At the same time, a question is whether the ratio of gains and losses is sufficiently high to maintain wetland functionality. For example, as a guideline, the existing regulations call for a minimum of a one-to-one acreage compensation ratio in the absence of any functional assessment.[8]

[8] 33 US Code § 332.3 (f). See also Corps and EPA (1990)

Figure 9: Net loss of wetland area in the Clean Water Act compensatory mitigation program



Compensation:	Estimated acres of total wetland area gains embedded in compensation transactions. (Source: own estimates and RIBITS)
Shaded area:	Estimate bounds based on the 95% confidence interval of $\widehat{\tau}$.
Impacts:	Wetland loss from impacts that required compensation from private mitigation banks. Only including impacts that would be included in administrative no net loss calculations. (Source: Corps 2020)

To address the gap, there are readily available regulatory solutions both on the demand and the supply side. A demand-side solution is to require more compensatory credits per impacted acre of wetland. Looking at Figure 9, had the regulator doubled the compensation requirements, the gap could have approximately closed.[9] On the supply side, the regulator may mandate more wetland establishment and re-establishment (area gains) instead of wetland enhancement. This can be achieved by adjusting the ratios according to which different types of compensation activities are awarded compensation credits.

We want to emphasize that our net loss estimates are based on an optimistic scenario. Our calculation assumes functional equivalence between the wetland area that was created as compensation and the wetland area that was lost due to impacts. The degree to which this assumption is fulfilled is pivotal to the success of the program. Yet, this aspect of

[9]This is assuming that, on the supply side, the ratio between area gains and improvements on existing wetlands would have stayed the same in the face of increased credit demand.

compensatory mitigation remains a contested topic in ecological literature (Levrel et al., 2017; Tillman et al., 2022).

8 Conclusion

In this paper, we estimate the causal impact of environmental offsetting activities on wetland area extent at mitigation banking sites within the US Clean Water Act Section 404 compensatory mitigation program. Using these estimates, we evaluate the degree to which wetland mitigation banking is achieving its stated goal of no net loss of wetland area.

Our analysis provides three major findings. First, we measure wetland area gains amounting to over 18,000 acres of established or re-established wetlands at the mitigation bank sites in our sample. Comparing these gains to those at planned but withdrawn project sites, we estimate that the causal impact of compensation site designation totals 15,900 acres (95% CI: 12,900–18,900). In other words, the majority of the gains would not have occurred without dedicated compensation activities.

Our second finding is that there is significant heterogeneity in the wetland area gains across administrative districts and that the opportunity cost of land use is likely the strongest driver of these differences. Wetland area increases are the greatest in regions with an abundance of low-cost agricultural land that can be converted to wetlands. In contrast, in regions where less agricultural land is available for conversion, compensation firms choose to earn credits by improving existing wetlands instead of converting agricultural land to wetlands. This suggests that the market-based offsetting scheme is functioning as intended in how it allocates land use, both between mitigation methods and between conservation and other land uses.

Third, we compare the estimated wetland area gains to the area losses for which they are compensating. Our results indicate that the mitigation banking program is resulting in a net loss of wetland area. This is a consequence of how the regulations allow a particular type of mismatch between compensation and impact: it is possible to compensate losses of wetland areas with qualitative improvements and preservation of existing wetland areas. When firms consider the choice of mitigation method, the opportunity cost of converting agricultural land to wetlands is arguably higher than the cost of improving existing wetlands that likely have few other profitable uses. In order to achieve the regulatory mandate of no net loss of wetland area, the regulator could incentivize wetland area increases (relative to qualitative improvements) by awarding more compensatory credits per acre of wetland created. Alternatively, the regulator could mandate permittees to surrender more compensation credits per impacted acre.

The most important limitation of our study is that we do not assess the functional quality of the created wetland areas. Instead, for the purposes of our calculations, we assume qualitative equivalence between a created and a lost acre of wetland. This assumption likely results in overstating the estimated environmental benefits and understating the estimated net losses. Further research should scrutinize the functional quality of both the compensation wetlands and the lost wetland areas.

Overall, our analysis contributes to a better understanding of the functioning of market-based environmental offsetting. While the mitigation banking program under Section 404 of the US Clean Water Act has succeeded in several aspects, our analysis identifies design choices that have resulted in net losses of wetland areas. It is important to consider these dynamics in the design of other existing and future offsetting policies. As in several studies before us, we want to emphasize the importance of transparent and temporally consistent monitoring data in making informed decisions about policy design. Producing such data should be a priority when implementing environmental offsetting schemes.

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Appendices

A Sensitivity

Outcome coding. Figure A.1 presents the regression results with the outcome coded as absolute acres of wetland area instead of normalizing by site area. In the main results, we chose to normalize the outcome because the average size of mitigation banks varies considerably across cohorts and regions. If the outcome is not normalized, the results in our heterogeneity analysis merely reflect the variability in mitigation bank site area. This heterogeneity would not be informative of our ultimate parameters of interest: the share of wetland area gains out of all types of compensation activities.

Nonetheless, when coding the outcome as absolute acres, the dynamic estimates display a pattern that is very similar to the pattern with the normalized outcome. The TWFE estimator is an exception in showing a stronger pre-treatment trend.

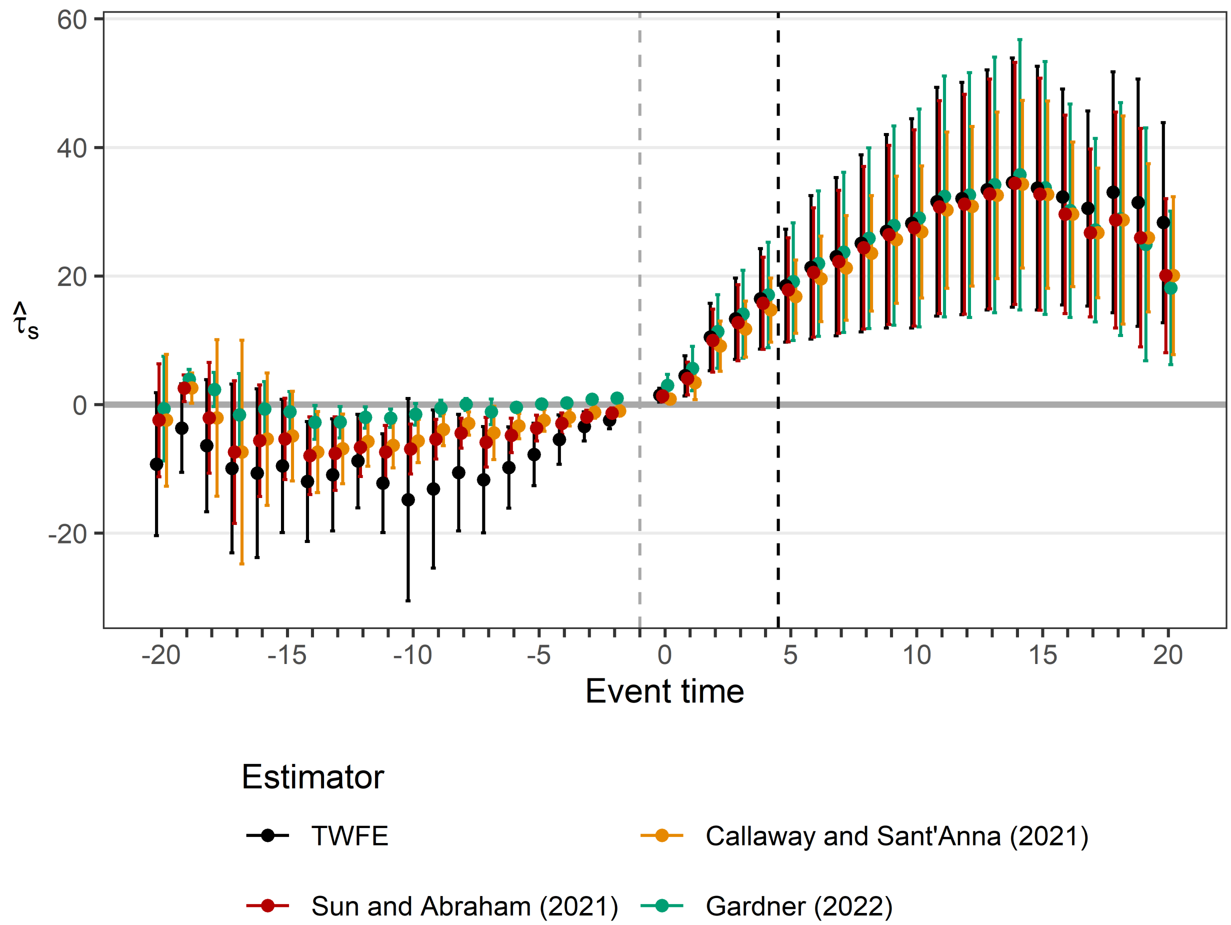
Treatment year and anticipation. The second robustness check concerns the definition or treatment year in estimation. In our main results, we chose to adjust the treatment year in estimation to five years before mitigation bank permit approval. The purpose was to account for possible treatment anticipation that would run counter to the identifying assumptions of our estimators.

Figure A.2 presents the estimation results when defining the treatment year as the permit approval year. The estimates show a pattern similar to the main results, in that the largest gains seem to have occurred during the first five years *before* permit approval. However, the estimates diverge substantially between estimators during the earliest pre-treatment periods.

Figure A.3 presents the results when defining the treatment year as 10 years before permit approval. In these estimates, the relative periods between 0 and 9 can be interpreted as anticipation effects. Here, a more stable and monotonic pre-treatment trend emerges, although the estimates increase the most during periods 5-9. Note that in this regression we lose the ever-treated sites from the five earliest cohorts; this happens because, with the treatment year adjusted 10 years back, they no longer have observed non-treated periods. This reduction in sample size explains the variance of the estimates in the last relative periods.

The estimates for the last five treated periods are higher than our preferred estimates in Figure 6. However, it is questionable whether the slightly increasing trend in relative periods 0–4 should be interpreted as an anticipatory effect. Considering the trend as endogeneity and deducting the projected increase (projection based on the rate of increase during relative periods 0–4) from the post-treatment estimates yields an aggregate estimate of 0.17 (95% CI: 0.12-0.22) in the last five relative periods.

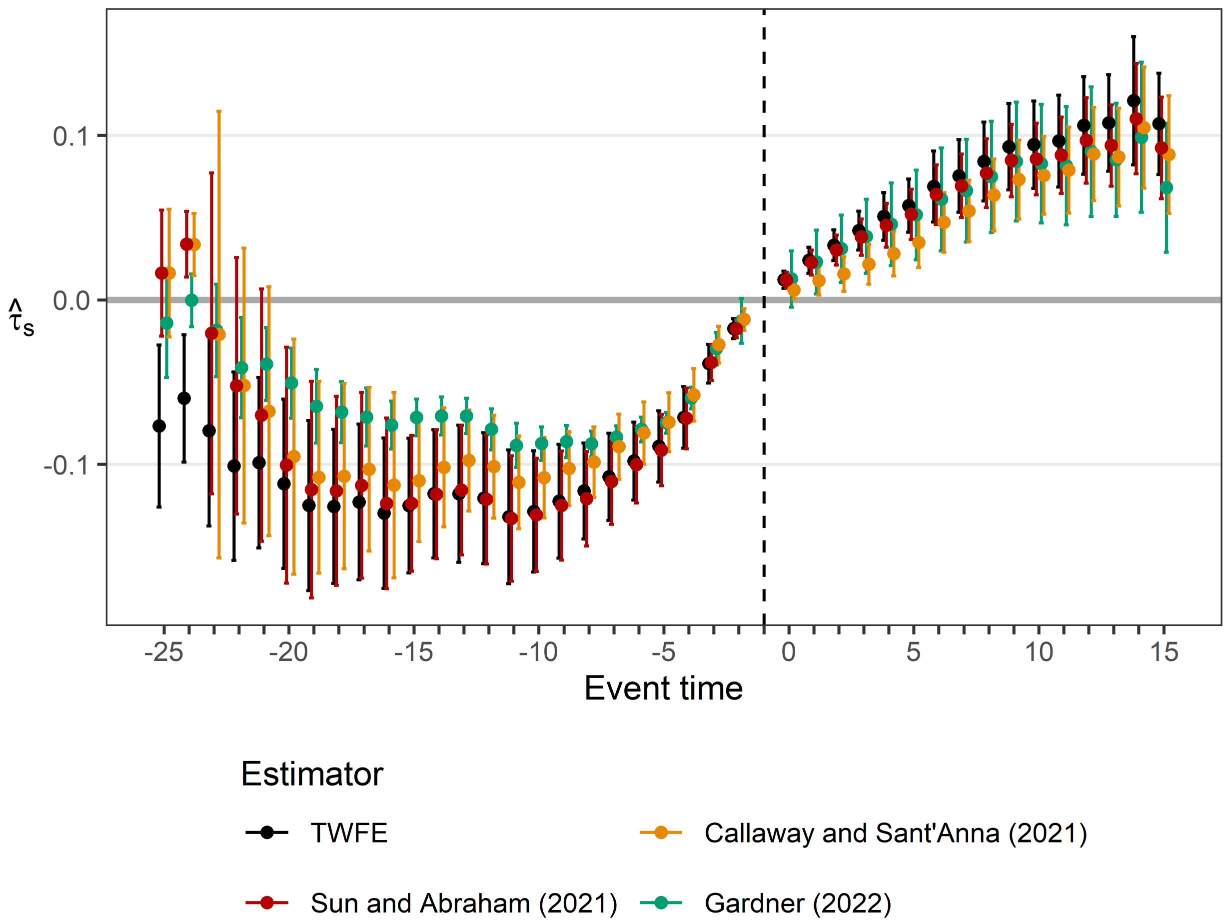
Figure A.1: Dynamic estimates. Outcome coded as acres of wetland area gains.



Point estimates of τ_s in eq. (3) and 95% pointwise confidence intervals. Standard errors clustered by state.

Dependent variable:	Wetland area gains (acres)
Treated units:	Private wetland mitigation bank sites (N = 400)
Control units:	Candidate private wetland mitigation bank sites (N = 141)
Dashed line, black:	The relative period 5 is the year of permit approval.
Dashed line, grey:	Reference period and the last untreated period in estimation.

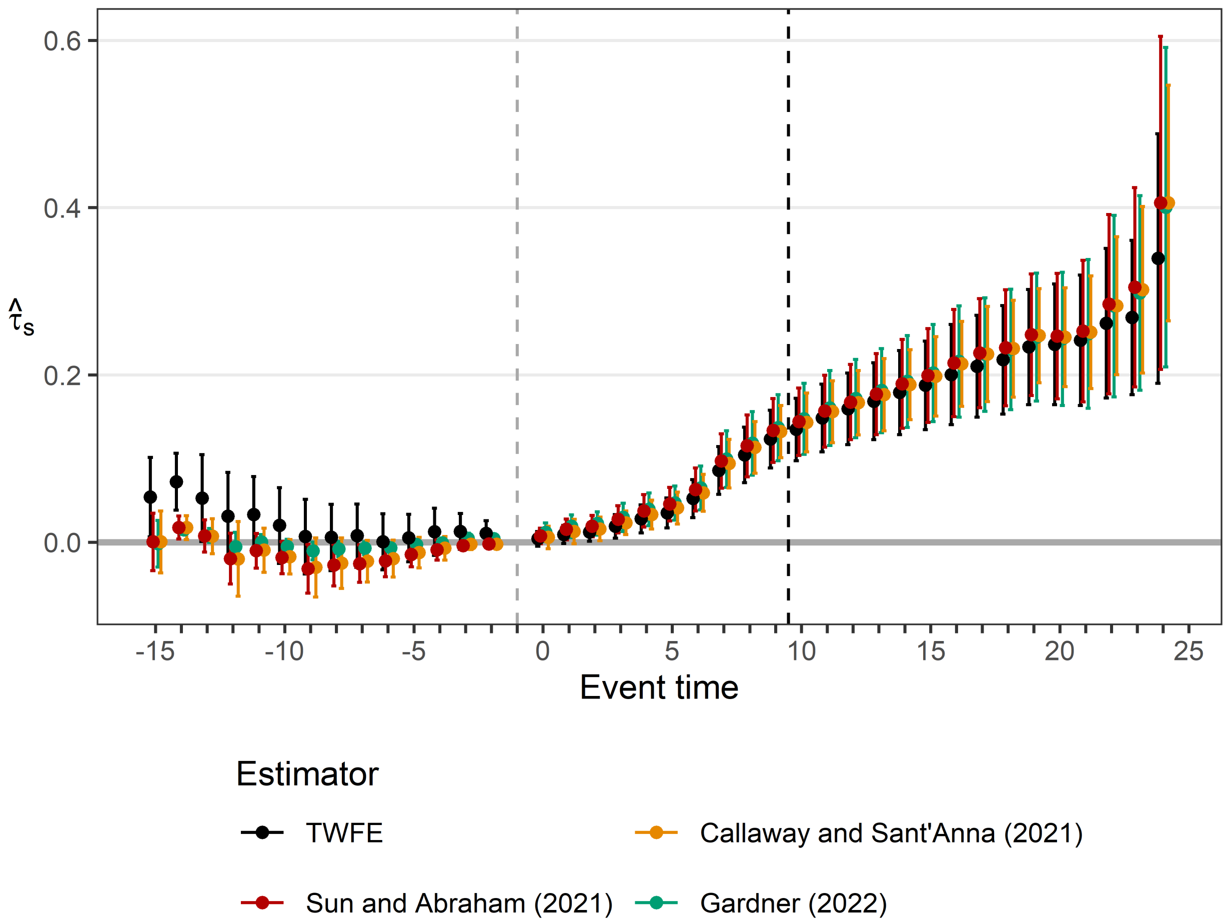
Figure A.2: Dynamic estimates. Treatment year in estimation = permit approval year.



Point estimates of τ_s in eq. (3) and 95% pointwise confidence intervals. Standard errors clustered by state.

Dependent variable:	Wetland area gains (share of site area)
Treated units:	Private wetland mitigation bank sites (N = 400)
Control units:	Candidate private wetland mitigation bank sites (N = 141)
Dashed line, black:	Reference period and the last untreated period in estimation. Relative period 0 is the year of permit approval.

Figure A.3: Dynamic estimates. Treatment year in estimation = permit approval year − 10 years.



Point estimates of τ_s in eq. (3) and 95% pointwise confidence intervals. Standard errors clustered by state.

Dependent variable:	Wetland area gains (share of site area)
Treated units:	Private wetland mitigation bank sites (N = 307)
Control units:	Candidate private wetland mitigation bank sites (N = 141)
Dashed line, black:	The relative period 10 is the year of permit approval.
Dashed line, grey:	Reference period and the last untreated period in estimation.

B Net loss of wetland area

This section describes the procedure to calculate net loss of wetland area, as discussed in Section 7 and presented in Figure 9.

We want to calculate net loss of wetland area within the compensatory mitigation programs as follows:

$$A_t^L - A_t^G \tag{5}$$

where

$$A_t^L = \text{Wetland area loss in year } t$$
$$A_t^G = \text{Wetland area gains that were used to compensate for } A_t^L$$

We observe A_t^L in the ORM data (Corps, 2020). We do not directly observe A_t^G, but we can estimate it based on our empirical results.

B.1 Impacts

We observe wetland losses, A_t^L, in the ORM2 data over 2012–2020. Data for years 2014 and 2015 are incomplete and total impacts for those years are projected. We only include the impacts that fulfill all of the following criteria:

1. The impact results from a discharge of dredged or fill material (regulated under CWA Section 404).
2. The impact results in a permanent loss of the aquatic resource.
3. The impact is compensated exclusively through private mitigation banks. (For impacts that are compensated through a combination of permittee-responsible mitigation, in-lieu fees and/or mitigation banks, we do not observe how many acres of lost wetland were compensated by each compensation method. Excluding these impacts will adjust the impact estimates slightly downward.)

B.2 Compensation

Let

$$A_t^G = \theta \cdot \overline{A}_t \tag{6}$$

where

$$\overline{A}_t = \text{Total compensation area, inclusive of all compensation activities.}$$

$$\theta = \frac{A_t^G}{\overline{A}_t} \ \forall\ t$$

The parameter θ represents the share of area gains out of the total area that was used to compensate for losses. We observe $\overline{A}_t$ in the credit ledger but we do not observe θ.

Above, θ is expressed in terms of acres embedded in credits that were used to compensate for impacts. Assume that we can also express θ in terms of *acres embedded in the credits that have been released to the banks but not yet used for compensation*. Then,

$$\theta = \frac{A_{rel}^G}{\overline{A}_{rel}} \tag{7}$$

where

$$A_{rel}^G = \text{Wetland area gains for which banks received compensation credits}$$

$$\overline{A}_{rel} = \text{Total area for which banks received compensation credits}$$

In other words, $\overline{A}_{rel}$ includes wetland area gains and enhanced wetland area. We observe $\overline{A}_{rel}$ in the credit ledger and we can estimate A_{rel}^G as follows:

$$\widehat{A_{rel}^G} = \widehat{ATT} \cdot \sum_i F_i \tag{8}$$

where $\widehat{ATT}$ is the estimated average percentage point increase in wetland area at a bank site. F_i is the area of the footprint of bank i (the property or the bank easement area).[10]

With an estimate for A_{rel}^G, we also have an estimate for θ and A_t^G:

$$\widehat{\theta} = \frac{\widehat{A_{rel}^G}}{\overline{A}_{rel}} \tag{9}$$

$$\iff \widehat{A_t^G} = \widehat{\theta} \cdot \overline{A}_t \tag{10}$$

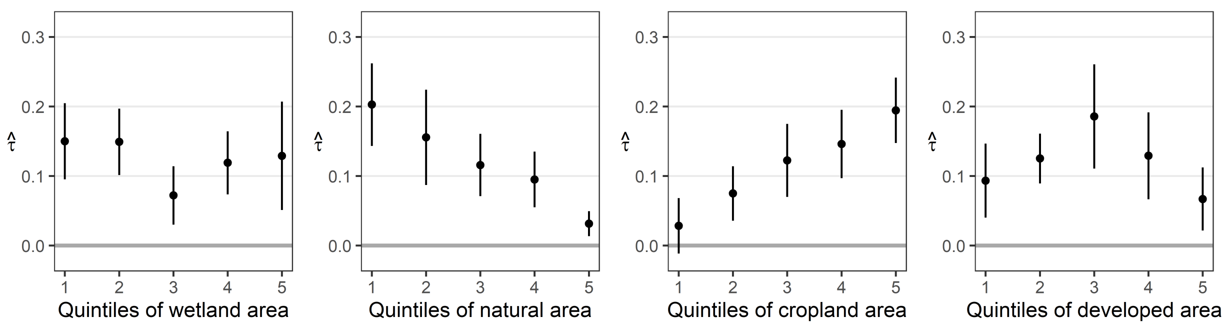
The wetland area losses, A_t^L, and estimates of the wetland area gains that were used to compensate for those impacts, $\widehat{A_t^G}$, are depicted in Figure 9.

[10]Note that in many cases $F_i \neq \overline{A}_{rel,i}^G$. We only observe the coordinates of F_i and not of $\overline{A}_{rel,i}^G$ and therefore we use F_i in obtaining the estimates.

C Heterogeneity

Figure C.1 shows how the estimated wetland gains vary according to the landscape characteristics of the treated units. The estimates are constructed by dividing the treated units into subsamples based on landscape characteristics (share of area belonging to a category) within a 1-kilometer buffer surrounding the treated site, measured at the treatment year.

Figure C.1: Wetland area gains across landscape characteristics



Point estimates and pointwise 95% confidence intervals of the effect of site establishment on wetland area (τ in eq. (2)) by subsamples according to quintiles of baseline values of selected variables for the treated units. Each estimate is obtained from a regression that includes the ever-treated sites belonging to that quintile and all never-treated sites. Variables are measured at 1 km buffers surrounding the treated sites. Quintiles of land cover variables are constructed according to the share of the land cover class out of the total site area. Estimator: Sun and Abraham (2021); see the notes in Table 2 for details on estimation. Land cover data source: USGS (2022).

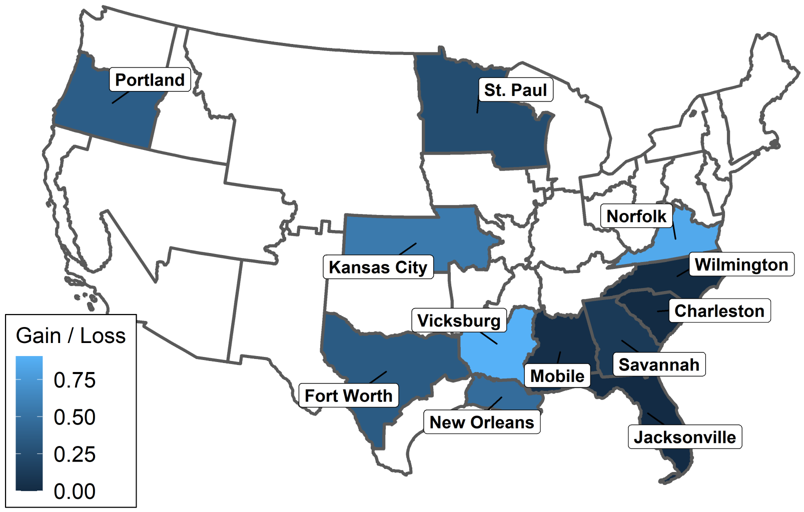
Two findings emerge from the estimates in Figure C.1. First, the wetland gains have occurred equally between landscapes that have differing amounts of pre-existing wetlands. An initial concern was that the wetland gains have occurred in landscapes with relatively large existing wetland areas. In such landscapes, the marginal functional value of additional wetland area is smaller than in landscapes with few existing wetlands. The results in Figure C.1 indicate that this is not the case.

Second, most increases in wetland extent have taken place in an agricultural landscape. The availability of suitable land area for conversion is the single most important determining factor for the type and success of compensation projects.

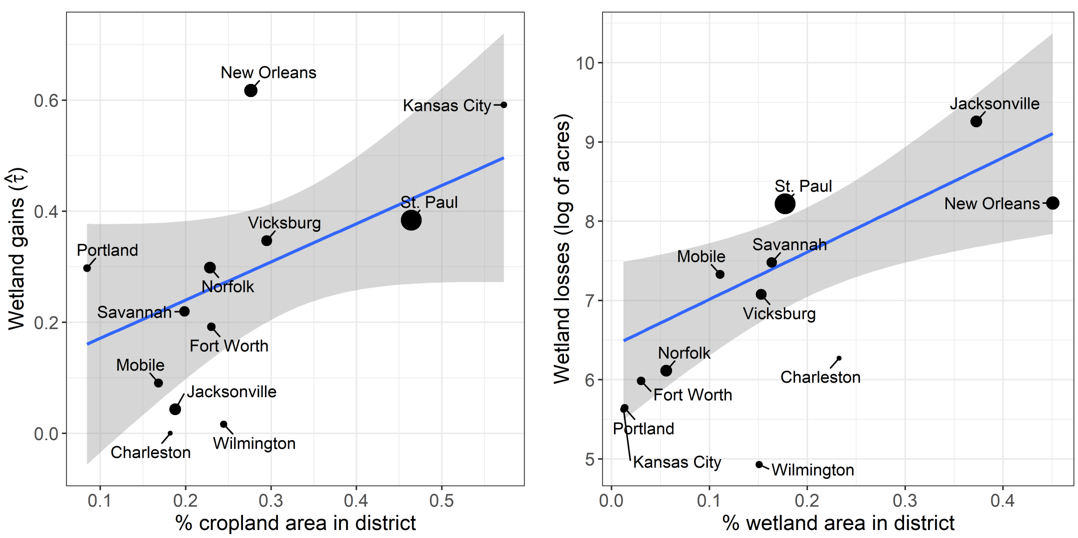
D Supplementary figures

Figure D.1: Heterogeneity of gains and losses by region

(a) Heterogeneity of net losses



(b) Land value and heterogeneity of wetland area gains



Panel (a): Estimated wetland gain/loss ratios by region. Gains: Each estimate is obtained from a regression that includes the ever-treated sites belonging to one region and all never-treated sites. Only regions with five or more ever-treated sites are included in this estimation sample. Losses: By region from ORM data (Corps, 2020).

Panel (b): Wetland gains and losses as in (a). Cropland and wetland shares within district from USGS (2022) and measured in 2000. Fitted line and 95% CI from a weighted linear regression where the weights (point sizes) correspond to the number of ever-treated sites in the full estimation sample.