Ecological Economics 239 (2026) 108755

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Environmental offsetting: What drives the choice of offset mechanism in the US Wetland Mitigation Program?[☆]

João Vaz [a], Jessica Coria [b,*], Ville Inkinen [c]

[a] Department of Economics, Nova School of Business and Economics, Universidade Nova de Lisboa, Portugal
[b] Environmental Social Science and Geography Unit, Department of Environmental Sciences, Aarhus University, Denmark
[c] Land, Environment, Economics and Policy Institute, Department of Economics, University of Exeter, United Kingdom

ARTICLE INFO

JEL classification:
D61
Q28
Q57

Keywords:
Offsets
Wetland mitigation
Mitigation banking
Clean Water Act
Market-based regulation
Cost-effectiveness
Regulatory choice

ABSTRACT

This paper examines offset method decisions under the US wetland mitigation program and compares the cost effectiveness of prescriptive on-site and market-based off-site approaches. By measuring costs through land values and benefits through flood control values, we highlight a clear trade-off between the two mechanisms. Prescriptive on-site compensation occurs in high-cost, high-benefit areas, whereas market-based off-site compensation occurs in low-cost, low-benefit areas. Our analysis also reveals that cost minimization heavily influences the regulator's choice of offset method, while flood control benefits appear to be absent from policy determinations. This finding, combined with the increased adoption of market-based offsets, suggests an overreliance on the market mechanism. Although policy guidelines promote market-based offsets due to their potential for environmental gains, they also require that both costs and benefits be considered in offset method determinations. Our findings indicate that regulatory decisions overlook the flood control benefits of prescriptive on-site compensation, revealing a divergence between policy intent and observed offset decisions.

1. Introduction

Environmental offsets are a potentially powerful tool for relieving the tension between development and conservation objectives. Aligned with the policy principle of "no net loss" (NNL), offsets seek to compensate for unavoidable impacts that remain after steps have been taken to avoid and minimize impacts on development sites. At present, more than 100 countries have offset policies in place or enabled, with 37 countries establishing mandatory offset requirements for development projects (GIBOP, 2019). Offsets are estimated to span over 150,000 km^2 (Bull and Strange, 2018), with annual transactions ranging between $US 6.3–9.2 billion (Deutz et al., 2020), representing the largest source of private finance for nature conservation (Deutz et al., 2020; OECD, 2020).

Although offset policies differ across countries and regions (depending on the specific environmental values that different programs seek to protect), offset mechanisms fall into two broad categories: a prescriptive approach, involving developer-led offsets at impact sites, and a market-based approach, involving offsets performed by a third-party off-site.[1] While the majority of offset programs are of the prescriptive kind, there has been a growing interest in, and adoption of, market-based offsets.[2] Given the increasing reliance on market-based offsets, it is important to scrutinize whether these mechanisms truly align with conservation goals or whether they inadvertently prioritize cost savings over environmental outcomes. Our study seeks to shed light on this important issue by analyzing whether the decisions made by the US Army Corps of Engineers (Corps) under the US wetland compen-

---

[☆] Financial support provided by Biodiversity and Ecosystem Services in a Changing Climate (BECC) research program, the Adlerbert Research Foundation, and from the BIOADD grant provided by the UK National Environment Research Council is gratefully acknowledged.

[*] Corresponding author.
E-mail address: Jessica.Coria@envs.au.dk (J. Coria).

[1] The environmental governance literature identifies voluntary offsets as a third type of offset mechanism. Voluntary offsets, however, play a limited role as a formal policy tool for achieving NNL goals, as they are driven by corporate social responsibility and are typically not subject to legal mandates or enforcement mechanisms. For a review of voluntary offsets in terms of development, context, and drivers, see Benabou (2014). See also Koh et al. (2019) and Darbi (2020) for alternative typologies of offset policies reflecting varying degrees of direct public intervention and decentralization.

[2] For a review of offset policies across countries and legislative frameworks, see McKenney (2005), McKenney and Kiesecker (2010), BBOP (2012), and OECD (2016). See also Bennett et al. (2017) for a comparative study of 99 offset programs across 33 countries. The authors reveal that, in 2016, 97% of offset activity (by area) was performed using the developer-led offset option. Market-based approaches are used in Australia, Canada, Germany, and the US, with trials for implementation in France, Switzerland, and the Netherlands (Morandeau and Vilaysack, 2012).

https://doi.org/10.1016/j.ecolecon.2025.108755
Received 25 March 2025; Received in revised form 30 July 2025; Accepted 1 August 2025

satory mitigation policy effectively balance the costs and benefits of conservation.

First established in the 1970s under the 1972 Clean Water Act, the US wetlands program is the oldest NNL policy framework, and it laid the foundation for similar programs globally (OECD, 2016). Administered by the Corps and the US Environmental Protection Agency (EPA), the program requires developers to offset unavoidable wetland impacts through compensatory mitigation to preserve wetland functions and values (Corps and EPA, 1990; Hough and Robertson, 2009). Initially, regulators preferred on-site wetland replacement by developers based on the understanding that wetland services are location-specific. However, recent regulations have shifted focus, emphasizing that offsets should be based on the most suitable type and location for compensating damages, including off-site and "out-of-kind" offsets performed by a third party (Corps and EPA, 2008).

This policy shift was driven by the limitations identified in developer-led offsets. These were criticized for often failing to deliver the required compensation and, even when successful, producing insufficient results due to the fragmented nature of project-specific offsets (NRC, 2001; Matthews and Endress, 2008; Moreno-Mateos et al., 2012). In contrast, third-party off-site compensation offers the potential for actions in locations with high environmental values and in advance of impacts, increasing the likelihood of offset success (Bekessy et al., 2010; Saenz et al., 2013). Today, the US wetland program explicitly states a preference for off-site compensation by mitigation banks, where third parties manage offset sites and sell wetland credits (i.e., quantified gains in wetland functions from restoration) to developers for meeting offset requirements.

Mitigation banking offers the possibility of a market approach to offset damages, as opposed to the prescriptive approach of on-site offsets performed by the developer. In cases where costs of offset provision vary across space, the ability to provide compensation off-site can lower the cost of meeting the NNL policy goal. In addition, the presence of multiple offset providers can lower the overall cost of NNL policies by offering more low-cost offset options and by spreading the cost of providing a given level of compensation across a larger pool of suppliers.[3] The question is whether these programs fulfill their regulatory purpose by providing compensation that adequately reflects the functions and values of wetland services lost to development at impact sites. Unlike typical commodities, the values of ecosystem services, in general, and those of wetlands, in particular, are highly specific to context and location. In contrast to on-site restoration, off-site restoration by banks promotes a redistribution of wetland services across the landscape; these services may be relocated to areas where they are less valued or needed. Moreover, the nonfungibility of ecosystem assets typically restricts the scale of potential markets. This may result in few offset suppliers and exchanges (Salzman and Ruhl, 2005), and thus undermine the allocative efficiency of a market-based approach due to the lack of adequate offset opportunities.

In this paper, we conduct a revealed preference analysis of offset policies, focusing on the decisions made by the Corps between prescriptive on-site and market-based off-site offsets under the US wetland mitigation program. Current regulations allow the use of both methods. Policy guidelines require that the Corps consider both the benefits and costs of wetland restoration in offset-method determinations (US Code 33 CFR §332.3). However, while the costs of restoration may be easily determined, the public benefits provided by wetlands are difficult to quantify. This is demonstrated by the fact that, while the overarching policy goal of NNL is framed in terms of maintaining neutrality with respect to wetland functions and values, offset implementation is frequently cast in terms of wetland area and hydrological functions alone. Achieving the NNL policy goal nevertheless requires that offsets consider not only the equivalence of wetland functions, but also which aspects of wetlands are valued and by whom.

In our analysis, we focus on the benefit of wetlands in terms of their protective value against flooding. Wetlands are water-saturated transition zones between land and water ecosystems. They protect surrounding areas from flooding by absorbing and retaining floodwaters. Although wetlands provide a number of other services that contribute to human welfare (e.g., water quality improvements, carbon sequestration, recreational opportunities, wildlife habitat), flood attenuation has been identified as one of the most significant economic benefits provided by all classes of wetlands (Conlisk et al., 2023). Flooding has also been reported as the deadliest and most costly type of natural disaster in the US (e.g., Gourley et al., 2017; Wing et al., 2020). While flood mitigation is but one of the many benefits delivered by wetlands, rich hydrological data on flood events and their interaction with wetland areas (Li et al., 2021), as well as recent causal estimates of the value of wetlands for flood mitigation (Taylor and Druckenmiller, 2022), allow for a tractable empirical evaluation of the contribution of wetland restoration to flood control.

We focus on two specific hypotheses. First, the lower the cost and the higher the benefit of off-site compensation, the more likely that the regulator chooses offsets performed by banks. This hypothesis is based on the efficiency criterion that locations offering lower cost-to-benefit ratios should be assigned a larger share of the offsetting effort. Second, the larger the size of the banking market, the higher the probability that the regulator chooses offsets by banks. This hypothesis is based on the observation that "thick" markets enable the distribution of compensation efforts across a larger set of offset providers, thereby reducing the overall cost of offset supply.

To investigate these predictions, we combined several datasets from government and scientific sources. We assembled (1) data on all impacts on wetlands requiring offset activities between 2012 and 2020, as well as the compensatory method chosen by the US regulator; (2) data on the characteristics of all banks in the wetlands program; (3) spatially explicit cost data associated with the cost of land conservation; and (4) spatially explicit benefit data in terms of the flood control value of wetlands from two academic sources.

The resulting combination of data enables us to empirically examine, ex post facto, the factors explaining the choice of offset method taken by the US regulator. Given that each offset method is associated to a specific location—impact site for developer-led offsets and bank sites for banking-led offsets—this spatial distinction allows us to evaluate whether offset decisions reflect the trade-offs between land costs and flood-control benefits at their respective locations. Specifically, we estimate the probability that the regulator selects banking over developer-led offsets, based on the relative costs and flood control benefits of compensation at impact and bank locations, as well as on the size of the banking market. More generally, these data allow us to characterize the costs and benefits of restoration across offset sites and to examine the distributional implications of offset siting decisions.

We provide several key empirical findings. First, while cost minimization (considering both conservation costs and the cost reduction effect of larger markets) significantly influences the choice between the two offset methods, flood control benefits are absent from policy determinations. Second, despite significant heterogeneity in the cost effectiveness of the two alternatives, we document an overreliance on banking in instances when prescriptive on-site compensation is associated with substantial cost-to-benefit advantages. Third, given the differences between wetland benefits lost on-site and those gained by banks off-site, the implied exchange ratio demands more compensation

---

[3] Beyond allocative efficiency, there are other sources of efficiency gains resulting from larger markets, such as the reduction in transaction costs (e.g., search and bargaining) and economic frictions (e.g., market power). For related literature, see Hahn (1984), Stavins (1995), Montero (1998), Liski (2001), Liski and Montero (2011), Singh and Weninger (2017), Baudry et al. (2021). Liski (2001), in particular, provides a formal treatment of how trading costs in permit markets evolve over time as a function of market size.

for meeting NNL than the average trading requirements set by regulators in the banking program. Finally, the banking mechanism has promoted a significant spatial redistribution of flood control benefits across the urban-rural landscape. Together, our findings convey both reassurance and concern. When choosing between prescriptive and market-based methods, the regulator of the US wetlands program capitalizes on the cost-reduction advantages of on- or off-site compensation but fails to internalize the benefit-reducing externality promoted by the decentralized banking mechanism.

This paper contributes to three primary strands of literature. First, we add to the empirical literature evaluating NNL policies, in general, and the US wetlands program, in particular. Several studies provide an overview of the opportunities and risks of NNL policies (e.g., Bekessy et al., 2010; Bull et al., 2013; Salzman and Ruhl, 2019). More recently, detailed geospatial and administrative data have allowed the evaluation of both the economic (BenDor et al., 2015, 2023; Aronoff and Rafey, 2023) and environmental (Inkinen et al., 2022; Theis and Poesch, 2022) performance of the offset industry.[4] Most empirical research focuses on the outcomes of banking, without comparing it to other offset mechanisms. Exceptions include studies contrasting the socioeconomic characteristics of communities served by wetlands at impact and bank sites in regional subsets of the US program (Ruhl and Salzman, 2006; BenDor et al., 2007; BenDor and Stewart, 2011).[5] Our evidence echoes previous findings of a significant migration of wetland services from urban to rural areas.[6] We nevertheless extend this literature by providing a comprehensive, program-wide evaluation of the redistribution of flood control benefits promoted by policy decisions. Moreover, our measure of restoration benefits allows us to explore how wetland relocation aligns with the goal of NNL of wetland values. This analysis, previously unexplored due to the lack of a direct mapping between socioeconomic characteristics and wetland values, offers new insights into the trade-offs involved in the US program.

Second, we contribute to the literature on the determinants of regulatory choice. Existing evidence shows that decisions by governmental agencies are influenced by various factors (e.g., economic conditions, political pressures, agencies' budget) across a variety of regulatory contexts (e.g., banking, health, public utilities).[7] A subset of this literature focuses on policy determinations by environmental agencies, with most studies examining the impact of special interest groups on enforcement stringency.[8] A smaller set of papers investigates the role of cost–benefit calculations in regulatory decisions, such as the banning of chemicals based on health and environmental risks (Cropper et al., 1992; Coria et al., 2022), the selection of contaminated sites for cleanup based on level of harm (Viscusi and Hamilton, 1999), the listing of species for protection based on degree of threat (Metrick and Weitzman, 1996, 1998; Dawson and Shogren, 2001), and the frequency of inspections of industrial facilities based on water quality of nearby streams (Chakraborti and McConnell, 2012). We contribute to this literature by exploring whether the costs and flood control benefits of wetland restoration influence the choice between on- and off-site compensatory mitigation by the regulator in the US wetland program.

Third, our work contributes to the literature by contrasting prescriptive versus market-based approaches in environmental regulation. The main theoretical finding is that incentive-based mechanisms are more likely to meet environmental goals at least cost by allocating more control to low-cost providers (Tietenberg, 1990; Stavins, 2003). This result does not necessarily generalize if marginal benefits are not constant across providers. This finding is reinforced by cost–benefit studies that contrast the two approaches in the context of ambient air pollution.[9] Despite evidence of spatially explicit benefits from land conservation (Ando et al., 1998; Polasky et al., 2008), few empirical studies compare the cost effectiveness of prescriptive versus decentralized policies. A notable exception is (Aronoff and Rafey, 2023), who estimate the private gains from wetland trades in Florida by comparing them to a scenario of direct conservation.[10] While their study contrasts a market-based approach with the alternative of a development prohibition, it does not address the choice of offset mechanism when development is allowed. By leveraging the concurrent use of developer-led and banking-led offsets in the US wetland program, we can directly compare the cost-effectiveness of prescriptive and market-based offsets using site-level benefit and cost estimates. This is important for policy decisions where the question is not whether to ban development altogether, but how best to mitigate its impact.

This paper is organized as follows. Section 2 presents a model of the cost-effective allocation of offsets, forming the basis for our two predictions regarding the choice of offset method based on cost–benefit differentials and the size of the banking market. Section 3 empirically examines the choice of method and the cost–benefit patterns observed within the US wetlands program. This section is divided into five subsections: Section 3.1 describes the program; Section 3.2 details our data sources; Section 3.3 outlines the measurement and rationale behind our benefit estimates; Section 3.4 provides an overview of the data; and Section 3.5 includes the regression analyses used to evaluate our theoretical predictions. Section 4 provides a discussion of the results and Section 5 concludes.

2. The economics of offsets

We develop a simple model of the choice of offset mechanism by the regulator to fix ideas and to motivate our empirical approach. The decision by the regulator is based on a given level of impact at the development site and on pre-existing characteristics at potential offset sites. Although NNL is the goal offset policies, achieving this goal at least cost is desirable from an economic perspective. In cases where offsets performed off-site at bank locations is optimal, a market can deliver the efficient allocation of offsets if property rights are clearly defined and there are no transaction costs. We analyze the efficiency properties of on-site offsets by the developer versus off-site offsets by banks under perfect market conditions.

---

[4] See also Levrel et al. (2017) and BenDor and Riggsbee (2011), who have conducted surveys among US mitigation bankers to examine how practitioners address the theoretical risks associated with mitigation banking. For a meta-review of earlier environmental evaluations of offset actions, see zu Ermgassen et al. (2019).

[5] See Kalliolevo et al. (2021) and Le Texier et al. (2024) for similar studies in Australia and France, respectively.

[6] Although all studies concur that the US program moves wetlands from high- to low-population density areas, the effect of this relocation on specific population groups is not consistent. For instance, BenDor et al. (2007) find that impact sites in the Chicago region of Illinois were located in areas with a lower average income and a higher percentage of minorities compared to bank sites, whereas (BenDor and Stewart, 2011) find that impact sites in North Carolina were located in more affluent, predominately white areas.

[7] See Scholz and Wei (1986), Deily and Gray (1991), Olson (1996), Helland (1998), Kroszner and Strahan (1999), Knittel (2006), Leaver (2009), Agarwal et al. (2014), Holland (2016), Kang and Silveira (2021).

[8] See Cropper et al. (1992), Ando (1999), Sigman (2001), Kosnik (2006, 2010), Langpap and Shimshack (2010), Grant and Grooms (2017), Langpap (2022).

[9] See Tietenberg (1995) for a review of earlier work and O'Ryan (2006), O'Ryan and Sánchez (2008) for two more recent contributions. See also Fowlie and Muller (2019) for a simulation of the gains from differentiated incentive-based policies due to heterogeneous marginal damages from NOx emissions in the US.

[10] Other empirical applications include Siikamäki and Layton (2007) and Busch and Grantham (2013), who simulate the potential costs and benefits between direct forest conservation strategies (protected areas) and incentive-based approaches (payments for ecosystem services) in Finland and in Indonesia. See also Robalino et al. (2015) and Sims and Alix-Garcia (2017) for two ex-post evaluations contrasting the impact of national parks and payments in terms of forest cover.

Consider a representative developer (indexed by 0) and n banks (indexed by $1, \dots, n$). The developer impacts land (or water areas) over the course of its development activities. After the implementation of avoidance measures aimed at minimizing development impacts, the residual amount of land degraded is of size $\overline{w} \in \mathbb{R}_+$. Let $D(w)$ with $D_w > 0$ (where subscript denotes partial derivative) represent the social cost of ecosystem functions and services that were lost due to the degradation of w units of land. To offset residual damages, the developer restores $l_0 \geq 0$ units of land on-site and each bank $k = 1, \dots, n$ restores $l_k \geq 0$ units of land off-site. Let $\eta_i \in \mathbb{R}_+$ for $i = 0, 1, \dots, n$ denote the site-specific parameter reflecting heterogeneous benefits of restoration across offset locations and let $B(l_i, \eta_i)$ denote the benefit of restoring l_i units of land at location i, where $B_l > 0$ and $B_\eta > 0$. The total benefit from restoration may thus be expressed as $\sum_{i=0}^{n} B(l_i, \eta_i)$.[11]

NNL is implemented by ensuring that condition $\sum_{i=0}^{n} B(l_i, \eta_i) \geq D(\overline{w})$ is met through on-site restoration by the developer and/or off-site restoration by banks. The objective of the regulator is that of minimizing the cost of meeting the NNL constraint. Let $\theta_i \in \mathbb{R}_+$ denote the site-specific parameter reflecting heterogeneous costs of restoration across offset locations and let $C(l_i, \theta_i)$ denote the cost of restoration at site i, where $C_l > 0$ and $C_\theta > 0$. The efficient distribution of offsets solves:

$$\min \sum_{i=0}^{n} C(l_i, \theta_i) \text{ subject to } \sum_{i=0}^{n} B(l_i, \eta_i) \geq D(\overline{w}) \text{ and } l_i \geq 0 \text{ for } i = 0, \dots, n. \tag{1}$$

Let $\{l_i^*(\boldsymbol{\theta}, \boldsymbol{\eta}, n)\}_{i=0}^{n}$ denote the solution to (1), where $\boldsymbol{\theta} = (\theta_0, \theta_1, \dots, \theta_n)$ and $\boldsymbol{\eta} = (\eta_0, \eta_1, \dots, \eta_n)$. The conditions necessary for an optimal allocation of offsets are:[12]

$$\frac{\partial C/\partial l_i}{\partial B/\partial l_i} \geq \lambda \quad \text{for } i = 0, \dots, n \tag{2}$$

with equality for an interior solution. These conditions correspond to the well-established equimarginal principle. At the interior optimum, the efficient allocation of offsets requires that the cost-to-benefit ratio of restoration must be equal at the margin across all producers of offsets.

From (2), we may derive the optimal choice of offset method employed by the regulator. Let $x_0 \equiv B(l_0, \eta_0)/D(\overline{w})$ define the share of damages compensated by the developer, with $1 - x_0$ representing the remaining share of damages compensated by banks. We may thus write the equilibrium share of developer-led offsets as:

$$x_0^* = x_0^*(\boldsymbol{\theta}, \boldsymbol{\eta}, n). \tag{3}$$

Note that, whenever $0 \leq x_0^* < 1$, only a subset of lost values will be reinstated by the banking market, with the remainder being compensated on-site by the developer. An efficient market will entail the purchase by the developer of $\{l_1^*, \dots, l_n^*\}$ units of restoration from each bank.[13]

Comparative statics show how the equilibrium share of restoration performed by the developer depends on the cost and benefit profiles of all available offset locations, as well as on the number of market participants. In particular:

$$\frac{\partial x_0^*}{\partial \theta_0} \leq 0, \quad \frac{\partial x_0^*}{\partial \theta_k} \geq 0, \quad \frac{\partial x_0^*}{\partial \eta_0} \geq 0, \quad \frac{\partial x_0^*}{\partial \eta_k} \leq 0 \tag{4}$$

for $k = 1, \dots, n$. That is, lower costs and higher benefits from on-site (off-site) restoration make developer-led (banking-led) offsets more likely to be chosen as the preferred offset method. This result is based on the principle that achieving NNL at least cost requires that offsets be allocated to locations that offer the highest environmental return for each dollar spent in restoration. In addition:

$$\frac{\Delta x_0^*}{\Delta n} \leq 0. \tag{5}$$

That is, the share of offsets performed by the developer (by banks) is always decreasing (increasing) with the number of banks. This result can be attributed to two effects. First, at the extensive margin, increasing the number of banks will expand the range of offset locations. This expansion could increase the availability of more cost-effective locations and thus lower the cost of meeting the NNL constraint through banking. And second, at the intensive margin, a larger number of banks may reduce the individual restoration effort required from each offset provider. If costs are convex with respect to restoration, an increase in market size will allow offset providers to operate at a lower, less costly point along their marginal cost schedule, with the drop in individual restoration costs being more pronounced than the corresponding drop in individual restoration benefits. As a result, maintaining the same level of aggregate benefits may be achieved at a lower unit cost whenever total restoration effort is distributed across more offset providers.[14]

Both effects work to decrease the cost of offsets through banking and thus lead to an increase in the choice of banking-led offsets with an increase in market size. This cost-reduction effect may nevertheless be conflated in empirical analyses, as the choice of banking-led offsets may dictate market entry and thus the size of the market. We return to this discussion in Section 3.5.

3. Empirical analysis

The theoretical framework highlights the fundamental principles that dictate the choice of offset method by the regulator. It allows us to make two key predictions.

1. *The smaller the cost and the larger the benefit of restoration on-site (off-site), the larger the share of offsets performed by the developer (by banks).*
2. *The larger the size of the banking market, the lower (higher) the share of offsets performed by the developer (by banks).*

In what follows, we investigate how these predictions characterize the US wetland program. In particular, we compare on-site restoration by the developer and off-site restoration by banks in terms of restoration costs and flood control benefits. Further, we examine whether cost–benefit differentials and the size of the banking market have affected the actual choice of compensation method selected by the regulator.

3.1. The US wetland mitigation program

US wetlands are protected under Section 404 of the 1972 Clean Water Act (CWA), which provides the Corps and the EPA with the authority to regulate impacts on aquatic resources. In a Memorandum of

---

[11] The assumption of strictly increasing and additively separable benefits from restoration ensure that offsets are both technologically possible as well as substitutable across offset locations.

[12] Condition (2) is also sufficient if $C_{ll}/C_l > B_{ll}/B_l$. That is, whenever the convexity of costs outweighs the convexity of benefits. If not, then benefits exhibit (strong) increasing returns to scale and increasing restoration at an individual location will yield more benefits relative to its cost. In that case, the optimal allocation will be such that all offsets are produced at one location alone. The optimal location is that which provides the lowest cost and the highest benefit for compensating all damages.

[13] In case the optimal allocation entails restoration by multiple banks, the decentralized solution can be achieved by setting a trading ratio (or exchange rate) between the developer and each bank. The optimal trading ratio corresponds to the ratio of marginal damages on-site to marginal benefits off-site: $\Delta l_k / \Delta \overline{w} = D_w(\overline{w}) / B_l(l_k^*, \eta_k)$ for $k = 1, \dots, n$.

[14] This effect applies if condition $C_{ll}/C_l > B_{ll}/B_l$ is satisfied. If not, then the cost-reduction effect of a larger market is attributed to the extensive-margin effect alone, since all damages will be compensated at one location alone. See Footnote 12.

Agreement (MOA) adopted in 1990, the Corps and the EPA established NNL as the guiding principle for reviewing permits for activities that impact wetlands (Corps and EPA, 1990).[15] Since then, permit applicants must offset unavoidable impacts—those that remain after avoidance and minimization efforts have been exhausted—through compensatory mitigation. Compensatory mitigation includes the restoration of degraded wetlands, the enhancement of functions of existing wetlands, or the creation of new wetlands from uplands. The two primary methods of compensatory mitigation are permittee-responsible mitigation (PRM), where the permittees themselves are responsible for the compensation project, and mitigation banking (MB), where a third-party develops a compensation project and sells offsets to permittees.[16]

The Corps and the EPA actively supervise the certification of offsets conducted by both permittees and banks. PRM and MB are similar in that both require an environmental assessment, a set of proposed restoration activities, and a detailed implementation program. These provisions are consolidated in a document called a "mitigation plan" (also referred to as "banking instrument" in the case of MB), which is a formal agreement between the regulators and either the developer or the bank owner. This agreement addresses responsibilities and goals for restoration plans (e.g., monitoring, performance standards, and financial assurances). The plan must include a site-protection instrument that places the offset site under a perpetual conservation easement restricting future uses and development.

The mitigation plan specifies how restoration activities on a compensation site will improve wetlands relative to their baseline condition. A comprehensive environmental evaluation will describe the initial state of the wetland, the ecosystem functions performed by the wetland, and the potential for improvement of these functions through restoration activities. The contribution of restoration activities to the improvement of wetlands is expressed in "credits", which are defined in terms of acres of wetland type (e.g., palustrine emergent or estuarine), as well as the nature of the restoration activity (e.g., creation or enhancement of wetlands). The determination of the number and type of credits is based on assessment methodologies designed to quantify the functions of wetlands in a systematic way.[17] Although assessment tools typically incorporate diverse criteria related to the biophysical processes that characterize wetlands (e.g., water storage capacity), credits do not directly account for the values derived from the functions that wetlands support (e.g., flood protection).

For wetland development, a similar environmental assessment is conducted to understand the extent of the damage and the type of offset that will be required. The regulator specifies the number and type of offset credits that the developer needs to implement (PRM) or purchase (MB) in order to proceed with permitted impacts. The developer who buys offsets from a bank is restricted to purchasing credits from banks operating within a pre-defined geographic area. These market boundaries, known as "service areas", are defined in the banking instrument; they approximate hydrological regions (e.g., watersheds and sub-watersheds).

In terms of offset trading, the regulator maintains a transaction ledger that tracks the allocation and release of credits from banks. When a bank is established, the regulator allocates a fixed quantity of credits to the bank. If MB is chosen as the compensation method, the regulator specifies the credits that developers must obtain and verifies whether they have secured enough credits to offset development impacts. Following the transaction's approval, the regulator withdraws the corresponding number of credits from the bank's balance. Although the regulator maintains the ledger, offset trades between developers and banks occur bilaterally, often with the help of private intermediaries. The lack of a formal transaction structure limits what we know about the exact market mechanism, and offset trading may involve a variety of imperfectly competitive characteristics.[18]

3.1.1. The choice between PRM and MB

The initial phase of NNL policy was prescriptive and did not involve offset trading. In the 1990 MOA, the Corps and the EPA expressed a preference for on-site and in-kind offsets performed by permittees. This preference was based on the recognition that the functions and values of wetlands are inherently tied to their location. As the program matured, several reports indicated that on-site PRM was yielding less-than-adequate restoration outcomes and that non-compliance rates were high due to limited resources for enforcement of individual offset projects (NRC, 2001; GAO, 2005). To secure offsets in advance of permitted impacts and to improve regulatory oversight over fewer offset locations, the two agencies have come to favor off-site compensation by banks. Recognizing that this adjustment might undermine the equivalence of offset activities, the service areas of banks were restricted to the same hydrological region as that of permitted impacts, so as to maintain a credible geographic link between losses and offsets of wetland functions. It is nevertheless the case that service areas often extend far beyond the immediate location of permitted impacts.[19]

Explicit regulatory preference for MB was incorporated in the 2008 Final Compensatory Mitigation Rule (Final Rule, Corps and EPA 2008). The current regulatory regime establishes that, when deciding between PRM and MB, the choice must be that which is environmentally preferable and that, in this determination, the regulator should evaluate factors such as the proximity of the compensation site to the impact site and the costs associated with the compensatory mitigation project (US Code 33 CFR §332.3). The policy states that, if permitted impacts fall within the service area of an approved bank and if the bank has the appropriate number and resource type of credits, then compensation should be performed through MB, with PRM being chosen only if these conditions do not hold. After the adoption of the Final Rule, MB became increasingly used as the preferred compensation method. While PRM represented about 60% of all offsets permitted by the Corps in

---

[15] Impacts regulated under this program typically include wetland fills for development, water projects (e.g., dams and levees), infrastructure development (e.g., highways and airport construction), and wetland conversion into agriculture land.

[16] A third method is in-lieu fee (ILF) programs, which have recently emerged as an alternative off-site mitigation option to MB. ILF programs are similar to MB but with two important distinctions. First, only government agencies or non-profit organizations may establish ILF programs. Second, unlike MB, which requires compensatory mitigation in advance of permitted impacts, ILF allows developers to pay a fee to the sponsoring entity, which then pools these fees to fund conservation projects at a later date. ILF programs are used in areas where off-site compensation is deemed the preferred offset method but MB is not an available option. Given that ILF does not require that the location of the offset be determined at the time of the impact, our analysis focuses on the comparison between MB and PRM alone.

[17] Examples of assessment methodologies include the Hydrogeomorphic Method (HGM) and the Uniform Mitigation Assessment Method (UMAM). These are quantitative tools that classify the hydrological and biological functions of wetlands and their improvement potential. Regulatory guidelines provide fixed exchange ratios that convert wetland attributes into credits. Conversion rates are based on factors such as the expected improvement in wetland function, likelihood of success, and uniqueness of habitat types. The specific methodology for calculating credits varies across jurisdictions depending on wetland characteristics and regulatory frameworks.

[18] For instance, government agencies frequently procure offsets through sealed-bid auctions (e.g., Department of Transportation in Georgia and Florida). On the other hand, private transactions involve bilateral negotiations, with some intermediaries providing price lists for potential clients.

[19] Service area boundaries are commonly defined by watershed. Watersheds are identified by an 8-digit hydrological unit code (HUC) by the US Geological Survey, which on average cover an area of 1,800 square kilometers (Seaber et al., 1987).

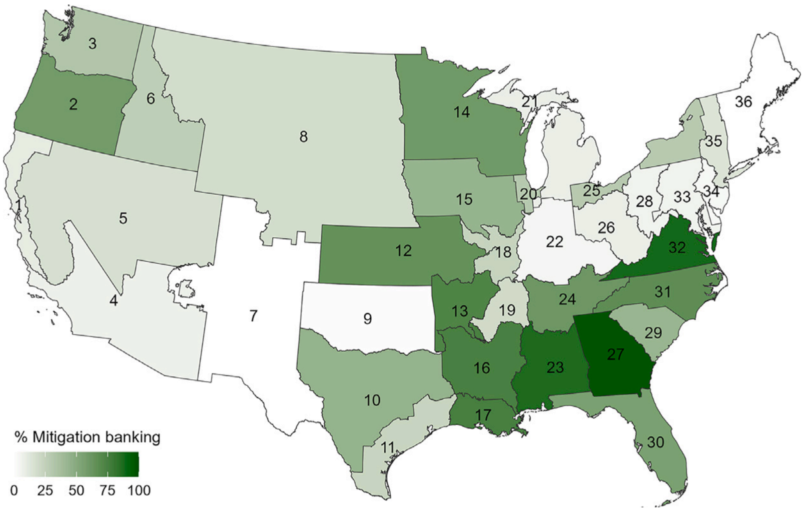

Fig. 1. Adoption of MB in the US wetlands program.
Shares of permit decisions on impacts to wetlands where MB was used for compensation over 2012–2020.

1: San Francisco
2: Portland
3: Seattle
4: Los Angeles
5: Sacramento
6: Wall Walla
7: Albuquerque
8: Omaha
9: Tulsa
10: Fort Worth
11: Galveston
12: Kansas City
13: Little Rock
14: St. Paul
15: Rock Island
16: Vicksburg
17: New Orleans
18: St. Louis
19: Memphis
20: Chicago
21: Detroit
22: Louisville
23: Mobile
24: Nashville
25: Buffalo
26: Huntington
27: Savannah
28: Pittsburgh
29: Charleston
30: Jacksonville
31: Wilmington
32: Norfolk
33: Baltimore
34: Philadelphia
35: New York
36: New England

Data source: Corps (2020).

2008 (IWR, 2015), by 2020 it represented only 31%. By contrast, MB now represents the choice of compensation method in more than half of all offset determinations (Corps, 2020).

Despite the widespread adoption of MB, its exact application is marked by regional differences. The Corps is organized into several geographical divisions and districts, which are defined in terms of watershed boundaries. Policy oversight is delegated to its 36 district engineers, each with the authority to choose the granting of permits, the environmental assessment method for credit calculation, and the compensation method for permitted impacts. This decentralization allows for considerable discretion in facilitating the emergence and viability of MB as a compensation option, in general, and in the choice between MB and PRM for offsetting a given impact, in particular. Fig. 1 shows the geographical boundaries of the 36 districts and the variation in the share of compensated impacts using MB within each district over the 2012–2020 period.

3.2. Data sources

Information on impact permits was obtained through Freedom of Information Act requests from the Operations and Maintenance Business Information Link Regulatory Module (ORM) administered by the Corps (Corps, 2020). The ORM database provides a detailed account of each impact, including the size of impact and the type of affected aquatic resource. For each impact, we observe whether compensatory mitigation was required and whether compensation was performed through MB or PRM. The data are observed over 2012–2020 and comprise 21,574 unique development projects with impacts to wetlands requiring compensatory mitigation. We observe the location coordinates of each impact and approximate its footprint with a circular buffer where the area corresponds to the reported size of the impact.

We obtained a complete record of wetland mitigation banks and credit transactions from the Regulatory In-lieu Fee and Bank Information Tracking System (RIBITS) (Corps, 2022). In addition to the characteristics and footprint polygons of individual banks, the database includes the polygons of service areas of banks and credit transaction ledgers. These data enable us to identify the banks that were available to supply compensation credits for a given impact and the total quantity of credits available for purchase.

To measure restoration costs, we use high-resolution maps of the market value of private lands, retrieved from Nolte (2020). This dataset was produced by training an ensemble of machine learning models on 6 million land sales across the contiguous US. The estimates provide a cross-sectional proxy for the opportunity cost of conservation strategies that restrict private property rights—as is the case with PRM and MB, since land used for offsets is placed under a perpetual conservation easement.[20]

As an alternative cost measure, we use agricultural land value census data from the USDA. Available at five-year intervals from 1997 to 2022, these data provide a temporal perspective on land values that is absent in Nolte (2020). While this allows us to capture trends in restoration costs over time, the USDA data are reported at the county level, which loses the within-county variation observed in Nolte (2020). As a result, with USDA data, variation of costs between impact and bank sites can only be detected when they are located in different counties.

We use LCMAP land cover data (USGS, 2022) to construct measures of land use dynamics around impact sites. The LCMAP dataset provides annual land cover classifications at a 30-meter resolution. These data allow us to track the extent of developed land and wetland areas over time. Specifically, we calculate the shares of developed land and wetland area within a 10 km buffer around each impact site. The interaction between these two measures will serve as the basis for capturing development pressure on wetlands, which we later incorporate into our

---

[20] It should be noted that conservation easements extinguish only a subset of property rights (e.g., development rights) in perpetuity, while landowners retain ownership of the land. In a validation exercise, Nolte (2020) find that their land-value estimates explain 73% of the variance in the appraised value of land placed under a conservation easement.

regression analysis as a proxy for economic factors influencing offset demand.

Wetland restoration benefits are approximated using two datasets. First, we use the US Flood Database (USFD) developed by Li et al. (2021). The USFD integrates several flood datasets and provides detailed information on flood events across the US, including location, duration, and geographic characteristics of the impacted area. This dataset allows us to link the benefit of wetland restoration directly to the physical characteristics of offset sites, specifically in terms of their potential for flood attenuation. Second, we use the monetized benefit estimates of US wetlands by Taylor and Druckenmiller (2022) (TD). The authors combine flood-insurance claims data with high-resolution wetland area data to estimate the value of wetlands in mitigating flood damages across the US. By integrating their main empirical estimates with geospatial data on urban development and other landscape features, the authors provide spatially explicit wetland values. This dataset provides us with an estimate of the monetary value of wetland restoration at a given location in terms of avoided flood damages based on the local level of development.

The precise measurement and rationale underlying our benefit estimates are detailed below.

3.3. Benefits of wetland restoration

We approximate flood control benefits with flood counts using the USFD high-resolution maps of flood occurrence. This measure of benefit assumes that the value of wetland restoration is positively related to the historical incidence of flooding. This assumption is anchored on expected utility theory, which asserts that the willingness to pay (WTP) for a reduction in risk is increasing with the baseline level of risk (Jones-Lee, 1974). The higher-baseline risk hypothesis is consistent with empirical studies that find that the WTP for flood risk mitigation is increasing with perceptions of flood risk and with flood experience.[21] To address the fact that the flood attenuation service of a wetland is not only local but occurs along its drainage area, we consider the sub-watershed as the unit of analysis, rather than the area extent of the offset site alone.[22],[23]

There are two main advantages of this measure of benefits. First, it is independent of (although correlated with) our cost measure. Second, it allows us to capture the variability of benefits in terms of exposure to flood risks. The disadvantage is that it does not account for the variability in flood damages owing to differences in development (i.e., exposed capital) and population density. To address this caveat, we complement the analysis with the monetary estimates from TD that specifically incorporate differences in value based on local levels of development.

We note two limitations in using TD estimates as the sole basis for our analysis. First, the estimates do not account for the flood protection benefits to agricultural assets. TD's valuation exercise relies on claims data from the US National Flood Insurance Program, which primarily covers residential and commercial property losses. Their spatially explicit measure considers the differential value of wetlands based on levels of urban development, but not on land conversion involving agricultural production, which is also susceptible to flood risks and economic losses. For that reason, their estimates might inadequately capture the flood control benefit of wetland restoration in rural settings, where off-site mitigation banking typically takes place.[24] The second limitation of the TD measure is that it does not reflect flood incidence of specific locations. Their estimates correspond to the average benefit of wetlands within a region, adjusted for local levels of development, but not for local flood vulnerability. This could lead to an overstatement of benefits in offset locations that are highly developed yet face minimal flood risks, while also reinforcing a positive correlation between land values and flood control benefits, since both are partially driven by levels of urbanization. Therefore, using both the physical and monetary measures of benefit offers a check on whether the observed trade-offs are driven by valuation approaches, and provides a complementary view of flood-control benefits across the landscape.

3.4. Data description

To provide an overview of the data, we compare the geographic distribution of impacts and banks to the distribution of land cover characteristics, market size, and cost and benefit measures. Fig. 2 illustrates these patterns in the state of Georgia, where the cost and benefit trade-offs are particularly salient. Panel (a) shows how wetland development occurs predominantly near existing developed areas, where wetlands are relatively scarce. In contrast, bank sites are fewer and typically located in rural landscapes with higher existing wetland density. Qualitatively, these patterns show that offset trading involves significant spatial reallocation of wetlands within each market. This reallocation includes both the relocation of wetlands from urban to rural areas and the consolidation of numerous small impacts into fewer, larger mitigation banks.

Panel (b) illustrates the variation in the size of markets that service impacts. The two delineated regions depict the service areas of two banks. As previously noted, if an impact is located within the service area of a bank, the developer may purchase compensatory credits from that bank. Although the service areas correspond to hydrological regions, service-area demarcations often have partial overlaps. Consequently, the size of banking markets are not uniquely defined by geographical boundaries. The background map in Panel (b) depicts the number of overlapping service areas or, equivalently, the number of banks that could provide compensation for an impact at a given location.

Panels (c) and (d) in Fig. 2 illustrate the relationship between impact and bank locations to restoration costs and benefits (in terms of flood incidence). These figures display two stylized facts that underpin our empirical analysis. First, the costs and benefits of wetland restoration are positively correlated, which implies a trade-off in the choice of offset locations. This pattern holds across both our flood-incidence and monetized measures of benefit, although the correlation between costs and benefits is stronger with the TD estimates due to their connection with development intensity. This consistency suggests that the observed trade-off reflects a broader spatial pattern of costs and flood-control benefits rather than a measurement artifact. Second, impacts to wetlands are concentrated in urban and suburban areas that have high land values and recurrent flooding, while banks are located in areas with lower land values and lower flood control benefits.

---

[21] Examples include Browne and Hoyt (2000), Botzen and van den Bergh (2012), Petrolia et al. (2013), Netusil et al. (2021), and Ando and Reeser (2022).

[22] Sub-watersheds are identified with a 12-digit HUC by the US Geological Survey. The interquartile range for the area of these regions is from 15.8 to 29.7 thousand acres.

[23] Flood protection by wetlands is achieved through three primary mechanisms: (1) absorption of floodwaters (both by surface water retention and soil infiltration), (2) evapotranspiration (due to wet vegetation), and (3) attenuation of flood flows along watercourses (Acreman and Holden, 2013). While the first two mechanisms provide local flood mitigation, the third highlights the landscape-wide impact of wetlands in reducing downstream flood risks across the drainage basin.

[24] TD find that cropland and pasture accounted for 35% of wetland loss and 58% of wetland gain. However, when testing for differential flood mitigation impacts by land use, the authors find that the loss of wetlands increases flood damages only when wetlands are converted into developed land, but not when they are converted into agricultural land. This result is likely attributable to the fact that agricultural production does not generate substantial claims in their data.

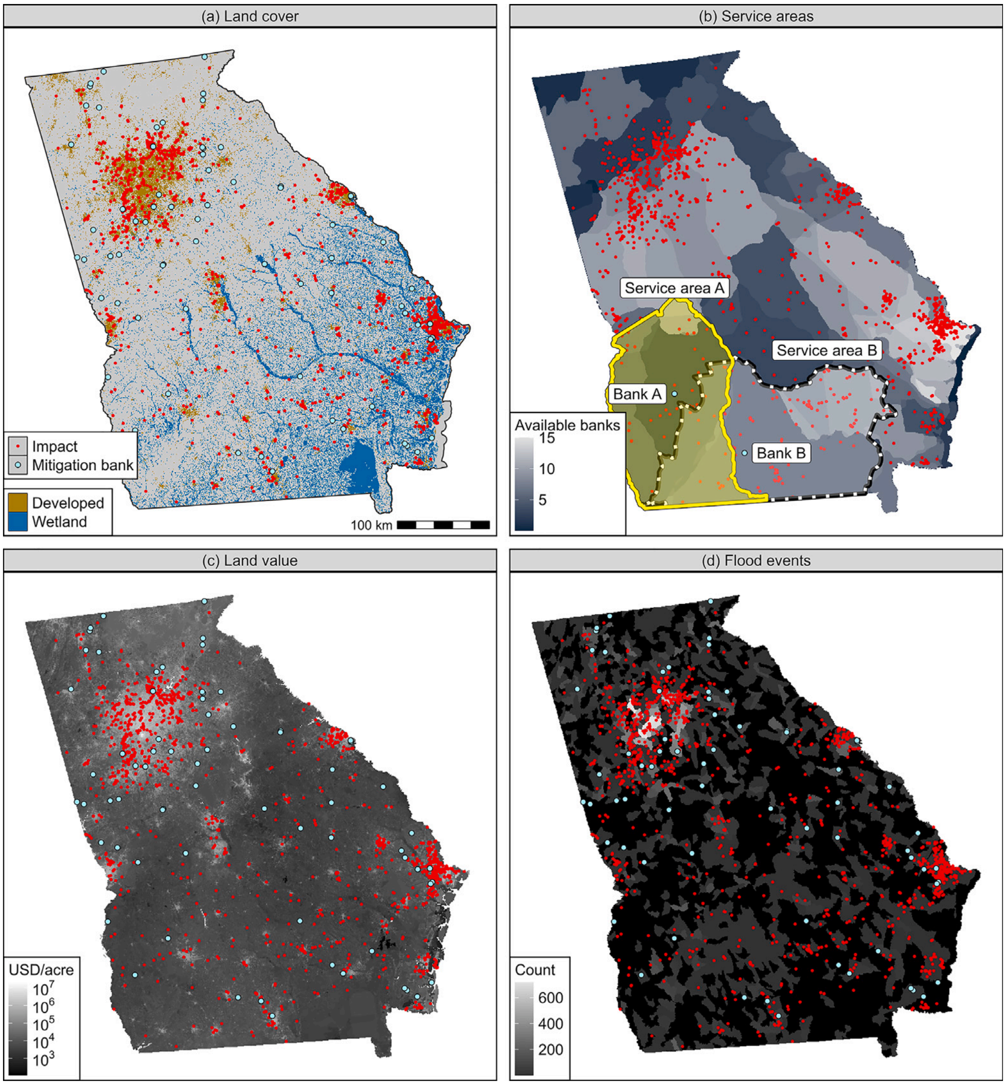

Fig. 2. The distribution of impacts and mitigation banks in Georgia.
Impacts to wetlands requiring compensatory mitigation and mitigation banks that were available to compensate those impacts in the state of Georgia from 2012 to 2020 (Corps, 2020, 2022). Panel (a): Land cover classification in 2021 (USGS, 2022), overlaid with the location of impacts and banks. Panel (b): Density of banks servicing impacts that fall within the corresponding region, overlaid with the location of actual impacts. Two examples of mitigation bank service areas are delineated in yellow and black. Panel (c): Expected land-sale prices in 2010 (Nolte, 2020), overlaid with the location of impacts and banks. Panel (d): Flood counts over 2002–2019 (Li et al., 2021), overlaid with the location of impacts and banks.

Consequently, there is an apparent cost-saving potential from choosing off-site compensation by banks (MB), while benefits are higher for on-site compensation by the developer (PRM).

Table 1 provides the descriptive statistics for the overall program in the contiguous US. The patterns shown in Fig. 2 generalize at the national level. On average, the land value at impact sites exceeds that at MB sites by 129,000 USD per hectare. This difference in restoration costs favors the choice of off-site MB. Conversely, our two benefit measures favor the choice of on-site PRM. Flooding occurs nearly twice as often at impact sites compared to bank sites, and the monetized flood control benefits of wetlands at impact sites are more than three times larger than those at bank sites.

Fig. 3 illustrates the trade-off between the cost and benefit of restoration and the correlation with the choice of offset method by the regulator. The data comprise the overall program in the contiguous US, aggregated annually over each of the 36 districts. Each data point corresponds to a specific year-district pairing. The color of the points indicates the choice of off-site MB, measured as the share of impacted area compensated by banks.

The left panel displays the cost advantage (x-axis) and benefit advantage (y-axis) of compensation at bank sites compared to impact sites for a given year and district. The figure reveals a strong positive association between the choice of off-site MB and the cost–benefit differential between on- and off-site compensation. This indicates that MB is more prevalent when the average cost-to-benefit advantage of MB over on-site PRM is high.

The right panel in Fig. 3 illustrates the relationship between the cost–benefit score of MB (calculated as the sum of the x- and y-axes in the left panel) and the number of banks. Two main insights can be drawn from this figure. First, the cost–benefit score of MB is positively correlated with the number of banks, which suggests that the cost and benefit advantages of off-site compensation are significant factors in the development of a banking market. Second, for a given cost–benefit score, MB is chosen more often when the market size is large. This pattern is consistent with our prediction that larger markets should favor the choice of MB.

Fig. 3 presents cross-sectional correlations that reflect the pattern across administrative districts in the program. Below, we perform a

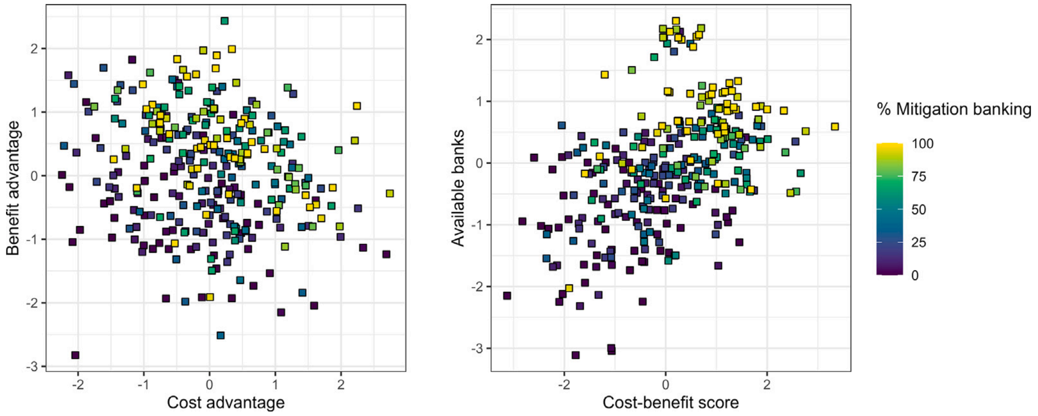

Fig. 3. Cost and benefit differentials and the choice of offset method.

Impacts to wetlands for 2012–2020, aggregated annually over the administrative districts of the US wetlands program. The color gradient indicates the share of impacted area that was compensated through MB. *Cost advantage*: Mean difference in land value between impact sites and bank sites that were available for compensation. *Benefit advantage*: Mean difference in the number of flood events between impact sites and bank sites that were available for compensation. A higher value in cost and benefit advantage implies that MB outperforms PRM. *Cost–benefit score*: Sum of cost advantage and benefit advantage. *Available banks*: Mean number of banks that were available for compensating impacts. All variables are log-transformed and standardized.

Data source: Corps (2020, 2022), Li et al. (2021), Nolte (2020).

Table 1

Descriptive statistics.

Data source: Nolte (2020), Li et al. (2021), Taylor and Druckenmiller (2022), Corps (2020, 2022).

Variable	Impact sites	Bank sites	Difference
Land value (US $1,000/ha)			
Mean	155.78	26.80	128.98***
Std. dev.	402.78	75.33	
Flood events (count, 2002–2019)			
Mean	28.82	15.00	13.82***
Std. dev.	94.90	51.36	
Wetland restoration benefit (US $1,000/ha/year)			
Mean	7.13	2.28	4.85***
Std. dev.	14.72	7.63	
Area (ha)			
Mean	1.35	196.64	−195.29***
Std. dev.	27.05	564.48	
Available banks			
Mean	5.64		
Std. dev.	10.47		
Mitigation method (% MB chosen)			
Mean	66.4%		
Std. dev.	47.2%		
N	28,291	1,390	

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Welch two-sample t-test.

Impacts to wetlands requiring compensatory mitigation and mitigation banks that were available to compensate those impacts from 2012 to 2020.

regression analysis to examine the relationship between the choice of offset method and both cost–benefit differentials and market size, while accounting for regional and time-specific effects.

3.5. Regression analysis

3.5.1. The influence of costs and benefits on the choice of offset method

First, we examine whether the association between costs, benefits, and the choice of mitigation method, as depicted in the left panel of Fig. 3, also holds after accounting for time-invariant regional characteristics and temporal trends. In particular, we estimate the following panel-regression model:

$$Y_{it} = \beta_1 C_{it} + \beta_2 B_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \tag{6}$$

where Y_{it} is the share of impacted wetland area compensated through mitigation banking in district i in year t, C_{it} is the average cost advantage of MB relative to PRM, B_{it} is the average benefit advantage of MB relative to PRM, α_i and γ_t are district and year fixed effects, and ε_{it} is the error term. The cost and benefit variables are calculated in terms of the log difference between their average value at the location of banks servicing a given impact and the value at the corresponding impact site. For both variables, a higher value implies that MB outperforms PRM. We also estimate (6) with impact-level data (repeated cross-section), where the binary outcome Y_i indicates whether MB was chosen as the offset method for impact i.

The regression results are shown in Table 2. The upper section presents district-level regressions with aggregated data, while the bottom section presents analogous impact-level logit regressions where the outcome is a binary indicator of the chosen mitigation method. The first column in the upper section corresponds to a pooled OLS regression on the data depicted in the left panel of Fig. 3. Here, both cost and benefit measures are strongly associated with the choice of offset method. The estimates indicate that a decrease in cost or an increase in the benefit of restoration at bank sites increases the choice of MB. Specifically, an increase of one standard deviation in both variables combined corresponds to a 29.2 percentage point increase in the predicted share of MB.[25] However, after including unit and year fixed effects, only the cost variable coefficient remains statistically significant, and its magnitude is reduced to less than a third of the pooled model estimate.

This finding is robust to various alternative specifications. In column (3), the data are aggregated by sub-basics (Hydrological Unit Code 8-digit regions) which approximate the size of banks' service areas. In columns (4) to (6), we introduce additional controls. Specifically, we control for the size of compensated impacts and for development pressure. The size of an impact is measured as the reported area extent of the impact, while development pressure is captured by the interaction between the trend in developed land around an impact site and the remaining wetland area at the time of the impact.[26],[27] Columns

---

[25] The reported coefficients are from standardized variables which are constructed as log differences between measurements at impact sites and mitigation bank sites. Without standardization, the results imply that a combined one percent increase in both the cost and the benefit differentials corresponds to a 0.32 percentage point increase in the predicted share of MB.

[26] The size of an impact may influence the feasibility of compensation through, e.g., land availability constraints. Descriptively, larger impacts tend to occur in rural areas, suggesting a non-uniform spatial distribution of impact sizes.

[27] The trend of developed land is measured as the share of developed landcover in LCMAP over the 10 years prior to an impact and within a 10 km buffer

(5) and (6) test the stability of our results by replacing the primary cost and benefit variables with alternative data sources. Column (5) uses USDA agricultural land values as a measure of cost, while column (6) uses the flood-control value estimates from Taylor and Druckenmiller (2022) as a measure of benefit.[28] Across specifications, the results remain consistent.

Finally, we examine the robustness of our results using logit estimates based on project-level data in the bottom section of Table 2. Columns (1) through (6) follow the same specifications as those described for the upper panel. Across different models, the estimates reinforce our main finding: the cost advantage of banks is positively associated with the choice of MB as an offset mechanism, while differences in flood control benefits do not significantly influence regulatory decisions.

3.5.2. The influence of market size on the choice of offset method

In this section, we examine the relationship between market size and the choice of offset method. Descriptively, the right panel of Fig. 3 shows that larger markets are associated with a higher uptake of MB. This aligns with theoretical predictions that larger markets reduce offset costs, thereby increasing the share of banking-led offsets. However, since banking uptake by the regulator may also influence market size by encouraging bank entry, the observed relationship could be confounded by offset demand.

To mitigate this effect, we estimate panel regression models similar to Eq. (6), incorporating the number of available banks as an explanatory variable, while controlling for demand-side factors. Specifically, we focus on regression models that include development pressure as a control variable. Development pressure, measured as the interaction between land development trends and wetland area at impact sites, reflects the increased offset demand in regions where high development activity coincides with significant wetland cover. By accounting for this variable, the model helps differentiate the impact of market size on banking uptake from demand-driven factors that may influence bank entry.

Table 3 presents regression results with alternative specifications analogous to those in Table 2. The estimates consistently indicate that increases in market size are associated with a higher uptake of MB. Columns (4) through (6), which include the development pressure control, confirm the stability of these findings. Model (4), in specific, indicates that a one percent increase in the number of available banks is associated with a 0.22 percentage point increase in the share of MB. In addition, the logit estimates from project-level data (lower panel) closely match the findings from the aggregate-level analysis (upper panel), further reinforcing the robustness of the results.

Also note that including the number of banks does not significantly alter the coefficients on cost (and benefit) differentials across specifications, as shown in Table 2. This reflects the fact that, while the cost–benefit score and market size variables are strongly correlated cross-sectionally (as shown in the right panel of Fig. 3), their changes over time are not. The regression results therefore indicate that changes in market size influence the share of mitigation banking beyond what site-level cost differences alone can explain. This supports the interpretation of market size as an independent driver of offset method choice, in line with theoretical predictions.

4. Discussion

Because the costs and benefits of restoration are closely tied to their location, the decision between prescriptive on-site and market-based off-site compensation directly influences the ability of offsets to achieve the policy goal of NNL. The choice between the two methods is nevertheless not straightforward when costs and benefits move in the same direction, as it becomes difficult to identify an option that is both more effective and less costly. Our data reveals a significant tension between the two methods: on-site locations exhibit higher restoration costs and flood control benefits, whereas off-site bank locations exhibit both lower costs and benefits. This trade-off underscores the importance of basing offset method determinations on cost-to-benefit assessments.

Our results nevertheless reveal that the influence of cost-effectiveness on regulatory choice is only partially significant. Specifically, while lower costs at off-site locations have a significant impact on the choice of banking-led offsets, no significant relationship exists between flood control benefits and the choice of mechanism. This is true when benefits are measured in terms of flood risk exposure as well as in terms of monetized estimates based on flood insurance claims.

This finding is important for three reasons. First, when combined with the observation that mitigation banking has increased significantly over time, it suggests an overreliance on the banking mechanism. The 2008 Final Rule states that banking should take precedence over other offset methods. Our results confirm the widespread adoption of banking and indicate strong regulatory adherence to the Final Rule. However, alignment with this policy directive should not preclude variation in the choice of mechanism explained by cost and benefit indicators. Policy guidelines explicitly state that offset decisions should be based on the costs of offset projects as well as on the benefits from wetland services. Although our findings suggest that the regulator exhibits some degree of cost sensitivity, they nevertheless reveal that on-site benefits are absent from policy determinations. By favoring banking as the primary offset method, regulators overlook the potential flood control advantages of on-site compensation, thereby deviating from the policy rule.

Second, our results raise concerns regarding the policy goal of achieving NNL of wetland values. Although the choice of a less efficient mechanism does not prevent the reinstatement of lost values—instead implying that more compensation might be required for full replacement—the fact that flood control benefits do not factor into regulatory decisions suggests that offsets may fail to deliver equivalent wetland values. Many authors have noted that trades in the wetland program are not based on service values but instead on wetland acreage and functions (e.g., King et al., 2000; Salzman and Ruhl, 2019). As a surrogate for value differentials, regulators typically stipulate that exchange ratios between wetland area restored and lost be greater than 1 : 1. Given the difference between benefits on-site and those at bank sites, the replacement of flood control values in our data would entail the restoration of 3.13 acres of land in exchange for 1 acre of original wetland.[29] This average ratio is relatively consistent with the range of ratios that are frequently employed in the program, which typically fall between 1 and 3 acres of created or restored wetland in exchange for 1 acre of impacted wetland (Hook and Shadle, 2013).[30] Nevertheless, if we were to focus on instances where on-site compensation had a higher cost–benefit score but banking was chosen, full replacement of flood control values would have required a ratio of 10 : 1, which is

---

around the impact site. Wetland area is measured as the share of wetland-cover in LCMAP within a 10 km buffer around the impact site at the time of the impact.

[28] USDA data are reported at the county level, which limits within-county variation in costs between impact and bank sites. In our sample, 86.1% of all impacts had at least one bank in a different county and 49.2% had all banks in a different county. The coarser resolution of USDA data may contribute to the attenuation of the cost coefficient observed in Table 2, cols.4–5.

[29] This assumes that flood control benefits vary linearly with area lost and restored.

[30] At the federal level, a minimum 1 : 1 ratio is required between acres compensated and acres impacted (Corps and EPA, 2008). Nevertheless, district divisions have discretionary power to establish their own ratios, which in general are set at a level greater than 1 : 1. They vary by, for instance, the type of offset (restoration, creation, etc.) and the type of wetland impacted.

Table 2
Costs, benefits, and the choice of mitigation method.

	(1)	(2)	(3)	(4)	(5)	(6)
Unit of observation: Region						
Dependent variable: share of MB chosen						
Cost advantage of MB						
(a) Land value	0.117***	0.037*	0.026**	0.042**		0.051**
	(0.023)	(0.016)	(0.009)	(0.015)		(0.018)
	[<0.001]	[0.029]	[0.005]	[0.008]		[0.008]
(b) Ag. land value					0.020***	
					(0.004)	
					[<0.001]	
Benefit advantage of MB						
(a) Flooding events	0.175***	0.013	0.024*	−0.010	−0.020	
	(0.030)	(0.027)	(0.010)	(0.029)	(0.028)	
	[<0.001]	[0.629]	[0.014]	[0.711]	[0.439]	
(b) Wetland benefit						0.019
						(0.018)
						[0.283]
Additional covariates				✓	✓	✓
Year and region FEs		✓	✓	✓	✓	✓
Region		District	Sub-basin	District	District	District
N	316	316	4529	316	316	316
R^2 adj.	0.247	0.658	0.436	0.673	0.670	0.674
Unit of observation: Development project						
Dependent variable: $\mathbb{I}$(MB chosen)						
Cost advantage of MB						
(a) Land value	1.242*	1.216**	1.374***	1.198*		1.138*
	(0.119)	(0.091)	(0.098)	(0.091)		(0.074)
	[0.024]	[0.009]	[<0.001]	[0.017]		[0.049]
(b) Ag. land value					1.006	
					(0.012)	
					[0.640]	
Benefit advantage of MB						
(a) Flooding events	1.080	1.009	0.972	0.994	0.960	
	(0.111)	(0.066)	(0.057)	(0.063)	(0.057)	
	[0.450]	[0.886]	[0.628]	[0.923]	[0.486]	
(b) Wetland benefit						0.868
						(0.074)
						[0.098]
Additional covariates				✓	✓	✓
Year and region FEs		✓	✓	✓	✓	✓
Region		District	Sub-basin	District	District	District
N	23 061	23 057	18 753	23 056	23 259	23 056
R^2 pseudo adj.	0.007	0.276	0.324	0.288	0.288	0.290

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. OLS estimates in upper panel and exponentiated logit estimates in lower panel. Standard errors in parentheses. P-values in square brackets. Standard errors clustered by the administrative districts of the compensatory mitigation program (N = 36). Cost advantage of MB: Standardized mean difference between the impact sites and mitigation bank sites in terms of (a) land value (Nolte, 2020) and (b) agricultural land value (USDA). Benefit advantage of MB: Standardized mean difference between mitigation bank sites and impact sites in terms of (a) the number of recorded flooding events (Li et al., 2021) and (b) monetized wetland benefits (USD/acre, (Taylor and Druckenmiller, 2022)). Additional covariates: Impact size, trend of developed land cover interacted with wetland area (USGS, 2022). Sample: Data on impacts to wetlands over 2012–2020 where compensatory mitigation was required and at least one mitigation bank was available. Upper panel: Annual means over the administrative districts of the US Clean Water Act compensatory mitigation program or subbasin (Hydrological Unit Code 8-digit region). (Corps, 2020, 2022)

well above the commonly applied exchange ratios. This discrepancy highlights the potential inadequacy of wetland trades in replacing values within the current program.

Third, our results reveal a substantial migration of flood control benefits from urban to rural areas. Many authors have expressed concern that mitigation banking leads to the relocation of service values across the landscape (e.g., Ruhl and Salzman, 2006; BenDor et al., 2008). As expected from market dynamics, developers seek to develop wetlands in urban areas where land is dear, and banks restore wetlands in rural areas where land is cheap. Trades in the banking program may thus result in wetlands moving out of areas where they provide valuable services to urban populations and into sparsely populated areas where their service provision may be less valuable. Aronoff and Rafey (2023) document this pattern in Florida and show that wetland trades led to losses in local flood protection that are not always reflected in offset prices. Our findings reinforce this concern but point to a broader issue. Not only might local flood externalities go unaccounted for by the pricing mechanism of the current market design, but they are enabled by the upstream decision of whether to use a market for offsets in the first place. Given that regulatory choices do not factor the disparity in flood protection between development sites and eligible banks, the program allows these relocations to occur without accounting for the externality effect of the practice.

Our final set of results relate to how market characteristics influence the cost-effectiveness of banking and thus its choice as the preferred compensation method. A key concern of markets for environmental offsets is that markets might be too “thin” to realize the full potential of a decentralized mechanism (Salzman and Ruhl, 2005; Shabman, 2004). Theoretically, we show that the larger the market size, the lower the cost of meeting NNL with banking. Empirically, we find that the number of banks is a strong predictor of the regulator’s choice of banking-led offsets. This result, together with the observation that the

Table 3
Market size and choice of mitigation method.

	(1)	(2)	(3)	(4)	(5)	(6)
Unit of observation: Region						
Dependent variable: share of MB chosen						
log(Available mitigation banks)	0.297^{***}	0.206^{*}	0.134^{***}	0.223^{*}	0.224^{*}	0.205^{*}
	(0.052)	(0.098)	(0.025)	(0.090)	(0.089)	(0.083)
	[<0.001]	[0.042]	[<0.001]	[0.018]	[0.017]	[0.019]
Cost advantage of MB						
(a) Land value	0.091^{***}	0.031	0.026^{**}	0.037^{*}		0.049^{**}
	(0.022)	(0.016)	(0.009)	(0.015)		(0.017)
	[<0.001]	[0.060]	[0.004]	[0.018]		[0.007]
(b) Ag. land value					0.014^{**}	
					(0.004)	
					[0.003]	
Benefit advantage of MB						
(a) Flooding events	0.059	−0.000	0.019	−0.030	−0.040	
	(0.031)	(0.027)	(0.010)	(0.027)	(0.027)	
	[0.064]	[0.897]	[0.056]	[0.282]	[0.140]	
(b) Wetland benefit						0.018
						(0.017)
						[0.304]
Additional covariates				✓	✓	✓
Year and region FEs		✓	✓	✓	✓	✓
Region		District	Sub-basin	District	District	District
N	316	316	4529	316	316	316
R^2 adj.	0.464	0.668	0.442	0.686	0.682	0.685
Unit of observation: Development project						
Dependent variable: $\mathbb{I}$(MB chosen)						
log(Available mitigation banks)	2.693^{***}	1.524^{***}	1.413^{**}	1.546^{***}	1.541^{***}	1.573^{***}
	(0.410)	(0.152)	(0.175)	(0.160)	(0.163)	(0.166)
	[<0.001]	[<0.001]	[0.005]	[<0.001]	[<0.001]	[<0.001]
Cost advantage of MB						
(a) Land value	1.310^{**}	1.211^{*}	1.371^{***}	1.196^{*}		1.129
	(0.112)	(0.093)	(0.097)	(0.092)		(0.079)
	[0.002]	[0.013]	[<0.001]	[0.020]		[0.084]
(b) Ag. land value					1.000	
					(0.012)	
					[0.988]	
Benefit advantage of MB						
(a) Flooding events	0.985	0.973	0.954	0.957	0.924	
	(0.087)	(0.062)	(0.056)	(0.059)	(0.051)	
	[0.862]	[0.668]	[0.419]	[0.471]	[0.154]	
(b) Wetland benefit						0.833^{*}
						(0.069)
						[0.028]
Additional covariates				✓	✓	✓
Year and region FEs		✓	✓	✓	✓	✓
Region		District	Sub-basin	District	District	District
N	23 061	23 057	18 753	23 056	23 259	23 056
R^2 pseudo adj.	0.121	0.286	0.325	0.298	0.298	0.300

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. OLS estimates in upper panel and exponentiated logit estimates in lower panel. Standard errors in parentheses. P-values in square brackets. Standard errors clustered by the administrative districts of the compensatory mitigation program (N = 36). Cost advantage of MB: Standardized mean difference between the impact sites and mitigation bank sites in terms of (a) land value (Nolte, 2020) and (b) agricultural land value (USDA). Benefit advantage of MB: Standardized mean difference between mitigation bank sites and impact sites in terms of (a) the number of recorded flooding events (Li et al., 2021) and (b) monetized wetland benefits (USD/acre, (Taylor and Druckenmiller, 2022)). Additional covariates: Impact size, trend of developed land cover interacted with wetland area (USGS, 2022). Sample: Data on impacts to wetlands over 2012–2020 where compensatory mitigation was required and at least one mitigation bank was available. Upper panel: Annual means over the administrative districts of the US Clean Water Act compensatory mitigation program or sub-basin (Hydrological Unit Code 8-digit region) (Corps, 2020, 2022).

choice of method is responsive to the cost of restoration, supports the notion that the regulator is mindful of achieving the economic goals of the offsets policy.[31] Nevertheless, the fact that flood control benefits are absent from method selection suggests that cost-minimizing objectives take precedence over environmental goals.

We emphasize that the observation that the choice of method is independent of flood control benefits does not imply that benefits do not influence regulatory decisions in general. The US wetland banking program is an environmental market and thus created by regulation. The regulator is responsible not only for deciding whether impacts should be compensated on-site or through banking, but also for the pre-approval of banks, the areas that they serve, and the credits that

---

[31] An alternative channel for the observed effect of the number of banks as a predictor of the choice of offset method may lie in lobbying activity by the mitigation banking sector. When offsets support new or expanded commercial markets, firms and trade associations can mobilize to defend those markets by lobbying regulatory bodies. Although we are unaware of empirical studies directly examining lobbying by mitigation banking, the broader literature shows that ‘green’ companies actively support environmental regulatory instruments through lobbying and policy engagement (see, e.g., Grey (2018) and Böhler et al. (2022)). Future research could test whether and to what extent the number and size of wetland banks correlate with lobbying expenditures or participation in rule-making processes.

they generate for trade. Whereas the choice of compensation method involves the ex-post decision of whether the offset should take place on- or off-site (given impact and bank locations), the design of the market (e.g., bank approval and service areas) is an ex-ante decision as to whether future impacts will be adequately compensated at bank sites. It is possible that regulatory decisions consider flood control benefits at the approval stage and that regulators therefore relax their scrutiny of benefits in downstream decisions.

Our data is at least consistent with this observation. We find a positive correlation between the number of banks in a given market and the average cost–benefit score of bank locations (see Fig. 3). This score reflects the combined advantage of market-based offsets relative to on-site compensation in terms of both lower costs and greater flood-control benefits. The fact that higher cost–benefit scores are observed in markets with more banks could indicate that regulators are more likely to approve banks in locations where restoration efforts provide significant flood control benefits. On the other hand, the number of banks and the cost–benefit score of their locations are likely influenced by factors unrelated to regulatory approval (e.g., economic development levels, agricultural productivity, and availability of land). Although the regulatory determinants of market entry, bank-site selection, and bank approval is beyond the scope of our analysis, it is nevertheless an important area for future research. Specifically, on how market design (e.g., service areas and trading ratios) influences the quantity and quality of restoration in off-site locations, and thus the extent to which offsets by banks internalize the cost of environmental losses.

Our work has a number of limitations. First, our analysis abstracts from uncertainties related to restoration success and focuses on the spatial characteristics of offset locations. This enables a consistent, program-wide comparison of spatial trade-offs between prescriptive and banking mechanisms but does not account for potential differences in compliance, baseline ecological conditions, or restoration outcomes. In practice, the effectiveness of an offset may differ depending on its implementation details. Mitigation banks often operate at a large scale, benefit from consolidated management, and are located in areas with low exposure to human disturbances (e.g. NRC, 2001; Salzman and Ruhl, 2005). In contrast, developer-led offsets near built environments face challenges related to land-use pressures, site fragmentation, pollution exposure, and low compliance rates (e.g., GAO, 2005; zu Ermgassen et al., 2021; Rampling et al., 2024). In addition, mitigation banks are typically established in advance of permitted impacts, reducing failure risks and allowing the adequacy of the offset to be known at the time of the trade. While these differences in restoration success are not captured by our spatial proxies, they may represent an important source of variation that could influence the effectiveness of both prescriptive and banking mechanisms.

Theoretically, the uncertainty of restoration outcomes across alternative mechanisms implies that the evaluation of costs and benefits should be made in expected terms. Although this modification would not change the direction of our theoretical predictions, it could have important implications for our empirical findings. If the probability of success is not constant across on- and off-site locations, then our relative measure of benefit would not reflect its true variation in expected terms. On the other hand, if on-site compensation is systematically riskier than banking, then our findings would still apply, with district-level fixed effects capturing regulators' preference for banking in general and their degree of risk aversion in particular. Risk aversion could, in that instance, be one potential explanation for the statistical insignificance of our benefit measure, as regulators might favor the certainty of banking over higher, though riskier, on-site benefits. This hypothesis is not without merit, as policy statements frequently emphasize that the preference for banking is justified, because it "reduces some of the risks and uncertainties associated with compensatory mitigation" (Corps and EPA, 2008). The extent to which regulatory risk aversion impacts the performance of offset programs is one important avenue for future research, because risk aversion may lead to the acceptance of lower but more predictable benefits at bank sites.

Second, our analysis is limited to flood control values and does not account for the value of other ecosystem services provided by wetlands, such as water filtration, recreational opportunities, and species habitat protection. Including these benefits could change the relative value of on- versus off-site restoration and thereby affect the influence of wetland benefits on regulatory decisions. For example, while on-site restoration might provide greater flood control benefits, restoration at bank sites might offer greater benefits in terms of habitat protection when located in high-priority areas, such as species migration corridors or adjacent to natural reserves. While deviating from the proximity principle that often guides offset policies, spatially targeting restoration in off-site locations may enhance both biodiversity and recreational outcomes (Mancini et al., 2024). Policy guidelines explicitly recognize these trade-offs, stating that "compensatory mitigation may be required on-site to offset losses of water quality and flood storage functions, while off-site compensation may be required to offset losses of habitat functions" (Corps and EPA, 2008, p.19604). Although left unspecified by the regulator which values are being prioritized to address specific impacts, it remains possible that wetland values other than flood attenuation take precedence in regulatory determinations.

Finally, we adopt a streamlined approach for the assessment of potential changes in flood risk at impact and offset sites. This is a significant simplification, given the diverse and complex nature of wetland impacts and restoration efforts. Permitted impacts requiring compensation vary widely in type and magnitude. For instance, some impacts may affect wetland vegetation, with minimal consequences for broader hydrological dynamics. Similarly, the type of offset—whether creation, enhancement, or preservation—may have different potential outcomes in terms of flood control. These outcomes also depend on the type and location of the wetland involved (e.g., forested or herbaceous), which differ in their water absorption capacity. A comprehensive analysis would require a detailed, case-by-case examination of the precise contribution of each impact and restoration effort to promoting or relieving flood risk. While we do not delve into this level of detail, we acknowledge that our approach simplifies the complex biophysical relationships between flood control and wetland area lost and restored.

5. Conclusion

The choice of offset method under the US wetlands program is being made, as intended, from a cost-minimizing perspective. The reduced restoration costs at off-site locations and the cost-reduction effect of a larger number of offset providers are both important determinants of the increased adoption of banking. Our results show that regulatory decisions leverage the cost-saving potential of banking-led offsets and thus align with the principle of economic efficiency from market-based approaches to environmental regulation.

However, as with any market involving the exchange of environmental commodities, it falls on the regulator to ensure the quality of what is being traded. Our analysis reveals that flood control benefits do not factor into the choice of offset method. While bank sites are associated with substantially lower restoration costs, they also exhibit significantly lower flood control benefits when compared to impact sites. Our results suggest that the current approach overlooks the flood-control value of the more costly, although potentially more beneficial, prescriptive approach of developer-led offsets at impact sites.

Our work raises two key concerns for policymakers who consider adopting market-based offsets over on-site prescriptive approaches. First, there is a risk of misalignment between impact sites and compensation sites, which, in the case of flood attenuation, may result in the relocation of ecosystem services away from areas where those services are needed. And second, there is a risk of prioritizing the means over the ends of offset policies, as the focus on cost savings might undermine the protection of environmental values. Both risks may lead to inadequate compensation and thus compromise the effectiveness of NNL policies.

To mitigate these risks, it is important that regulators integrate environmental values into policy decisions. This remains a challenge, as ecosystem service values are notoriously difficult to quantify. Regulators often rely on crude proxies (e.g., land area) due to the complexity of measuring ecosystem functions and their benefits. A comprehensive valuation exercise requires two steps. First, an understanding of how changes in ecological structure and function influence ecosystem service flows; and second, the application of valuation methods to quantify those changing flows. Both steps are data-intensive and methodologically complex, given the interconnected nature of ecosystem services and the variability of their values over time and space.

These valuation challenges point to a broader issue in offset policy design. Although many programs–including the US wetlands program–adopt the goal of achieving NNL of ecosystem values, regulators often leave unspecified which values should be maintained or the baseline against which losses and gains should be measured (Maron et al., 2018; Kujala et al., 2022). As a result, offset determinations rarely document which functions and values were affected by development or how those losses are being addressed through compensation. In the absence of a clear link between authorized impacts, compensatory actions, and the values that an offset is meant to preserve, it becomes impossible to verify whether NNL is being achieved, either at the project level or across broader spatial scales.

Although information on physical trade-offs and values will almost surely be incomplete, this should not prevent policy from being based on more reliable indicators of environmental value. As this study demonstrates, using one dimension of value to evaluate the redistribution effects of an offsets scheme can provide insights to help mitigate the externalities involved in decentralized policies. Moreover, advances in big data, remote sensing, and ecological modeling now offer unprecedented opportunities to incorporate spatially explicit, data-driven approaches into environmental policy (Runting et al., 2020; Hoffmann, 2022). Leveraging these tools can help move beyond simple cost–benefit metrics and toward policies that reflect true conservation trade-offs. Failure to do so could undermine the effectiveness of environmental offsets, which—given the growing urgency of balancing economic development with global conservation commitments—we cannot afford to get wrong.

CRediT authorship contribution statement

João Vaz: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jessica Coria:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Ville Inkinen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Acreman, M., Holden, J., 2013. How wetlands affect floods. Wetlands 33, 773–786.

Agarwal, S., Lucca, D., Seru, A., Trebbi, F., 2014. Inconsistent regulators: Evidence from banking. Q. J. Econ. 129 (2), 889–938.

Ando, A.W., 1999. Waiting to be protected under the endangered species act: The political economy of regulatory delay. J. Law Econ. 42 (1), 29–60.

Ando, A., Camm, J., Polasky, S., Solow, A., 1998. Species distributions. Land Values, Effic. Conserv. Sci. 279 (5359), 2126–2128.

Ando, A.W., Reeser, C., 2022. Homeowner willingness to pay for a pre-flood agreement for a post-flood buyout. Land Econ. 98 (4), 560–578.

Aronoff, D., Rafey, W., 2023. Conservation priorities and environmental offsets: Markets for florida wetlands. National bureau of economic research (NBER). Working Paper (31495) Retrieved from https://www.nber.org/papers/w31495. (Accessed on 3 Mar 2025).

Baudry, M., Faure, A., Quemin, S., 2021. Emissions trading with transaction costs. J. Environ. Econ. Manag. 108, 102468.

BBOP, 2012. Standard on Biodiversity Offsets, [Business and Biodiversity Offsets Programme]. BBOP, Washington, DC, Retrieved from https://www.forest-trends.org/publications/standard-on-biodiversity-offsets/. (Accessed on 3 Mar 2025).

Bekessy, S.A., Wintle, B.A., Lindenmayer, D.B., McCarthy, M.A., Colyvan, M., Burgman, M.A., Possingham, H.P., 2010. The biodiversity bank cannot be a lending bank. Conserv. Lett. 3 (3), 151–158.

Benabou, S., 2014. Making up for lost nature?: A critical review of the international development of voluntary biodiversity offsets. Environ. Soc. 5 (1), 103–123.

BenDor, T., Brozovic, N., Pallathucheril, V.G., 2007. Assessing the socioeconomic impacts of wetland mitigation in the chicago region. J. Am. Plan. Assoc. 73 (3), 263.

BenDor, T., Brozović, N., Pallathucheril, V.G., 2008. The social impacts of wetland mitigation policies in the United States. J. Plan. Lit. 22 (4), 341–357.

BenDor, T.K., Kwon, J., Lester, T.W., 2023. Assessing the size and growth of the US wetland and stream compensatory mitigation industry. PLoS One 18 (9), e0285139.

BenDor, T., Lester, T.W., Livengood, A., Davis, A., Yonavjak, L., 2015. Estimating the size and impact of the ecological restoration economy. PLoS One 10 (6), e0128339.

BenDor, T.K., Riggsbee, J.A., 2011. A survey of entrepreneurial risk in US wetland and stream compensatory mitigation markets. Environ. Sci. Policy 14 (3), 301–314.

BenDor, T., Stewart, A., 2011. Land use planning and social equity in north carolina's compensatory wetland and stream mitigation programs. Environ. Manag. 47, 239–253.

Bennett, G., Gallant, M., ten Kate, K., 2017. State of Biodiversity Mitigation 2017: Markets and Compensation for Global Infrastructure Development. Forest Trends' Ecosystem Marketplace, Washington, D.C., Retrieved from https://www.forest-trends.org/publications/state-biodiversity-mitigation-2017/. (Accessed on 2 August 2024).

Böhler, H., Hanegraaff, M., Schulze, K., 2022. Does climate advocacy matter? The importance of competing interest groups for national climate policies. Clim. Policy 22 (8), 961–975.

Botzen, W.W., van den Bergh, J.C., 2012. Risk attitudes to low-probability climate change risks: WTP for flood insurance. J. Econ. Behav. Organ. 82 (1), 151–166.

Browne, M.J., Hoyt, R.E., 2000. The demand for flood insurance: Empirical evidence. J. Risk Uncertain. 20, 291–306.

Bull, J.W., Strange, N., 2018. The global extent of biodiversity offset implementation under no net loss policies. Nat. Sustain. 1 (12), 790–798.

Bull, J.W., Suttle, K.B., Gordon, A., Singh, N.J., Milner-Gulland, E.J., 2013. Biodiversity offsets in theory and practice. Oryx 47 (3), 369–380.

Busch, J., Grantham, H.S., 2013. Parks versus payments: Reconciling divergent policy responses to biodiversity loss and climate change from tropical deforestation. Environ. Res. Lett. 8 (3), 034028.

Chakraborti, L., McConnell, K.E., 2012. Does ambient water quality affect the stringency of regulations? Plant-level evidence of the clean water act. Land Econ. 88 (3), 518–535.

Conlisk, E., Chamberlin, L., Vernon, M., Dybala, K.E., 2023. Evidence for The Multiple Benefits of Wetland Conservation in North America: Carbon, Biodiversity, and Beyond. Point Blue Conservation Science, Petaluma, CA, US, Retrieved from https://www.pointblue.org/wetland-multiple-benefits. (Accessed on 3 Mar 2025).

Coria, J., Kristiansson, E., Gustavsson, M., 2022. Economic interests cloud hazard reductions in the European regulation of substances of very high concern. Nat. Commun. 13 (1), 6686.

Corps, 2020. Operations and maintenance business information link regulatory module (ORM). Retrieved from the Corps through Freedom of Information Act requests.

Corps, 2022. Regulatory in-Lieu fee and bank information tracking system (RIBITS). Retrieved from https://ribits.ops.usace.army.mil/. (Accessed on 30 Sep 2022).

Corps and EPA, 1990. Memorandum of agreement between the environmental protection agency and the department of the army concerning the determination of mitigation under the clean water act section 404(b)(1) guidelines. Retrieved from https://www.epa.gov/cwa-404/memorandum-agreement-regarding-mitigation-under-cwa-section-404b1-guidelines-signed-0. (Accessed on 3 Mar 2025).

Corps and EPA, 2008. Compensatory Mitigation for Losses of Aquatic Resources, vol. 70, pp. 19593–19705, Final rule. 73 Fed. Reg.

Cropper, M.L., Evans, W.N., Berardi, S.J., Ducla-Soares, M.M., Portney, P.R., 1992. The determinants of pesticide regulation: A statistical analysis of EPA decision making. J. Politi. Econ. 100 (1), 175–197.

Darbi, M., 2020. Biodiversity Offsets Between Regulation and Voluntary Commitment. Springer International Publishing..

Dawson, D., Shogren, J.F., 2001. An update on priorities and expenditures under the endangered species act. Land Econ. 77 (4), 527–532.

Deily, M.E., Gray, W.B., 1991. Enforcement of pollution regulations in a declining industry. J. Environ. Econ. Manag. 21 (3), 260–274.

Deutz, A., Heal, G.M., Niu, R., Swanson, E., Townshend, T., Zhu, L., Delmar, A., Meghji, A., Sethi, S.A., Tobin-de la Puente, J., 2020. Financing Nature: Closing the Global Biodiversity Financing Gap. The Paulson Institute, The Nature Conservancy, and the Cornell Atkinson Center for Sustainability..

zu Ermgassen, S.O.S.E., Baker, J., Griffiths, R.A., Strange, N., Struebig, M.J., Bull, J.W., 2019. The ecological outcomes of biodiversity offsets under no net loss policies: A global review. Conserv. Lett. 12 (6), e12664.

zu Ermgassen, S.O.S.E., Marsh, S., Ryland, K., Church, E., Marsh, R., Bull, J.W., 2021. Exploring the ecological outcomes of mandatory biodiversity net gain using evidence from early-adopter jurisdictions in England. Conserv. Lett. 14 (6), e12820.

Fowlie, M., Muller, N., 2019. Market-based emissions regulation when damages vary across sources: What are the gains from differentiation? J. Assoc. Environ. Resour. Econ. 6 (3), 593–632.

GAO, 2005. Wetlands Protection: Corps of Engineers Does Not Have an Effective Oversight Approach to Ensure That Compensatory Mitigation Is Occurring. Government Accountability Office, US, Retrieved from https://www.gao.gov/products/gao-05-898. (Accessed on 2 August 2024).

GIBOP, 2019. Global inventory of biodiversity offset policies. Retrieved from https://portals.iucn.org/offsetpolicy/.

Gourley, J.J., Flamig, Z.L., Vergara, H., Kirstetter, P.-E., Clark, R.A., Argyle, E., Arthur, A., Martinaitis, S., Terti, G., Erlingis, J.M., et al., 2017. The flooded locations and simulated hydrographs (FLASH) project: Improving the tools for flash flood monitoring and prediction across the United States. Bull. Am. Meteorol. Soc. 98 (2), 361–372.

Grant, L.E., Grooms, K.K., 2017. Do nonprofits encourage environmental compliance? J. Assoc. Environ. Resour. Econ. 4 (S1), S261–S288.

Grey, F., 2018. Corporate lobbying for environmental protection. J. Environ. Econ. Manag. 90, 23–40.

Hahn, R.W., 1984. Market power and transferable property rights. Q. J. Econ. 99 (4), 753–765.

Helland, E., 1998. The revealed preferences of state EPAs: Stringency, enforcement, and substitution. J. Environ. Econ. Manag. 35 (3), 242–261.

Hoffmann, S., 2022. Challenges and opportunities of area-based conservation in reaching biodiversity and sustainability goals. Biodivers. Conserv. 31 (2), 325–352.

Holland, A.C., 2016. Forbearance. Am. Political Sci. Rev. 110 (2), 232–246.

Hook, P.W., Shadle, S.T., 2013. Navigating Wetland Mitigation Markets: A Study of Risks Facing Entrepreneurs and Regulators. Ecosystem Marketplace, Washington, D.C., Retrieved from https://www.cbd.int/financial/offsets/usa-offsetmitigationrisks.pdf. (Accessed on 3 Mar 2025).

Hough, P., Robertson, M., 2009. Mitigation under section 404 of the clean water act: Where it comes from, what it means. Wetl. Ecol. Manag. 17, 15–33.

Inkinen, V., Coria, J., Vaz, J., Clough, Y., 2022. Using markets for environmental offsetting: Evaluation of wetland area gains and losses under the US clean water act. University of Gothenburg, Working Paper. Retrieved from https://www.gu.se/sites/default/files/2022-11/JMP_Ville_Inkinen.pdf. (Accessed on 2 August 2024).

IWR, 2015. The Mitigation Rule Retrospective: A Review of the 2008 Regulations Governing Compensatory Mitigation for Losses of Aquatic Resources. Institute for Water Resources, Alexandria, VA, Retrieved from https://www.epa.gov/sites/default/files/2015-11/documents/mitrule_report_october_2015.pdf. (Accessed on 3 March 2025).

Jones-Lee, M., 1974. The value of changes in the probability of death or injury. J. Political Econ. 82 (4), 835–849.

Kalliolevo, H., Gordon, A., Sharma, R., Bull, J.W., Bekessy, S.A., 2021. Biodiversity offsetting can relocate nature away from people: An empirical case study in western Australia. Conserv. Sci. Pr. 3 (10), e512.

Kang, K., Silveira, B.S., 2021. Understanding disparities in punishment: Regulator preferences and expertise. J. Political Econ. 129 (10), 2947–2992.

King, D.M., Wainger, L.A., Bartoldus, C.C., Wakeley, J.S., 2000. Expanding wetland assessment procedures: Linking indices of wetland function with services and values. In: US Army Corps of Engineers,Engineer Research and Development Center, Wetlands Research Program Final Report, ERDC/EL TR-00-17. Retrieved from https://erdc-library.erdc.dren.mil/server/api/core/bitstreams/81b728f8-8814-4ef8-e053-411ac80adeb3/content. (Accessed on 3 March 2025).

Knittel, C.R., 2006. The adoption of state electricity regulation: The role of interest groups. J. Ind. Econ. 54 (2), 201–222.

Koh, N.S., Hahn, T., Boonstra, W.J., 2019. How much of a market is involved in a biodiversity offset? A typology of biodiversity offset policies. J. Environ. Manag. 232, 679–691.

Kosnik, L., 2006. Sources of bureaucratic delay: A case study of FERC dam relicensing. J. Law, Econ. Organ. 22 (1), 258–288.

Kosnik, L., 2010. Balancing environmental protection and energy production in the federal hydropower licensing process. Land Econ. 86 (3), 444–466.

Kroszner, R.S., Strahan, P.E., 1999. What drives deregulation? Economics and politics of the relaxation of bank branching restrictions. Q. J. Econ. 114 (4), 1437–1467.

Kujala, H., Maron, M., Kennedy, C.M., Evans, M.C., Bull, J.W., Wintle, B.A., Iftekhar, S.M., Selwood, K.E., Beissner, K., Osborn, D., et al., 2022. Credible biodiversity offsetting needs public national registers to confirm no net loss. One Earth 5 (6), 650–662.

Langpap, C., 2022. Interest groups, litigation, and agency decisions: Evidence from the endangered species act. J. Assoc. Environ. Resour. Econ. 9 (1), 1–26.

Langpap, C., Shimshack, J.P., 2010. Private citizen suits and public enforcement: Substitutes or complements? J. Environ. Econ. Manag. 59 (3), 235–249.

Le Texier, M., Gelot, S., Pioch, S., 2024. Big cities, big impacts? A spatial analysis of 3 335ecological offsets in France since 2012. J. Environ. Manag. 357, 120704.

Leaver, C., 2009. Bureaucratic minimal squawk behavior: Theory and evidence from regulatory agencies. Am. Econ. Rev. 99 (3), 572–607.

Levrel, H., Scemama, P., Vaissière, A.-C., 2017. Should we be wary of mitigation banking? Evidence regarding the risks associated with this wetland offset arrangement in florida. Ecol. Econom. 135, 136–149.

Li, Z., Chen, M., Gao, S., Gourley, J.J., Yang, T., Shen, X., Kolar, R., Hong, Y., 2021. A multi-source 120-year US flood database with a unified common format and public access. Earth Syst. Sci. Data 13 (8), 3755–3766.

Liski, M., 2001. Thin versus thick CO_2 market. J. Environ. Econ. Manag. 41 (3), 295–311.

Liski, M., Montero, J.-P., 2011. Market power in an exhaustible resource market: The case of storable pollution permits. Econ. J. 121 (551), 116–144.

Mancini, M.C., Collins, R.M., Addicott, E.T., Balmford, B.J., Binner, A., Bull, J.W., Day, B.H., Eigenbrod, F., zu Ermgassen, S.O.S.E., Faccioli, M., et al., 2024. Biodiversity offsets perform poorly for both people and nature, but better approaches are available. One Earth 7 (12), 2165–2174.

Maron, M., Brownlie, S., Bull, J.W., Evans, M.C., von Hase, A., Quétier, F., Watson, J.E.M., Gordon, A., 2018. The many meanings of no net loss in environmental policy. Nat. Sustain. 1 (1), 19–27.

Matthews, J.W., Endress, A.G., 2008. Performance criteria, compliance success, and vegetation development in compensatory mitigation wetlands. Environ. Manag. 41, 130–141.

McKenney, B, 2005. Environmental offset policies, principles, and methods: A review of selected legislative frameworks. Biodiversity Neutral Initiative, Amherst, NH, Retrieved from: https://search.issuelab.org/resources/23404/23404.pdf . (Accessed on 3 March 2025).

McKenney, B.A., Kiesecker, J.M., 2010. Policy development for biodiversity offsets: A review of offset frameworks. Environ. Manag. 45, 165–176.

Metrick, A., Weitzman, M.L., 1996. Patterns of behavior in endangered species preservation. Land Econ. 72, 1–16.

Metrick, A., Weitzman, M.L., 1998. Conflicts and choices in biodiversity preservation. J. Econ. Perspect. 12 (3), 21–34.

Montero, J.-P., 1998. Marketable pollution permits with uncertainty and transaction costs. Resour. Energy Econ. 20 (1), 27–50.

Morandeau, D., Vilaysack, D., 2012. Compensating for damage to biodiversity: An international benchmarking study. In: Economy, Evaluation and Integration of Sustainable Development Service (SEEIDD) At the General Commission for Sustainable Development (68) France. Retrieved from: https://www.forest-trends.org/wp-content/uploads/imported/ED68EN.pdf. (Accessed on 3 March 2025).

Moreno-Mateos, D., Power, M.E., Comín, F.A., Yockteng, R., 2012. Structural and functional loss in restored wetland ecosystems. PLoS Biol. 10 (1), e1001247.

Netusil, N.R., Kousky, C., Neupane, S., Daniel, W., Kunreuther, H., 2021. The willingness to pay for flood insurance. Land Econ. 97 (1), 17–38.

Nolte, C., 2020. High-resolution land value maps reveal underestimation of conservation costs in the United States. Proc. Natl. Acad. Sci. 117 (47), 29577–29583.

NRC, 2001. Compensating for Wetland Losses Under the Clean Water Act. [National Research Council], National Academies Press, Washington, D.C.

OECD, 2016. Biodiversity Offsets: Effective Design and Implementation. OECD Publishing, Paris, France, http://dx.doi.org/10.1787/9789264222519-en, Retrieved from. (Accessed on 3 March 2025).

OECD, 2020. Comprehensive Overview of Global Biodiversity Finance. OECD Publishing, Paris, France, Retrieved from https://www.oecd.org/en/publications/a-comprehensive-overview-of-global-biodiversity-finance_25f9919e-en.html. (Accessed on 3 March. 2025).

Olson, M., 1996. Substitution in regulatory agencies: FDA enforcement alternatives. J. Law, Econ. Organ. 12 (2), 376–407.

O'Ryan, R.E., 2006. Factors that determine the cost-effectiveness ranking of second-best instruments for environmental regulation. J. Regul. Econ. 30, 179–198.

O'Ryan, R., Sánchez, J.M., 2008. Comparison of net benefits of incentive-based and command and control environmental regulations: The case of santiago. Chile. World Bank Econ. Rev. 22 (2), 249–269.

Petrolia, D.R., Landry, C.E., Coble, K.H., 2013. Risk preferences. Risk Perceptions Flood Insur. Land Econ. 89 (2), 227–245.

Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., et al., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biol. Cons. 141 (6), 1505–1524.

Rampling, E.E., Zu Ermgassen, S.O.S.E., Hawkins, I., Bull, J.W., 2024. Achieving biodiversity net gain by addressing governance gaps underpinning ecological compensation policies. Conserv. Biol. 38 (2), e14198.

Robalino, J., Sandoval, C., Barton, D.N., Chacon, A., Pfaff, A., 2015. Evaluating interactions of forest conservation policies on avoided deforestation. PLoS One 10 (4), e0124910.

Ruhl, J.B., Salzman, J.E., 2006. The effects of wetland mitigation banking on people. Natl. Wetl. Newsl. 28 (2).

Runting, R.K., Phinn, S., Xie, Z., Venter, O., Watson, J.E.M., 2020. Opportunities for big data in conservation and sustainability. Nat. Commun. 11 (1), 2003.

Saenz, S., Walschburger, T., González, J.C., León, J., McKenney, B., Kiesecker, J., 2013. A framework for implementing and valuing biodiversity offsets in Colombia: A landscape scale perspective. Sustainability 5 (12), 4961–4987.

Salzman, J.E., Ruhl, J.B., 2005. 'No net loss'–instrument choice in wetlands protection. In: Duke Law School Science, Technology, and Innovation Research Paper Series No. 1. Duke University, Durham, NC.

Salzman, J., Ruhl, J.B., 2019. Currencies and the commodification of environmental law. In: Environmental Law. Routledge, pp. 3–90.

Scholz, J.T., Wei, F.H., 1986. Regulatory enforcement in a federalist system. Am. Political Sci. Rev. 80 (4), 1249–1270.

Seaber, P.R., Kapinos, F.P., Knapp, G.L., 1987. Hydrologic Unit Maps. US Government Printing Office, Washington, D.C.

Shabman, L., 2004. Compensation for the impacts of wetlands fill: The US experience with credit sales. In: Proceedings of the OECD Workshop on Ex-Post Evaluation of Tradable Permits: Methodological and Policy Issues. pp. 155–169.

Sigman, H., 2001. The pace of progress at superfund sites: Policy goals and interest group influence. J. Law Econ. 44 (1), 315–343.

Siikamäki, J., Layton, D.F., 2007. Potential cost-effectiveness of incentive payment programs for the protection of non-industrial private forests. Land Econ. 83 (4), 539–560.

Sims, K.R., Alix-Garcia, J.M., 2017. Parks versus PES: Evaluating direct and incentive-based land conservation in Mexico. J. Environ. Econ. Manag. 86, 8–28.

Singh, R., Weninger, Q., 2017. Cap-and-trade under transactions costs and factor irreversibility. Econom. Theory 64, 357–407.

Stavins, R.N., 1995. Transaction costs and tradeable permits. J. Environ. Econ. Manag. 29 (2), 133–148.

Stavins, R.N., 2003. Experience with market-based environmental policy instruments. In: Handbook of Environmental Economics, vol. 1, Elsevier, pp. 355–435.

Taylor, C.A., Druckenmiller, H., 2022. Wetlands, flooding, and the clean water act. Am. Econ. Rev. 112 (4), 1334–1363.

Theis, S., Poesch, M.S., 2022. Assessing conservation and mitigation banking practices and associated gains and losses in the United States. Sustainability 14 (11), 6652.

Tietenberg, T.H., 1990. Economic instruments for environmental regulation. Oxf. Rev. Econ. Policy 6 (1), 17–33.

Tietenberg, T.H., 1995. Tradeable permits for pollution control when emission location matters: What have we learned? Environ. Resour. Econ. 5, 95–113.

USGS, 2022. LCMAP collection 1.3 science products, earth resources observation and science (EROS) center. In: US Geological Survey. http://dx.doi.org/10.5066/P9W1TO6E, Retrieved from . (Accessed on 30 September 2022).

Viscusi, W.K., Hamilton, J.T., 1999. Are risk regulators rational? Evidence from hazardous waste cleanup decisions. Am. Econ. Rev. 89 (4), 1010–1027.

Wing, O.E.J., Pinter, N., Bates, P.D., Kousky, C., 2020. New insights into US flood vulnerability revealed from flood insurance big data. Nat. Commun. 11 (1), 1444.