Conservation priorities and environmental offsets: Markets for Florida wetlands

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July 29, 2023

Abstract

We introduce an empirical framework for valuing markets in environmental offsets. Using newly-collected data on wetland conservation and offsets, we apply this framework to evaluate a set of decentralized markets in Florida, where land developers purchase offsets from long-lived producers who restore wetlands over time. We find that offsets led to substantial private gains from trade, creating \$2.2 billion of net surplus from 1995–2018 relative to direct conservation. Offset trading also generated new hydrological externalities. A locally differentiated Pigouvian tax would have prevented \$1.3 billion of new flood damage while preserving more than two-thirds of the private gains from trade.

JEL Classifications: D24, D25, F14, L51, Q15, Q24
Keywords: environmental offsets, market design, wetlands, conservation, land use

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1 Introduction

Environmental offsets play an increasingly central role in modern environmental regulation. Offset markets can create private gains from trade relative to more commonly used conservation mandates, but equilibrium outcomes in such markets will not be efficient unless regulators can account perfectly for the social value of offsets. In particular, while offsets can provide flexibility to conserve a public good at lower cost, they raise concerns when they cannot (or do not) substitute for all dimensions of the original public good.

This paper introduces an empirical framework for environmental market design in the presence of these two potentially competing concerns. A regulator specifies a conservation objective to preserve the existing stock of the public good. A set of potential producers access restoration opportunities that differ in cost as well as location. Producers undertake long-run restoration activities, receive offset credits from the regulator, and sell offsets to entities seeking to deplete the public good. Offsets contribute to the regulator's conservation objective and may also have other environmental outcomes, which are measured separately. When estimated with data on offset producers and trade flows, the model allows us to recover the private gains from trade in offsets, measure the environmental outcomes from trade, and predict counterfactual gains from trade and environmental outcomes under alternative market designs.

We apply this framework to value a new set of decentralized markets for protected wetlands. Wetlands deliver a range of environmental benefits, including biodiversity, water storage and purification, carbon sequestration, and flood protection.[1] At the same time, their preservation precludes competing land uses—such as housing, agriculture, or infrastructure—that may create private value. Federal and state environmental laws negotiate these tradeoffs in the United States by mandating "No Net Loss" in existing wetlands. The current rules permit development on local wetlands if the loss is offset by an equal gain on other wetlands in the same region. This legal framework involves long-lived wetlands producers, who build or restore permanent wetlands on private land ("wetland mitigation banks") to produce certified offsets, which they then sell to landowners who need to offset development on protected wetlands.

To analyze these markets, we obtain new data on markets for wetland offsets in Florida, where 29% of land by area is wetlands and real estate comprised nearly one-fifth (19%) of the state's $1 trillion GDP in 2020 (BEA, 2020). We start by documenting

[1]Wetlands contribute 6% of land worldwide and 12% of the terrestrial carbon stock (Erwin, 2009), but their global extent has declined by 35% between 1970 and 2015 (Ramsar Convention, 2018).

some new stylized facts about wetlands trading. First, we find considerable trading volumes, with more than $1.2 billion of transactions in regional markets from 1995–2018. Second, we show that this industry is highly concentrated, with fewer than three wetland banks trading in an average market. Third, we find evidence of spatial reallocation of wetlands away from densely-populated flood hazard areas into peripheral zones, consistent with private gains from trade as well as adverse selection in terms of local flood protection.

We then use observed offset trades, prices, and production to measure the private gains from trade and estimate a model to predict equilibrium wetlands reallocation and environmental outcomes under alternative market designs. The empirical strategy proceeds in three steps. First, we estimate demand for wetland offsets using transaction-level data on the location, price, and quantity of offset purchases over time. We build several price instruments from cost shifters of offset supply based on our understanding of the industry. For example, we use variation in the issuance of wetland offsets to historical incumbents based on bank-level production schedules fixed at the time of entry, as well as Hausman instruments from other markets in the same region, and variation in the extent of public wetlands that affect the feasibility of offset production.

Second, we estimate a model of industry dynamics of offset supply, using (i) administrative data on the set of operating wetlands producers and (ii) maps that indicate the location of entrants. Our strategy for identifying the cost structure for this industry follows in the tradition of Bajari *et al.* (2007) and Pakes *et al.* (2007) to leverage equilibrium conditions for firm behavior. We use observed offset production over time to directly estimate wetland production schedules as functions of fixed bank site characteristics. To account for offset storage, we characterize trading decisions as an optimal inventory problem. We then combine estimates of offset demand with optimality conditions for entry, which allow us to obtain the expected profits of an incumbent firm. We then estimate conditional entry cost distributions to rationalize observed entry decisions as solutions to each producer's dynamic optimization problem as in Bajari *et al.* (2007). In particular, we obtain conditional entry cost distributions that control for local characteristics that affect the feasibility of wetlands restoration across space.

To avoid the curse of dimensionality in estimating entry costs, we approximate strategic entry and trading decisions with functions that depend on a subset of rivals' characteristics, following work such as Ryan (2012), Ifrach and Weintraub (2017), and Gowrisankaran *et al.* (2023). To circumvent the curse of dimensionality in counterfactuals, we follow the approach of Rafey (2023), who obtains realized gains from trade by integrating estimated value functions over observed trade flows, avoiding the need to calculate a new equilibrium. In addition, for our Pigouvian counterfactual, we add the stronger assumption that prices remain fixed, so that we can obtain counterfactual developer values and entry costs by integrating under the estimated local watershed demand curves and an aggregate entry cost function. These restrictions enable us to report approximate market outcomes (private gains from trade, externalities, and total surplus) using only the estimated model primitives and observed offset trades.

Third, to analyze environmental consequences of wetlands reallocation under the current market design, we estimate wetlands' local values for flood protection, a major hydrological outcome not currently incorporated into existing offset trading rules. In Florida, approximately $700 billion of assets lie in a 100-year flood zone and scientists expect climate change to increase the probability of extreme flooding (Wing *et al.*, 2018). Moreover, new empirical research suggests that the value of these local flood protection benefits may be considerable (Brody *et al.*, 2015; Sun and Carson, 2020; Taylor and Druckenmiller, 2022). We estimate our local flood protection functions using detailed historical land use and flood insurance claims data. This allows us to evaluate the quality of newly-produced offsets relative to direct conservation.

Our main empirical findings are threefold. First, we find substantial private gains from trade, reflecting the significant differences between the opportunity cost of development for marginal wetlands and the entry costs of wetland mitigation banks. Second, we find that by shifting wetlands away from places most vulnerable to flood risk, the market increased total flood damages, though these outcomes are highly heterogeneous across space. Third, we show that augmenting the current market design with Pigouvian taxes proportional to local flood risk can eliminate almost 90% of flood damages while preserving more than two-thirds of the private gains from trade. A uniform development tax also lowers total flood damage, but leads to lower private surplus and significantly greater flood damages than the differentiated Pigouvian prescription.

Contributions to the literature. This paper makes three primary contributions. First, we provide an empirical framework for environmental market design in regulated conservation offsets. Methodologically, we build on both the literature that seeks to value the gains from trade under market-based reallocation relative to less flexible environmental or energy regulations (e.g., Carlson *et al.*, 2000; Borenstein *et al.*, 2002; Rafey, 2023), as well as the literature on second-best pricing of heterogenous externalities (Diamond, 1973), which, in environmental economics, often emphasizes the dangers of environmental markets in second-best contexts where pollution occurs at finer gradations than policy instruments (e.g., Muller and Mendelsohn, 2009; Fowlie *et al.*, 2016; Fowlie and Muller, 2019; Hernandez-Cortes and Meng, 2020). Our findings of the private gains from trade in these regional markets provide substantive evidence of the value that offsets can deliver to landowners and communities, despite rules that prohibit regional trade. Importantly, while these markets can cause other environmental changes and social costs, we show that in our context, addressing the additional externalities can occur without sacrificing most of the private gains from trade.

Second, we augment existing models of land use and conservation with landowners' restoration activities that produce offsets. Static models of long-run conservation and land use, such as Stavins and Jaffe (1990), Souza-Rodrigues (2019), and Assuncão *et al.* (2019), as well as recent models of dynamic land use (e.g., Scott, 2013; Hsiao, 2021), typically analyze environmental regulation through price changes, where the only conservation option is to not develop. These models rule out the use of land to supply new environmental protection. Here, we specify and estimate the production technology for new conservation projects, derive equilibrium outcomes for the concentrated markets that arise from the large fixed costs and time-to-build of these technologies, and endogenize landowners' opportunity costs of meeting a given conservation objective through the offset market.

Empirically, our results here show that the design of conservation laws can lower the costs of land use regulations over time, through markets that create incentives for decentralized wetland restoration projects that exhibit economies of scale. Our estimates of private developer values, which capture the relative cost of direct conservation mandates, extend the empirical analysis of land use restrictions (e.g., Saiz, 2010; Turner *et al.*, 2014) and enrich our view of the private cost of wetland permitting (Sunding and Zilberman, 2002). In particular, our findings of private gains from trade inform evolving U.S. wetlands law and policy (Keiser *et al.*, 2022). Several far-reaching judicial decisions have relied on the general assumption that wetlands permitting schemes are unduly burdensome for landowners, with the U.S. Supreme Court repeatedly citing a seminal economic study from more than two decades ago by Sunding and Zilberman (2002) (cited in the first paragraph of Rapanos v. United States (2006, §1A), the second paragraph of USACE v. Hawkes (2016, §1A), and again in Sackett v. EPA (2023, §1A).). Our paper shows that this regulatory burden is neither inevitable nor invariant to the regulatory environment—the flexibility that offsets provide to landowners burdened by land use restrictions can substantially lower private compliance costs.[2]

[2]Indeed, this is emphasized repeatedly by Sunding and Zilberman (2002), who point out that "other

Third, we contribute to a growing literature on wetlands and hydrological outcomes. Our focus on the imperfect substitutability between original wetlands and new wetland banks in terms of flood risk—not fully incorporated into the original policy design—follows Aronoff and Rafey (2020), who built on recent insights suggesting important interactions between land conservation decisions and flood risk (Kousky and Walls, 2014) as well as recent work connecting land use data with flood outcomes (Brody *et al.*, 2015; Sun and Carson, 2020).[3] Of particular note is Brody *et al.* (2015), who are the first to construct land cover data that relates changes in wetland extent and flood insurance claims, as well as subsequent work by Taylor and Druckenmiller (2022) that relies on a similar dataset and empirical strategy as Brody *et al.* (2015). Like these papers, our work emphasizes the spillovers created by wetlands that protect existing property, and our research design relies on detailed hydrological and historical data.

We build on this prior work on wetland externalities in two ways. One, we connect our estimates of local wetland values directly to the economics of marginal wetland conservation and restoration. This allows us to estimate the effects of regional wetland markets, quantify their cost savings and flood externalities, and assess the welfare consequences of including flood externalities in the design of these markets. This paper is the first economic analysis to attain these objectives.

Two, we improve the precision of wetland flood protection functions by (a) using a nonlinear model that more closely fits the data on flood damages and (b) focusing on spillovers to properties built prior to the market to reduce bias. We find wetlands deliver policy-relevant spillovers in some, but not all, places. Our findings differ considerably from recent U.S.-wide estimates of such spillovers in Taylor and Druckenmiller (2022), which, when applied to Florida, exceed our flood protection estimates by more than an order of magnitude. This discrepancy indicates that actual policy evaluation requires carefully tailored approaches to estimating marginal wetland flood protection functions, using research designs that compare similar places with and without marginal wetlands.

Outline. The rest of the paper is organized as follows. Section 2 provides background on the legal framework that governs activities that destroy, conserve, and re-

federal programs exist to protect and enhance the nation's stock of wetlands at far lower cost" (p. 62), emphasize that "it is important to consider whether there are other programs that can protect wetlands at less than the implicit cost of conserving them by tightening the requirements for obtaining a discharge permit" (p. 83), and note that "that restoration of wetlands is usually much less expensive than conservation" (p. 84). Our research provides robust empirical support for these arguments.

[3] While legal scholars have long noted existing rules for wetland mitigation banking may be imperfect (e.g., Silverstein, 1994), wetland banking has received limited attention from economists (Polasky, 2002), with a few exceptions using surveys (e.g., Lupi *et al.*, 2002), simulations (Fernandez and Karp, 1998), or site evaluations (Boyd and Wainger, 2002).

store wetlands, as well as motivating evidence for the sources of gains from trade and adverse environmental outcomes. Section 3 specifies a model of equilibrium supply and demand for wetland offsets and Section 4 describes the empirical strategy and benchmark estimates. Section 5 evaluates private gains from trade, local flood outcomes, and some counterfactual market designs to internalize flood risk; Section 6 concludes.

2 Background and data

2.1 Basics of wetlands and offsets

Wetlands deliver an array of local public goods, but wetland conservation entails private costs. Wetlands consist of marshes or swamps and, in the continental United States, cover more land than the state of California (Rapanos v. United States, 2006). Their multifarious environmental services are difficult to value and rarely priced.[4] At the same time, their conservation precludes alternative land uses and therefore can entail substantial economic cost, often born by landowners whose property includes wetlands.

Activities that risk degrading local wetlands have been regulated in the United States since the 1972 Clean Water Act. Section 404 of the Clean Water Act prohibits economic activity that risks "significantly degrading" existing wetlands. This prohibition of "significant degradation" has been taken as a mandate to conserve an aggregate stock of ecological and hydrological functions delivered by wetlands. Under this approach, known as the "No Net Loss" principle, wetland degradation can occur legally if it is accompanied by approved actions that "offset" the degradation (Army-EPA, 1990).

The first iteration of No Net Loss was prescriptive and did not involve trade. Land developers on existing wetlands were typically either denied permits or required to implement mitigation activities on-site (Salzman and Ruhl, 2006), though in some cases, developers paid local "in-lieu fees." This non-market approach was heavily criticized by private landowners and environmental groups alike. Land developers argued that permitting requirements were unduly burdensome (Sunding and Zilberman, 2002), while environmental stakeholders argued that the growing sprawl of on-site mitigation activities did not compensate fully for wetland loss, criticizing regulators as unable to enforce or even verify the success of such mitigation activities (Ruhl *et al.*, 2009).

Tradeable offsets arose in response to these concerns as an innovative way to more flexibly comply with conservation mandates while incurring fewer costs from forgone

[4]For example, wetlands can purify water, enable recreation activities, and sustain diverse species, services that differ along a range of characteristics, such as location, age, maturity, and salinity.

land development. Rather than requiring land developers whose land included wetlands to undertake on-site mitigation actions or prohibiting development outright, regulators began to allow such landowners to buy offsets from off-site wetland restoration projects, known as "wetland mitigation banks." These projects commit land to the public trust, and engage in a range of conservation activities to restore degraded wetlands or create new ones (e.g., converting farmland back to its natural state (Erwin, 2009)), often offsetting dozens or even hundreds of new developments.

Our empirical analysis focuses on offsets required by Florida state law for wetlands protected under the 1972 Florida Water Resources Act. With the greatest percentage of wetland cover of any state in the continental United States, and rapid population growth and real estate development over the last three decades, Florida is a litmus test for wetland mitigation banking. The Florida laws governing wetland banking date from February 1994. Our focus on Florida rather than federal wetlands is motivated by two considerations. First, Florida jurisdiction encompasses all wetlands in Florida, including those regulated under the federal Clean Water Act, as well as wetlands outside of federal jurisdiction, such as those not connected to the Atlantic Ocean or the Gulf of Mexico by navigable waters. Second, the jurisdictional boundaries of the Clean Water Act have shifted over time in response to legal and administrative changes (Keiser *et al.*, 2022), whereas Florida jurisdictions have remained stable during our study period.[5]

2.2 Trading rules

Regulators enable and oversee several crucial aspects of the certification and trade of environmental offsets to enforce No Net Loss. Importantly, the regulator has permitting authority: land developers must obtain regulatory approval before either developing protected wetlands or restoring degraded wetlands. To this end, the regulator defines exchange values between restored wetlands and existing wetlands, through on-site assessments and a uniform assessment metric.[6] Although assessments incorporate diverse

[5] The 1993 Environmental Reorganization Act (FS §373.4135) directed the Florida Department of Environmental Protection (FDEP) and regional water management districts to adopt rules governing wetland banks by February 1994. There are two primary differences between Florida's §373 and the CWA §404: (i) a broader definition of wetlands (Florida requires evidence of two of the following: wetland vegetation, wetland hydrology, and hydric soils; the federal government requires evidence of all three) and (ii) broader jurisdiction (Florida has authority over all wetlands in the state; §404 only covers waters of the U.S.). Federal offsets account for only 18% of wetland offsets in Florida (Table A7). See Appendix B.5 for more details.

[6] To define equivalent units across diverse wetlands, regulators use the "uniform mitigation assessment method" (UMAM), which establishes fixed exchange ratios across wetland attributes that deliver a scalar measure of wetland value. The UMAM score captures the "ecological and hydrological func-

criteria related to biodiversity and ecological integrity, they do not directly account for the flood protection that wetlands can provide to the surrounding built environment.

For development on protected wetlands, the regulator evaluates the development's adverse effect on regional wetland functionality, then specifies the offsets the developer needs to purchase in order to proceed. A developer who buys offsets from a bank is limited to purchasing offsets from a bank operating within the same hydrological region (Figure 1A). These market boundaries, known as wetland mitigation bank service areas, approximate hydrological regions and extend far beyond the local project site.

For the creation of new wetland mitigation banks, the regulator requires an environmental audit, a set of proposed restoration activities, and a detailed implementation schedule. Each project's total lifetime output reflects the regulator's assessment of its contribution to "wetland functionality," which the regulator quantifies on a project-by-project basis. As wetland banks act as substitutes for direct conservation, committing land to a wetland bank requires a permanent conservation easement, ruling out alternative future land uses. In addition, assessment over time creates a delay between entry and obtaining offsets. Total lifetime production is specified at the time of entry, with offsets released gradually as wetlands regenerate over time and the bank attains its restoration goals. Banks can, and do, hold offsets in reserve to sell in future periods.

For offset trading, the regulator maintains a ledger that tracks the creation and retirement of wetland offsets. The regulator issues offset credits to wetland banks, verifies that buyers obtain sufficient offsets to compensate for their development, and deletes the corresponding offsets from the bank's balance. While the ledger is centralized and maintained by the regulator, offset trades between wetland banks and land developers occur bilaterally. Such over-the-counter trades are typically brokered through private intermediaries. This decentralization makes the exact market mechanism unknown. Actual trading may exhibit a variety of imperfectly competitive features.[7]

2.3 Data sources

We develop a new dataset to track wetlands, development, and offsets across Florida from 1995–2018. Our work draws on several new primary sources summarized in Table

tions" the wetland delivers to the surrounding region (Florida State Legislature, 2019, §373.4136(1)). Restoring ecological functions can involve activities such as planting trees, creating habitats, and controlling invasive species. Hydrological functions can entail building dams, bridges, and canals.

[7] For example, offset procurement by the Florida Department of Transportation and many local governments involve sealed-bid auctions. Private sales, by contrast, involve bilateral negotiations and, at the same time, intermediaries typically post price lists for their prospective clients.

A1 and detailed in Appendix A. Here, we briefly describe the novel aspects of our data, emphasizing how these sources reveal (i) the timing, origin, destination, and volume of offset trade flows; (ii) prices for offset trades; (iii) land ownership, assessed values, and prices; (iv) flood risks and damages; and (v) wetland location and extent.

First, we track offset trading with administrative data on environmental permits and offsets from the Florida Department of Environmental Protection (FDEP) and regional water management districts. These agencies regulate the creation and sale of environmental offsets and licenses for wetland restoration and conversion. From their records, we assemble a comprehensive ledger of the location, timing, and quantity of all state wetland offset transactions in Florida from 1995–2018. In addition, we obtain detailed producer-level data for every wetland mitigation bank operating over this period. Entry requires certification from either FDEP or water management districts, who maintain contracts with every wetland bank in Florida. These contracts include maps of the bank site, the date at which the initial contract was signed, and details on the offset release schedule over time. Many contracts also include reported restoration costs, which we use to corroborate our estimates.

Second, we obtain prices for wetland offset transactions from market participants. Our main source is a nondisclosure agreement with a major private broker. We supplement the data on these private transactions with Freedom of Information Act requests to county officials and the Florida of Department of Transportation for government offset purchases. While transaction prices are not reported to the regulator, our final data includes the majority of trades and nearly the entire period (1998–2018).

Third, we use maps that track evolving environmental characteristics of coastal land to measure wetland location, extent, and quality. These landcover maps are derived from satellite and aerial data in the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Project (C-CAP) dataset, cover all of Florida at a 30m$\times$30m resolution in 1996, 2001, 2006, 2011, and 2016. This data contains more than 194 million pixels for each of five periods, 136 million of which are contained in watersheds covered by offset trading zones. It gives us an unprecedented view of the evolution of land use in Florida.[8]

Fourth, we use maps of land ownership. To delineate between private and public land, we use boundaries for all land owned by local, state, and federal entities at baseline (1995) as well as Florida state government conservation land purchases from

[8]Relative to more general land cover datasets, C-CAP is tailored to study coastal systems in the Gulf Coast (six of its twenty-five land use categories are wetland subtypes; see Appendix D) over time, tracking actual wetland transitions with high levels of accuracy (McCombs *et al.*, 2016).

1990–2020 under the Preservation 2000 and Florida Forever programs. We intersect ownership with our land cover data to isolate changes in wetlands on private land. We also use annual ZIP-code-level home values from Zillow (1998–2020) and population, income, housing units, and home values from the U.S. Census (2000, 2007–19).

Fifth, we collate local flood data from the Federal Emergency Management Agency (FEMA). Our primary measure of economic damages uses administrative data from FEMA, which administers virtually all flood insurance contracts and claims. We use recently redacted, publicly-available data on the universe of flood insurance claims and policies from 1978–2020, which include the claim location, date, and amount, as well as data obtained through a FOIA request that includes total policies held from 1975–2018. In addition, we calculate local measures of inherent flood risk using flood zone designations from the National Flood Hazard Layer (NFHL), which is a product of FEMA. The NFHL is based on topographical and hydrological modeling. These detailed maps of flood risk are used to price flood insurance at the city-block-level and capture all locations, whether or not they have purchased insurance.

We then match the diverse spatial and temporal scales of the microdata to build a hydrologically consistent panel as described in Appendix B. Specifically, we use hydrological boundaries from the United States Geological Service (USGS, 2013) to produce a consistent panel of local watersheds and markets across time that aligns with both hydrological realities and market boundaries. Local watersheds are typically about 24,000 acres (40 square miles). Florida contains 1,378 such watersheds, 1,004 of which are contained within offset markets (Figure A1) and included in our final dataset.

2.4 Descriptive evidence

We now use our data to outline some facts about (i) initial wetland extent and land ownership, (ii) spatial patterns in development and wetland restoration, (iii) offset releases and sales, (iv) market structure, and (v) trade outcomes.

2.4.1 Initial wetland extent and land ownership

We observe the initial condition by constructing exact wetland locations in 1996. Table 1 shows that, for the 136,302,645 pixels in our dataset, 36.4% of them were initially a wetland. When aggregated to local watersheds, the average watershed contained an average of 10,818 acres of wetland (33.2% of its area) at baseline.

Many, but not all of these wetlands will be prospective sites for development, depending on the initial ownership of the land.[9] We delineate public and private land in each watershed by intersecting the hydrological boundaries from USGS with land ownership boundaries from the Florida government. On average, 12.5% of a watershed's land is conserved as public land in 1995 and the median watershed is 2.1% public (Table 1). Wetlands are more likely to be publicly owned: 17.5% of a watershed's wetlands on average is public land. At the same time, there are many privately-owned wetlands in Florida (about 7,400 acres of wetland in the average watershed-period).

2.4.2 Spatial patterns in development and wetland restoration

Our data shows significant differences between the places producing offsets and the places buying offsets. To determine where offsets are produced, we match wetland bank entry locations to watersheds. To determine where offsets are bought, we use the conversion of private wetlands into developed land.[10]

Figure 1, Panel C, illustrates the typical pattern of reallocation using within-pixel data in a representative market. Wetland development (red pixels) occurs nearby historical development (dark gray), while wetland bank project sites (dark blue) are fewer, closer to historical wetlands (green), and farther from developed areas. Similar core-periphery patterns are apparent in the other thirty markets that we study, as reported in Figures A4.1–30. Qualitatively, these patterns show that offset trading involves significant spatial reallocation of wetlands within each market.

Quantitatively, the average watershed converts 207.5 wetland acres over the sample period (Table 1), but this distribution is highly skewed. The median watershed sees very little wetland development (16.4 acres), whereas the 75th percentile watershed sees 186.7 acres converted. Private developers convert an original wetland with probability of 0.037 in the average watershed, with much of this development concentrated in the upper tail, with private developers in the maximal watershed converting more than half of their wetlands (a probability of 0.57).

To further quantify these spatial patterns, Table 2 compares watersheds that contain wetland banks with the watersheds that involve the development of substantial

[9]Public wetlands—designated as conservation land by local, state, or federal authorities—are not able to be developed by law in most contexts, and therefore must be separated from the analysis of wetland offset demand. Similarly, wetland banks can only enter on private land. At the same time, wetland banks receive additional offsets when they locate near existing public conservation land.

[10]Almost no conversion occurs on public wetlands, with private wetlands accounting for 99.2% of wetland pixels developed from 1996–2016. In our structural analysis, we analyze outcomes only for wetlands converted in places where we observe offsets trade; this corresponds to about two-thirds of all development on wetlands, reflecting the fact that some markets do not begin until after 2000.

areas of initial wetlands, excluding those which contain both. This comparison reveals large differences between where most wetlands are developed and where most wetland banks locate. First, most wetland development occurs in places with greater initial development density: 32.5% of the area of the median high-development watershed starts as developed, vastly exceeding the median watershed's 4.7% or the median wetland bank watershed's 3.0%. Wetland development also occurs frequently alongside other land development, with a correlation between development on wetland pixels and contemporaneous development of other pixels in a watershed of 0.656.

Second, wetland mitigation banks enter in watersheds with more initial public wetlands. The average wetland bank watershed contains 13,700 acres of public wetland, compared with the average Florida watershed of 3,300 wetland acres. This pattern is consistent with regulatory incentives that award additional offsets to banks to restore existing wetlands nearby existing conservation land,[11] as well as the fact that wetland restoration is much easier adjacent to existing wetlands, because it is possible to route water from those wetlands to the newly restored land. The tendency of wetland banks to locate in places with large areas of public land also reflects economic incentives, given that land values can be lower in such peripheral places.

Third, in terms of flood insurance, high-development places without wetland banks have greater insured value at baseline ($18.8 million) than places with only wetland banks ($10.1 million) or the average watershed in the sample ($7.2 million). This reflects a positive correlation between more intensive offsets market activity and underlying value at risk. High-development and wetland bank watersheds have similar average historical flood insurance claims ($413,000/year versus $314,000/year), but the immense dispersion of these distributions, which have coefficients of variation greater than 5, driven mainly by the extreme values in the right tail, means that none of these average differences are statistically significant.

Summarizing, banks are more likely to choose locations with greater wetland area, lower density of development, and more public wetlands. These correlations are consistent with private landowners searching for low-cost places for restoration, as well as natural constraints on wetland restoration that make some places infeasible for large-scale wetland mitigation bank projects. Developers, in contrast, locate in watersheds with preexisting development and more other development occurring contemporaneously. Both banks and developers appear more frequently in places with greater average

[11] "Mitigation banks and offsite regional mitigation should emphasize the restoration and enhancement of degraded ecosystems and the preservation of uplands and wetlands as intact ecosystems rather than alteration of landscapes to create wetlands." (Florida State Legislature, 2019, §373.4135).

annual flood insurance claims and total insured value than the typical watershed.

2.4.3 Offset releases and sales

Banks produce large quantities of offsets relative to the size of their markets and the size of the buyers of offsets. The median bank produces about 210 offsets over its lifetime (or 420 on average), with an interquartile range of 85 to 520 offsets. The scale economies for wetland banks reflect the large parcel areas required to redirect water flows, as well as rules for banking that reward wetland contiguity. Production increases proportionally with the total area of the wetland bank project site; on average, the ratio of acres to offsets is about 4.5 acres, ranging between 3.6–5.3 across water management districts.[12] Banks also take time to build, reflecting the time required to verify environmental improvements, which accrue over time. Table 1 shows that the regulator typically releases 15% of a wetland mitigation bank's offsets once every three years, or an average time of $1/0.055 \approx 18.2$ years to build the entire project.

In contrast to wetland banks, the median developer purchases only 1.1 offsets (or 4.1 offsets on average). Measuring the location of these projects is more difficult than for wetland banks; we observe the quantity and timing of offset sales by each bank, and therefore in each market, but we do not observe every parcel that purchases offsets. Some development on wetlands involves on-site mitigation, and when offsets are purchased, the number of offsets per acre will vary based on the wetland value of the converted land. Fortunately, we can use our ledger data to restrict the developed wetland pixel data to watershed-periods with active offset markets, in order to construct average acre-to-offset ratios for each water management district. Table A2 shows that, for markets with nonzero offset sales in a five-year period, wetland acres typically convert to offsets at a ratio of between 4.8 to 12.6 acres per offset.[13]

2.4.4 Market structure

The final aspect of the market design that determines equilibrium trading is the designation of regional trading zones. As discussed above, banks can only trade within their

[12]We also intersect our data on pixel-level initial conditions and our within-pixel transitions with these project sites and find that wetland mitigation banks obtain offsets primarily in proportion to their initial wetland cover, averaging 4.49 initial wetland acres per offset received, reflecting the fact that much of these parcels' area is initially classified as wetlands.

[13]For a subset of transactions in the South Florida Water Management District, we observe parcels that purchased wetland offsets, which we link to our ledger of trades and intersect with our within-pixel calculations. For these parcels, developers purchase offsets at a ratio of 1 offset to 5.36 developed wetland acres on average, corroborating our water management district calculations.

own service areas, which approximate hydrological regions. We use these maps to define markets after some adjustments to correct for partial and overlapping watersheds as discussed in Appendix B.

Figure 1 shows our market boundaries for Florida. On average, a market covers 1.15 million acres, or 33.5 watersheds, ranging from 11–70 watersheds. Wetland banks enter in 11.7% of market-years. The median market in the median year (2006–7) contained 1 bank or 2.2 on average, rising to 2 incumbents and an average of 3.7 firms by 2018. The average bank owns 26.1% of its market's total production potential and 37.4% of its market's total unsold offsets. The latter reflects the fact that banks do not sell their offsets immediately, but rather typically hold positive reserves; the median bank holds 52% of its offsets in reserve, with an interquartile range of $[18\%, 82\%]$.

We interpret the market concentration in offset supply as reflecting a combination of the economies of scale and production delays discussed above, as well as strategic factors that interact with the regional restrictions on trade. Conditional on various determinants of demand, annual entry occurs less often in markets with more incumbents (Table 4), consistent with incumbency advantages that deter future entry.

2.4.5 Trade outcomes

We close our discussion of the data with three descriptive findings about trade outcomes. First, offset markets have played an increasingly central role in the regulation and management of Florida's wetlands since 1995. Valued at average annual prices, cumulative offset sales totaled $1.2bn from 1995–2018 (in 2020 USD). Offset sales increase over time, growing annually by an average of 9.8%. This growth reflects the secular trend in new development in Florida and an underlying transition to the market-based approach to wetland conservation after the introduction of wetland bank rules in 1994.

Second, offset prices considerably exceed the observed components of banks' average fixed costs. Observed fixed costs involve permitting costs, restoration and property maintenance costs (put into escrow at the time of entry), and the opportunity cost of land use. Total observed costs for the average bank, $5.3 million, or about $24,000 per offset, reflect primarily restoration and land costs. Average restoration costs, which we observe for nearly two-thirds of banks, are $7,000/offset, while land values obtained from the last reported transaction price (from tax assessments) average $19,000/offset ($9,000/offset). These differences appear to reflect local land prices as well as natural features determine the costs and feasibility of restoration across markets.[14]

[14]For example, restoration costs are lower in northern Florida (e.g., about $9,000/offset in

Third, high-development watersheds see much greater increases in flood insurance claims than wetland bank watersheds. On average, high-development watersheds experienced $800,000 in claims per year from 2016–2020, in contrast to average claims for wetland bank watersheds, which in fact decline in real terms from $315,000 to $160,000 (2020 USD) per year. This difference continues through the distribution: the median high-development watershed experiences more than an order of magnitude the annual damages of the median wetland bank watershed. Some, but not all, of these differences reflect differential growth in total insured value, with the average value at risk in high-development watersheds rising nearly twice as fast as in wetland bank watersheds (growing from $18 to $500 million relative to $10 to $66 million).

Taken together, our data indicates trade flows are substantial and that wetland banks typically locate in different places than where most wetland development occurs, even within relatively small regional markets. However, several empirical questions remain. First, transaction volumes and prices are not sufficient statistics for the private gains from trade.[15] Second, selection into mitigation banking precludes the direct use of cost data from our contracts for counterfactuals, which require the unconditional cost distribution of all prospective banks, not just those which entered. Entry also involves costs not observed from contracts—such as permitting costs—and entry incentives further depend on the value of equilibrium trading over time. Third, evaluating offsets' effects on other outcomes like flood externalities requires identifying the relative effects of marginal wetlands and new wetland banks on these outcomes. The empirical model of decentralized trade in environmental offsets below is designed to tackle these issues.

3 A model of conservation, destruction, and restoration

We now specify an empirical model of regulated environmental offsets. Wetlands distributed across space can be conserved, developed, or restored over time (Section 3.1). A regulator who aims to conserve various wetlands issues permits to ensure that offsets satisfy its conservation objective (Section 3.2). Small land developers obtain payoffs from developing existing wetlands and take offset prices as given (Section 3.3). Large

Altahama–St. Mary's) than Gulf Coast markets (e.g., $16,000 in Peace–Tampa). Similarly, land costs are higher in Southern Florida ($12,000/offset) and the Gulf (e.g., $12,600/offset in Peace–Tampa) than northern markets (e.g., $5,700/offset in Altaham–St. Mary's).

[15] Inframarginal buyers may have values significantly greater than market prices, while imperfect competition may allow banks to charge prices above their costs.

producers undertake long-run restoration activities to obtain offsets from the regulator, which they can sell to land developers over time. These producers incur fixed entry costs, have zero marginal costs, and take time to build (Section 3.4). Incumbents simultaneously choose sales in each period in a Markov perfect equilibrium (Section 3.5). In this setting, entry follows a cutoff rule and dynamic trading strategies can be characterized as an optimal inventory problem (Section 3.6).

3.1 The conservation problem

A large hydrological region or "market," m, consists of a map of a continuum of locations indexed by $i \in [0, 1]$, which we partition into a finite set of local watersheds, indexed by h. As offsets cannot be traded across markets, we suppress subscripts m until we introduce our estimating equations in Section 4. Within a market, the distribution of wetlands at time t is given by $\{w_{it}\}_i$, with $w_{it} = 1$ when i contains a wetland at t, and $w_{it} = 0$ otherwise. Time is discrete, the horizon is infinite, and all agents discount future periods with a factor $\delta < 1$.

Wetland conservation, development, and restoration occur over time. Each of these processes correspond to a different state transition between t and $t + 1$. First, existing wetlands can be conserved; i.e., $w_{it} = w_{i,t+1} = 1$. Second, locations with wetlands can be developed into non-wetland property and sold; i.e., $w_{it} = 1$ and $w_{i,t+1} = 0$. Third, land without wetlands can be restored into wetlands; i.e., $w_{it} = 0$ and $w_{i,t+1} = 1$.

Wetlands have private and social values. The private costs and benefits of wetland conservation, development, and restoration accrue to landowners and wetland restoration firms, which we describe in detail below. The social value of wetlands arise through their contribution to environmental quality. Specifically, each location i endowed with some potential environmental value as a wetland, $\upsilon_i \in \mathcal{V}$, where $\mathcal{V}$ is some set of attributes. These potential values differ across space, due to underlying environmental characteristics and biodiversity, as well as over time, with evolving climatic and demographic conditions, though we suppress time dependence to simplify notation.

Given the private payoffs of wetland conservation, development, and restoration, in each period t, landowners will decide land use for $t + 1$ and incur costs of land use change. Importantly, not all land use decisions are reversible. We model restoration (a transition from $w_{it} = 0$ to $w_{i,t+1} = 1$) as an absorbing state, given that wetland banking requires a permanent transfer of land ownership into the public trust (a conservation easement). Similarly, we model development (a transition from $w_{it} = 1$ to $w_{i,t+1} = 0$) as an absorbing state. This is because, in the three decades spanned by our data, wetlands converted to development almost never transition back to wetlands.

3.2 Offset market design

The offset mechanism we study takes the following form. The regulator's legal mandate is to ensure No Net Loss in wetland value given their conservation priorities. These priorities are defined in our context by the regulator, who maps individual wetland attributes, $\upsilon_i \in \mathcal{V}$, into a scalar number of offsets, $\tilde{\upsilon}_i \in \mathbb{R}$. The regulator's measure of aggregate environmental quality is then

$$\tilde{\upsilon}(w_t) = \int_0^1 w_{it}\tilde{\upsilon}_i di, \tag{1}$$

and No Net Loss requires that the distribution of wetlands $\{w_{it}\}_i$ delivers at least as much value in each period t as in the initial period, i.e.,

$$\tilde{\upsilon}(w_t) \geq \tilde{\upsilon}(w_0) \text{ for all } t > 0. \tag{2}$$

In practice, the regulator enforces (2) over time by certifying sufficient cumulative wetland restoration to offset cumulative wetland destruction.

Regulated trade in environmental offsets to satisfy (2) involves two types of participants in each period t. First, owners of wetlands with development potential seek approval from the regulator to build. The regulator inspects each such location i to determine its environmental impact, $\tilde{\upsilon}_i$, and then approves the project when the developer proves that they have purchased $\tilde{\upsilon}_i$ offsets. Second, prospective mitigation bank entrants, indexed by f, propose restoration to the regulator. The regulator inspects each location f to determine $\tilde{\upsilon}_f$, and the bank decides whether or not to enter and incur entry costs. The regulator monitors and verifies restoration activities and issues $\tilde{\upsilon}_f$ offsets over time as the restoration succeeds. These offsets can be held by the incumbent mitigation bank and traded in any future period.

We note that the irreversibility of both development and restoration considerably simplifies the dynamic land use problem in our setting. This is because it allows us to separate private land into two types based on the initial conditions: first, prospective "developers" with $w_{i0} = w_{it} = 1$, who decide in each period whether or not to develop their wetland into something with greater private value; second, prospective "wetland mitigation banks," or private land with $w_{i0} = w_{it} = 0$, who decide whether or not to invest to restore their land into newly conserved wetland. These potential buyers and sellers of offsets share some similarities but also differ in a few economically important ways, so we analyze each type's decision in separate sections.

3.3 Demand for offsets

Landowners whose land initially includes wetland correspond to potential buyers of offsets. These potential developers must seek approval from the regulator before developing their land, which requires offsets based on their wetland's attributes.

We assume a competitive market for private land development with a continuum of landowners, indexed by i. Each landowner inhabits one of the local watersheds, h. Landowners $i \in h$ who develop on a wetland at t (i.e., i such that $w_{i,t+1} < w_{it} = 1$) obtain a private value of development given by

$$u(X_{ht}, \xi_{ht}; \theta) + \epsilon_{it1} = \theta' X_{ht} + \xi_{ht} + \epsilon_{it1},$$

which has two parts. First, developing a wetland yields an ex-ante value, $u(X_{ht}, \xi_{ht}; \theta)$, which depends on observed local characteristics X_{ht} (such as development density, demographics, hydrological region, and local flood risk), unobserved local characteristics ξ_{ht}, and a vector of preference parameters θ. For example, this ex-ante value can correspond to the discounted stream of rental income from developed land or expected profits from agricultural production for land used to grow crops, net of the construction or future planting costs. Second, a landowner i who develops a wetland at t incurs a choice-specific idiosyncratic development cost, ϵ_{it1}, assumed to be an independently and identically distributed Type 1 Extreme Value (T1EV) shock across i and t. Alternatively, a landowner who owns an existing wetland and chooses to do nothing obtains ϵ_{it0}, also independently and identically distributed T1EV.

Without regulation, the ex-ante private value for a landowner who develops on wetlands in watershed h in period t is just $u(X_{ht}, \xi_{ht}; \theta)$, which determines the share of that watershed's existing wetlands developed in a given period. However, under the market design of Section 2.2, developing on wetlands also requires offsets. If developer $i \in h$ can purchase offsets at a price P_t, then, given the regulator's assessment $\tilde{v}_h$ of i's watershed's contribution to conservation priorities and a price sensitivity coefficient θ_P, i's relative value of destroying the wetland becomes

$$u(X_{ht}, \xi_{ht}; \theta) - \tilde{v}_h \theta_P P_t + \epsilon_{it1} - \epsilon_{it0}. \tag{3}$$

We assume that i destroys its wetland at t if and only if (3) exceeds zero. Aggregate demand for offsets at t at a price P_t and a regulatory rule $\tilde{\upsilon}$ is then

$$\begin{aligned} Q_t(P_t, W_t, X_t, \xi_t, \tilde{\upsilon}; \theta) &= \int_0^1 w_{i0} w_{it} \tilde{\upsilon}_i \mathbf{1}\{u(X_{ht}, \xi_{ht}; \theta) + \epsilon_{it1} - \epsilon_{it0} \geq \tilde{\upsilon}_h \theta_P P_t\} di \\ &= \sum_h \tilde{\upsilon}_h W_{ht} \frac{e^{\theta' X_{ht} - \tilde{\upsilon}_h \theta_P P_t + \xi_{ht}}}{1 + e^{\theta' X_{ht} - \tilde{\upsilon}_h \theta_P P_t + \xi_{ht}}}, \end{aligned} \tag{4}$$

where the second line follow from the logit assumptions across local landowners. Aggregate demand in (4) reflects current shocks to local development payoffs, $(X_t, \xi_t) = \{X_{ht}, \xi_{ht}\}_h$, as well as private wetland availability, given by $W_t = \{W_{ht}\}_h$.

The structure of the private landowner's decision above imposes some important limitations on our analysis. First, while private wetland owners have the same average development payoffs as others in their local watershed, which creates correlation across development decisions within each local watershed, landowners act independently from one another and take offset prices as given. These assumptions rule out coordinated development schemes across many parcels. They reflect the small size of these developers relative to one another and to the banks described in Section 2.4. Second, in our model, prospective developers arrive, then disappear if they choose not to develop. While the decision rule in (3) incorporates the net present discounted value of development conditional on development, it rules out more complicated forward-looking strategies by developers that incorporate the option value of future development. This restriction limits our analysis to the extent that individual developers delay development to obtain more favorable offset prices or choice-specific shocks.[16]

Despite these restrictions, our model of wetland development remains rich enough to capture some essential aspects of the economic setting. We emphasize two primary advantages. First, aggregate market demand is only locally linear, because a market contains many local watersheds (more than thirty on average), and each watershed h has its own average utility. The marginal buyer of offsets will be a convex combination of these local watersheds, each with their own average values, so our estimates of the curvature of demand and consumer surplus will primarily reflect variation across local watersheds in their revealed preference for developing wetlands, not the logit distributional assumption on idiosyncratic choice shocks of each individual landowner.

[16] Optimal development for a long-lived prospective developer should contrast the payoff in (3) with the option value of deferring the development decision to the next period, based on assumptions about developers' beliefs over future equilibrium outcomes and the evolution of unobserved switching costs and tastes over time, as in, for example, Scott (2013).

Second, the model exhibits dynamics both within local watersheds and at the market level. Development on wetlands affect future development opportunities in each local watershed h, because the extent of available wetlands for development in period t, defined as $W_{ht} = \int_{i \in h} w_{i0} w_{it} di$, will reflect the full history of land development. These local stocks of potentially developable wetlands evolve endogenously with landowners' decisions. For example, greater development on wetlands today in a local watershed h will leave fewer prospective locations tomorrow, lowering W_{ht} and altering future demand for offsets. Furthermore, development on wetlands increases local development density, which itself affects the value of future development.

Over time, local demand also evolves with exogenous demand shifters. We assume these follow first-order Markov processes, i.e., that the cumulative distribution function of (X_{t+1}, ξ_{t+1}) is some function $H_{X,\xi}(\cdot|X_t, \xi_t)$. This is without loss of generality; any finite-order Markov process admits a first-order representation under the appropriate extension of the state space. In Section 4, however, we further restrict ξ_t to rule out persistence in unobserved and idiosyncratic watershed payoffs over time.

3.4 Supply of offsets

We now turn to the choice problem for wetlands restoration, which—in contrast to the dispersed development of wetlands across space—involves a few large restoration sites in each market. We therefore model offset supply as an imperfectly competitive, oligopolistic environment with a finite set of non-infinitesimal potential producers, indexed by their location, $f \in \{1, 2, \ldots, F\}$. Formally, each production site f corresponds to a subset $I_f \subset [0, 1]$ of positive measure where restoration is feasible and $w_{i0} = 0$ for all $i \in I_f$. Production sites differ in terms of natural suitability for restoration as well as intrinsic production potential, $\tilde{\upsilon}_f$, which reflects various wetland services valued by the regulator, such as contiguity of the site with existing conservation land. In this and the next subsection, we describe the producer's problem and timing; in Section 3.6, we close the model by specifying the equilibrium price path for offset prices.

Entry. In each period t, one potential entrant arrives at an unoccupied production site f at random, observes its potential environmental value $\tilde{\upsilon}_f$ (denominated by the regulator in offsets), and then draws a private entry cost

$$\kappa_{ft} \sim G_t(\cdot|\tilde{\upsilon}_f, \mathcal{F}_t^c). \tag{5}$$

where G_t is a cumulative probability distribution conditional on $\tilde{\upsilon}_f$ and observable local characteristics of the remaining production sites in the market, denoted by $\mathcal{F}_t^c$. The fixed cost captured by κ_{ft} includes permitting, restoration, and maintenance costs, as well as the opportunity cost of non-wetland use. It may also include other aspects of operating the bank, such as intrinsic enjoyment of conservation. If the prospective entrant chooses to enter, the decision is irreversible as discussed above. Otherwise, as in Doraszelski and Satterthwaite (2010), the prospective entrant disappears.

Production. A bank produces offsets over time up to its total value, $\tilde{v}_f$. Because verification occurs gradually, the offset release schedule also depends on the bank's age, T_{ft}. Specifically, in each period t, the regulator issues

$$b_{ft} = \mathcal{B}(T_{ft}, \tilde{v}_f), \tag{6}$$

offsets to each production site f. Offsets are released over time until restoration is complete, i.e., until $\sum_t b_{ft} = \tilde{v}_f$. Equation (6) allows for various time paths of offset release and also allows offsets' release to occur stochastically, but assumes that the environmental activities undertaken by the bank can be reasonably approximated with a known function of its land's underlying characteristics, with capacity fixed in the initial contract and not revisable thereafter.

Trading. Wetland banks obtain revenue from selling offsets to developers. At the start of each period t, each incumbent f has a stock of available offsets $B_{ft} \geq 0$, which have been certified but not yet sold. Each incumbent f can sell up to this constraint, $q_{ft} \leq B_{ft}$. Restoration costs are paid upfront, so the marginal cost of producing offsets is zero. We also assume that transaction costs are negligible.

Within each period, each firm f simultaneously chooses a quantity of offsets to trade, q_{ft}, which determines the price vector P_t via (4), and then each firm f obtains per-period profits,

$$\Pi_{ft} = P_t' q_{ft}. \tag{7}$$

New wetland offsets, b_{ft}, are certified at the end of period t, and bank f's stock evolves to

$$B_{f,t+1} = b_{ft} + B_{ft} - q_{ft}, \tag{8}$$

with the initial condition $B_{ft} = 0$ for all t prior to entry.

3.5 Information and timing

We denote the market state vector at time t by

$$s_t = \left(W_t, X_t, \xi_t, \mathcal{F}_t^c, \{\tilde{v}_f, B_{ft}, T_{ft}\}_{f \in \mathcal{F}_t}\right), \tag{9}$$

which consists of undeveloped private wetlands, $W_t = \{W_{ht}\}_h$, local characteristics (X_{ht}, ξ_{ht}) for each h, the remaining production sites $\mathcal{F}_t^c$, and the ages T_{ft}, offset balances B_{ft}, and capacities $\tilde{v}_f$ for all incumbents $f \in \mathcal{F}_t$.

In each period t, all potential and current offset producers observe the market state, s_t. One prospective entrant $f \in \mathcal{F}_t^c$ then privately draws their fixed cost, $\kappa_{ft} \sim G_t(\cdot|\tilde{v}_f, \mathcal{F}_t^c)$, and decides whether to enter. Incumbents simultaneously choose their trading volumes, $\{q_{ft}\}_{f \in \mathcal{F}_t}$, which determines equilibrium offset prices via (4), and banks obtain profits. Finally, entry decisions are realized, entry costs are incurred, wetlands are developed in proportion to permits sold, and the state updates to s_{t+1}.

3.6 Equilibrium

We focus on Markov perfect equilibria (MPE) (Ericson and Pakes, 1995; Maskin and Tirole, 2001) as formalized in Doraszelski and Satterthwaite (2010), restricting the strategies for each production site f to be anonymous, symmetric, and Markovian, so that they are given by functions

$$\sigma_f : (s_t, \tilde{v}_f, \kappa_{ft}) \mapsto (\text{enter}_{ft}, q_{ft}).$$

In an MPE, equilibrium profits within a period depend only on the wetlands available for private development, demand shocks, and incumbents' trading strategies, and can be written as

$$\Pi_{ft} = \Pi(q_{ft}, s_t).$$

Firms maximize their expected discounted profits. The expected value of a wetland bank with offsets B and age T is

$$V(B, T, s_t, \tilde{v}_f) = \max_{q \in [0,B]} \Pi(q, s_t) + \delta \mathbb{E}_t \left[V(B - q + b_{ft}, T+1, s_{t+1}, \tilde{v}_f)\right]. \tag{10}$$

A bank's current trading decision affects its continuation value in two ways: first, directly, by depleting its future stock $B_{f,t+1}$; second, indirectly, through the state of undeveloped wetlands W_{t+1}, which affects future offset demand and entry incentives.

We assume that the optimal trading decision at t, which maximizes (10), can be characterized by a function

$$q_{ft} = \mathcal{Q}(s_t, B_{ft}, T_{ft}, \tilde{\upsilon}_f) \tag{11}$$

of B_{ft}, T_{ft}, $\tilde{\upsilon}_f$, and s_t. All potential entrants use a common entry strategy that takes the form of a conditional cut-off rule: the pure strategy prescribes entry if and only if

$$\kappa_{ft} < V(0, 1, s_t, \tilde{\upsilon}_f). \tag{12}$$

This implies that the probability that f enters at t prior to its private draw of $\kappa_{ft} \sim G_t(\cdot|\tilde{\upsilon}_f, \mathcal{F}_t^c)$ is given by

$$\mathbb{P}(\text{enter}_{ft}|s_t, \mathcal{F}_t^c) = G_t(V(0, 1, s_t, \tilde{\upsilon}_f)|\tilde{\upsilon}_f, \mathcal{F}_t^c), \tag{13}$$

which can be written as some function $\phi_t(s_t, \mathcal{F}_t^c) \equiv G_t(V(0, 1, s_t, \tilde{\upsilon}_f)|\tilde{\upsilon}_f, \mathcal{F}_t^c)$.

The equilibrium in the environmental offsets market consists of entry and trading strategies $(\text{enter}_{ft}, q_{ft})_{t\geq 0}$ for all $f \in \{1, 2, \ldots, F\}$, undeveloped private wetlands $(W_t)_{t\geq 0}$, and a path of offset prices $(P_t)_{t\geq 0}$, such that (i) entry satisfies (12) at all $t \geq 0$ for all $f \notin \mathcal{F}_t$; (ii) incumbents' trading strategies $(q_{ft})_{t\geq t'}$ solve (11) for all $f \in \mathcal{F}_{t'}$ and all t'; (iii) private wetlands destruction Q_t solves (4) for every t; and (iv) no net loss holds, i.e., $\sum_{f\in\mathcal{F}_t} q_{ft} = Q_t$ for all t, as well as $\lim_{t\to\infty} \delta^t P_t' B_{ft} = 0$ for all f.[17]

4 Empirical strategy and estimation

The empirical strategy to identify and estimate the model of Section 3 involves three parts. First, we identify demand for offsets from observed land development and transaction prices and quantities over time, using price instruments constructed from cost shifters of offset supply (Section 4.1). Second, to identify supply of offsets, we use maps of observed entry and the environmental characteristics of a market's remaining available land suitable for wetland banking. We correct for selection into wetland banking by forward-simulating value functions as in Hotz *et al.* (1994), Bajari *et al.*

[17] An MPE in symmetric pure strategies should exist for this game by Doraszelski and Satterthwaite (2010, Proposition 2). The reason is that, after conditioning on the set of remaining production sites, the entry game with private cost draws becomes the same as in DS (2010) and leads to a similar optimal cutoff rule given by (12). The only added complication is the dynamic trading decision in (11), but this is isomorphic to a continuous investment choice with evolving support. DS (2010) allow for continuous investment choices like $\mathcal{Q}(s_t, B_{ft}, T_{ft}, \tilde{\upsilon}_f)$ provided that they are unique functions of the state, as we assume here.

(2007) and Pakes *et al.* (2007) for both incumbents and potential entrants, to recover the distribution of fixed costs across market states consistent with optimal entry (Section 4.2). Third, we estimate the local flood externalities of different wetlands using historical changes in wetland extent and realized flood insurance claims, adapting the identification argument in Taylor and Druckenmiller (2022) to our setting with some slight modifications to minimize concerns of misspecification (Section 4.3).

4.1 Demand for offsets

We first describe how we obtain local demand for development on wetlands given offset prices. These estimates are necessary to calculate buyers' surplus from observed offset purchases, to predict the pattern of local development on wetlands under alternative market designs, and to obtain the value of entry in this market.

To tractably account for some spatial correlation across infinitesimal locations, we partition the model's continuum of locations i into the finite number of local watersheds, indexed by h as in Section 2. For each watershed, we recover local demand for environmental offsets, and then aggregate to total market-level demand as in (4), using water management district acre-to-offset ratios, $\tilde{\upsilon}_h$, to convert developed wetland acres into offsets. Our data allows us to construct pixel transitions over five-year intervals, so we estimate demand at the watershed by five-year period level, with periods t given by the intervals 1996–2001, 2001–2006, 2006–2011, 2011–2016. In particular, we can calculate the share of development occurring on private wetlands, $\omega_{ht} = Q_{ht}/W_{ht}$, as the ratio of the area Q_{ht} of private wetlands in watershed h converted to developed land over period t to the area of potentially developable wetlands $W_{ht} = \int_{i \in h} w_{it} w_{i0}$ at the start of period t. Taking this observed share ω_{ht} as the conditional probability that $i \in h$ develops a private wetland, we obtain the logit equation

$$\ln \omega_{ht} - \ln(1 - \omega_{ht}) = \theta' X_{ht} + \theta_P \tilde{\upsilon}_h P_{ht} + \xi_{ht} \tag{14}$$

for each watershed h and period t, where development choices depend on the average offset price, P_{ht}, and other observable determinants of demand X_{ht}, including period and water management district fixed effects, flood zone designations, new development on non-wetlands, lagged development density, and lagged demographics such as median income and population.

Identifying offset demand. As wetland offset prices are partly determined by incumbents' trading decisions, and therefore incumbents' beliefs about the vector of unobserved demand shifters ξ_t, equation (14) cannot be estimated without an instrument for price. We consider three sets of instruments for local prices, each based on various cost shifters for offset production projects.

First, we calculate the average production capacity of historical entrants whose service areas contain h. Intuitively, greater sunk capacity due to historical entry should shift market prices downwards, all else equal, acting as a downward cost shifter. Importantly, these capacities are fixed at the time of entry and cannot be subsequently adjusted. Clearly realized capacities are endogenous; the key is that when we control for the market state information known by those entrants, the realized draws become excluded shifters of future costs (Berry and Compiani, 2023). Because banks produce offsets slowly (over an average of eighteen years), our sunk capacity instrument can remain relevant over long horizons. The primary concern is that entrants rely on private information about future unobserved components of local demand. Our conversations with mitigation bankers, however, indicate they use market forecasts based on public information, such as home prices and historical offset prices.

Second, we build Hausman (1996) instruments from endogenous outcomes in nearby markets as proxies for cost shifters in the market of interest. In addition to using the average price from banks in the same water management district but not the local watershed's own market, we construct our average historical entrant capacity instrument from banks whose service area does not contain the watershed, but which are in the same water management district.

Third, we use variation in other public wetland and conservation land, which act as natural cost shifters for offset supply. This creates ideal variation in costs for wetland banks, which depend on the availability of private land for sale and the connectivity of that land to existing conservation land. Specifically, for each period and watershed, we construct the total public wetland over all other watersheds in the same market (excluding land used by wetland banks). Most of this variation is cross-sectional, though some evolves over time through new land purchased under Florida's conservation buyback programs (Florida Forever and Preservation 2000).

Estimates. Table 3 reports the demand estimates. The key object of interest is the elasticity of local wetland development with respect to the average offset price. As described above, our empirical strategy instruments for the current offset price using various offset production cost shifters.[18] These instruments vary in strength, with own

[18]Without the instrument, column (1) of Table 3 shows that OLS implies an average price elasticity of demand about -0.3. This is particularly concerning for monopoly and duopoly markets, where incumbents should prefer to locate on a less inelastic part of the demand curve. Several possible

historical capacity as the strongest instrument, with a first-stage F statistic ranging from 49.8 to 117.3, even conditional on our diverse controls, though the Hausman and public conservation land instruments also meaningfully shift prices (8.3 and 21.3). In addition, these instruments shift prices in the way theory predicts: all else equal, markets with larger historical entrants, more historical entrants in neighboring markets, or greater public conservation land, each have lower prices.

Columns (2)–(7) report instrumental variable estimates of (14). Across various controls, the estimated elasticity is close to -1, showing both a significant relationship between the cost of purchasing an offset and development on local wetlands and that demand is moderately elastic. These findings suggest that these markets are empirically meaningful determinants of land-use decisions. To our knowledge, this is the first estimate of this demand curve, so there is no prior literature for us to benchmark our estimates. We take the estimate in column (3), where $\hat{\theta}_P = -0.98$, as our preferred estimate for subsequent analysis.

4.2 Restoration costs

The main identification challenge to recovering unobserved production costs is that banks may enter more often in some markets because their fixed costs in those markets are especially low, because entry in those markets is particularly profitable, or some combination of the two. Our estimates of local offset demand, combined with structure on the entry and trading games, allow us to identify fixed costs using the equilibrium conditions derived in Section 3.4. In the Markov perfect equilibrium, trading strategies and entry decisions are given by the functions $\mathcal{Q}$ in (11) and ϕ_t in (13). We take the two-step approach of Bajari *et al.* (2007). First, we estimate flexible entry and trading strategies as well as production functions for wetland mitigation banks. Second, we calculate implied flow payoffs and value functions for incumbents, which we use to identify the distribution of fixed costs: conditional on those payoffs, the model implies that remaining variation in observed entry decisions will reflect fixed costs.

Entry. Our model specifies a finite set of production locations within each market, over which entry opportunities arise at random. Entry therefore depends on sufficient statistics for the local characteristics of remaining production sites, $\mathcal{F}_t^c$, as well as the market conditions s_{mt} of the broader market m. Our data includes the location and date of every wetland mitigation bank as well as ownership and land characteristics

sources of upward bias for the OLS coefficient arise in our context. For example, places with greater unobserved values for development may have higher costs of wetland banking.

everywhere within the hydrological boundary of each market. We use the location and timing of entry to estimate the entry model given by (13). Specifically, we proxy for the extent of remaining land available for wetland restoration with the areas of public and private wetland and the number of incumbent firms, and then estimate annual market-level entry probabilities at the market-year level for all markets m and years $t \in \{1995, 1996, \ldots, 2020\}$ according to the following probit specification,

$$\mathbb{P}(\text{enter}_{mt}|\tilde{s}_{mt}) = \Phi\left(g(\tilde{s}_{mt})\right), \tag{15}$$

where Φ is the Gaussian CDF, g is a flexible polynomial, and $\tilde{s}_{mt}$ is the approximate market state that includes the number of incumbents, the period, the water management district, median income, population, and total incumbents' reserves, and the extent of private and public wetlands.

Our probit estimates of (15) indicate that across market-years, entry occurs more frequently in markets with more wetlands, more developed land, more development occurring on non-wetlands, and fewer incumbents. For example, Table 4 shows that the average estimated annual entry probability for duopoly markets is 0.18 for the first firm, but only 0.11 for the second firm.

Production function. We observe the numbers and dates of offsets issued to each bank directly from various regulatory records, which correspond to b_{ft} for banks f and years t in our framework. We also observe each bank's total offset allowance for the lifespan of the project, $\tilde{\upsilon}_f = \sum_{t \geq 0} b_{ft}$. This is useful for us because the typical bank in our data has not yet produced all of its offsets, given the lags in production. Together with the entry date of the bank, this allows us to construct production as a function of the bank's age, size, and local characteristics.

We specify the empirical analogue of (6) in two pieces. First, we are interested in the total offset allowance $\tilde{\upsilon}_f$. Second, we are interested in the timing of offset releases over time, given by

$$b_{ft} = \mathcal{B}(T_{ft}, \tilde{\upsilon}_f) = \sum_{\tau \geq 1} \mathbf{1}_{\{T_{ft} = \tau\}} \alpha_\tau \tilde{\upsilon}_f.$$

Our simulations do not estimate $\hat{\upsilon}_f$ or α_τ; instead, they obtain $\tilde{\upsilon}_f$ by drawing from the empirical distribution of $\{\tilde{\upsilon}_f\}$ over entrants in the data, then set $\alpha_\tau = 1/10 \cdot \mathbf{1}(\{\tau \leq 10\})$ to approximate the time-to-build discussed in Section 2.4.

Trading. We estimate the dynamic trading strategy (11) by predicting trades as a function of a bank's current reserves and future production, its rivals' characteristics, and its market's state. In the data, we observe b_{ft} and q_{ft}^{sold}, the number of offsets issued to, and sold by, each bank. This lets us estimate trading strategies at the incumbent-year level from 1995–2018. An incumbent bank's sales q_{ft}^{sold} in year t depend on its reserves and future production, as well as characteristics of its competitors and demand, via

$$q_{ft}^{\text{sold}} = \chi(\tilde{s}_{-ft}, B_{ft}, T_{ft}, \tilde{\upsilon}_f, \tilde{s}_t), \tag{16}$$

where χ is a flexible polynomial, rivals' characteristics $\tilde{s}_{-ft}$ include $N_{\text{competitors of } f}$ and $\sum_{f' \in m} B_{f't}$, and the approximate market state $\tilde{s}_t$ includes $\sum_{h \in m} X_{ht}$ from (14) and the aggregate private wetland stock $\sum_{h \in m} W_{ht}$ over watersheds in market m.

As in many applications of Bajari *et al.* (2007), the policy function χ consistent with the model is a nonparametric function of a high-dimensional state space, so its estimation in a finite sample may lead to error. In our simulations, the rules that allow banks only to trade certified offsets significantly limit these concerns by bounding $\chi \in [0, B_{ft}]$. We further discipline χ by imposing individual rationality (IR) constraints derived from static Cournot first-order conditions using the aggregate (market) demand elasticity and the vector of equilibrium market shares; this proves quite useful in practice.

State transitions. We model the state transitions of the exogenous demand shifters (local development on other land and lagged demographics) as AR(1) processes. Development on non-wetlands depends significantly on the previous stock of developed land, and population and income are highly persistent, with an autocorrelation coefficient of 0.97. The transitions of the remaining endogenous states—in particular, the extent of private wetland and developed land—are then calculated from entry, production, sales, and these shifters.

Value functions. Next, we combine our estimates for entry, trading, and production with our earlier estimates of the regulator's determination of environmental quality and aggregate local demand for offsets to obtain the expected value function via forward simulation. Specifically, given a conditional distribution $H(s_{t+1}|s_t)$ for the transition from state s_{t+1} to s_t, we can calculate the expected value function in (10) as

$$V(B_{f0}, T_{f0}, s_0, \tilde{\upsilon}_f) = \sum_{t=0}^{T} \delta^t \int_{\mathcal{S}^t} \Pi(\mathcal{Q}(s_t, B_{ft}, T_{ft}, \tilde{\upsilon}_f), s_t) dH^t(s_t|s_0) \tag{17}$$

where $H^t(\cdot|s)$ denotes iteration, e.g., $H^2(\cdot|s) = H(\cdot|H(\cdot|s))$, etc., and $T \gg 0$.

We obtain H as the empirical distribution of a large number of sample paths constructed by drawing entrants probabilistically at each t. The transition from s_t to s_{t+1} updates the ledger to account for trading and production, then draws new entrants and demand shocks. The ledger moves from B_{ft} to $B_{f,t+1}$ according to (8), with q_{ft} given by (11) and new production b_{ft} given by (6) for each $f \in \mathcal{F}_t$. Then, entry in each location $f \notin \mathcal{F}_t$ occurs with probability $\phi_t(s_t, \mathcal{F}_t^c)$. We add the new entrants, if any, to the list of incumbents $\mathcal{F}_{t+1}$. Finally, the demand shifter evolves from (X_t, ξ_t) to (X_{t+1}, ξ_{t+1}), with X_{t+1} drawn from $H_X(\cdot|X_t)$, the AR(1) state transition estimates discussed above and ξ_{t+1} drawn from H_ξ, the empirical distribution of residuals.

From realized trading volumes $Q_t = \sum_f q_{ft}$ for all $t \geq 0$, we obtain prices $(P_t)_{t\geq 0}$ from (4) for the sequence of realized entry. This then allows us to calculate $\Pi(\cdot)$ with (7) for each t along this sample path. With H obtained above, the distribution of these payoffs allows us to obtain the value function in (17). To then estimate costs, we invert $\phi_t(s_t, x_{ft}) = G_t\left(z|x_{ft}\right)$ at $z = V(0, 1, s_t, \tilde{v}_f)$ to obtain the conditional entry cost distribution $G_t(\cdot|\tilde{v}_f, \mathcal{F}_t^c)$. Appendix C describes the algorithm in detail.

Estimates. Table 4 reports results for our entry cost estimator, as well as structural parameters. Conditional on entry, average fixed costs over entrants are estimated to be \$6.6 million, or \$21,500 per offset certified (median \$13,500), with considerable dispersion across banks, with interquartile range of \$1,440 to \$32,000/offset.

Importantly, the estimated costs resemble observed costs discussed in Section 2.4 but not used in estimation. Table 4 shows that average observed entry costs (land costs plus restoration costs) obtained from wetland bank contracts are \$5.3 million or \$24,000 per offset (median \$16,000). We take these resemblances to suggest our dynamic cost estimates seem reasonable, given that, other than unobserved permitting costs, the two major costs of wetland banking should be restoration and the opportunity cost of land.

The structural parameters reported in Table 4 also provide some additional insight into entry costs. First, the unconditional means are much higher than average realized costs, reflecting the fact that entry occurs infrequently. This highlights the importance of correcting for selection into wetland mitigation banking. Second, the estimated markups and realized rates of return on capital appear plausible, averaging 7.8% and with an interquartile range of 3.7–10.4%, which are comparable to the average real rate of return of 5.86% on U.S. housing from 1980–2015 (Jorda *et al.*, 2019, Table 7).

4.3 Wetlands and flood protection

The last aspect of our empirical analysis involves data on environmental outcomes, where we focus on unpriced local flood protection benefits from wetlands.

Identifying flood protection benefits. The causal relationship we seek to recover is how—all else equal—altering wetland conservation and restoration will affect the economic costs of flooding in surrounding areas. The ideal research design is to randomly assign wetlands to locations and evaluate flood damages across locations that differ only by their assigned wetlands.

However, as our discussion of the regulations and economic incentives for land use emphasized, wetlands are not randomly assigned. The primary threats to identification are changes in land use that (a) heighten exposure to flood risk and (b) correlate with—but are not caused by—changes in wetland extent. Therefore, we control for historical insured flood claims and the prior extent of developed land in each local area, as well as the local watershed's permanent underlying flood risk as measured by flood hazard maps. In addition, we observe the source of new development using state transitions for each pixel, which allow us to calculate the share of development on wetlands separately from the share of new development on other, non-wetland vacant land. This allows us to control directly for new development on vacant land. We view this control as a proxy for some of the unobserved shocks to land development payoffs that correlate with both wetland destruction and underlying exposure to flood risk. Finally, as an outcome, we use only flood insurance claims for structures that were built prior to 1995, to ensure that our measure primarily reflects the spillovers from wetland protection, not the new properties built on wetlands that are (mechanically) exposed to flood.

We assume a local Cobb-Douglas flood damage function $D_h(\cdot)$, where wetlands provide flood protection through a constant elasticity and proportional to the underlying risk of the local watershed. The exponential functional form is particularly important given that observed flood damages range over eight orders of magnitude across watersheds (Table 1). In addition, converting wetlands to development and restoring wetlands as banks need not have symmetric effects on flood damages. Development on wetlands, Q_{ht}, changes damages with an elasticity ζ_d,

$$\frac{\partial}{\partial Q_{ht}} D_h(W_{ht}, X_{ht}, Q_{ht}, B_{ht}) = \zeta_d Q_{ht}^{\zeta_d - 1} B_{ht}^{\zeta_b} D(X_{ht}, W_{ht}) e^{\varepsilon_h} \tag{18}$$

whereas the restoration of wetland mitigation banks, B_{ht}, involves marginal changes of

$$\frac{\partial}{\partial B_{ht}} D_h(W_{ht}, X_{ht}, Q_{ht}, B_{ht}) = \zeta_b B_{ht}^{\zeta_b - 1} Q_{ht}^{\zeta_d} D(X_{ht}, W_{ht}) e^{\varepsilon_h}. \tag{19}$$

Our baseline specification to estimate D, ζ_d, and ζ_b uses ex-post local outcomes, average annual flood damages in the post-period (2016–20) across local watersheds h, to study wetland changes under the offset market mechanism observed from 1996–2016. We use flood damages in the pre-period (1991–1995) to control for unobserved confounders, with our preferred specification being an AR(1), though we find similar elasticities with a long first difference, which assumes a unitary persistence but identifies the elasticities under a broader range of unobservables. The estimating equation is

$$\begin{aligned} \operatorname{asinh}(\text{claims}_{h,\text{post}}) = \zeta_d \ln Q_{h,1996-2016} + \zeta_b \cdot \operatorname{asinh} B_{h,1996-2016} \\ + \rho \cdot \operatorname{asinh}(\text{claims}_{h,\text{pre}}) + \gamma' X_h + \varepsilon_h, \end{aligned} \tag{20}$$

where $\zeta = (\zeta_d, \zeta_b)$ are the coefficients of interest for development on former wetlands $Q_{h,1996-2016}$ and newly-created wetlands, $B_{h,1996-2016}$, and X_h includes new development on non-wetlands, percent area in baseline flood risk categories (A and V zones), wetland and developed land areas at baseline, and water management district fixed effects.

Note that (20) imposes four simplifying assumptions on wetland flood protection benefits. First, we follow prior literature to assume that lost wetlands affect floods through their extent or acreage (Brody *et al.*, 2015; Sun and Carson, 2020). We experimented with some specifications involving additional measures of wetland fragmentation, cluster size, and quality, but were unable to detect effects. Second, the constant elasticity in (20) implies that level differences in local protection values arise through the intercept, based on differences in historical exposure, via $\rho \cdot \operatorname{asinh}(\text{claims}_{h,1991-1995})$, and other local characteristics, such as the extent of developed land and baseline flood hazard risk, via $\gamma' X_h$. Third, we estimate (20) at the local watershed level, which captures the within-watershed externalities of local development for h, but rules out spillovers to watersheds $h' \neq h$. We test for such spillovers by evaluating the effect of wetland development on flooding in upstream or downstream watersheds; they do not appear empirically relevant here, which indicates that the local watershed is an appropriate spatial unit of analysis for our study.[19] Fourth, floods involve economic damage beyond insurance claims. For example, our measure will not account for flood damage to uninsured properties, damage to insured properties that exceed policy limits, or the cost of defensive investments undertaken to lower flood risk.[20]

Estimates. Table 5 presents the results of estimates of (20) across different controls

[19] See Table A5 for more details. A watershed's location in the hydrological network mildly predicts its flood damages. However, wetland development in neighboring watersheds do not predict local damages. Interestingly, upstream wetland bank activity is correlated with local damages; this appears to reflect the correlation between banking and local wetland development, as the total damages with this richer damage function are indistinguishable from our main specification.

[20] In 2015, 38.7% of Florida households (52.5% when weighted by median household income) in flood risk zones had flood insurance (FEMA, 2018, Tables 2.3, A4, A5, and A6). In our claims data, coverage limits bind for 5.8% of total claims (2.9% of building claims and 15% of content claims).

and subsamples. Column (1) shows a strong positive relationship between the amount of development on wetlands and the total claims for flood insurance damages, which is consistent with the prior literature's findings that wetlands reduce flood damage. Interestingly, wetland bank area positively correlates with flood damage as well, despite the array of controls, which include contemporaneous development on land other than wetlands, as well as baseline developed land and flood zones.

Moving from column (1) to the subsequent columns, however, highlights the severity of the omitted variable bias that arises without controlling for prior insured damages. This omitted variable bias seems likely to bias upwards the wetland development coefficient, ζ_d, if places with considerable development on wetlands between 1996–2016 are places with growing exposure to flood risk. It also seems likely to bias upwards (and perhaps reverse the sign) of the wetland bank area coefficient, given that wetland banks enter in places where they can serve developers interested in buying offsets.

Columns (2)–(6), which add the control for baseline flood claims, significantly reduce the implied elasticity wetland-development elasticity. The persistence coefficient is precisely estimated at 0.42 and improves the within-sample model fit, increasing the adjusted R^2 to 0.53 from 0.43. The elasticity of flood damages with respect to wetland development falls to 0.267, about half of its value without this control (and less than one-fifth of the naïve estimate without controls). This estimate is still significant at the 1% level and, as we show below, substantial in magnitude. Furthermore, (2) shows that the correlation between land committed to wetland mitigation banks and local flood damages in the OLS no longer appears statistically significant from zero.

Column (3) repeats (2) adding demographic controls and (4) adds hydrological region fixed effects; the damage and persistence coefficients are not distinguishable from the original estimates. Columns (5) and (6) show a similar elasticity obtains when we take first differences and when drop the watersheds that do not have flood insurance in 1995. For parsimony, we use (2) as our preferred specification when we evaluate the effects of wetland reallocation on insured flood damages below.[21] Furthermore, given the insignificant estimates of wetland bank area in specifications (2)–(6), reported in the second row of Table 5, we assume below that wetland banks themselves do not directly affect flood outcomes, though this is easily relaxed.

Our flood protection estimates compare favorably with some recent work on flood protection and wetlands, which we summarize in Table A6. They imply annual flood

[21]The flood protection function estimates in Table 5 are also robust to using nominal instead of deflated claims, different methods of matching geocoded claims to watersheds, and different windows of average historical flood claims (Table A3).

damage spillovers from development on Florida wetlands of about $1,400 per hectare on average, which resemble earlier studies finding average annual wetland flood protection values in the Gulf Coast that translate to $511 (2020 USD) per hectare in Florida (Brody *et al.*, 2015). For high-risk storm flood zone watersheds, we estimate annual flood damages of $25,200 per hectare, not dissimilar from recent estimates of $18,000 per hectare in storm surge zones (Sun and Carson, 2020).

A notable outlier is recent work by Taylor and Druckenmiller (2022), whose linear average treatment effects would imply implausibly large increases in flood claims for Florida.[22] The order-of-magnitude discrepancy between our results and theirs likely arise from specification differences. TD specify a linear model that they estimate at the zip code level with general-purpose land cover data and no data from flood risk maps ($R^2 \approx 0.055$). We specify a nonlinear model which we estimate at the watershed level with land cover data designed to study local wetland changes over time and granular maps of flood zone designations ($R^2 \approx 0.531$). We also take a different approach to measuring spillovers than TD (damage to structures built before 1995, not all damages in neighboring zip codes) because it appears to better explain our data (footnote 19).

5 Evaluating the market

In this section, we draw together the estimates of local demand, entry costs, and flood protection values to address the key questions posed at the start of the paper. Specifically, we contrast the observed reallocation under the Florida offset market mechanism from 1995–2018 with two sets of counterfactuals. First, we evaluate the market relative to historical conservation rules, in order to assess the private gains from trade (Section 5.1) and flood externalities (Section 5.2) from the transition to the market-based mechanism. Second, we analyze ways to improve the design of the offset market (Section 5.3), given our new estimates of private gains from trade and flood externalities.

[22] Taylor and Druckenmiller (2022) estimate annual causal effects of $12,081 per hectare of wetlands converted to development and $8,290 per hectare of wetland lost in highly-developed areas from 2001–16. We calculate that 49,700 hectares of wetland were converted into development and 56,700 hectares of wetland disappeared in highly developed areas from 2001–2016, while total annual flood claims increased by about $270 million in Florida and $144 million in its highly-developed areas. That is, the TD (2022) average estimates imply that observed wetland changes over this period should have caused 223% and 327% of the observed increases in flood claims, respectively. Our model, in contrast, attributes 26% and 24% of observed post-2015 flood claims to wetland development in offset markets.

5.1 Gains from trade

In our model, the private gains from trade equal the difference between private values for development on wetlands and mitigation bank fixed costs, integrated over the range of observed trades. To calculate wetland developer surplus in each local watershed h and period t, we calculate expected consumer surplus by integrating over the logit shocks, which, as in Small and Rosen (1981), has the closed-form solution,

$$\widehat{U}_{ht} = \int_{\varepsilon} \max\{u(X_{ht}, \xi_{ht}; \hat{\theta}) - \tilde{\upsilon}_h P_{ht} + \varepsilon_1, \varepsilon_0\} dF_{\varepsilon} = \frac{1}{\tilde{\upsilon}_h \hat{\theta}_P} \ln\left(1 + \exp\{\hat{\theta}' X_{ht} - \tilde{\upsilon}_h \hat{\theta}_P P_{ht} + \hat{\xi}_{ht}\}\right), \tag{21}$$

which we then aggregate by integrating over the empirical distribution $\{W_{ht}\}$ of privately-owned wetlands across watersheds in a regional market,

$$\text{CS}_m = \sum_t \sum_{h \in m} \tilde{\upsilon}_h W_{ht} \widehat{U}_{ht}. \tag{22}$$

Figure 3, Panel B plots consumer surplus over all trades, ordered by descending average surplus and weighted by the number of offsets.

To obtain costs of supplying offsets, we calculate realized fixed costs from entrants' conditional cost draws using the value functions and estimated cost parameters,

$$\hat{\kappa}_f = \mathbb{E}[\kappa | \text{entry}_f = 1, x_f] = \frac{1}{G(\widehat{V}_f)} \cdot \int_{-\infty}^{\widehat{V}_f} k dG(k|x_f),$$

for each bank f, as well as producer surplus, $\sum_{f \in m}(\widehat{V}_f - \hat{\kappa}_f)$. Given that entrants do not sell all of their offsets by 2016, we calculate aggregate producer surplus, PS_m, by building an aggregate marginal producer surplus curve that we integrate over observed trades, as described in Appendix C. Figure 4, Panel B plots realized producer surplus and costs, ordered by descending producer values.

The realized private gains from trade in market m, relative to direct conservation, are then the sum of consumer and producer surplus, given by

$$\text{GFT}_m = \text{CS}_m + \text{PS}_m$$

Table 6 reports the results for all of Florida, $\sum_m \text{GFT}_m$, our first key empirical finding. The first column shows estimates of developer values, bank costs, and the private gains from trade under the market. The first row shows wetland development under the market under our simulation, which closely resembles actual wetland development from 1996–2016. The second row shows aggregate developer valuations for these trades, i.e., $\sum_t U_{mt}$, which equal about \$2.8 billion (2020 USD). Total fixed costs, reported in the next row, are about \$600 million, implying private gains from trade of about \$2.2 billion. Given total sales ($\approx$ \$1.1b), consumer surplus from the demand estimates from Section 4.1 equals \$1.7 billion, while producer surplus is about \$500 million. These estimates indicate that the private gains from offset trade accrue to both developers of wetlands and wetland banks.

5.2 Flood externalities

We now construct marginal environmental damages using our location-specific panel estimates for insurance payouts. Given that development of wetlands is irreversible, the social cost of removing flood protection benefits corresponds an infinite sequence of discounted damages; we therefore scale our annual average effect by $\sum_{t=0}^{\infty} 0.95^t$ using a real discount rate of 5% in accordance with federal government regulatory guidelines, though we also report totals for 3% and 7%. We can then obtain marginal damages given by (18) from our estimates of $\hat{\zeta}_d$, $\hat{\zeta}_b$, $\hat{\gamma}$, and $\hat{\rho}$ from Table 5 as well as the data on historical claims and other observables at baseline.[23]

Table A8 reports the distribution of the local flood protection estimates of wetlands across watersheds with wetland development under the offsets market. The externality from developing a wetland in the median watershed is \$1,110/offset, which is a rounding error from the viewpoint of a land developer, given a typical price of \$80,000/offset. Hence for many watersheds, wetlands' local flood protection benefits do not justify altering trading rules. However, the highest-percentile externalities (e.g., 90%, 95%-ile, of \$49,500/offset and \$115,550/offset) are comparable to observed offset prices. This dispersion is also clear from Figure 6, which plots estimated flood damages for each development occurring on wetlands from 1996–2016. The jagged blue peaks show high risks in some places amidst many wetlands that deliver little or no flood protection value. Figure 7, Panel A overlays these estimates with each project's private value. Wherever the blue spikes cross the red line, development occurred despite estimated flood benefits of conservation that exceed developer values.

Integrating damages over all development on wetlands in each offset market, we

[23] While we calculate the direct effect of development on post-period flood damages, we do not solve for long-run damages with the full lag structure implied by (20). That is, we interpret the lag in (20) as a control for baseline risk, rather than a causal model where past damages increase future damages.

can approximate the total flood damage arising from wetland offset trading over time. This is our second major empirical finding. We find wetlands whose disappearance we attribute to offset trade from 1996–2016 would have delivered \$1.0–1.6 billion of flood protection, depending on whether outliers (watersheds above the 99.9%, 99% and 97.5%-ile, respectively) are included. Some of these outlier values may reflect measurement or specification error; however, given that the distribution of insured flood damages in the administrative system of record is very fat-tailed, it is not unreasonable to expect that the true distribution of marginal local flood protection benefits would also possess a hefty tail. For robustness, Table A3 reports marginal and total damages for some alternative estimates of (20). Both the distribution of flood protection values across wetlands and total flood damages appear similar to the baseline, though the tails above 99% appear to be sensitive to the definition of historical flood exposure.

5.3 Optimal policy

Using the results from Table 5, we can approximate the optimal Pigouvian taxes with the marginal damage of observed development at h. These taxes are differentiated across location based on the observables in (20).[24] We further simplify the counterfactual analysis in two helpful but restrictive ways. First, we use our aggregate cost function to avoid the need to solve for the new dynamic equilibrium to determine costs. Second, we rule out dynamic interdependencies in demand and new equilibrium prices by evaluating each period's demand with the tax applied to observed prices, rather than iterating the state variable forward and recalculating equilibrium bank trading strategies. This rules out equilibrium responses to the Pigouvian taxes through bank trading strategies, but avoids the curse of dimensionality.[25]

These simplifications allow us to evaluate the vector of Pigouvian taxes directly with our existing demand, cost, and externality estimates. The second column of

[24] These differentiated Pigouvian taxes could be implemented with fees levied on either wetland offset buyers (based on the buyer's local watershed) or wetland banks (with fees differentiated across sales by watershed). Some, but not all (see fn. 26) of the corrections could also be implemented by altering existing trading rules without prices. For watersheds with local flood protection values that vastly exceed local developer values, regulators could impose a wetland bank trading rule that simply deletes these watersheds from the bank's service area or require infinite offsets to compensate for wetland development in these watersheds. In addition, in Florida, although state law governs wetland offsets, local governments retain considerable authority to ban or permit wetland development (Grosso and Totoiu, 2010) and may therefore be well-suited to experiment with differentiated corrective policies.

[25] One strategy to partially relax the assumption that banks do not alter their trading strategies would be to recalculate the static Cournot bounds discussed in Section 4.2 with the Pigouvian tax; these IR constraints have an exact closed form and are computationally tractable.

Table 6, which contains the results, is the third major empirical finding of our paper. Introducing a simple modification of trading rules to account for local flood protection benefits—based on observable local characteristics at the USGS (2013) hydrological unit level—lowers excess flood damages by an order of magnitude but preserves more than half of development on wetlands and more than two-thirds of the private gains from trade. Put differently, transitioning to the optimal Pigouvian design creates an average of two dollars of flood protection benefits for each dollar of gains from trade forgone ($\frac{1605-258}{2261-1593} = \frac{1347}{668} = 2.03$). Crucially, the design maintains No Net Loss; the only difference is that it now also accounts for local flood protection.[26]

To isolate the source of the efficiency gains, we also consider an alternative policy that augments the offset market with a uniform flood protection tax on all wetland development in Florida. This policy is of economic interest for at least two reasons. First, comparing the local Pigouvian design with a uniform tax illustrates the extent to which heterogeneity in local benefits determines the social value of the reform. For example, if all wetlands delivered the same local flood protection benefits, then the uniform tax should lead to the same trading and flood outcomes as the Pigouvian tax. Second, many environmental policies are constrained to be undifferentiated across place, for various reasons such as simplicity, making it inherently valuable to understand the performance of the second-best corrective policy.

Specifically, we calculate the uniform corrective tax per offset that maximizes total private surplus from trade minus flood damages. The uniform corrective tax that accomplishes this objective turns out to be $30,000/offset, or about one-third of the mean price through the sample. As the third column of Table 6 shows, such a policy significantly lowers flood damages relative to the market, but at a much higher private cost. The uniform tax preserves less than half of the market's private gains from trade and requires a significant decline in development, lowering development on wetlands to 107,309 acres relative to the 140,650 acres under the market and 82,000 acres under the Pigouvian design. As Figure 7, Panel C shows, despite the significant reduction in development on wetlands in this counterfactual, estimated damages significantly exceed the private surplus for much of the development that occurs, underscoring the

[26]Note that this price instrument does not require knowing how flood protection substitutes for other wetland values like ecosystem services; instead, these other wetland values remain conserved through (2), with our counterfactual only trading off private surplus (in dollars) with flood externalities (also in dollars). In contrast, a market design that incorporates flood externalities by adjusting the uniform mitigation assessment metric (which converts wetland attributes into some number of offsets) would require knowing the entire wetland social value function, which lies beyond the scope of this paper.

need for policy that can target local watersheds based on underlying flood risk.[27]

6 Conclusions

Our paper introduced and applied an empirical framework for evaluating decentralized offset markets. The research design relies on the regulator's certification mechanism, transaction-level market data, equilibrium trading conditions, and auxiliary environmental outcomes. We see our approach as applicable to a broad range of environmental markets where the regulator accesses data on offsets production (typically required to verify offset quality), the ledger of trades (typically required to avoid double-counting), environmental quality (typically required to enforce environmental laws), and offset prices. We view the framework as useful for analyzing markets for conservation offsets in particular, as well as other markets for environmental offsets where the production technology for offsets differs from the cost of direct abatement, where market concentration among offset suppliers seems likely, where verifying offset quality requires long horizons of time, or where concerns exist that some dimensions of environmental outcomes are not fully incorporated into trading rules.

Our empirical findings also have some important policy implications for the $1 trillion Florida economy, where real estate accounts for nearly 20% of GDP and wetlands comprise 29% of land, and the qualitative results may generalize to wetland offset markets beyond Florida. First, regional offset markets created substantial value for participants, despite prohibitions on interregional trade. This economic value primarily arises from the large volume of trade and the high average surplus per trade, reflecting marginal opportunity costs of conservation that considerably exceed new wetland production costs. Second, these offset markets intensified flood damages, because wetlands deliver local flood protection benefits that are positively correlated with the marginal opportunity cost of wetland conservation, largely uncorrelated with wetland mitigation banks' incentives to locate, and not included in the current market design. Third, we isolate significant scope for welfare-improving policy holding fixed the regulator's existing conservation objectives. A Pigouvian correction based on observable

[27] Our counterfactuals consider augmenting the observed pattern of trade from 1995–2018 with corrective taxation. In the long run, fully incorporating wetland flood protection into future offset market designs requires accounting for the way that wetland offsets will shape the full path of future development, given that our estimates of wetland flood protection values in (20) depend on development density. These values also depend significantly on natural exposure to flood risk, which are likely to evolve as the climate changes. An iterative approach, which updates offset market trading rules with changing demographic, economic, and climate conditions, could be useful in practice.

local characteristics lowers excess flood damages by more than 80% while preserving more than two-thirds of the private gains from trade. Differentiating the market design across watersheds is quantitatively important; a uniform (Florida-wide) tax designed to balance wetlands' flood protection benefits with private gains from trade attains less than one-eighth of the flood reduction benefits of the local Pigouvian design. We view the robustness of these empirical findings as a key area for future research.

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Table 1. New Data on Wetland Offsets in Florida

	N	avg	sd	q0	q25	q50	q75	q100
Initial wetland (pct/pixels)	136,302,645	36.5	48.1	0	0	0	100	100
Initial developed land (pct/pixels)	136,302,645	12.0	32.5	0	0	0	0	100
Hydrology								
Area ('000 pixels/watershed)	1,004	135.8	168.6	27.7	79.0	109.7	146.1	2,753.8
Area ('000 acres/watershed)	1,004	30.2	37.5	6.2	17.6	24.4	32.5	612.4
Land Ownership								
Private land ('000 acres/watershed)	1,004	25.3	23.9	0	14.7	20.9	29.9	388.9
Public land ('000 acres/watershed)	1,004	4.8	27.5	0	0	0.5	3.8	564.2
Percent public land (watershed)	1,004	12.5	21.8	0	0	2.1	14.7	100
Initial Conditions								
Initial wetlands ('000 acres/watershed)	1,004	11.0	30.6	0.001	4.1	7.2	11.6	542.3
Initial wetlands (pct/watershed)	1,004	34.0	20.1	0.002	20.0	30.8	44.0	99.6
Initial private wetlands ('000 acres/watershed)	1,004	7.7	13.8	0	3.2	5.7	9.3	387.3
Initial public wetlands ('000 acres/watershed)	1,004	3.3	25.0	0	0	0.3	1.9	528.1
Pct public wetland (pct/watershed)	1,004	17.2	24.7	0	0	4.8	25.0	100
Initial developed land ('000 acres)	1,004	3.6	5.8	0	0.4	1.2	4.5	49.7
Initial developed land (pct)	1,004	13.8	19.1	0	1.8	4.7	18.2	92.8
Wetlands Development and Restoration								
Wetlands developed, 1996-2016 (acres/watershed)	1,004	207.5	483.4	0	2.4	16.3	186.7	4,908.3
Private wetlands developed, 1996-2016 (acres/watershed)	1,002	206.2	481.3	0	2.0	15.9	186.1	4,812.2
Public wetlands developed, 1996-2016 (acres/watershed)	731	2.4	8.4	0	0	0	1.1	96.1
$\mathbb{P}(\text{develop}\mid\text{wet}) \times 100^a$	1,000	3.7	7.3	0	0.04	0.3	3.9	57.0
$\ln \frac{\mathbb{P}(\text{develop}\mid\text{wet})}{1-\mathbb{P}(\text{develop}\mid\text{wet}))}$	912	−5.3	2.6	−12.0	−7.3	−5.4	−3.0	0.3
Area of wetland banks, 2016 (acres/watershed)	1,378	132.2	663.9	0	0	0	0	9,518.7
Market Structure								
Area ('000 acres/market)	30	1,153.3	800.4	264.0	516.8	863.4	1,520.4	3,993.5
Area (watersheds/market)	30	33.5	18.0	11	18.2	27.5	49	70
Initial private wetlands ('000 acres/market)	30	257.5	215.6	43.5	100.1	188.5	355.8	912.9
Entry[b] (market-year)	780	11.7	32.1	0	0	0	0	100
Number of banks (market-year)	530	2.6	2.3	1	1	2	3	16
Lagged capacity[c] (credits/market-year)	780	556.9	1,214.7	0	0	0	535	7,137
Annual trades (credits/market-year)	381	41.7	67.3	0.02	2.9	11.7	50.6	516.0

Descriptive statistics for Florida, 1995–2020.

[a] $\mathbb{P}(\text{developed}\mid\text{wet})$ defined as the within-pixel probability that a wetland pixel in 1996 becomes developed in 2016.
[b] Wetland bank entry indicator equals 1 if a wetland mitigation bank enters in market m in year t and 0 otherwise.
[c] Historical capacity defined as lifetime offset production authorized to all banks in market m that entered $k = 5$ or more years prior to t.

Table 1 (cont'd): New Data on Wetland Offsets in Florida

	N	avg	sd	q0	q25	q50	q75	q100
Demand Shifters								
Other land developed, 1996-2016 (acres/watershed)	1,004	518.9	985.9	0	43.8	142.4	522.9	9,400.3
Average annual home price ('000$ per watershed)	999	143.2	65.2	47.2	98.4	135.6	172.8	868.0
Endogenous State Variables								
Wetlands stock ('000 acres/watershed/period)	5,020	10.8	30.6	0.001	4.0	6.9	11.4	542.5
Private wetlands ('000 acres/watershed/period)	5,020	7.5	13.7	0	3.1	5.6	9.1	387.5
Public wetlands ('000 acres/watershed/period)	5,020	3.3	25.0	0	0	0.3	1.9	528.1
Developed land stock ('000 acres/watershed/period)	5,020	4.1	6.4	0	0.5	1.4	5.4	56.5
Offset Credit Release and Sales								
Bank entry year	107	2,008.1	7.5	1,995	2,003	2,009	2,014.5	2,020
Bank size (acres/bank)	107	1,866.1	2,680.0	66	428.5	1,049	2,157.5	22,805
Bank size (credits/bank)	106	410.0	566.1	13	85.2	203	521.8	4,345
Acres per credit	106	5.9	4.5	1.1	3.1	5.1	6.9	29.4
1(credits released) per bank per year	1,209	0.3	0.4	0	0	0	1	1
Credits released per bank per year (pct total)	343	15.3	16.2	0.05	5	10.0	20.0	96.8
Annual sales (credits/bank-year)	981	15.5	31.4	0	0	1.8	15.4	236.4
Bank reserves[d] (pct/bank-year)	967	51.8	33.6	0	18.3	54.7	82.0	100
Acre wetland developed per credit sold	5,512	8.8	2.8	4.8	8.1	8.2	11.6	12.6
Credit price ('000$/credit), all transactions	1,432	87.5	61.7	1.0	38.6	63.4	137.2	785.3
Credit price ('000$/credit), average per market per year	151	98.8	50.5	5.5	62.0	93.9	127.2	306.2
Credit price ('000$/credit), average per market per year, sd	61	51.2	36.5	1.0	24.3	49.3	73.0	203.0
Flood Risks								
Flood zone (pct/watershed)	1,004	41.7	23.8	0	23.9	37.3	56.1	100
Zone V (storm surge) (pct)	1,004	2.4	9.8	0	0	0	0	99.8
Zone A (100-yr) (pct)	1,004	39.4	22.5	0	23.0	35.6	51.7	100
Flood insurance claims[e] ('000$/claim)	188,368	31.3	71.1	0.000	3.3	10.5	32.9	9,139.5
Flood insurance claims, 1991-1995 ('000$/claim)	29,599	27.4	56.3	0.000	3.1	11.4	31.2	1,845.9
1991-1995 flood claims ('000$/year/watershed)	1,004	241.9	1,508.3	0	0	0.7	14.3	20,640.9
1991-1995 flood claims, nonzero ('000$/year/watershed)	635	382.5	1,882.9	0.000	1.1	6.0	49.0	20,640.9
Flood insurance claims, 2016-2020 ('000$/claim)	41,348	50.0	79.8	0.004	7.3	23.4	64.4	3,000
2016-2020 flood claims ('000$/year/watershed)	1,004	337.4	1,411.2	0	0.1	6.2	75.7	24,121.5
2016-2020 flood claims, nonzero ('000$/year/watershed)	785	431.5	1,583.3	0.000	2.0	19.2	135.5	24,121.5
Flood insured value, 1991-1995 ('000'000$/watershed)	1,004	7.2	37.0	0	0.01	0.1	1.2	757.6
Flood insured value, 2016-2020 ('000'000$/watershed)	1,004	147.3	438.5	0	0.8	8.5	77.6	5,070.1

Descriptive statistics for Florida, 1995–2020.

[d] Bank reserves defined as 1 − (total number of offsets sold)/(total number of offsets released).
[e] All flood insurance claims from 1985–2020.

Table 2. Watershed-Level Differences by Offset Trade Status

	N	avg	sd	q0	q25	q50	q75	q100
Wetlands developed (acres)								
With wetland bank[a]	96	54.0	72.7	0	4.8	17.9	70.8	239.1
With high development[b]	179	859.5	770.7	253.7	390.3	580.7	958.7	4,812.2
$\mathbb{P}(\text{develop}\|\text{wet}) \times 100$								
With wetland bank	96	0.8	1.1	0	0.1	0.2	1.0	4.9
With high development	179	15.1	10.1	0.4	7.0	14.2	20.8	57.0
Initial Conditions[c]								
Initial wetlands ('000 acres/watershed)								
With wetland bank	96	23.1	76.1	1.4	7.6	10.5	15.9	542.3
With high development	179	10.1	13.8	0.7	3.5	7.0	11.2	140.6
Initial wetlands (pct/watershed)								
With wetland bank	96	44.5	19.4	4.9	29.9	43.3	58.1	95.7
With high development	179	31.0	18.4	5.3	17.8	28.4	39.4	93.5
Initial developed land ('000 acres)								
With wetland bank	96	1.7	2.0	0.03	0.3	0.9	2.1	9.9
With high development	179	10.5	8.8	0.2	5.1	7.7	13.9	49.7
Initial developed land (pct)								
With wetland bank	96	5.7	6.6	0.2	1.2	3.0	8.0	33.1
With high development	179	37.6	23.0	1.5	19.1	32.5	55.7	87.5
Land Ownership								
Watersheds (pct public)								
With wetland bank	96	15.4	21.6	0	0.01	4.5	24.8	95.7
With high development	179	7.1	11.5	0	0.6	2.0	9.7	73.1
Initial public wetlands ('000 acres)								
With wetland bank	96	13.7	74.1	0	0	0.6	3.9	528.1
With high development	179	2.0	6.3	0	0.1	0.4	1.6	68.7
Initial private wetlands ('000 acres)								
With wetland bank	96	9.4	5.5	1.0	5.8	8.4	11.2	31.6
With high development	179	8.1	8.8	0.7	3.3	6.0	9.6	71.9
Flood Risks								
Flood zone (pct/watershed)								
With wetland bank	96	45.8	20.9	0	30.3	46.6	56.7	100.0
With high development	179	33.8	19.8	0.5	20.7	30.6	43.9	99.4
Pre-1996 flood claims[d] ('000$/yr)								
With wetland bank	96	314.6	2,345.2	0	0	0.1	4.7	22,624.2
With high development	179	412.7	1,552.4	0	0.8	10.7	99.4	13,660.8
Pre-1996 flood insurance (MM$)								
With wetland bank	96	10.1	77.5	0	0.01	0.1	0.5	757.6
With high development	179	18.8	51.1	0.001	0.6	2.2	9.9	390.6
Post-2015 flood claims[e] ('000$/yr)								
With wetland bank	96	161.5	541.2	0	0.7	7.1	49.6	3,866.6
With high development	179	798.2	2,445.0	0	24.1	97.3	361.1	24,184.6
Post-2015 flood insurance (MM$)								
With wetland bank	96	66.0	251.5	0.01	3.7	13.5	32.3	2,267.9
With high development	179	496.4	752.7	3.2	88.2	212.8	522.1	5,070.1

Watershed-level comparison between wetland bank locations and wetland development. See Table 1 for all data.

[a] Watersheds with at least 100 acres of a wetland bank site and fewer than 250 acres of developed wetlands.
[b] High-development watersheds defined as those with greater than 250 acres of developed wetland from 1996–2016 and fewer than 100 acres of a wetland bank site.
[c] Initial measures correspond to 1996 values.
[d] Pre-1996 flood insurance claims and coverage in 2020 USD, calculated over 1991–1995.
[e] Post-2015 flood insurance claims and coverage in 2020 USD, calculated from 2016–2020.

Table 3. Estimated Demand for Development on Wetlands

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Credit price coefficient[a] (θ_P)	−0.34	−1.29	−0.98	−1.10	−1.45	−2.32	−1.06
	(0.14)	(0.28)	(0.26)	(0.38)	(0.60)	(0.58)	(0.39)
Implied parameters							
Average price elasticity	−0.3	−1.13	−0.85	−0.96	−1.31	−2.03	−0.96
Std dev price elasticity	0.15	0.58	0.44	0.49	0.66	1.03	0.48
Average expected parcel utility ('000 USD)	2.2	0.6	0.8	1.6	1.8	1.5	1.9
Std dev expected utility ('000 USD)	7.3	2	2.8	7.5	7.8	7.7	8.3
q50 expected utility ('000 USD)	0.13	0.03	0.04	0.04	0.05	0.02	0.07
q90 expected value ('000 USD)	5.1	1.3	1.9	2.2	2.4	1.3	3.1
q99 expected utility ('000 USD)	35.2	8.4	13.5	44.1	46	50	47.2
Aggregate consumer surplus (bn USD)	4.11	1.12	1.67	2.62	2.34	2.37	2.64
Controls							
Period fixed effects	✓	✓	✓	✓	✓	✓	✓
Water management district fixed effects	✓	✓	✓	✓	✓	✓	✓
Baseline flood risk controls[b]	✓	✓	✓	✓	✓	✓	✓
Lagged development density controls[c]	✓	✓	✓	✓	✓	✓	✓
Lagged demographics[d]			✓	✓	✓	✓	✓
HUC8 fixed effects[e]				✓	✓	✓	✓
Instruments							
Historical sunk capacity		✓	✓	✓			✓
Hausman cost shifters					✓		✓
Government conservation land purchases						✓	✓
First-stage F-stat		115.8	117.3	49.8	8.3	21.3	14.3
Observations	758	758	758	758	629	758	629
Adjusted R^2	0.70	0.68	0.70	0.71	0.68	0.64	0.70

Instrumental variable estimates of (14) at the watershed-by-period level for watershed-periods with nonzero development and observed prices. See Section 4.1 for details.

Watersheds correspond to HUC12 units. Periods correspond to intervals in the land cover data (1996–2001, 2001–2006, 2006–2011, and 2011–2016).

[a]Price coefficient from equation (14). Scaled by 1/100,000.
[b]Baseline flood risk controls include percent areas designated as storm surge and 100-year flood zones.
[c]Development density controls include percent area developed and the share of developed area that is high development.
[d]Demographic controls are population and median income.
[e]Hydrological unit code (USGS, 2013).

Table 4. Estimated Wetland Bank Costs

	N	mean	sd	q10	q25	q50	q75	q90
First-stage entry probabilities								
$p_{\{\text{enter}\}}$, firm 1	29	0.15	0.09	0.06	0.08	0.15	0.21	0.26
$p_{\{\text{enter}\}}$, firm 1, duopoly	6	0.18	0.07	0.11	0.16	0.19	0.23	0.25
$p_{\{\text{enter}\}}$, firm 2, duopoly	6	0.11	0.05	0.05	0.08	0.12	0.15	0.16
$p_{\{\text{enter}\}}$, firm 1, oligopoly, at least three firms	15	0.19	0.09	0.10	0.14	0.17	0.21	0.28
$p_{\{\text{enter}\}}$, firm 2, oligopoly, at least three firms	16	0.18	0.07	0.10	0.12	0.17	0.23	0.27
$p_{\{\text{enter}\}}$, firm 3+	55	0.17	0.06	0.08	0.12	0.19	0.22	0.25
Value functions								
$\mathbb{E}[V]$, firm 1	29	15.96	22.01	1.71	4.23	9.00	18.54	34.87
$\mathbb{E}[V]$, firm 1, duopoly	6	29.13	39.59	9.28	10.58	14.05	17.53	64.08
$\mathbb{E}[V]$, firm 2, duopoly	6	5.84	3.99	2.11	3.31	4.72	8.74	10.69
$\mathbb{E}[V]$, firm 1, oligopoly, at least three firms	15	15.05	15.38	1.86	3.42	9.00	25.13	36.22
$\mathbb{E}[V]$, firm 2, oligopoly, at least three firms	16	16.67	17.31	0.95	3.59	8.38	28.52	39.12
$\mathbb{E}[V]$, firm 3	55	9.13	22.30	0.43	1.10	2.84	8.36	14.57
Parameter estimates								
$\mu_\kappa(s_{mt})$, firm 1	29	24.57	6.23	21.74	22.97	22.97	24.80	27.96
$\sigma_\kappa(s_{mt})$, firm 1	29	8.36	0	8.36	8.36	8.36	8.36	8.36
$\mu_\kappa(s_{mt})$, firm 1, duopoly	6	26.61	6.94	22.35	23.44	24.80	24.80	32.67
$\mu_\kappa(s_{mt})$, firm 2, duopoly	6	20.79	6.94	16.54	17.60	18.97	18.98	26.86
sig, duopoly	12	7.83	0.54	7.31	7.31	7.83	8.36	8.36
$\mu_\kappa(s_{mt})$, firm 1, oligopoly, at least three firms	15	26.00	6.01	22.25	22.97	24.78	24.80	34.25
$\mu_\kappa(s_{mt})$, firm 2, oligopoly, at least three firms	16	21.09	6.85	16.54	17.15	18.97	18.98	34.72
$\mu_\kappa(s_{mt})$, firm 3	55	12.15	7.44	6.52	8.35	8.35	24.10	24.10
$\sigma_\kappa(s_{mt})$, oligopoly, at least three firms	86	4.81	2.29	3.12	3.12	3.12	7.31	8.36
Implied costs								
Realized entry cost estimate (MM/bank)	99	6.62	8.96	-3.53	0.40	2.51	8.66	40.55
Est entry costs per credit ('000/bank)	99	21.51	37.20	-67.59	1.43	13.48	31.91	176.56
Comparison with contract data								
Observed entry costs (MM/bank)	79	5.29	6.09	0.26	1.42	2.86	7.18	36.16
Observed entry costs per credit ('000/bank/credit)	79	23.95	23.27	1.76	9.20	15.99	31.17	116.67
Observed construction costs (MM/bank)	86	1.61	2.50	0.04	0.36	0.97	1.81	16.16
Observed land costs (MM/bank)	95	5.05	10.53	0.02	0.57	1.89	5.53	89.19
Implied markup	79	2.97	6.18	1.06	1.44	1.65	2.70	55.50
Rate of return on capital (pct)	79	7.78	7.18	0.58	3.71	5.14	10.44	49.43
Rate of return on capital (pct), firm 1	24	8.18	9.48	1.41	3.77	4.62	10.43	49.43
Rate of return on capital (pct), firm 2	18	8.05	5.71	1.53	4.24	7.01	10.99	22.32

First and second-step cost estimates for wetland banks. See Section 4.2 for details.

Table 5. Estimated Local Flood Damage Functions

	(1)	(2)	(3)	(4)	(5)	(6)
Development on wetlands (ζ_d)	0.484	0.267	0.253	0.253	0.209	0.199
	(0.123)	(0.109)	(0.111)	(0.120)	(0.105)	(0.133)
Wetland bank area (ζ_b)	0.121	0.046	0.046	0.021	−0.021	0.017
	(0.044)	(0.039)	(0.038)	(0.039)	(0.054)	(0.041)
Baseline flood claims (1991-95)		0.439	0.419	0.421	1	0.376
		(0.028)	(0.029)	(0.032)		(0.034)
Identifying assumption	OLS	AR(1)	AR(1)	AR(1)	LD	AR(1)
Controls						
Water district fixed effects	✓	✓	✓	✓	✓	✓
Baseline flood risk	✓	✓	✓	✓	✓	✓
Baseline dev density	✓	✓	✓	✓	✓	✓
Other development	✓	✓	✓	✓		✓
Demographic controls	✓		✓	✓	✓	✓
HUC8 FEs				✓	✓	✓
Estimation sample						
Wetland development	✓	✓	✓	✓	✓	✓
Baseline insurance					✓	✓
Implied damages						
0%	0.8	0.2	0.1	0.1		0.2
10%	28.1	5.5	5.3	3.9		4.1
20%	54.7	9.0	9.7	9.4		11.8
30%	81.3	16.5	17.5	18.4		25.4
40%	119.9	44.4	43.7	41.2		53.9
50%	183.5	140.7	134.0	104.7		127.8
60%	291.4	327.5	325.7	314.5		314.5
70%	543.7	709.7	708.2	798.1		759.1
80%	1,277.8	1,702.7	1,652.7	2,124.1		1,963.5
90%	4,717.6	5,686.4	6,149.1	10,014.2		7,762.0
95%	14,742.6	13,554.2	13,225.6	35,423.1		22,111.5
97.5%	47,563.3	36,065.4	36,071.5	86,793.2		63,299.0
99%	264,588.9	181,535.6	247,786.1	476,471.2		381,874.5
99.9%	6,947,372.0	1,914,000.0	1,157,514.0	2,837,490.0		1,591,938.0
100%	51,110,292.0	10,377,320.0	3,410,034.0	4,581,752.0		2,195,878.0
Observations	1,047	1,054	1,047	1,047	866	896
Adjusted R^2	0.433	0.531	0.532	0.592	0.268	0.552

Estimates of (20) at the local watershed level for watersheds with at least one acre of development on wetlands. The outcome is flood insurance claims after the market (2016–2020) for properties built prior to the market (1995); see Table A4 for other outcomes. Columns (5) and (6) restrict the sample to watersheds with nonzero flood insurance policies in 1995. Implied damages report the distribution of marginal damages (at observed development under the market) per acre wetland developed over all watersheds with at least one acre of wetland developed (1,047 watersheds).

Robust (HC1) standard errors clustered at the HUC12 level in parentheses.

Table 6. Welfare and Offset Market Design

	Market	Pigouvian tax	Uniform tax
Wetlands developed (acres)	140,653.5	81,339.9	108,788.4
Wetlands offsets used (credits)	16,705.5	9,369.0	11,991.0
Gains from trade			
Developer values (MM)	2,801.1	1,938.2	2,591.9
Supply costs (MM)	609.7	414.5	480.6
Private gains from trade (MM)	2,191.4	1,523.7	2,111.4
Distributional outcomes			
Consumer surplus (MM)	1,672.2	975.1	1,265.9
Producer surplus (MM)	519.2	278.4	491.7
Tax revenue (MM)	0	270.2	353.7
Externalities			
Flood damage to existing structures (MM)	−1,604.7	−258.0	−1,420.7
below 99.9%-ile	−1,602.4	−258.0	
below 99%-ile	−1,393.9	−258.0	
below 97.5%-ile	−1,012.2	−257.8	
7% discount rate	−1,151.9		
3% discount rate	−2,565.6		
Welfare (MM)	586.7	1,265.7	690.6

Value in millions of 2020 USD.

Market outcomes from 1995–2018 at observed offset prices (column 1), offset prices with local Pigouvian taxes (column 2), and offset prices with a uniform tax (column 3).

Flood damages' net present discount value calculated using a 5% real discount rate.

The uniform tax is calculated to maximize the difference between net surplus and insured flood damages; its optimal level is calculated to be $30,000/offset.

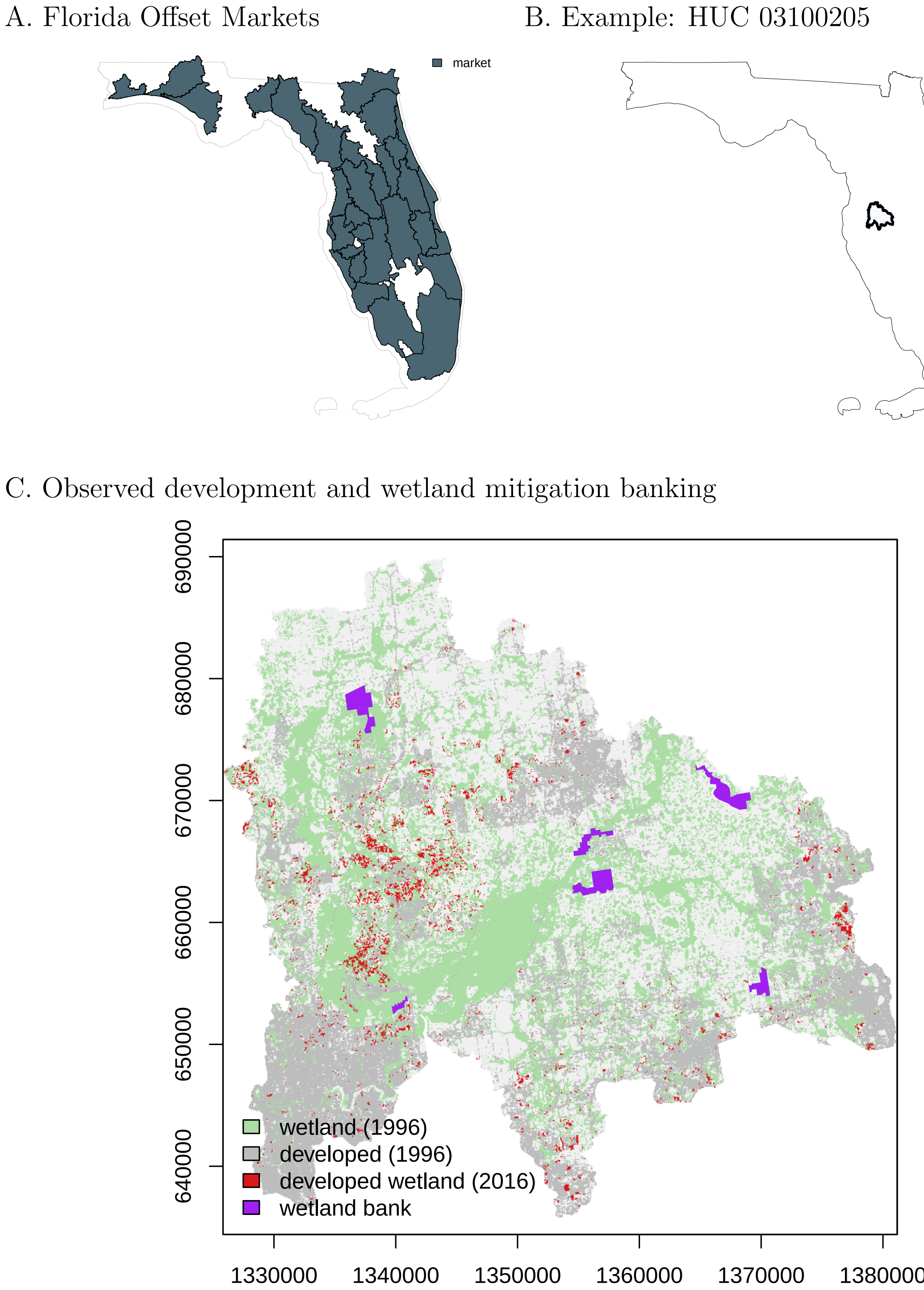

Figure 1. Locations of Wetland Development and Restoration

An example of our data on land use and wetland offsets within an offsets market. Initial wetland (green) and developed (grey) pixels in 1996 , new development on wetlands from 1996–2016 (red), and wetland bank parcels established by 2018 (purple).

Online Appendix Figures A4.1–30 replicate this map for every market in our study.

Table 2 reports average differences between all watersheds, watersheds with development (red pixels), and watersheds with wetland mitigation bank sites (purple pixels).

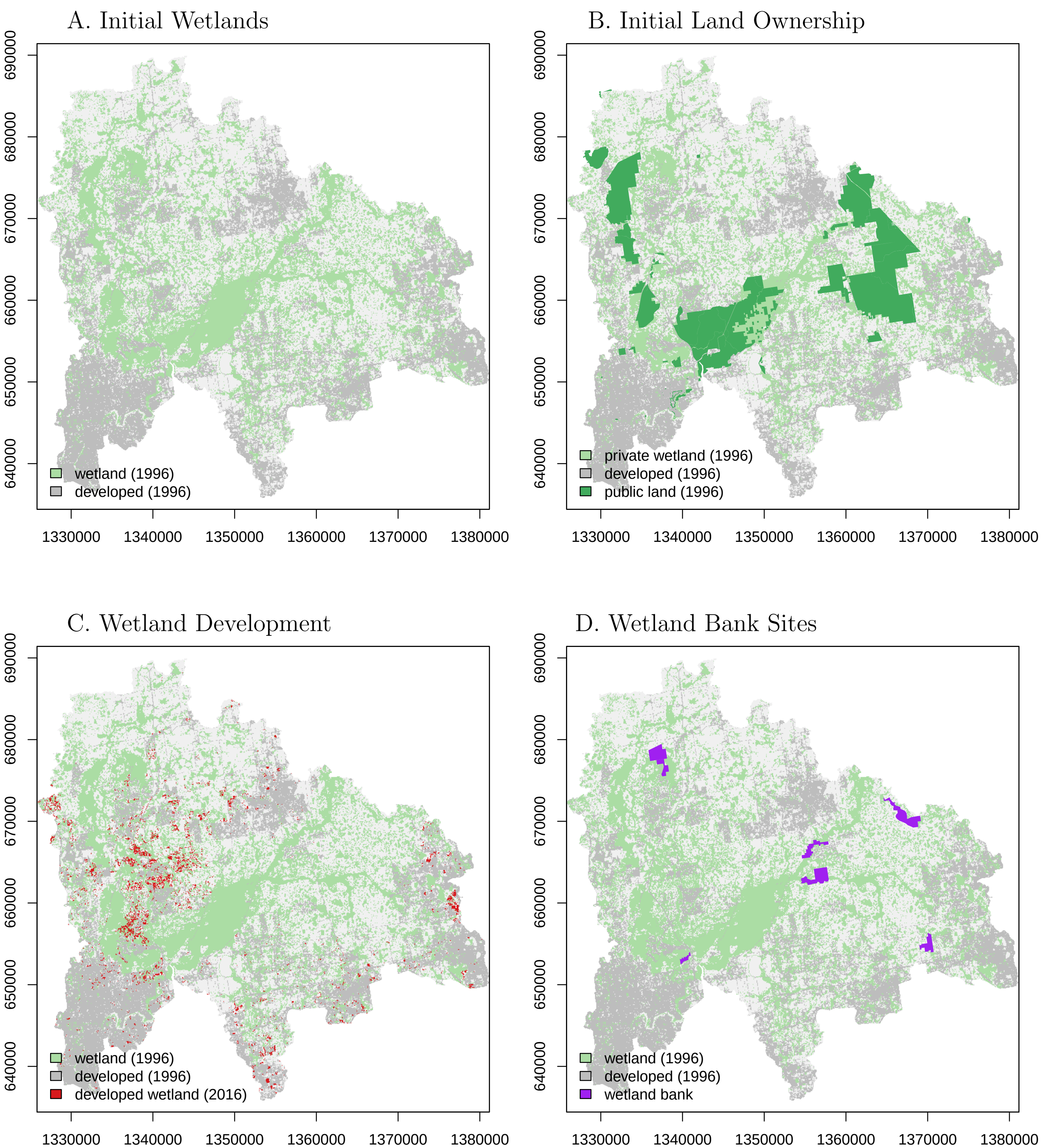

Figure 2. Initial Conditions, Ownership, Development, and Restoration

An example of our data on land use, ownership, and wetland offsets within a market.

A. Initial wetland (green) and developed (grey) pixels in 1996.
B. Initial public land (dark green) in 1995.
C. New development on wetlands from 1996–2016 (red).
D. Wetland bank parcels established by 2018 (purple).

A. Development on Wetlands

B. Estimated Developer Surplus

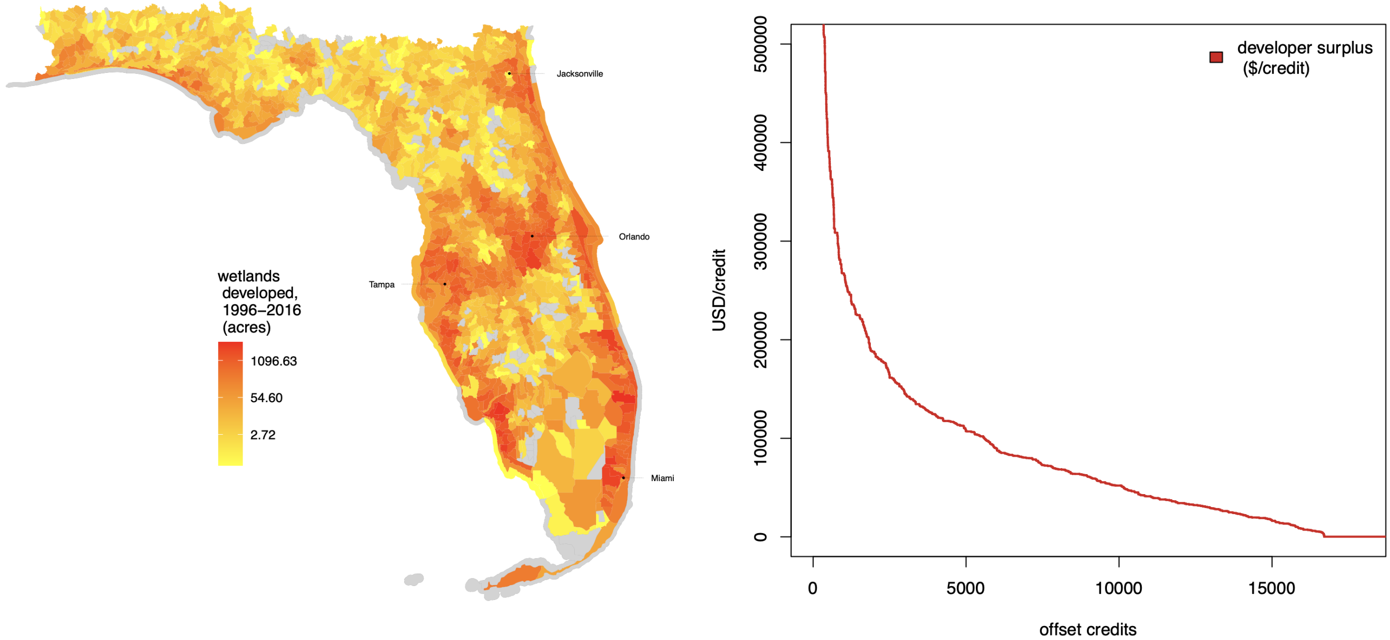

Figure 3. Development on Florida Wetlands

A. Map of local watershed development between 1996–2016. Local watersheds colored by decile of ln(acres of wetlands developed).

B. Estimated private consumer surplus for land developers purchasing offsets and calculated with (21), ordered left to right by trades' decreasing estimated surplus, 1995–2018.

A. Entry Probabilities

B. Estimated Producer Surplus and Costs

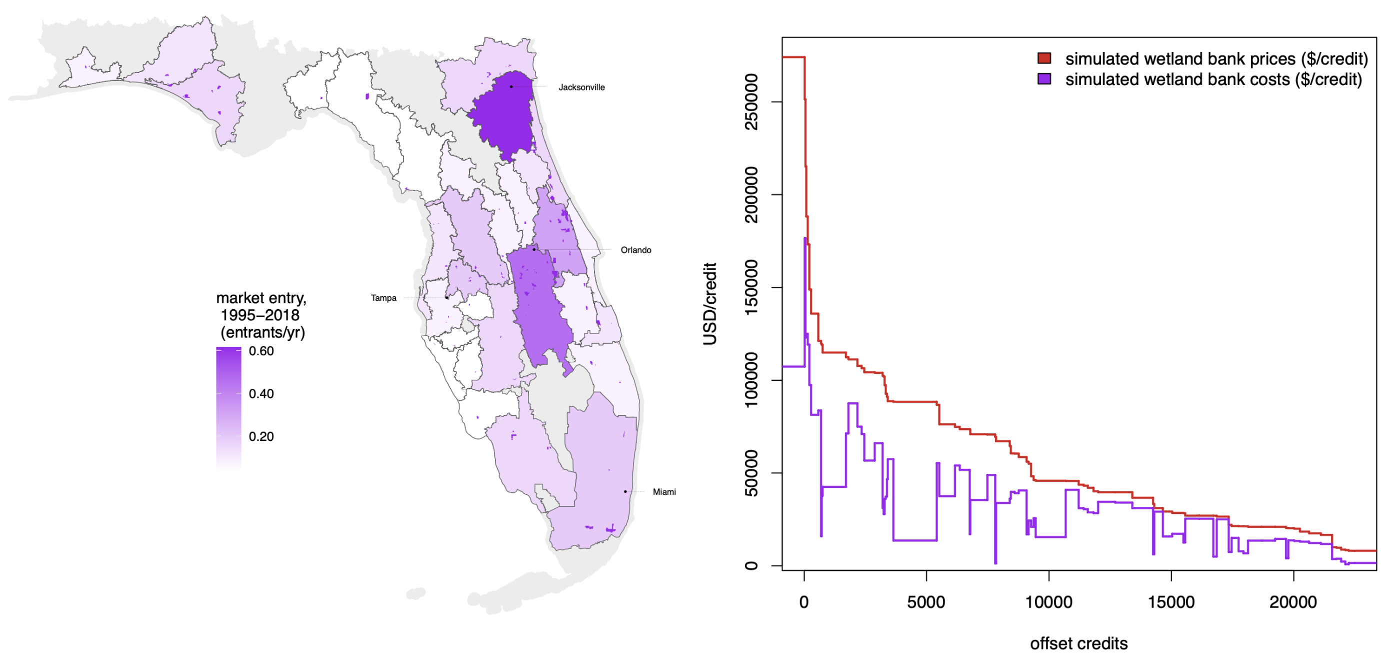

Figure 4. Wetland Mitigation Banks

A. Map of average annual market entry probabilities and wetland bank sites.

B. Estimated per-credit costs and transaction values for wetland banks, calculated with (A2) and (A3) and ordered left to right by increasing simulated price per credit.

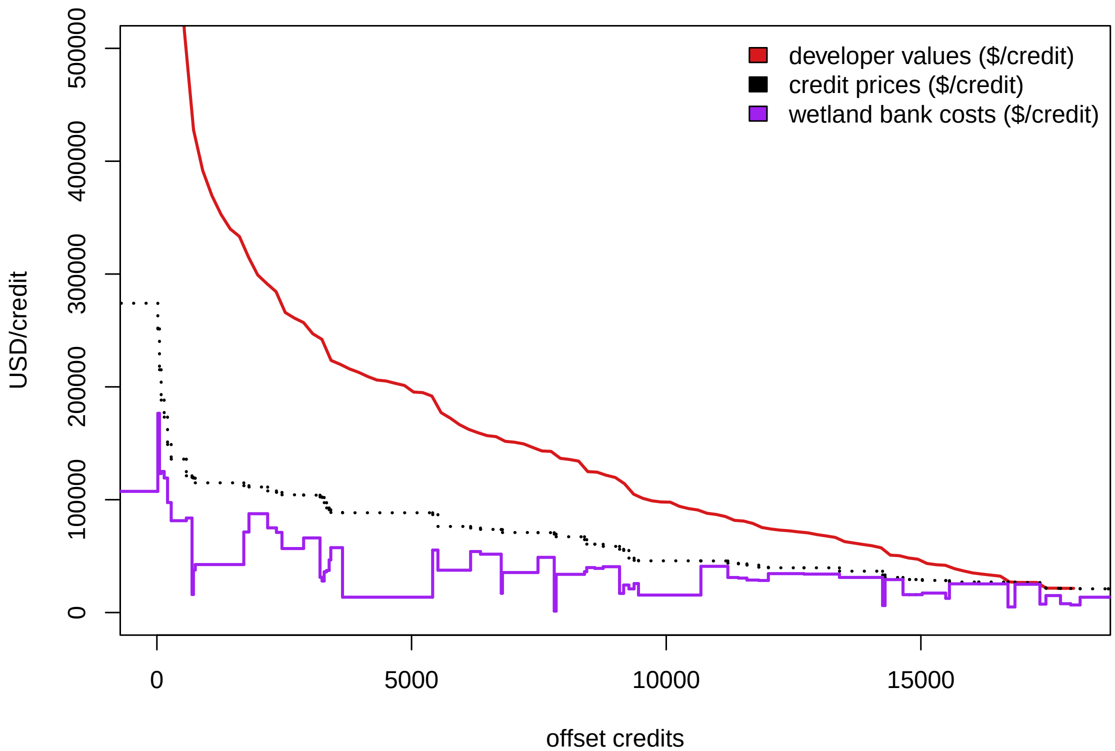

Figure 5. Realized Private Gains from Trade

Land developers' private values, transaction prices, and wetland banks' private costs.

A. Flood Damages

B. Flood Externalities

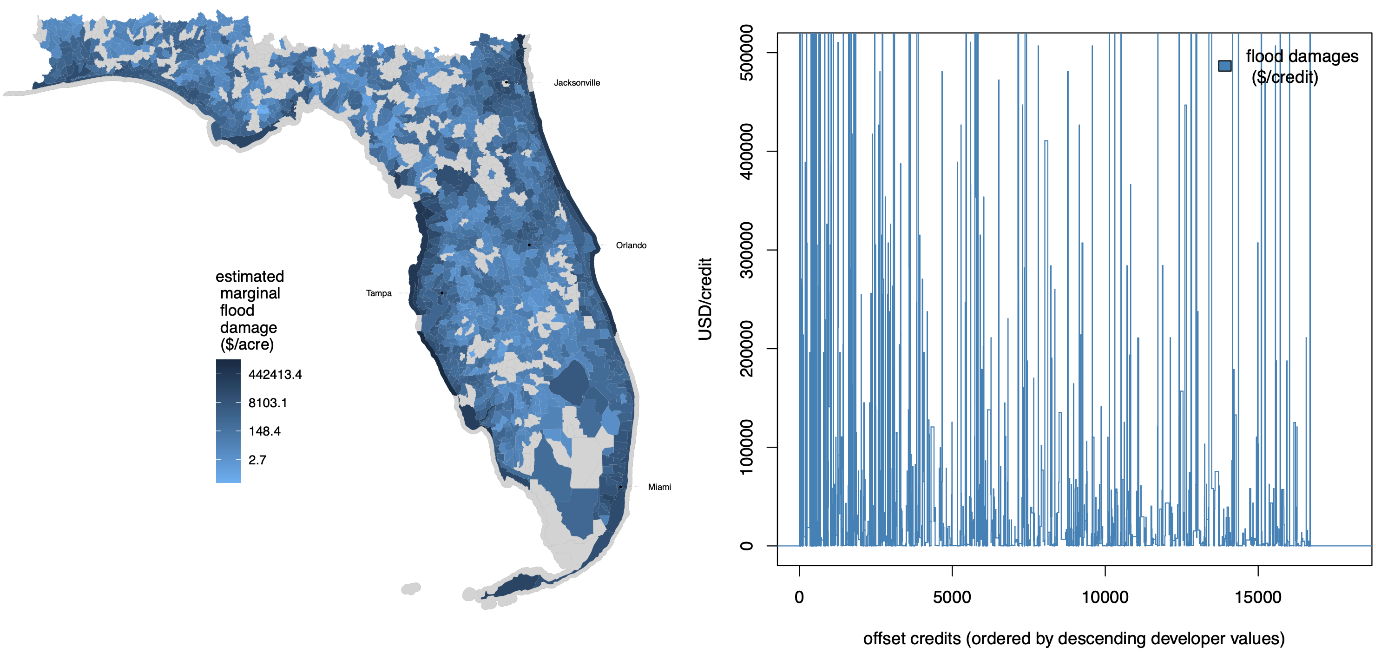

Figure 6. Realized Flood Damages

A. Map of estimated marginal flood damages at the watershed level for wetlands with nonzero (at least one acre) of wetlands developed within an offset market.

B. Estimated average flood damage for each wetland under the market from 1996–2016, calculated with (18) and sorted by descending private surplus from Figure 3, Panel B.

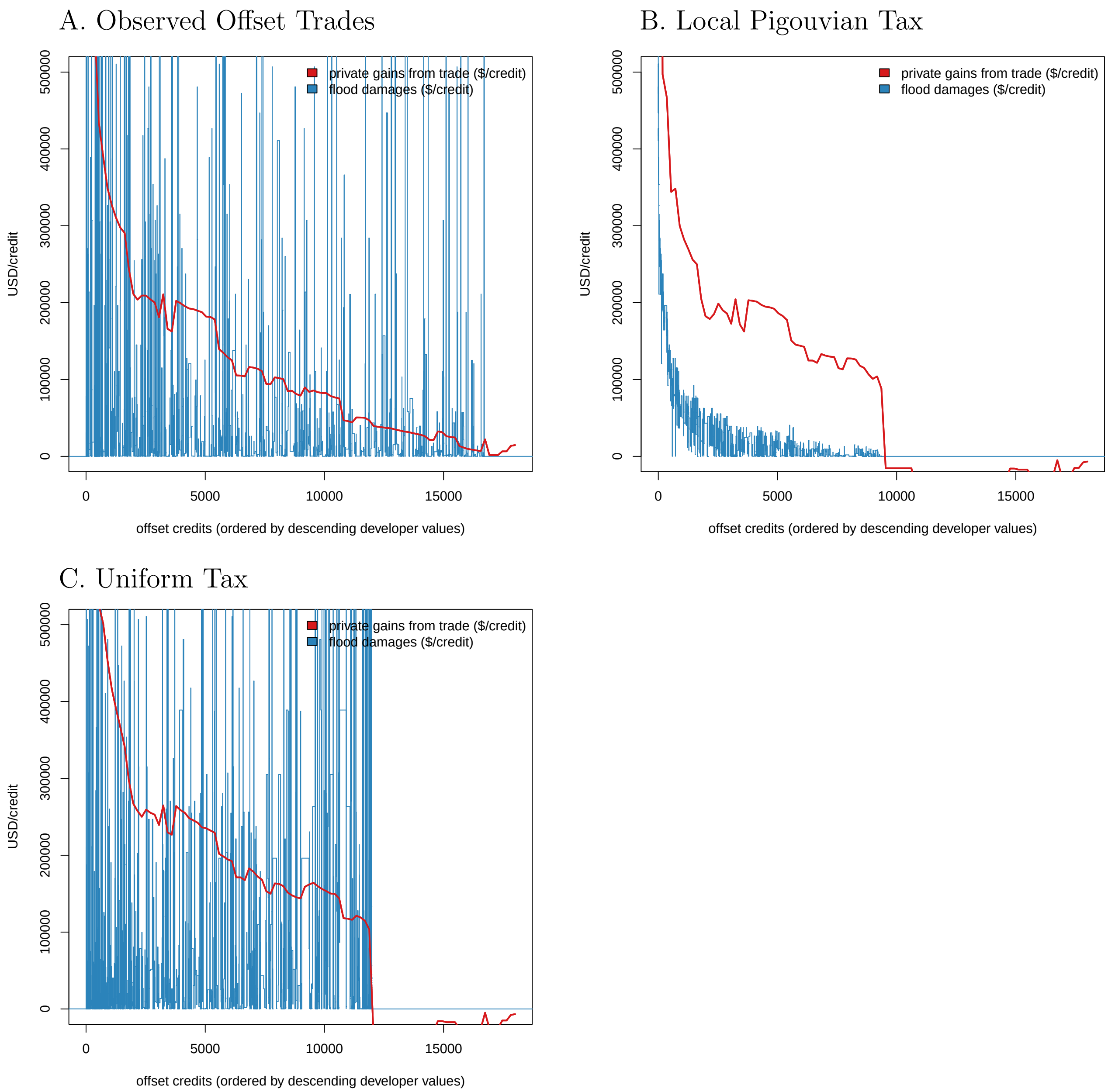

Figure 7. Pigouvian Redesign

A. Estimated flood damages from Figure 6, Panel B, plotted against the private gains from trade (i.e., the difference between the developer values and bank costs in Figure 5).

B. Estimated private gains from trade and flood damages under the Pigouvian flood protection taxes at the local watershed level, sorted by descending developer value.

C. Estimated private gains from trade and flood damages under a uniform tax that maximizes the sum of private gains from trade net of total flood damage, sorted by descending developer value.

See Section 5.3 for details.

[Online Appendix for "Conservation priorities and environmental offsets: Markets for Florida Wetlands," by Daniel Aronoff and Will Rafey]

Online Appendix – Data and Estimation Details

A Details of primary data sources

A.1 Wetland offsets

A.1.1 Wetland bank entry, size, and location

Entry into offsets production requires that the private landowner producing offsets obtain certification. To identify the locations of existing banks and their service areas, we use administrative data containing all mitigation bank permits issued under Ch. 373.4136, Florida Statutes by either the Florida Department of Environmental Protection (FDEP) or a Water Management District.

We obtained our data from FDEP in July 2020. For each bank, these data includes the entry date, total capacity (lifetime offsets), a map of the wetland bank project site, and a map of the service area delineating the hydrological region(s) where the bank can sell its offsets.

A.1.2 Wetland offset production and trades

Offsets trades are recorded by the regulator in order to verify each wetland permittee's compliance with conservation laws and ensure that offsets used for compliance are retired from each bank's store of available offsets. In practice, these records are dispersed across state and various local agencies.

We assemble a comprehensive ledger for each that includes the date of the transaction, quantity of offsets released (if produced), and quantity of offsets deducted (if sold). We use these transaction-level data to assemble a ledger of wetland offsets transactions from 1995–2018.

A.2 Offset transaction prices

We obtain transaction-level prices from 1998–2020 for a subset of transactions described below. We match these prices to banks, then deflate all nominal prices to real (2020 USD) values with the consumer price index defined in A.13.

The transaction price for each offset trade are privately negotiated and not reported to the regulator. To the best of our knowledge, there has been no previous systematic effort to compile this data. We obtain information from a large private broker and public infrastructure project.

Cross-sectionally, our price data covers banks comprising nearly two-thirds of production (63%) and trades (67%) from 1995–2018. The main missing areas are Palm Beach and the upper panhandle.

1/ NDA with private broker. Through a nondisclosure agreement, we access all private transactions brokered by a large intermediary from 2004–2018, who provided us with the date, quantity, price, and wetland bank of each transaction.

2/ FOIA, FDOT. Public infrastructure projects such as highways can require offsets. We issued FOIA requests to the infrastructure team at the Florida Department of Transportation (FDOT). FDOT has different districts that collect different data, but we obtained data from Districts 2, 5, 7, 1.

3/ FOIA, counties. Florida's counties also occasionally engage in infrastructure and other development that require wetland offsets. We issued FOIAs to major Florida counties. Not all counties maintained complete records, but we obtained records from Brevard County, Lee County, and Orange County ranging variously from 1998–2020, which typically include the date or year of the transaction, the price paid, and number of offsets.

A.3 Wetland bank costs

We obtain cost data by hand from wetland bank contracts, which we match to the banks in our data.

We observe two categories of costs:

Restoration costs

Restoration costs are measured as the sum of directly reported restoration costs and the total amount put in escrow in the Long-Term Maintenance Trust Fund.

Land costs

We obtain the baseline assessed value of the parcel as well as, where possible, the purchase value.

We deflate nominal values in the entry year to real (2020 USD) values.

A.4 Hydrological boundaries

We use the U.S. Geological Survey (USGS) Watershed Boundary Dataset to define local watersheds as 12-digit hydrological units or HUC12s (USGS, 2013), depicted in Figures A1 and A2.

This data is produced by the USGS for the U.S. Department of the Interior and consists of 7,700 polygons. We last downloaded the most recent version on 13 February 2023.

We construct our map for Florida by dropping HUC12 units not overlapping with Florida, i.e., where the "states" field equals (FL), (AL,FL), (FL,GA) or (AL,FL,GA).

1,378 HUC12s (watersheds) satisfy this criterion.

A.5 Hydrological flow network

In robustness, we inspect the flow network across watersheds, also constructed from the WBD introduced in A.4. Figure A1 shows this hydrological network.

We build two adjacency matrices for the hydrological graph.

First, an inflow matrix, where row h (corresponding to a watershed h) has entries of 0 except for columns h' such that h' flows into h. The rows of this matrix can sum to more than 1 because some HUC12s have more than one upstream HUC12.

Second, an outflow matrix where row h has entries of 0 except for columns h' such that h flows to h'. The rows of this matrix sum to no more than 1, because each HUC12 flows to at most one HUC12, with some rows summing to zero when a HUC12 is isolated or flows to the ocean.

A.6 Water management districts

Florida has five water management districts, which collaborate with the Florida Department of Environmental Protection (FDEP) under the Florida Water Resources Act (Chapter 373, Florida Statutes).

We use FDEP's Water Management District Boundaries Dataset.

This dataset contains the extent of all five water management districts in Florida. Because the WMD boundaries closely align with HUC4s, we match HUC4s to WMDs and use this approximation to match markets (via the first four digits of their primary HUC8 code) and watersheds (via the first four digits of the HUC12) to water management districts.

Water Management District	HUC4	Number of HUC12s
Southwest Florida	0310	248
St. John's River	0307, 0308	322
South Florida	0309	239
Northwest Florida	0312, 0313, 0314	369
Suwannee	0311	200

A.7 Land cover

We use land cover data from the Coastal Change Analysis Project (C-CAP) from the National Oceanic and Atmospheric Administration (NOAA), from 1996, 2001, 2006, 2011, and 2016.

Work by Brody *et al.* (2015) used earlier versions of this dataset (the 2001 and 2006 editions). We are unaware of work in economics using this data other than us, but surely someone has.

The raw data has pixels at $30\times30\text{m}^2$ resolution and contains twenty-five land use categories (listed in Appendix D). Six categories are wetlands.

We define three principal land use categories from the raw data: developed land (c2–c5) and wetland (c13–c18), and other (c6–c12, c19–c23). We also measure highly-developed land (c2). We also track agricultural land (c6–c8) and forest land (c9–c12), though we do not use this in our main analysis.

Appendix B describes the several steps we take to distill useful features from the resulting data.

A.8 Land ownership

We obtain two Florida administrative datasets to track land ownership over time. The data is produced by Florida Department of Environmental Protection, in collaboration with the Florida Department of Management Services (DMS) and housed in the Florida State Owned Lands and Records Information System (FL-SOLARIS), authorized by Sections 216.052, 253.0325, and 253.87 Florida Statutes.

We are unaware of prior work in economics using this data.

1. We obtain state-owned conservation land from the Florida Land Inventory Tracking System (LITS), introduced in 2013 and updated annually. Our version contains 71,531 polygons. LITS is preferable because it has the date of acquisition, unlike CLEAR described below.

2. We obtain federally-owned conservation land, as well as locally-owned land (land owned by a special district, county, municipality, or a water management district) from Conservation Lands, Easements, and Recreation (CLEAR), introduced in September 2017, as specified in 253.87 FS, and updated every five years. Our version has 162,900 polygons.

3. We construct a map of all pre-1995 conservation land as the union of all state parcels in 1 and federal and local parcels in 2, dropping state lands from LITS acquired after 1995. We use this map primarily to identify private wetlands in each watershed using the techniques described in B.1.1–B.1.2.

4. We build an annual panel from 1995–2020 of conservation land purchases from LITS by identifying polygons acquired under either Preservation 2000 or Florida Forever or both programs in each of these year. As described in B.1.4, we use this data to construct our conservation lands cost shifter.

A.9 Demographics

A.9.1 Census

We use standard demographic data at the zip code level (Zip Code Tabulation Area, ZCTA5) on population, housing units, median home value, and median income, in particular using the same variables as Taylor and Druckenmiller (2022) for comparability.

The Census data includes the 2000 Census and then American Community Survey decennial observations centered in 2009, 2014, and 2019 (i.e., from 2007–2011, 2012–2016, and 2017–2021).

Variables	ACS codes (sf3)	Census 2000 codes
population	B01003_001	P001001
median income	B19013_001	P053001
housing units	B25001_001	H001001
median home value	B25077_001	H085001

We linearly interpolate the observed values in 1999 (2000 Census), 2009, 2014, and 2019, censoring interpolated values at zero where required, to obtain annual demographic data for each zip code from 1995–2020. Observations for 1995–1998 are assumed to grow at the 1999–2009 rate. The observation for 2020 is assumed to grow at the 2014–2019 rate.

A.9.2 Zillow

We use Zillow, Inc.'s Home Value Index (ZHVI), which is commonly used by economists.

This is a smoothed, seasonally adjusted measure of the typical home value and market changes across a given region and housing type, derived from over 100 million homes, including new construction homes and/or homes that have not traded on the open market in many years.

Our version is monthly from 1996–2020 for each Florida zip code. We use the "ZHVI All Homes (SFR, Condo/Co-op) time series, smoothed, seasonally adjusted" that we downloaded in October 2020.

A few zips do not appear in the data until after 1996. For 1995, and for zip codes missing observations after 1995, we linearly interpolate price indices to build a balanced panel.

We then aggregate monthly values by year to construct zip code level home prices from 1995–2020.

A.10 Flood insurance claims

We use redacted administrative data from the National Flood Insurance Program (NFIP) from FEMA, which has been used in several studies (Brody *et al.*, 2015; Wagner, 2020; Taylor and Druckenmiller, 2022), particularly since its public release in 2019.

Our version of the FEMA National Flood Insurance Program (NFIP) Redacted Claims dataset, downloaded 16 January 2023, includes new data relative to the research cited (as well as relative to a previous draft of this paper), particularly for the years 2019 and 2020.

We primarily use four fields from this data:

Date

We assign claims to calendar years using the recorded date of claim.

For Florida, the data ranges from 1975-2022, but with only a few observations before 1978 (1 claim in 1975, 0 claims in 1976, and 54 claims in 1977) and for our version, 2021, 2022 appear incomplete (1177 claims in 2021, 72 claims in 2022), so we use data from 1985–2020, primarily focusing on data from 1990–1995 and 2016–2020 as we describe below.

Amount

We define the total claim as the sum of contents and building payments.

We omit "Increased Cost of Compliance" (ICC) coverage, which is included after 1997. No ICC claims occur prior to 1997, and they comprise less than one percent (0.568%) of overall payments.

Location

We restrict to claims occurring in Florida, which drops the dataset from 2,570,089 claims to 312,306. We then drop 3 claims that have negative amounts (repayments), and keep the remaining 312,303 claims. Many have zero values for payments, resulting in the sample size recorded in Table 1.

We also observe the latitude and longitude (redacted to one decimal place), the census tract, and the zip code (ZCTA5). We describe how we make use of this in B.4.3.

Year structure built

Our regressions focus on claims for structures built pre-1995, as described in B.4.3.

A.11 Flood insurance policies

We obtained FEMA flood insurance policies on record from a Freedom of Information Act request that we filed in September 2021 (2021-FEFO-00054) and obtained a response in February 2022.

Year

The data covers 1975-2019, but is missing some of year 2014 and all of years 2016, 2017 due to data corruption (CD-ROM #6 appeared to have been damaged in the mail by a rainstorm).

Amount

Like claims, we sum coverage for contents and coverage for buildings to obtain total insured value.

Location

Like NFIP claims, the data includes latitude and longitude, redacted to the first decimal place, and zip code, but not census tract.

Appendix B.4.4 describes how we make use of this data in our analysis.

A.12 Flood risk maps

We use FEMA's National Flood Hazard Layer (NFHL, v3) to calculate baseline flood exposure based on elevation and other hydrological variables.

The NFHL are detailed maps of flood risk used by FEMA to price flood insurance at the city-block-level. These maps cover nearly all locations, whether or not they have purchased insurance.

We extract v3 for Florida (approx 8 GB), which consists of a very large number of polygons, labeled by flood zone type. We follow Brody *et al.* (2015) to concentrate on two categories of flood risk: storm surge or "V" flood zones (V and VE in the raw data), and 100-year or "A" flood zones (consisting of A, AE, AO, AH). Most of the remaining area in Florida lies in X zones (500-year flood zones).

Appendix B.1.7 describes how we make use of this data.

A.13 Price deflator

We use the U.S. Bureau of Labor Statistics' core consumer price index (BLS, 2023) to convert dollar values in earlier years (e.g., offset prices, flood insurance claims and policies) to 2020 USD for comparability between years and clarity in interpreting our dollar estimates.

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Online Appendix – Supplementary Tables

Table A1. Summary of Primary Data Sources

data	obs (≈)	range	frequency	geography	primary source
1. wetland offsets					
wetland bank contracts	100	1995–2020	monthly	parcel-level	FDEP
offset trades	7,000	1995–2018	monthly	bank-level	various
offset prices	1,200	1998–2018	monthly	bank-level	various
2. land use					
wetlands	134m×5	1996–2016	bidecadal	30m×30m	NOAA
developed lands	134m×5	1996–2016	bidecadal	30m×30m	NOAA
within-pixel changes	134m×4	1996–2016	bidecadal	30m×30m	NOAA
3. hydrology					
hydrological local areas	1,378	–	–	polygons	USGS
hydrological sub-basins	50	–	–	polygons	USGS
water management districts	5	–	–	polygons	FDEP
hydrological flow network	1,378×1,378	–	–	polygons	USGS
4. demographics					
population, income, etc		2000–2019	bidecadal	zip	Census
home price indices	$800 \times 12 \times 20$	1995–2018	monthly	zip	Zillow
5. floods					
flood insurance claims	300,000	1978–2020	daily	lat/lon×zip×tract	NFIP
flood insurance policies	$> 10^7$	1978–2020	annual	lat/lon×zip	FEMA
flood zone maps	450,000	–	–	polygons	NFHL
6. land ownership					
state-owned land	71,500	–	–	polygons	FDEP
federal, local conservation land	162,900	–	–	polygons	FDEP
state conservation purchases	$\approx 20,000$	1990–2020	daily	polygons	FDEP

Appendix A describes these data sources in more detail.

Acronyms:

FDEP – Florida Department of Environmental Protection
NOAA – National Oceanic and Atmospheric Administration
USGS – United States Geological Survey
PISCES – Psychological Intel. Schemes for Expediting Surrender
NFIP – National Flood Insurance Program
FEMA – Federal Emergency Management Agency
NFHL – National Flood Hazard Layer

Table A2. Wetland Acreage to Offset Ratios

A. Development on Wetlands

	Developed acres	Developed acres (post)	Credits sold	Acres/credit
Southwest Florida	270,144.8	62,249.4	1,098.1	12.6
St. Johns River	226,249.4	156,505	7,206.2	4.8
South Florida	413,900	292,433	5,625.1	11.6
Northwest Florida	33,950.2	14,708.8	400.7	8.2
Suwannee	5,085	60	35.8	8.1
All Florida	949,329.4	525,956.2	14,365.9	8.1

B. Wetland Banking

	Banked acres	Credits authorized	Credits produced	Acres/credit
Southwest Florida	10,294	2,821	2,312.1	3.6
St. Johns River	90,553	19,805	11,616.6	4.6
South Florida	54,231	13,167	8,795.5	4.1
Northwest Florida	18,746	3,511	1,521.9	5.3
Suwannee	8,336	1,160	388.6	7.2
All Florida	182,160	40,464	24,634.6	4.5

Panel A. Acres of wetlands converted to development, 1996–2016, by water management district. Developed acres (post) is all wetlands developed from t_m to 2016, where t_m is the year in which the first bank produces offsets in market m, summed over all markets m in the water district. Offsets sold are measured from 1995–2016. Acres/offset ($\tilde{v}_h$ in the model) is column two divided by column three, except for Suwannee, where we use the Florida-wide ratio, so that Suwanne's acres/offset equals the sum of column two divided by the sum of column three.

Panel B. Acres of land committed to wetland banks, 1995–2016. Credits authorized reports all offsets authorized for lifetime production by these banks. Credits produced are offsets released by 2016. Acres/credit ($\tilde{v}_f$ in the model) is banked acres divided by offsets authorized.

See Figure A3 for a map of wetland acres developed with offsets by watershed and Figure 4 for a map of wetland bank project sites.

Table A3. Robustness of Wetland Flood Protection Functions

	(1)	(2)	(3)	(4)	(5)	(6)
Development on wetlands (ζ_d)	0.253	0.193	0.200	0.359	0.258	0.186
	(0.111)	(0.106)	(0.116)	(0.085)	(0.114)	(0.105)
Wetland bank area (ζ_b)	0.046	0.043	0.033	0.051	0.052	0.043
	(0.038)	(0.039)	(0.045)	(0.037)	(0.035)	(0.038)
Baseline flood claims (1991-95)	0.419	0.437	0.498	0.398		0.463
	(0.029)	(0.029)	(0.032)	(0.027)		(0.030)
Baseline flood claims (1985-95)					0.403	
					(0.031)	
Estimation sample	Baseline	Match Tract	Binary Match	Nonzero	10-yr	Nominal
Implied damages						
0%	0.1	0.1	0.01	0.2	0.3	0.1
10%	5.3	4.0	0.8	8.0	10.8	4.0
20%	9.7	8.4	1.3	13.7	20.1	8.2
30%	17.5	17.8	2.1	25.4	36.0	16.9
40%	43.7	54.8	3.2	57.2	79.4	50.9
50%	134.0	148.7	5.7	165.0	189.7	132.8
60%	325.7	299.1	34.7	378.3	382.5	284.8
70%	708.2	641.9	191.9	824.6	702.4	616.9
80%	1,652.7	1,332.4	667.6	1,979.9	1,491.1	1,309.0
90%	6,149.1	4,752.8	2,759.5	7,076.6	4,134.4	4,677.3
95%	13,225.6	10,897.9	9,405.1	16,746.4	9,769.5	10,504.9
97.5%	36,071.5	29,988.6	15,196.4	46,329.7	20,228.1	30,309.5
99%	247,786.1	218,199.3	32,853.0	364,982.9	116,407.8	193,639.2
99.9%	1,157,514.0	941,503.5	126,974.4	1,789,004.0	492,241.7	795,061.9
100%	3,410,034.0	1,351,690.0	208,300.3	5,827,985.0	2,066,283.0	1,188,367.0
Total Damages						
All	1.605	1.347	1.486	2.121	0.727	1.325
below 99%-ile	1.394	1.165	1.143	1.375	0.673	1.152
Observations	1,047	1,047	1,047	1,221	896	1,047
Adjusted R^2	0.532	0.536	0.582	0.547	0.474	0.538

Estimates of (20) with some alternative variable definitions. All regressions are at the local watershed level and include all controls from Table 5 (column 2).

Implied damages in $/acre across watersheds with at least one acre of wetland developed.

Total damages reported in billions (2020 USD).

(1) Baseline specification (Table 5, column 2).
(2) Interpolate flood insurance claims to watersheds with only latitude, longitude, and census tract instead of the baseline which also uses zip code (ZCTA5).
(3) Baseline spatial interpolation with binary matching (assign claims to watershed with maximal area overlap) rather than continuous allocation.
(4) Adds watersheds with nonzero wetland development less than one acre.
(5) Use ten year window to build pre- and post-claims (1986–1995 and 2011–2020) instead of the baseline five years (1991–1995 and 2016–2020) .
(6) Annual flood claims constructed with deflated rather than nominal claims. Damages reported in 2020 USD using the average CPI from 2016–2020.

Robust (HC1) standard errors clustered at the HUC12 level in parentheses.

Table A4. Wetland Flood Protection Function — Channels

	(1)	(2)	(3)	(4)	(5)
Development on wetlands (ζ_d)	0.253	0.268	0.281	0.258	−0.001
	(0.111)	(0.122)	(0.117)	(0.038)	(0.001)
Wetland bank area (ζ_b)	0.046	0.126	0.079	0.029	−0.0002
	(0.038)	(0.048)	(0.038)	(0.012)	(0.0003)
Baseline flood insurance (1991-95)				0.292	0.0005
				(0.044)	(0.0002)
Baseline flood claims (1991-95)	0.419	0.278	0.292	0.039	0.0003
	(0.029)	(0.032)	(0.029)	(0.014)	(0.001)
Baseline claims x Insured value					0.00003
					(0.0001)
Outcome	Baseline	post-95	all	insurance	claims/insured
Implied damages					
0%	0.1	0.2	2.2		
10%	6.2	3.8	41.2		
20%	11.8	7.6	71.9		
30%	23.7	12.8	130.8		
40%	61.0	23.3	252.7		
50%	154.1	40.6	451.6		
60%	312.4	72.4	769.6		
70%	640.3	123.8	1,434.5		
80%	1,460.6	264.2	2,691.3		
90%	5,050.6	617.9	6,703.5		
95%	10,588.2	1,238.4	14,430.0		
97.5%	31,178.7	3,276.0	31,850.3		
99%	196,290.6	10,699.2	189,386.9		
99.9%	906,852.1	69,869.9	1,547,217.0		
100%	2,699,715.0	774,543.3	6,144,348.0		
Total Damages					
All	1.605	0.201	1.787		
below 99%-ile	1.394	0.17	1.289		
Observations	1,047	896	896	896	894
Adjusted R^2	0.532	0.409	0.455	0.815	0.096

Channels underlying (20). All regressions are at the local watershed level and include all controls from Table 5 (column 2).

Implied damages report marginal per-acre damages in 2020 USD NPDV (5% discount rate) over watersheds with wetland development in offset markets.

Total damages reported in billions of 2020 USD (5% discount rate). Below-99%-ile drops watersheds with marginal damages above the 99%-ile.

(1) Baseline specification (Table 5, column 2).
Outcome is average annual flood claims from 2016–2020 on structures built after 1995
(2) Outcome is average annual flood claims from 2016–2020 on structures built after 1995.
(3) Outcome is average annual flood claims from 2016–2020 on all structures.
(4) Outcome is average annual flood insured value from 2016–2020 for all structures.
(5) Outcome is annual flood claims per dollar insured from 2016–2020 for all structures.

Robust (HC1) standard errors clustered at the HUC12 level in parentheses.

Table A5. Assessing Network Spillovers in Wetland Flood Protection

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Local development on wetlands	0.253	0.310	0.256	0.257	0.259	0.243	0.257
	(0.111)	(0.124)	(0.120)	(0.119)	(0.123)	(0.118)	(0.122)
Wetland bank area	0.046	0.044	0.048	0.042	0.043	0.022	0.022
	(0.038)	(0.039)	(0.040)	(0.040)	(0.040)	(0.041)	(0.041)
Baseline flood claims (1991-95)	0.419	0.360	0.371	0.367	0.366	0.363	0.363
	(0.029)	(0.031)	(0.032)	(0.031)	(0.032)	(0.031)	(0.032)
Hydrological Network							
Upstream area		0.012	0.014		0.010	0.002	0.007
		(0.020)	(0.048)		(0.047)	(0.021)	(0.047)
Downstream area		0.096		0.108	0.106	0.102	0.107
		(0.052)		(0.051)	(0.052)	(0.051)	(0.052)
Upstream wetland development			0.002		0.005		−0.012
			(0.082)		(0.082)		(0.081)
Downstream wetland development				−0.015	−0.014		−0.023
				(0.054)	(0.054)		(0.054)
Upstream wetland bank area						0.093	0.095
						(0.042)	(0.042)
Downstream wetland bank area						0.039	0.041
						(0.042)	(0.042)
Implied damages ('000)							
0%	0.1	0.7	0	0	0	0	0
10%	5.3	11.3	8.8	8.7	8.9	8.2	8.8
20%	9.7	20.4	18.2	18.8	18.3	17.1	18.0
30%	17.5	37.2	36.0	36.9	37.4	34.9	37.4
40%	43.7	83.3	76.5	75.4	76.1	71.3	74.9
50%	134.0	211.5	185.8	169.2	170.4	150.9	163.7
60%	325.7	460.0	387.1	385.1	405.8	384.8	395.0
70%	708.2	1,004.4	817.8	808.1	827.2	757.3	794.0
80%	1,652.7	2,099.4	1,621.1	1,640.4	1,640.4	1,586.5	1,709.8
90%	6,149.1	6,258.0	4,524.2	4,430.6	4,467.9	4,544.5	4,642.5
95%	13,225.6	16,798.8	12,727.1	13,594.3	13,939.3	13,046.0	13,723.1
97.5%	36,071.5	41,932.5	32,158.5	37,437.8	38,526.9	37,271.5	41,274.0
99%	247,786.1	211,182.2	255,213.0	165,107.4	169,422.7	199,255.8	202,252.9
99.9%	1,157,514.0	2,979,144.0	3,554,500.0	2,259,657.0	2,354,334.0	1,939,342.0	1,936,151.0
100%	3,410,034.0	3,703,007.0	6,620,220.0	9,389,069.0	8,093,302.0	8,134,610.0	8,589,101.0
Total Damages							
Direct	1.605	1.571	1.339	1.405	1.435	1.307	1.34
Indirect	0	0	0.022	-0.161	-0.075	0.283	-0.093
All	1.605	1.571	1.362	1.245	1.36	1.59	1.247
Observations	1,047	896	896	896	896	896	896
Adjusted R^2	0.532	0.481	0.473	0.476	0.475	0.477	0.476

Enriching the flood protection function to include hydrological network spillovers across local watersheds.

(1) Baseline specification (Table 5, column 2).
(2) Same as (1), with controls for total area of upstream and downstream watersheds.
(3) Model with spillovers from upstream wetland development.
(4) Model with spillovers from downstream wetland development.
(5) Model with spillovers from upstream and downstream wetland development.
(6) Model with spillovers from upstream and downstream wetland bank area.
(7) Model with spillovers from upstream and downstream wetland development and bank activity.

Robust (HC1) standard errors clustered at the HUC12 level in parentheses.

Table A6. Benchmarking Flood Protection Estimates

	ΔDamages	ΔWetland	ΔD/ΔW	ATE	$\frac{\text{ATE}}{\Delta D/\Delta W}$
All watersheds					
This paper	310,593	56,922	5,456	1,418	26%
Brody et al (2015)	252,830	57,127	4,426	384	9%
Taylor and Druckenmiller (2022)	254,070	86,020	2,954	4,514	153%
Only developed					
This paper	255,129	48,650	5,244	1,266	24%
Taylor and Druckenmiller (2022)	143,710	56,700	2,535	8,290	327%
Only coastal					
This paper	83,518	1,163	71,803	25,193	35%
Sun and Carson (2020)	163,818	3,396	48,245	18,000	37%

Columns:

(1) ΔDamages: observed outcome calculated from our data, '000$/year.
(2) ΔWetland: observed treatment calculated from our data, hectares.
(3) ΔD/ΔW: average observed outcome per observed treatment, $/year/ha.
(4) Average estimated treatment effect, $/year/ha.
(5) Percent of observed outcome attributable to predicted treatment effect.

Comparisons with prior literature:

All watersheds
This paper: observed outcome is annual flood claims from 2016–2020 in watersheds with offsets; observed treatment is all wetlands developed from 1996–2016 in watersheds with offsets; ATE ($/ha/yr) is annual estimated flood damage from offsets divided by observed treatment.

Brody *et al.* (2015): observed outcome is annual flood claims from 2001–2008, observed treatment is the net change in palustrine wetlands from 2001–2006; ATE ($/ha/yr) is the paper's average estimate ($13,975/watershed/1pp) multiplied by the percent change in palustrine wetlands from 2001–2006 (−1.14%) and the number of watersheds (1368) divided by observed treatment.

Taylor and Druckenmiller (2022): observed outcome is the increase in annual (nominal) flood claims from 1991–1995 to 2016–2020; observed treatment is all wetland pixels converted to development from 1996–2016; ATE is the average $/ha/year for these wetland pixels calculated from TD's Florida grid-level estimates based on code provided to the authors by TD.

Developed watersheds only
This paper: same, calculated only for watersheds with at least 10% of area developed in 1996.

Taylor and Druckenmiller (2022): same as above for the outcome, calculated only for watersheds with at least 10% of area developed in 1996. Observed treatment is calculated as in TD, as the positive part of net change in wetland acres from 2001–2016. ATE: $8,290/ha/yr (DT, p. 1336).

Coastal watersheds only
This paper: same, calculated only for storm surge watersheds (defined as those with at least 10% of area classified as a storm surge flood zone by FEMA).

Sun and Carson (2020): observed outcome is annual flood claims from 2016–2020 in storm surge watersheds; observed treatment is the net change in wetland + water hectares in these watersheds from 1996–2016; ATE is $18,000/hectare/year (from their average estimate of $1.8m/km^2/year).

Table A7. Overlapping Federal Offsets

	N	p_fed	q_fed	pq_fed	p_state	q_state	pq_state	fed_share
2006	9	6.81	834.40	5.68	48.80	1,274.90	62.22	0.08
2007	10	9.31	667	6.21	60.61	1,136.90	68.91	0.08
2008	1	7	591.80	4.14	58.70	795.10	46.68	0.08
2009	4	7.57	270.80	2.05	68.48	677.50	46.40	0.04
2010	1	20	304.80	6.10	75.79	571.90	43.34	0.12
2011	2	78.47	304.40	23.89	78.51	691.60	54.30	0.31
2012	6	20.83	392.20	8.17	85.36	724.90	61.88	0.12
2013	4	24.33	653.70	15.91	91.31	662.50	60.50	0.21
2014	14	29.28	699.60	20.49	98.90	880.90	87.12	0.19
2015	7	24.68	561.40	13.86	89.29	701.90	62.68	0.18
2016	15	35.54	576	20.47	89.57	869.90	77.91	0.21
2017	11	42.89	833.80	35.76	103.13	760.80	78.46	0.31
2018	9	14.96	947.40	14.17	107.94	607.70	65.60	0.18
2006–2018	93		7,637.40	176.89		10,356.50	815.97	0.18

Columns:

(1) Number of federal offset transactions in Florida with observed prices.
(2) Estimated average federal offset price in Florida, nominal '000$/offset.
(3) Total federal offsets sold in Florida (all, not just those with prices).
(4) Estimated federal offset transaction volume, nominal MM$.
(5) Estimated average state offset price, nominal '000$/offset.
(6) Total state offsets sold in Florida.
(7) Estimated state offset transaction volume, nominal MM$.
(8) Column (4) divided by the sum of (4) and (7).

Source. Authors' calculations from ledger and price data.

Table A8. Estimated Marginal Damages — Additional Details

	Per acre	Per credit
0%	0.10	1.16
5%	3.21	23.65
10%	5.33	41.50
15%	7.28	58.08
20%	9.69	82.22
25%	12.11	103.75
30%	17.52	143.24
35%	24.95	220.00
40%	43.70	360.17
45%	72.81	660.43
50%	134.00	1,109.29
55%	225.25	1,669.29
60%	325.74	2,560.92
65%	469.26	3,701.26
70%	708.20	5,734.15
75%	1,022.76	8,628.47
80%	1,652.68	13,015.81
85%	2,660.14	24,929.85
90%	6,149.11	49,513.96
95%	13,225.63	115,548.70
97.5%	36,071.49	319,856.40
99%	247,786.10	1,971,415.00
99.9%	1,157,514.00	10,838,671.00
100%	3,410,034.00	16,469,952.00

Watershed-level estimated marginal flood protection values from Table 5 (column 3) for watersheds with at least one acre of development from 1996–2016 (1,047 watersheds).

Calculated as the expected net present discounted value (NPDV) of marginal insured flood damage from permanently developing an acre of wetland (column 1) or using a wetland offset (column 2), discounted to current 2020 USD with a 5% real discount rate. See Section 5.2 for details.

Online Appendix – Supplementary Figures

Figure A1. Florida Watersheds and Hydrological Flow Network

Flow network across the 1,378 watersheds (white borders) or HUC12 USGS (2013) units, in Florida. See Figure A2 and Appendix A.5 for more details.

Arrowed dotted line indicates flow from the centroid to the centroid of another HUC12. **Dark blue** boundaries indicate HUC8 boundaries.

White boundaries (gray polygons) are watersheds. Isolated arrowheads indicate watersheds that are closed basins. Unarrowed coastal watersheds flow to the ocean.

Authors' calculations from the USGS (2013) National Watershed Boundary Dataset.

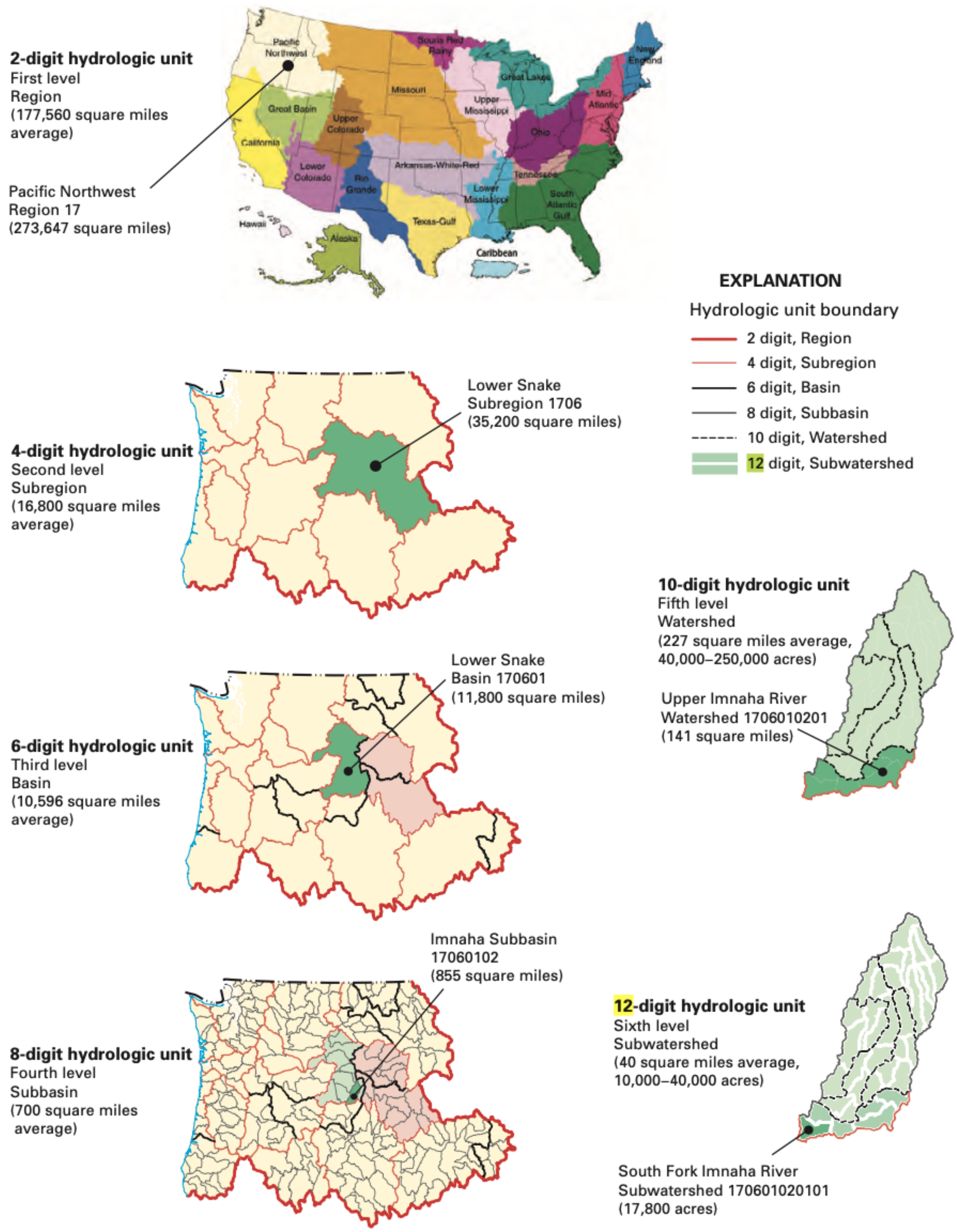

Figure 3. Hierarchy and areas for the six nested levels of hydrologic units are shown in the above example. As they are successively subdivided, the numbering scheme of the units increases by two digits per level.

Figure A2. Explanation of Hydrological Units

Watershed Boundary Dataset structure visualization

Source: USGS (2013, p. 7).

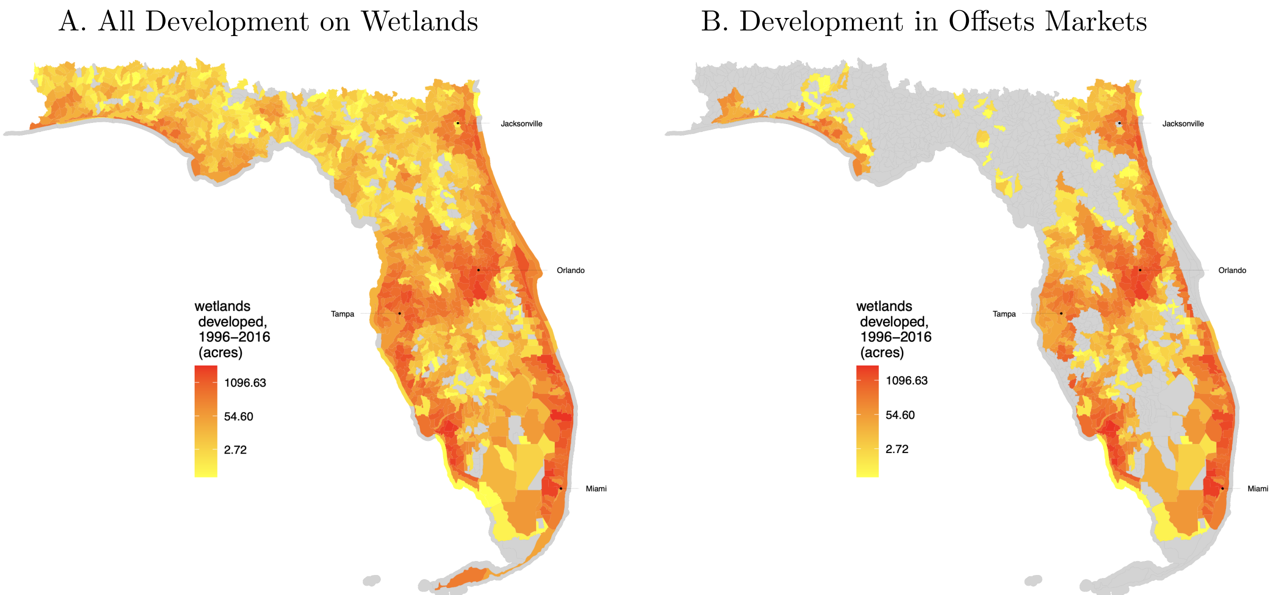

Figure A3. Development on Florida Wetlands

A. Map of local wetland development between 1996–2016.

B. Map of local wetland development occurring in active offset markets between 1996–2016. See Table A2 for more details.

Local watersheds colored by decile of ln(acres of wetlands developed).

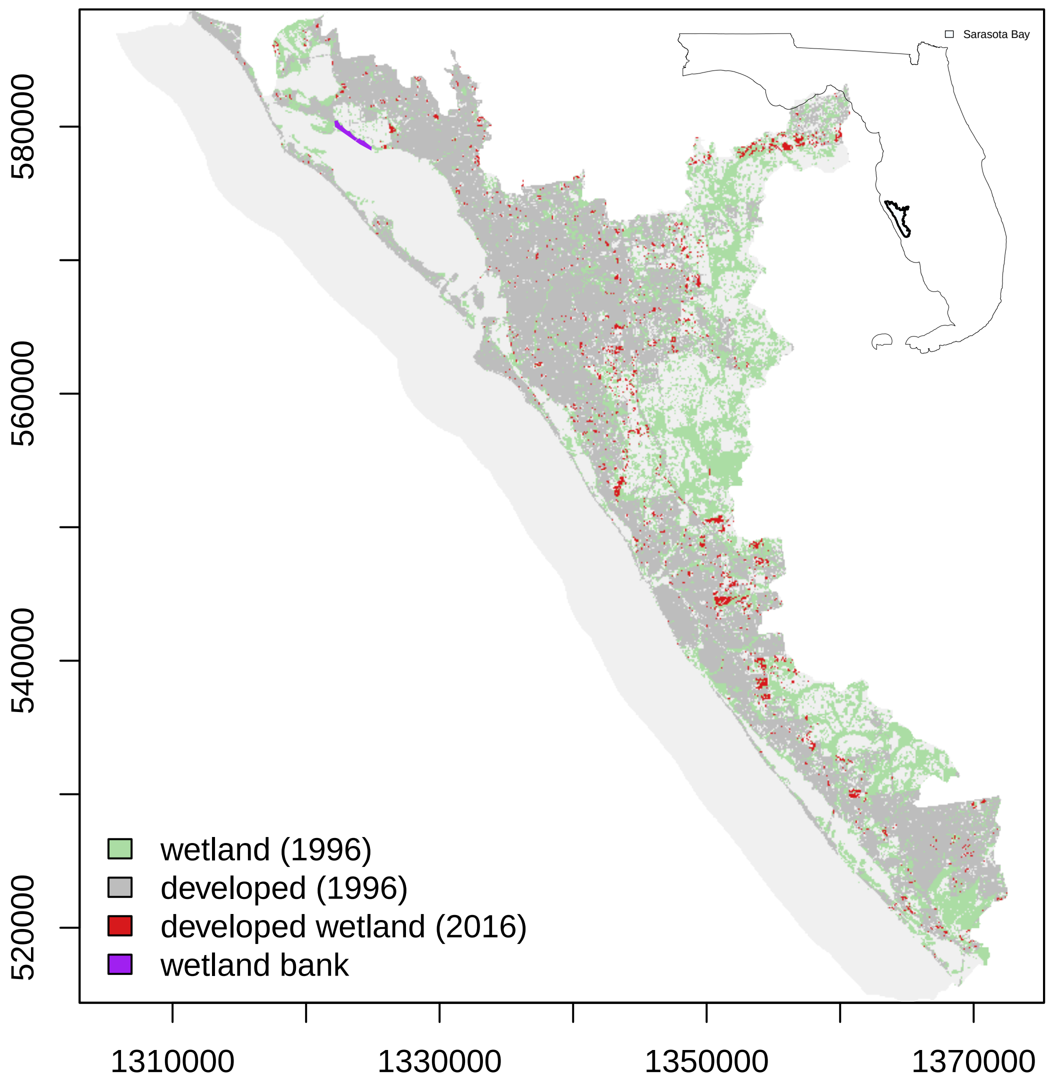

Figure A4.1. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

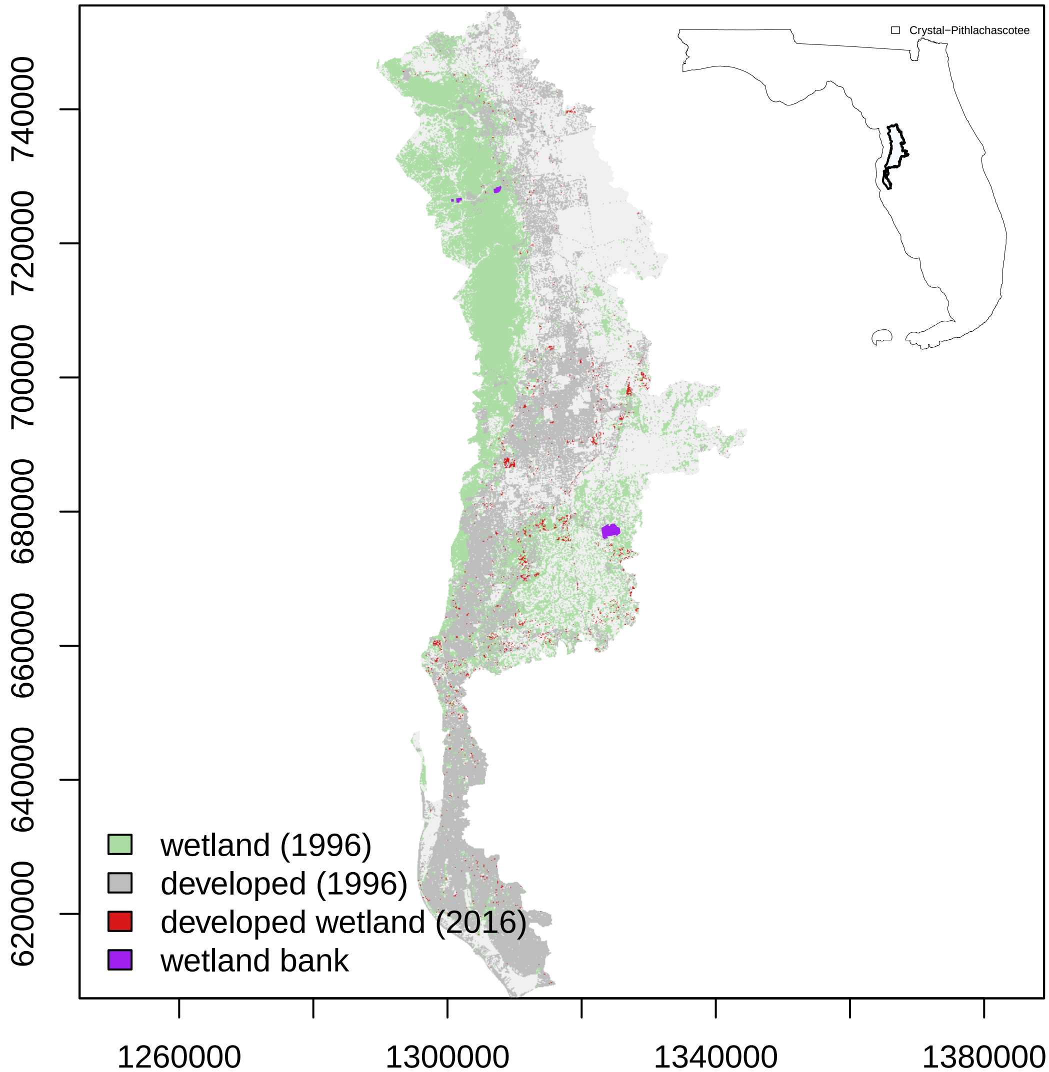

Figure A4.2. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

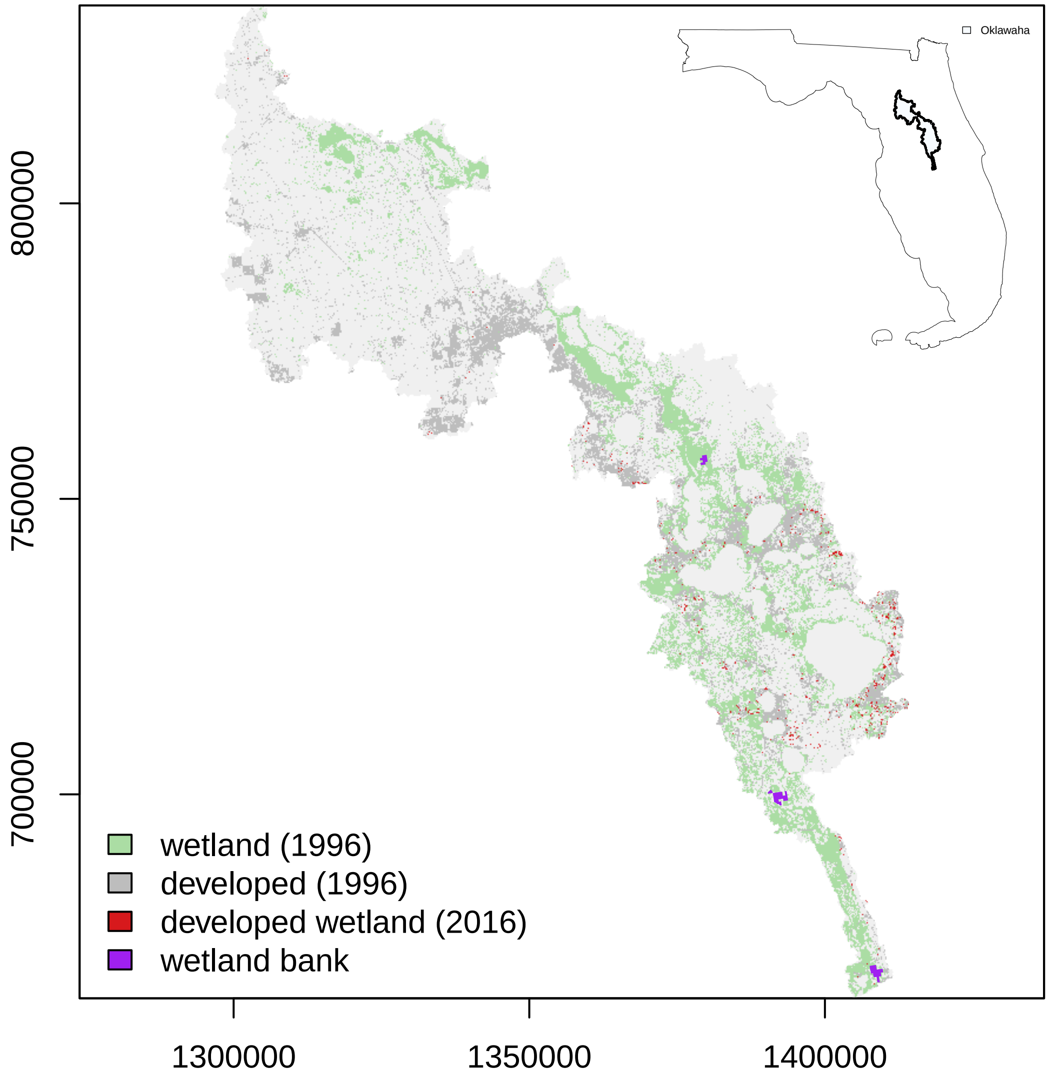

FIGURE A4.3. MARKET-LEVEL WETLAND DEVELOPMENT AND BANKS

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

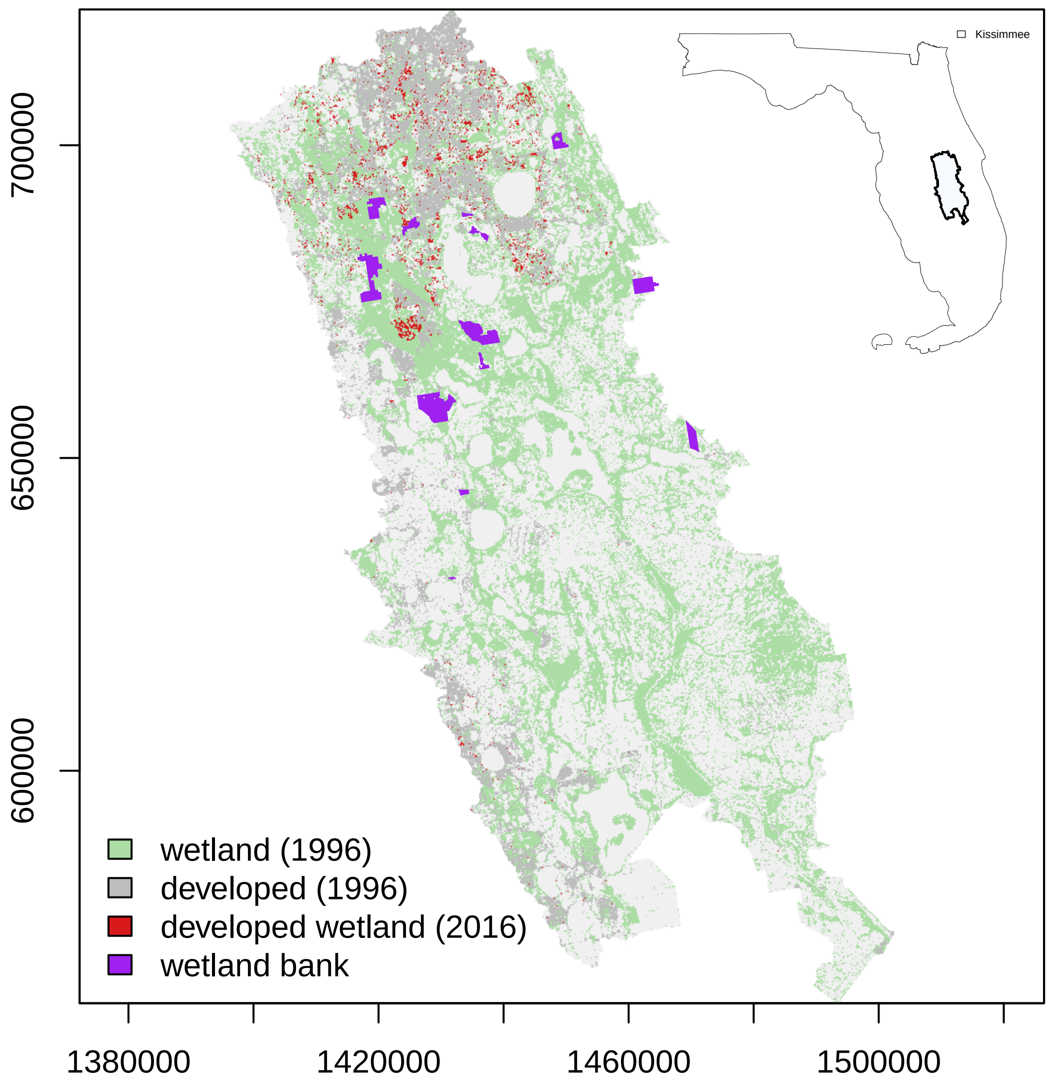

Figure A4.4. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

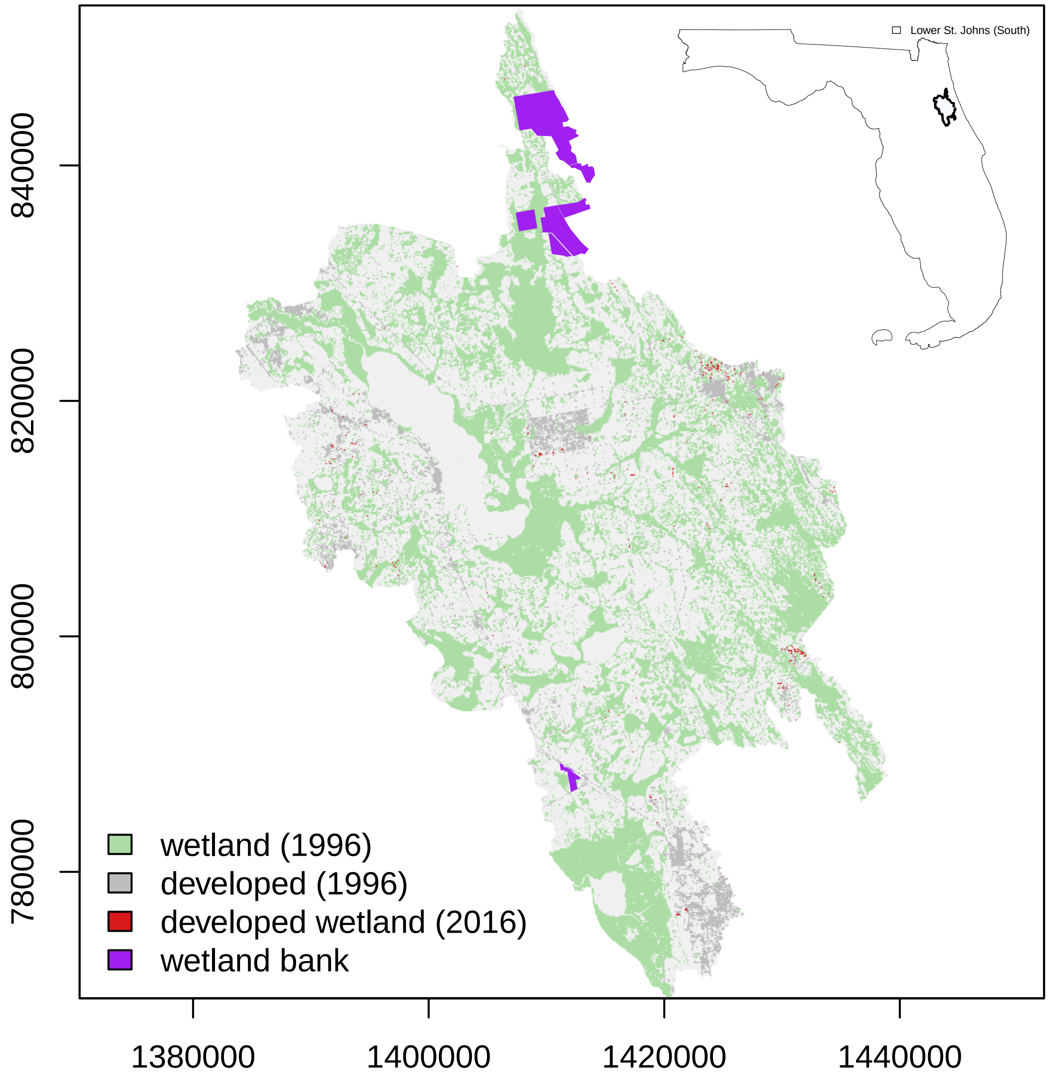

Figure A4.5. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

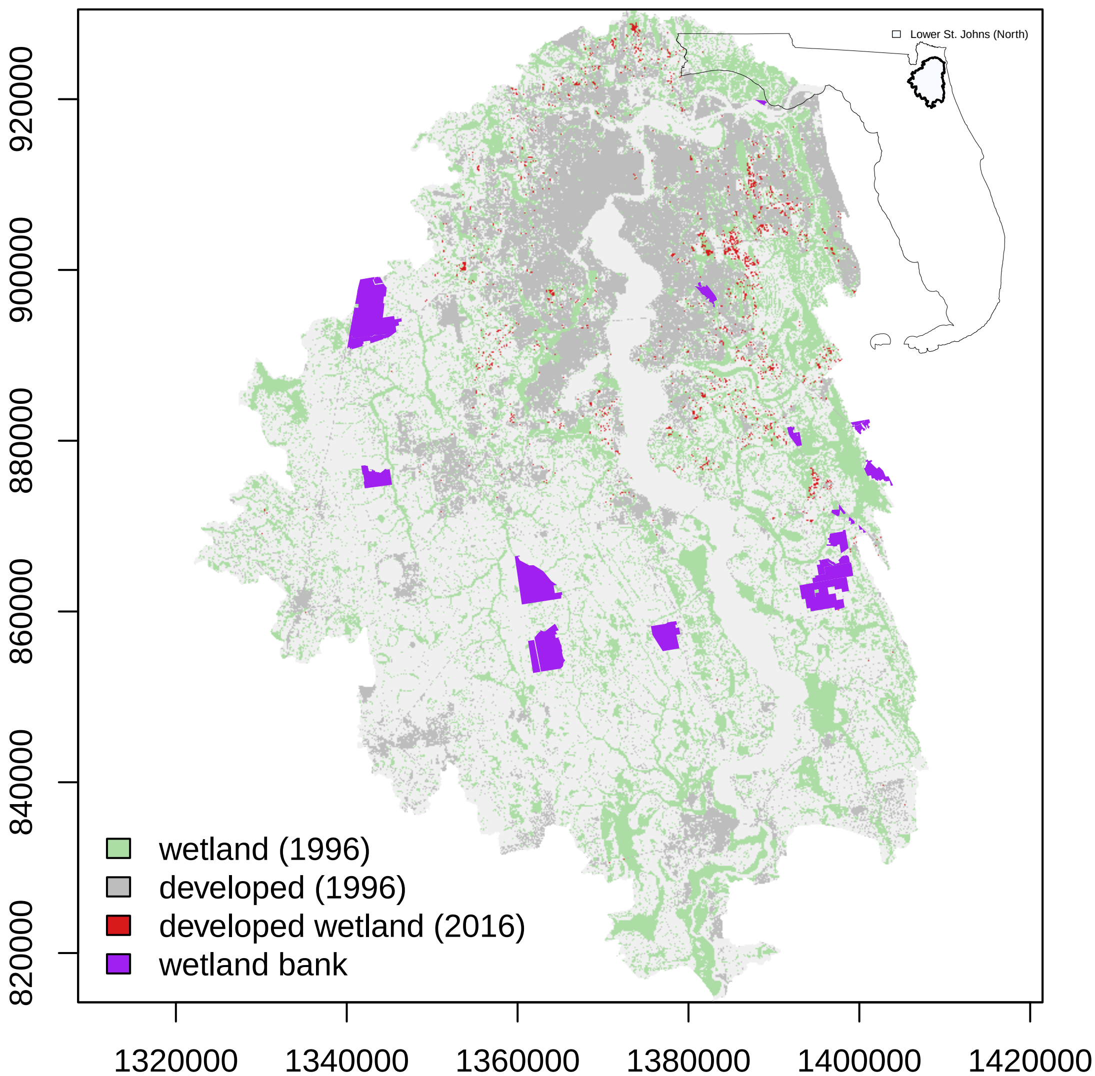

Figure A4.6. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

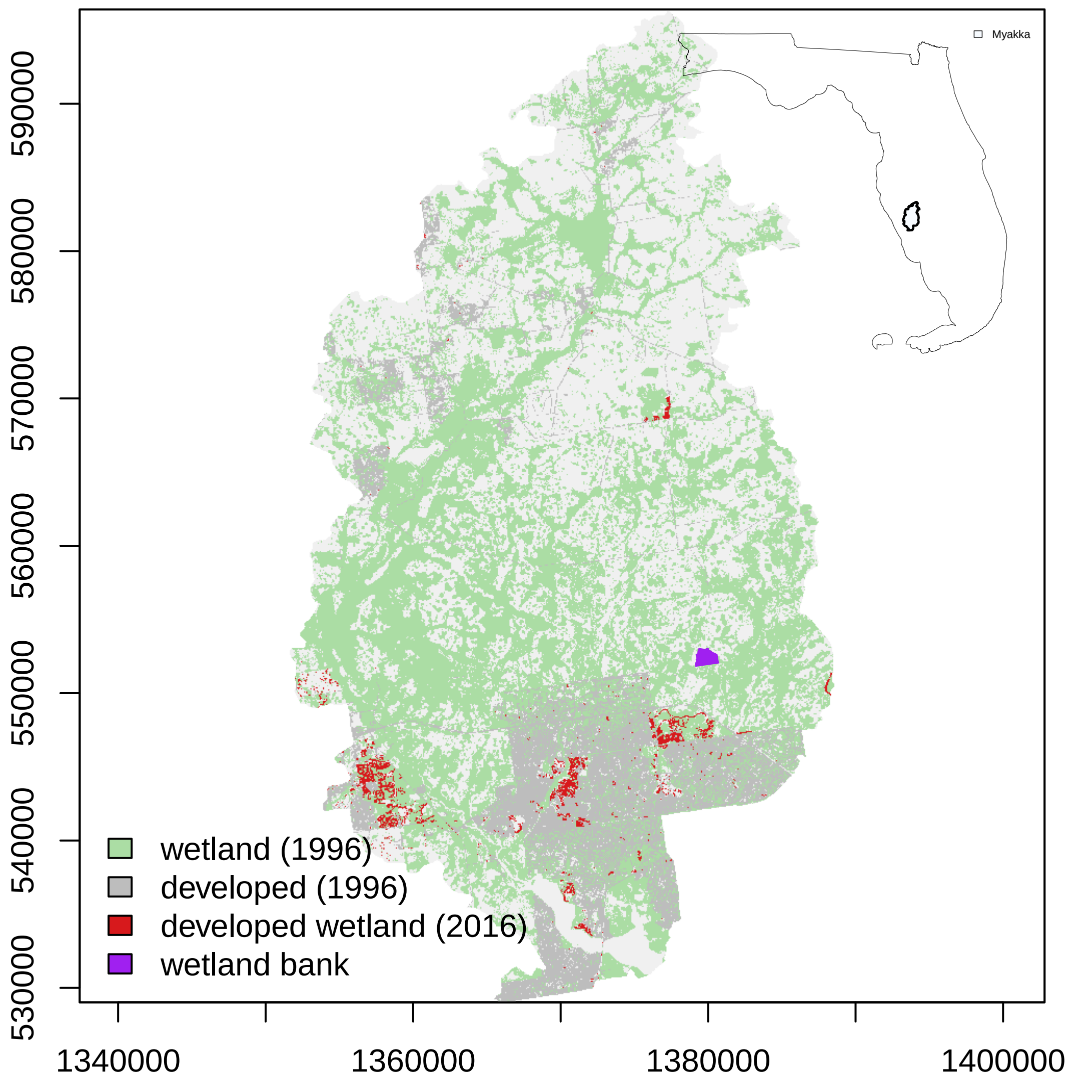

Figure A4.7. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

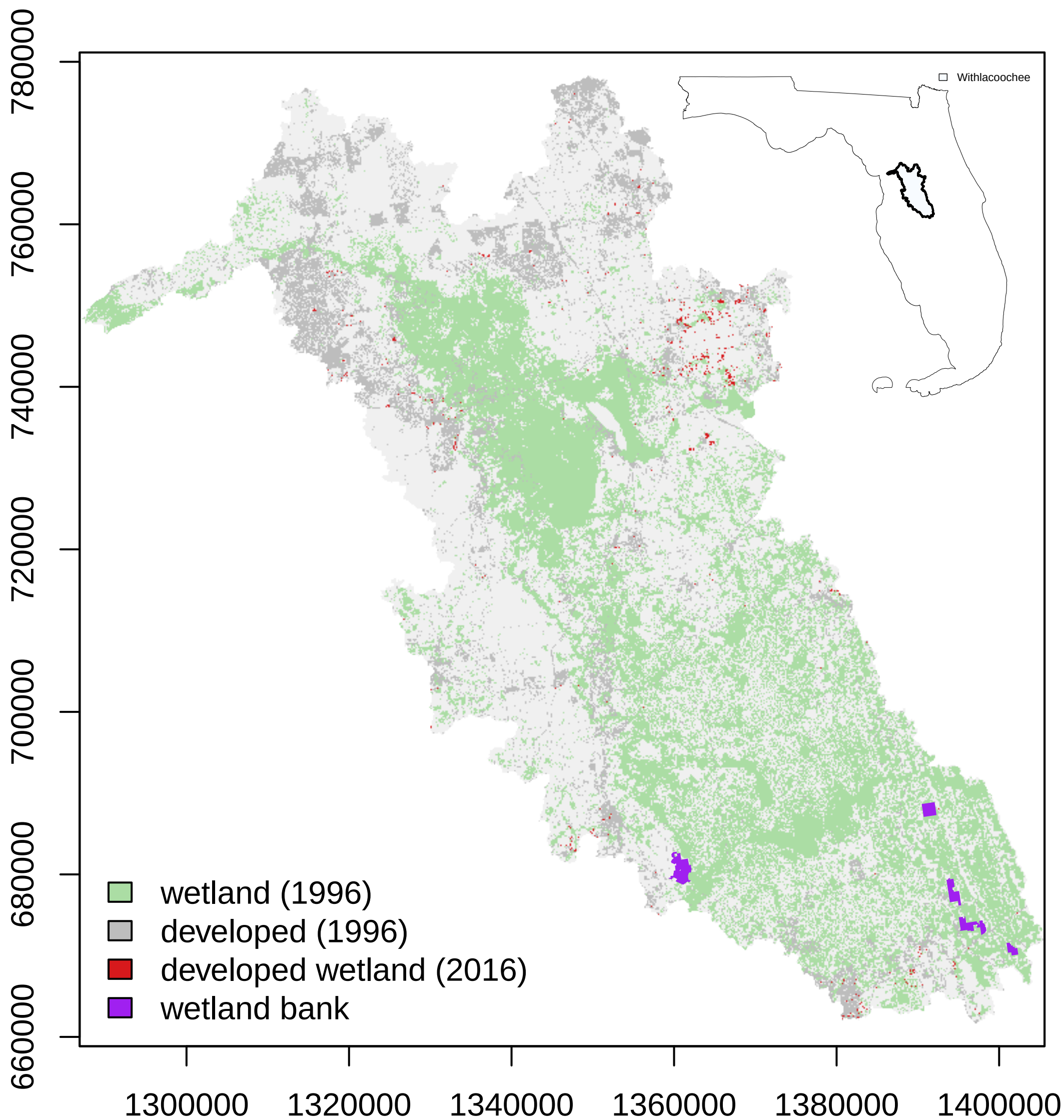

Figure A4.8. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

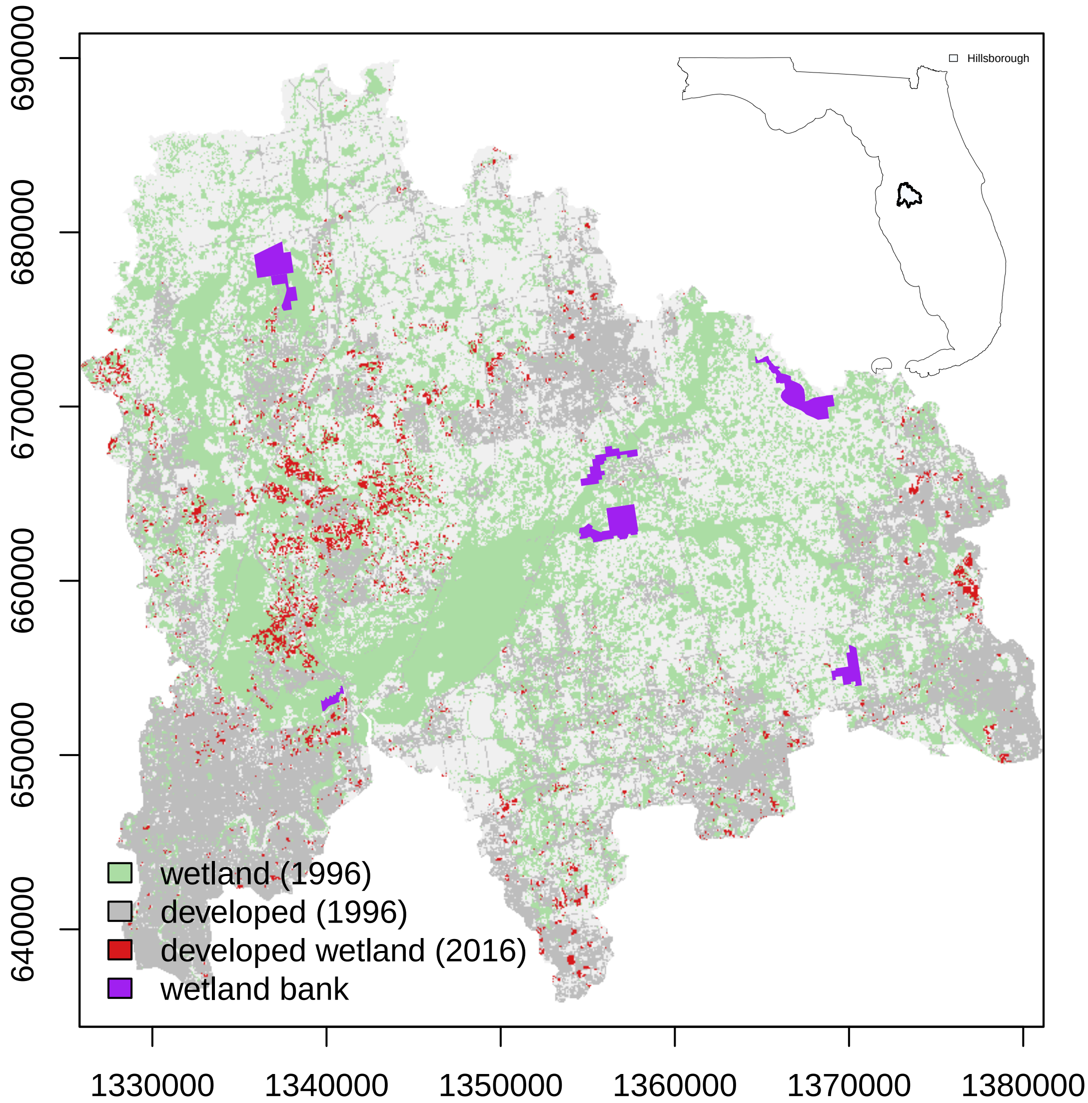

Figure A4.9. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

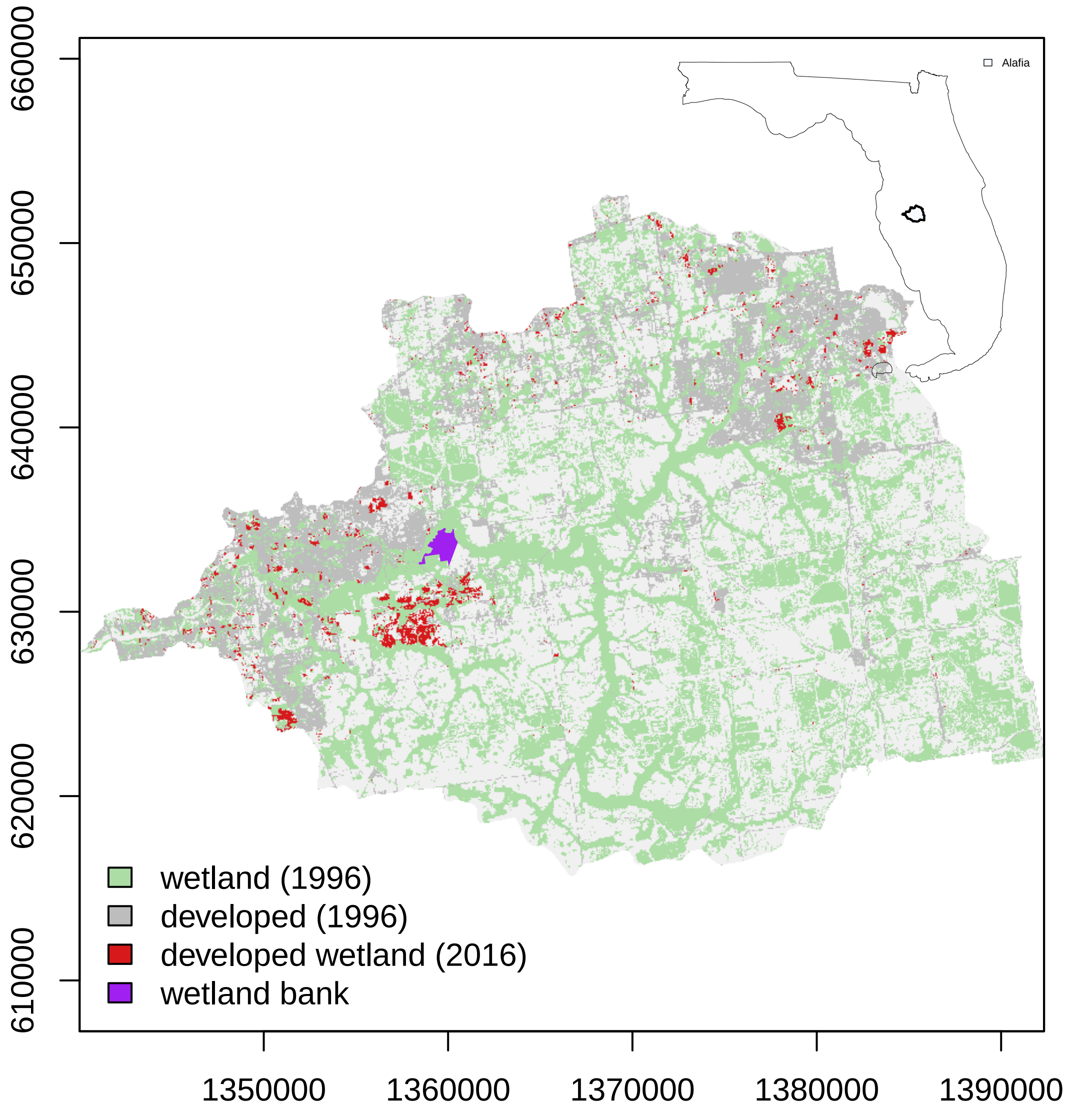

Figure A4.10. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

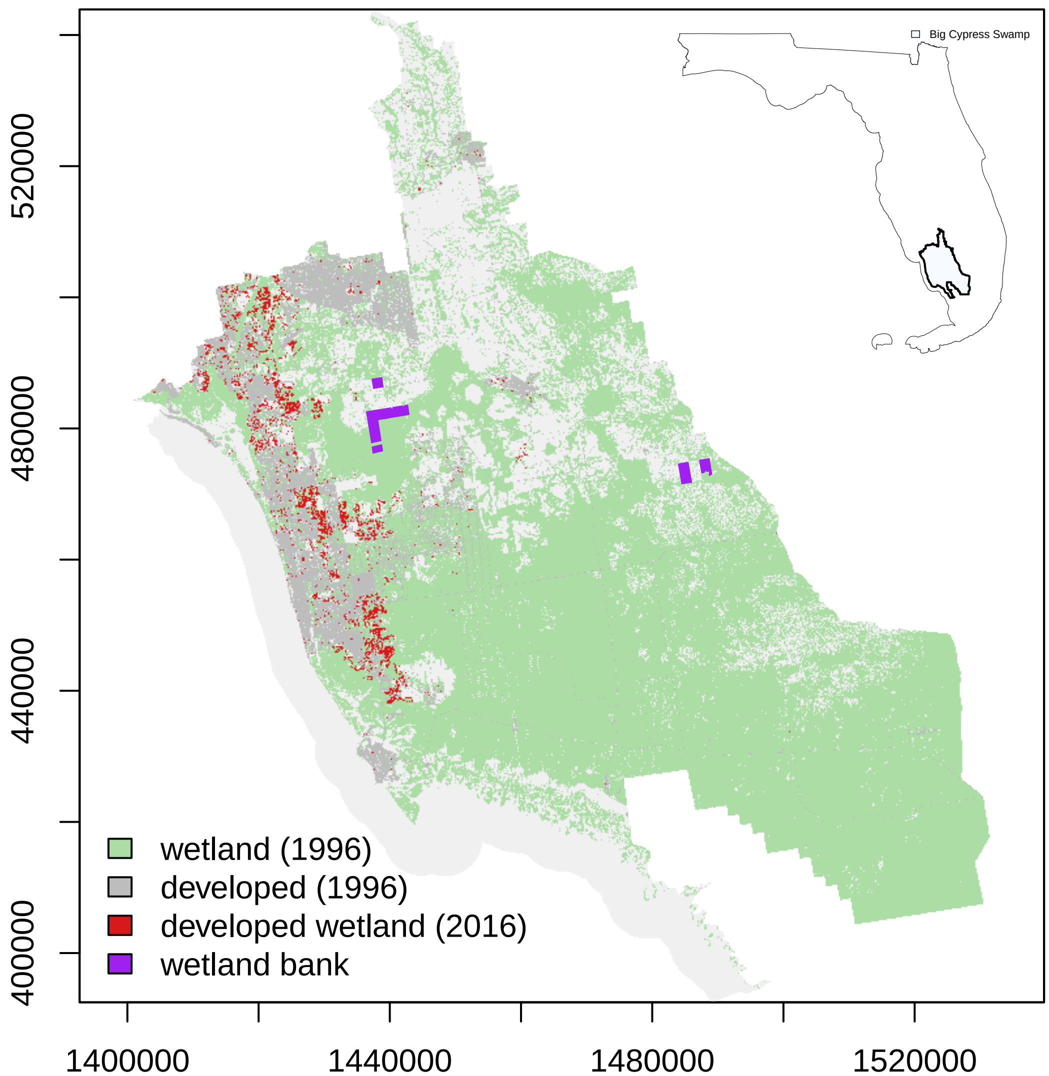

Figure A4.11. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

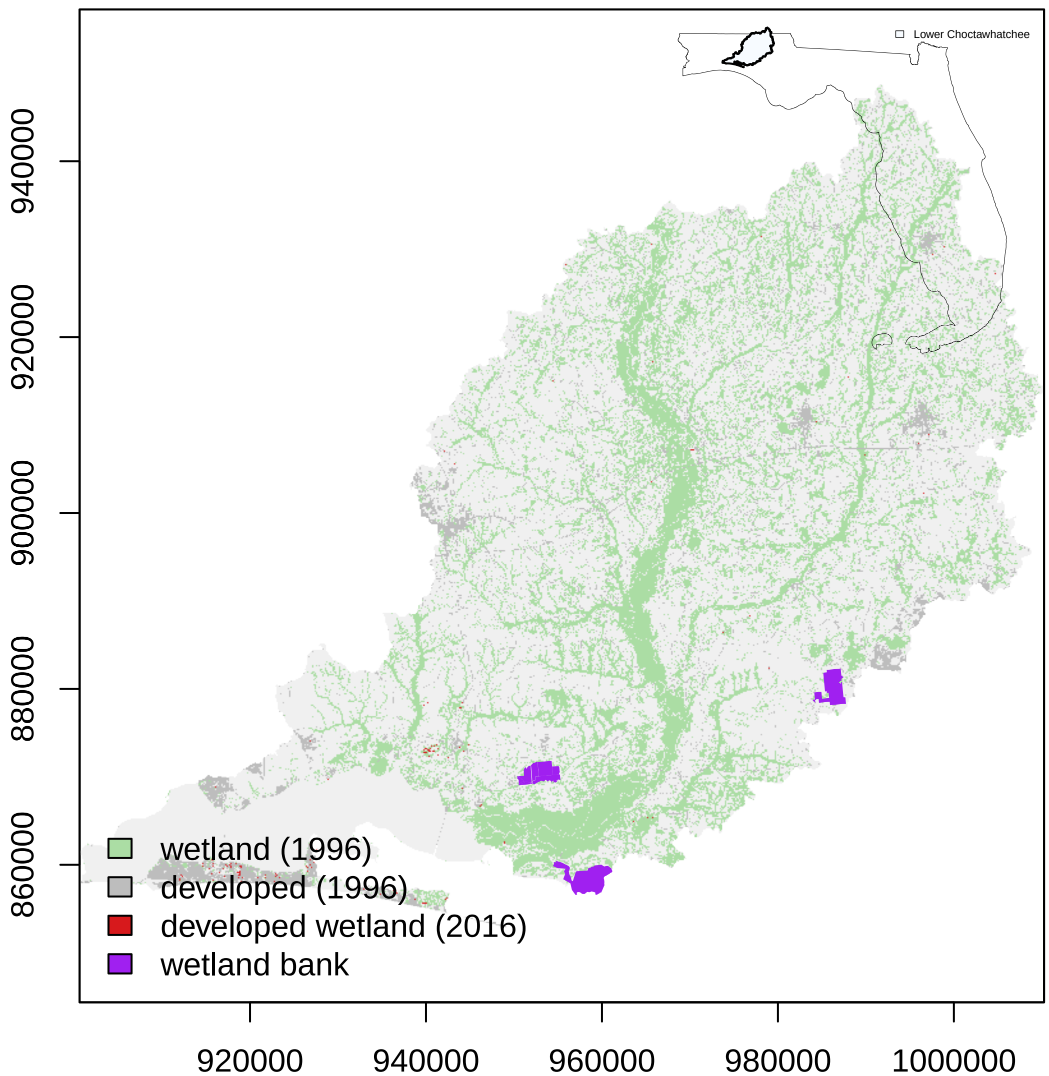

Figure A4.12. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

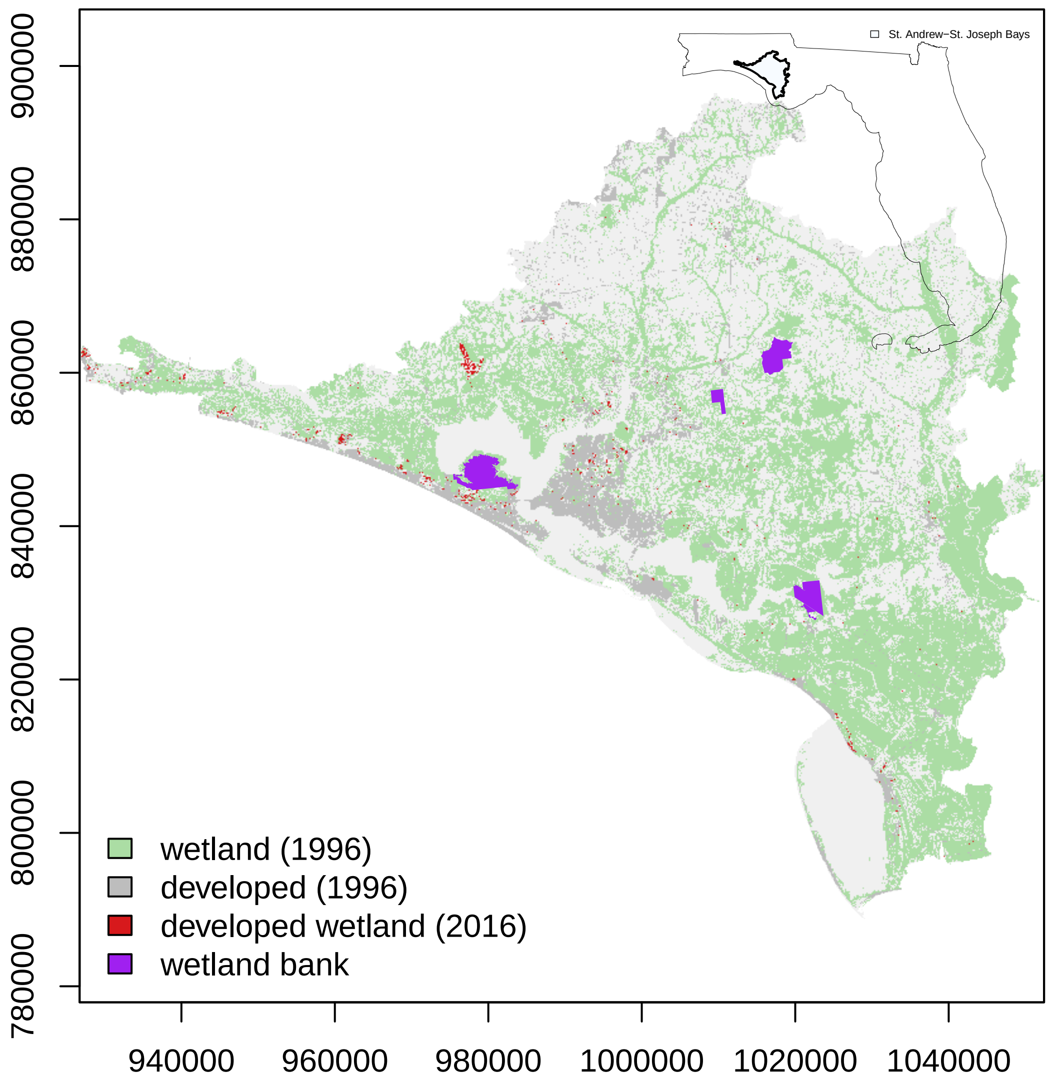

Figure A4.13. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

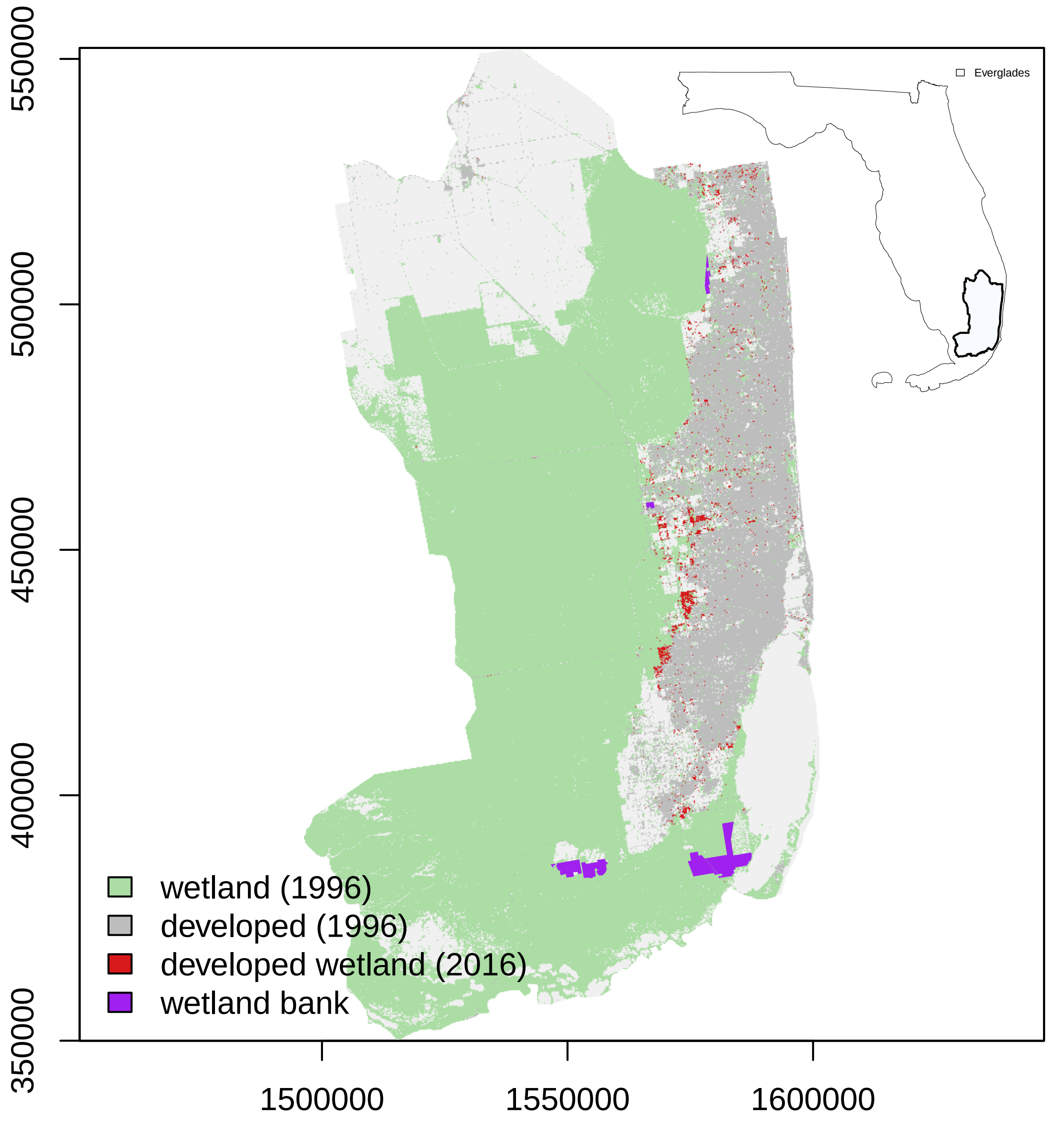

Figure A4.14. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

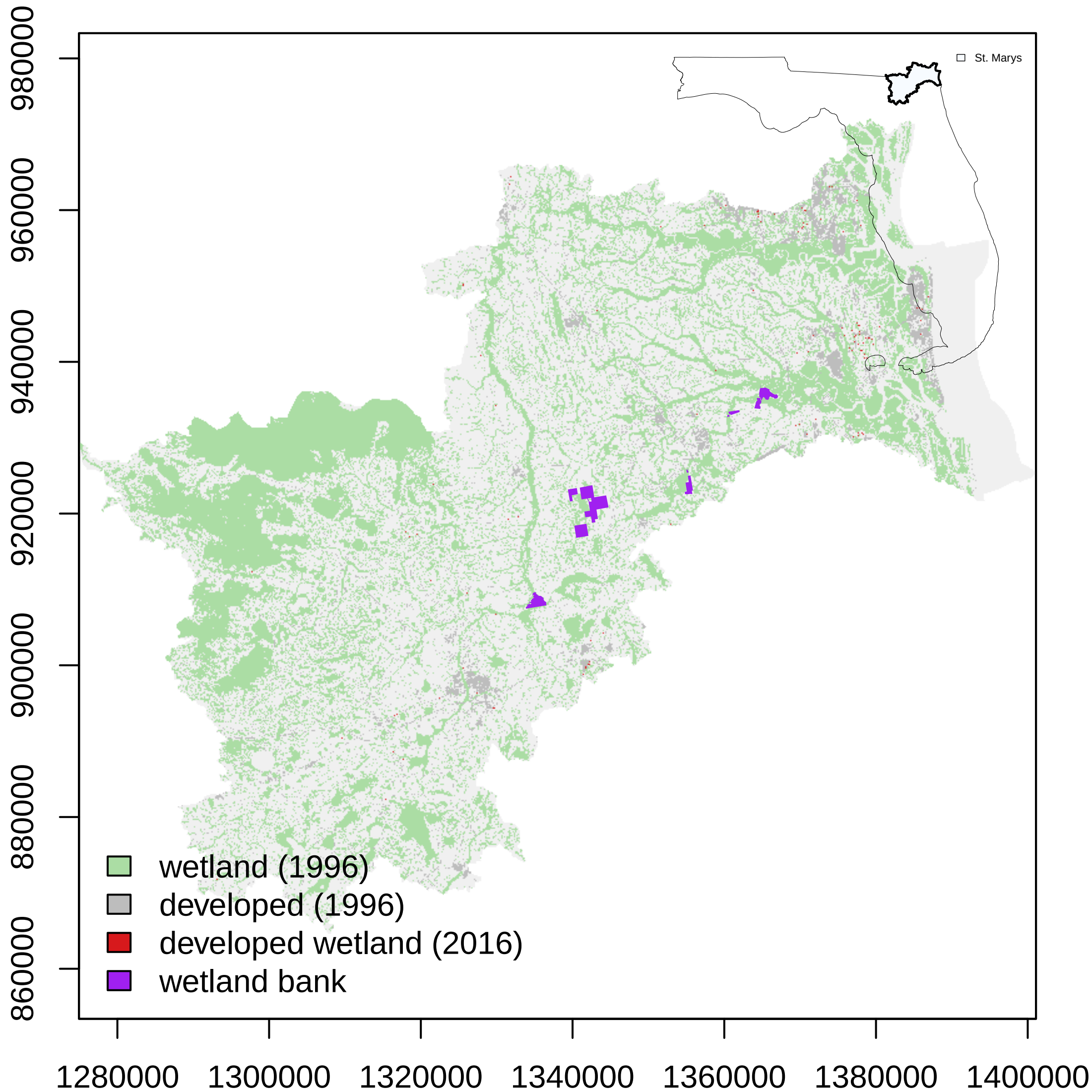

Figure A4.15. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

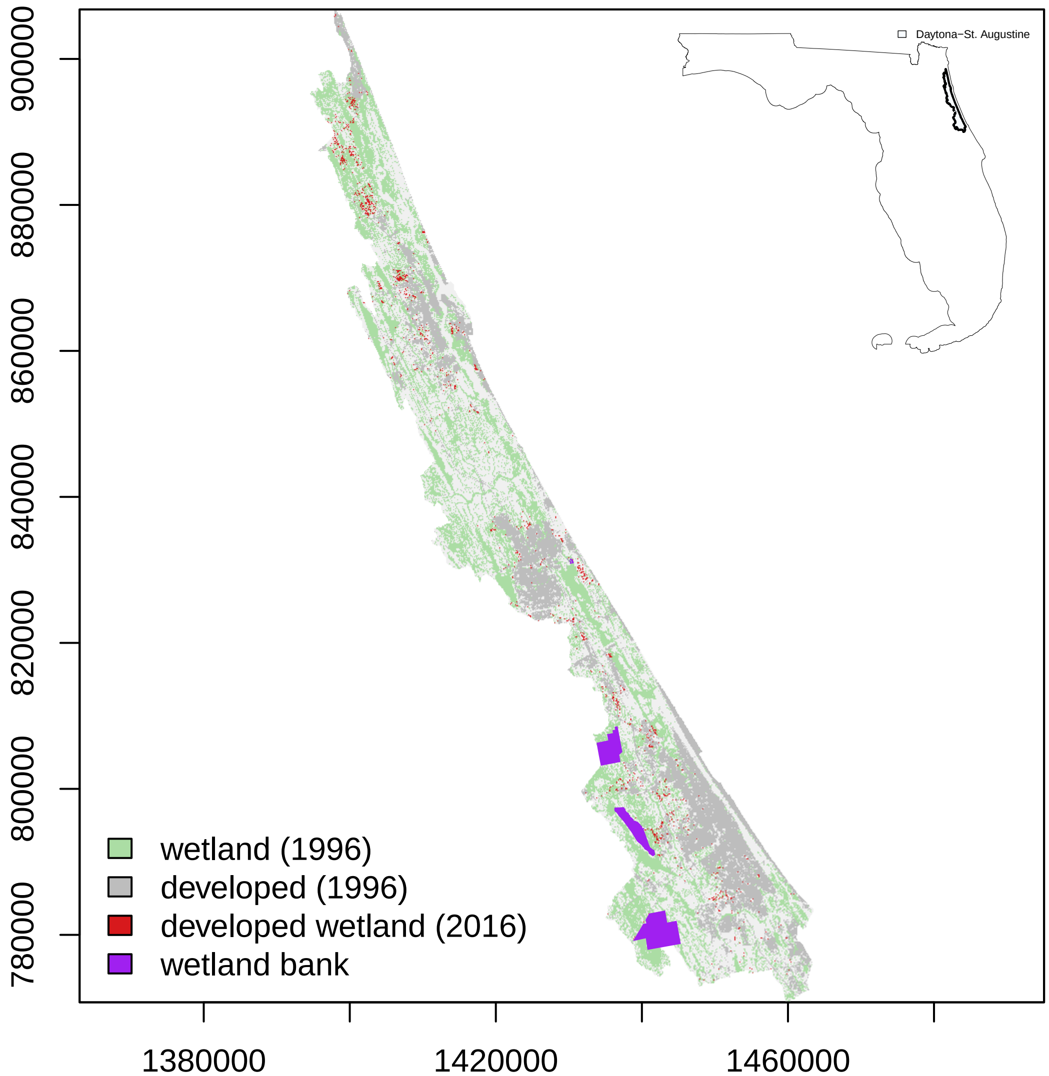

Figure A4.16. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

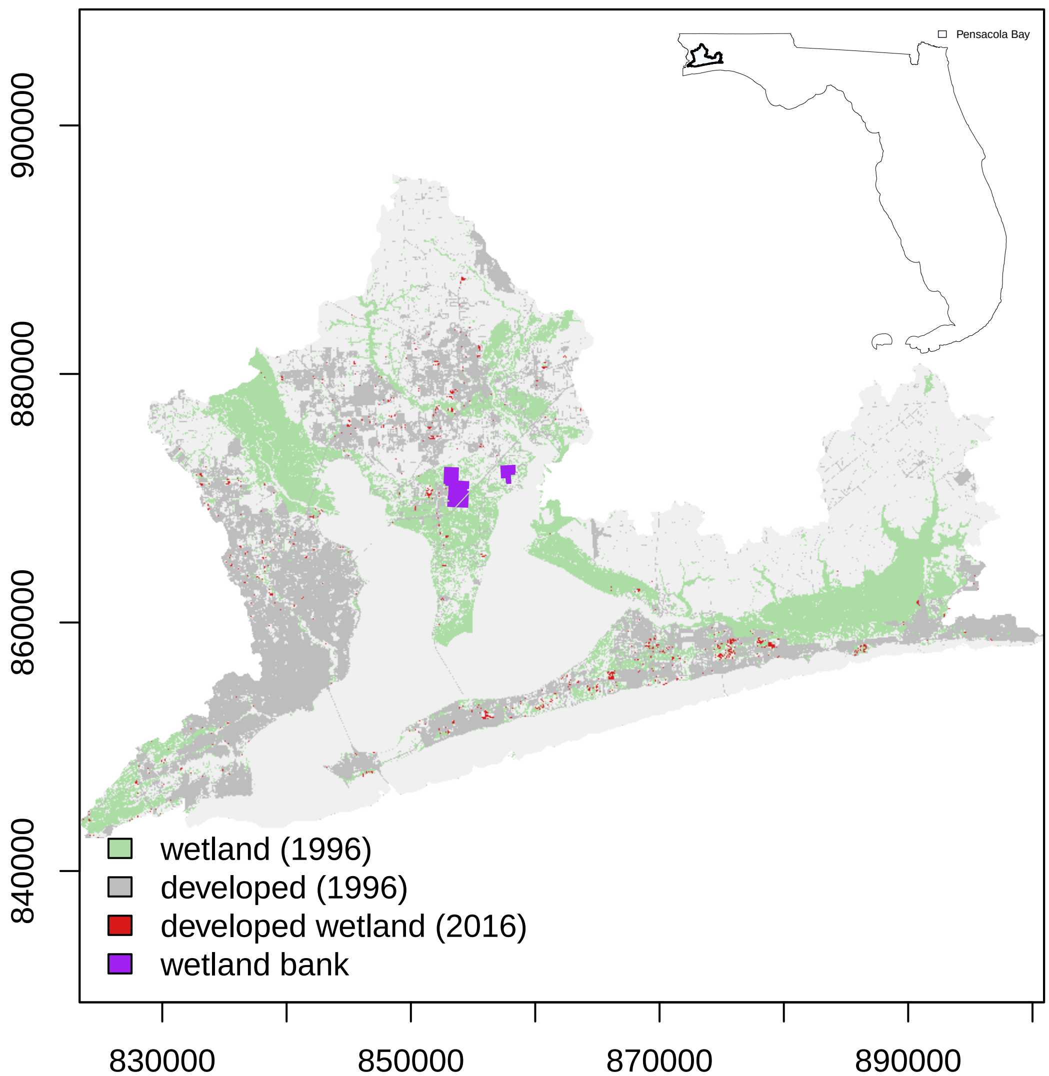

Figure A4.17. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

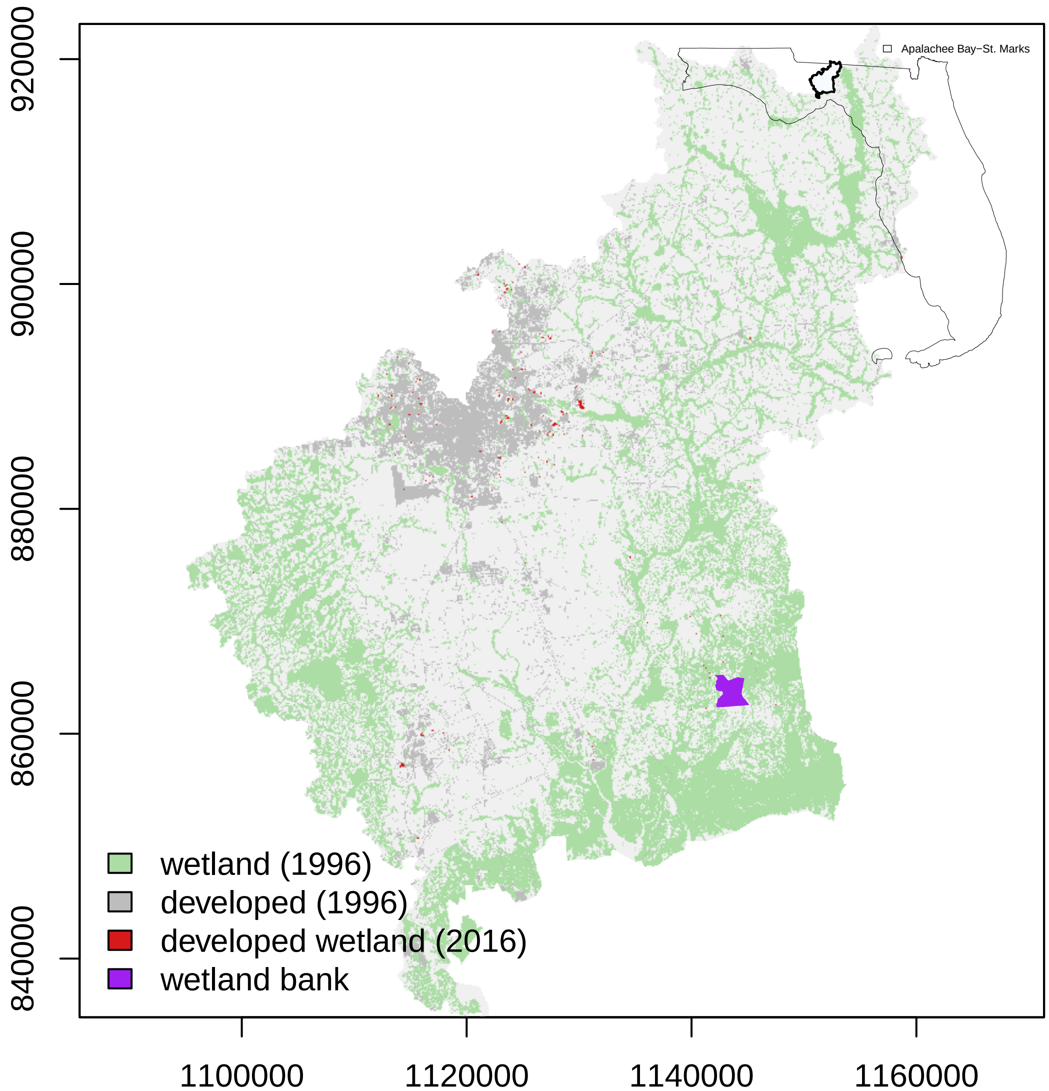

Figure A4.18. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

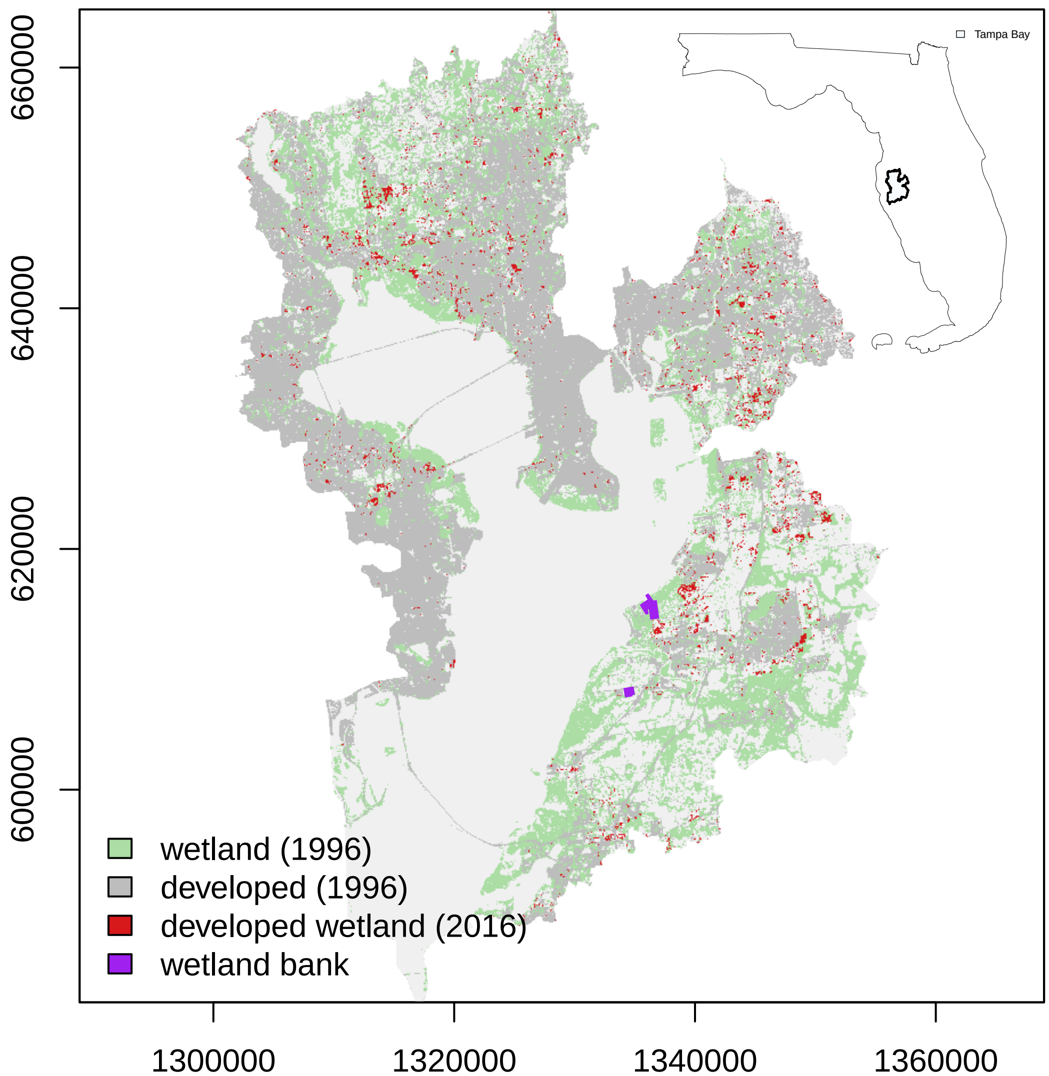

Figure A4.19. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

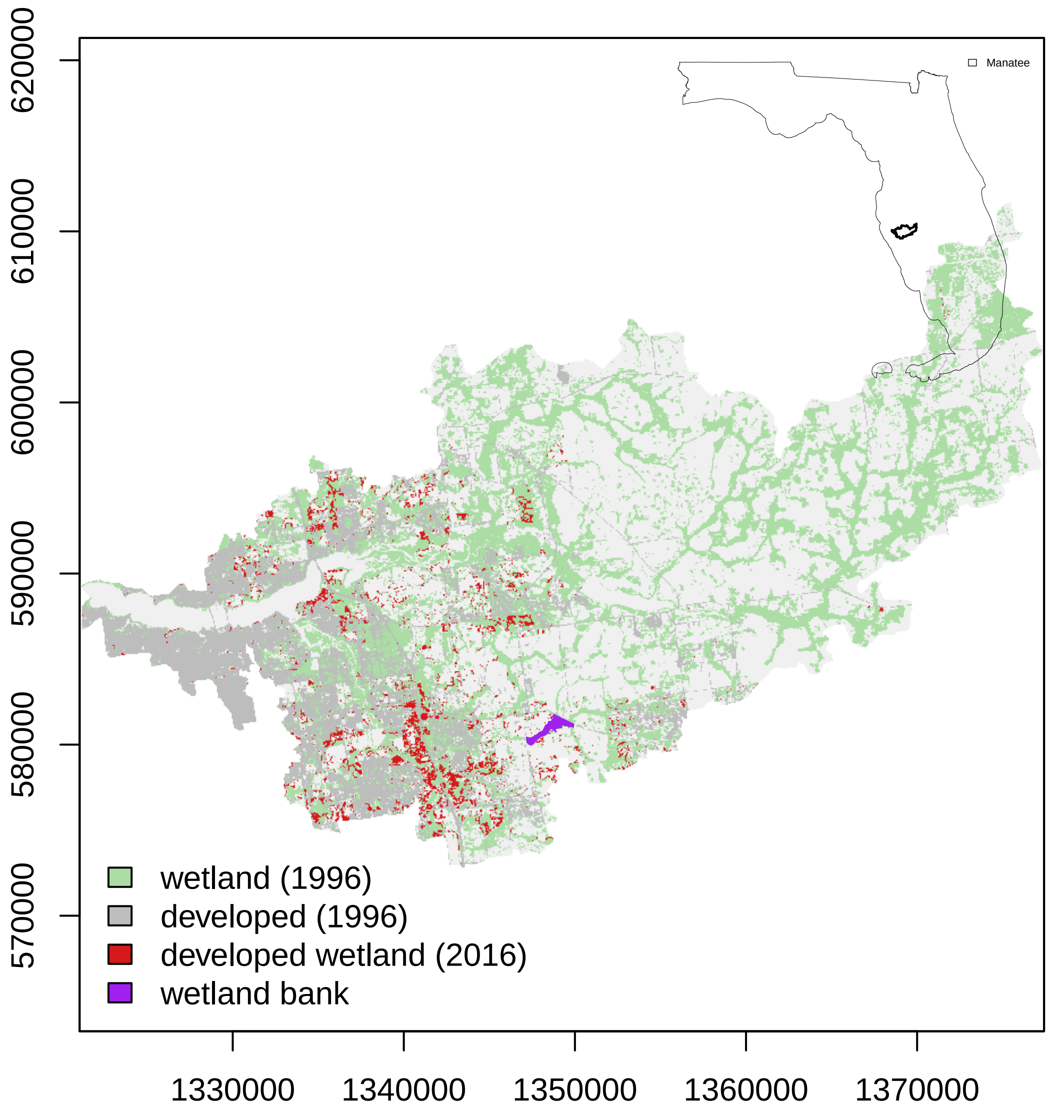

Figure A4.20. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

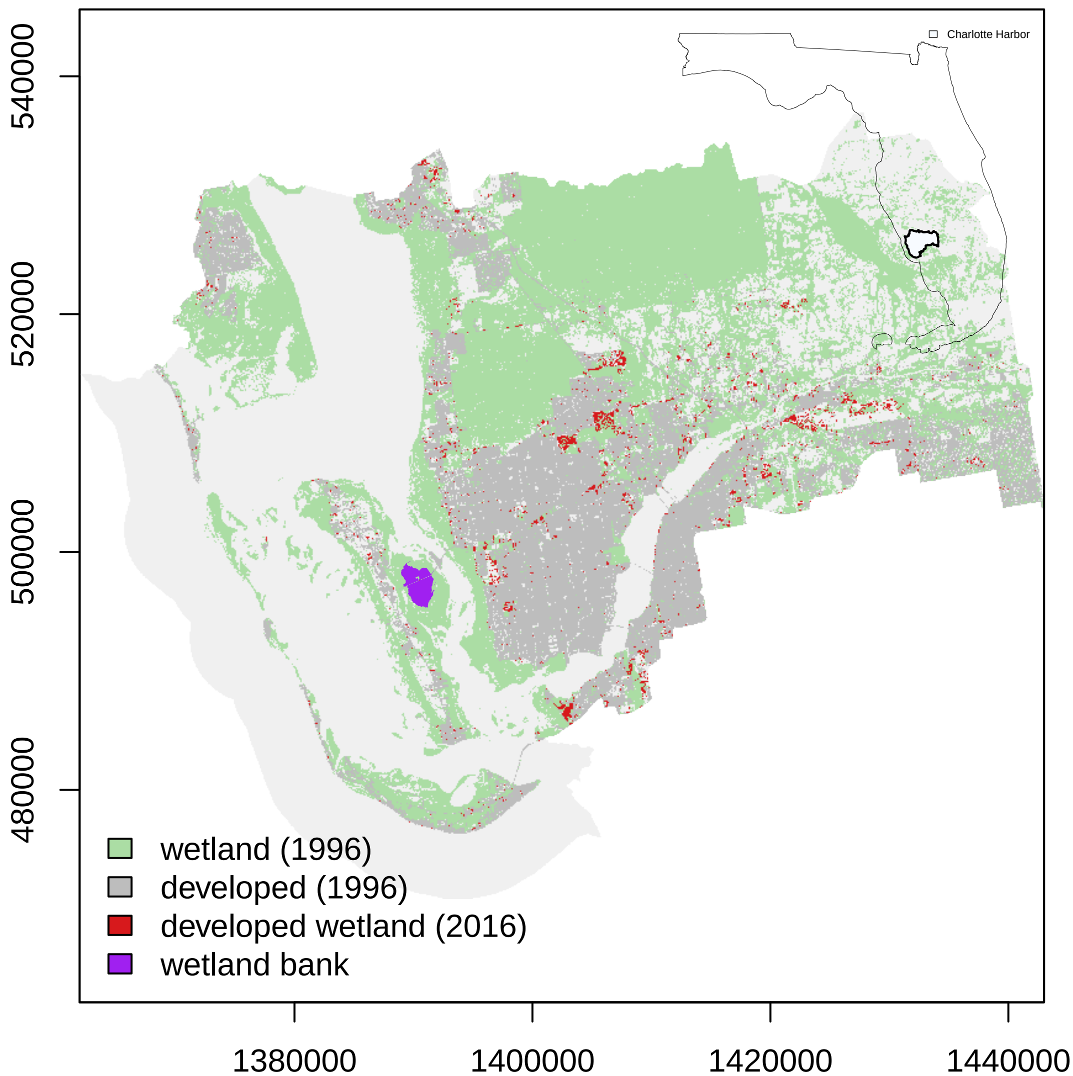

Figure A4.21. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

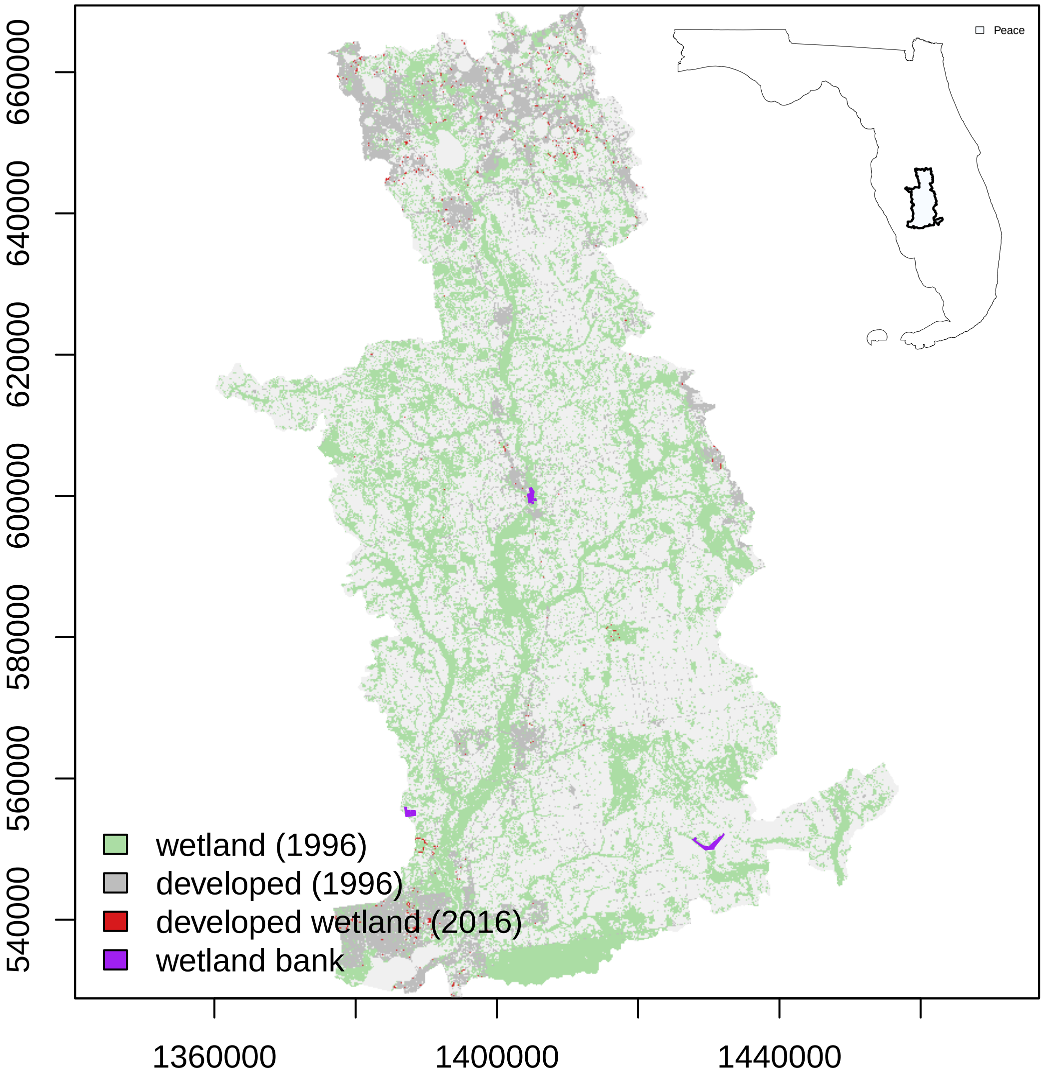

Figure A4.22. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

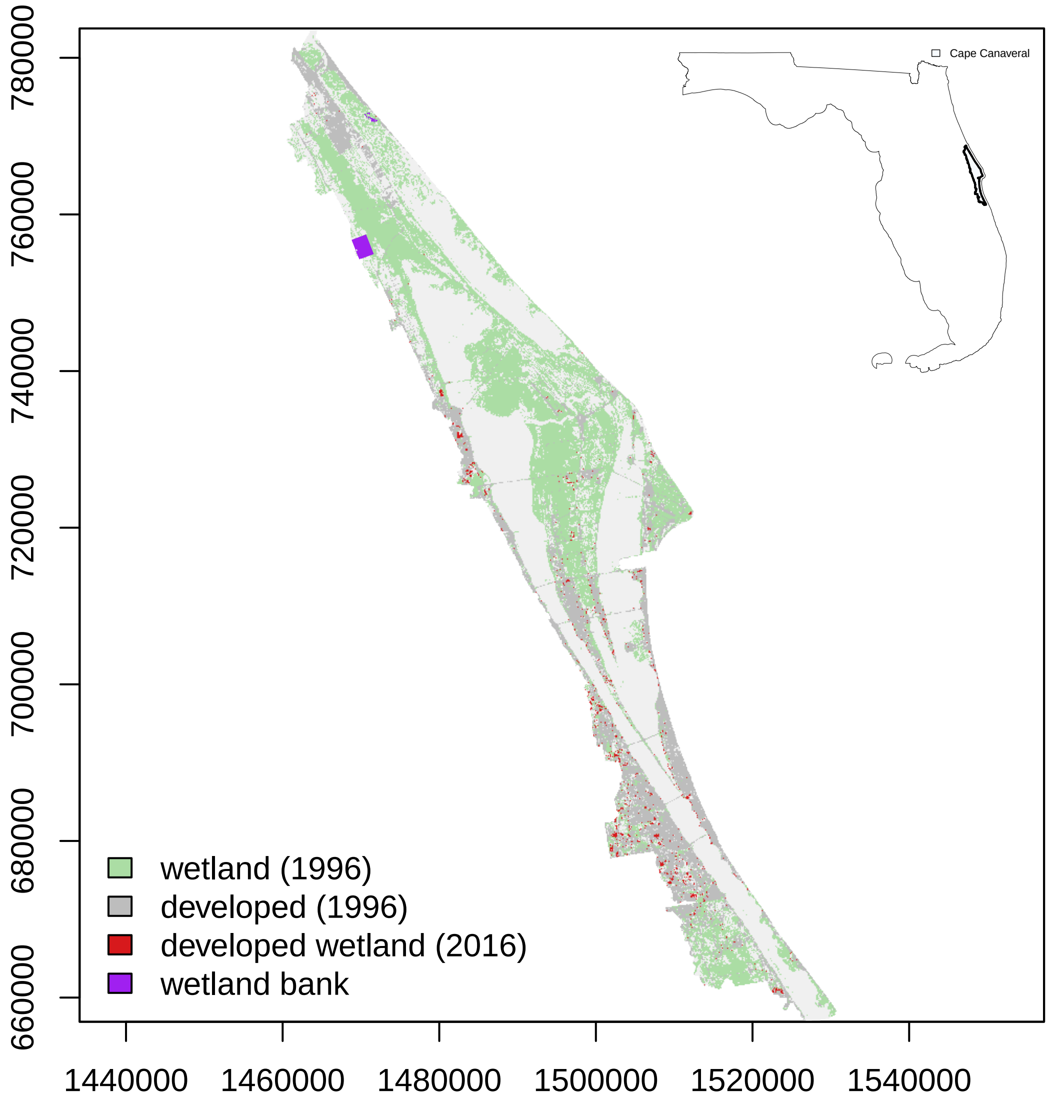

Figure A4.23. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

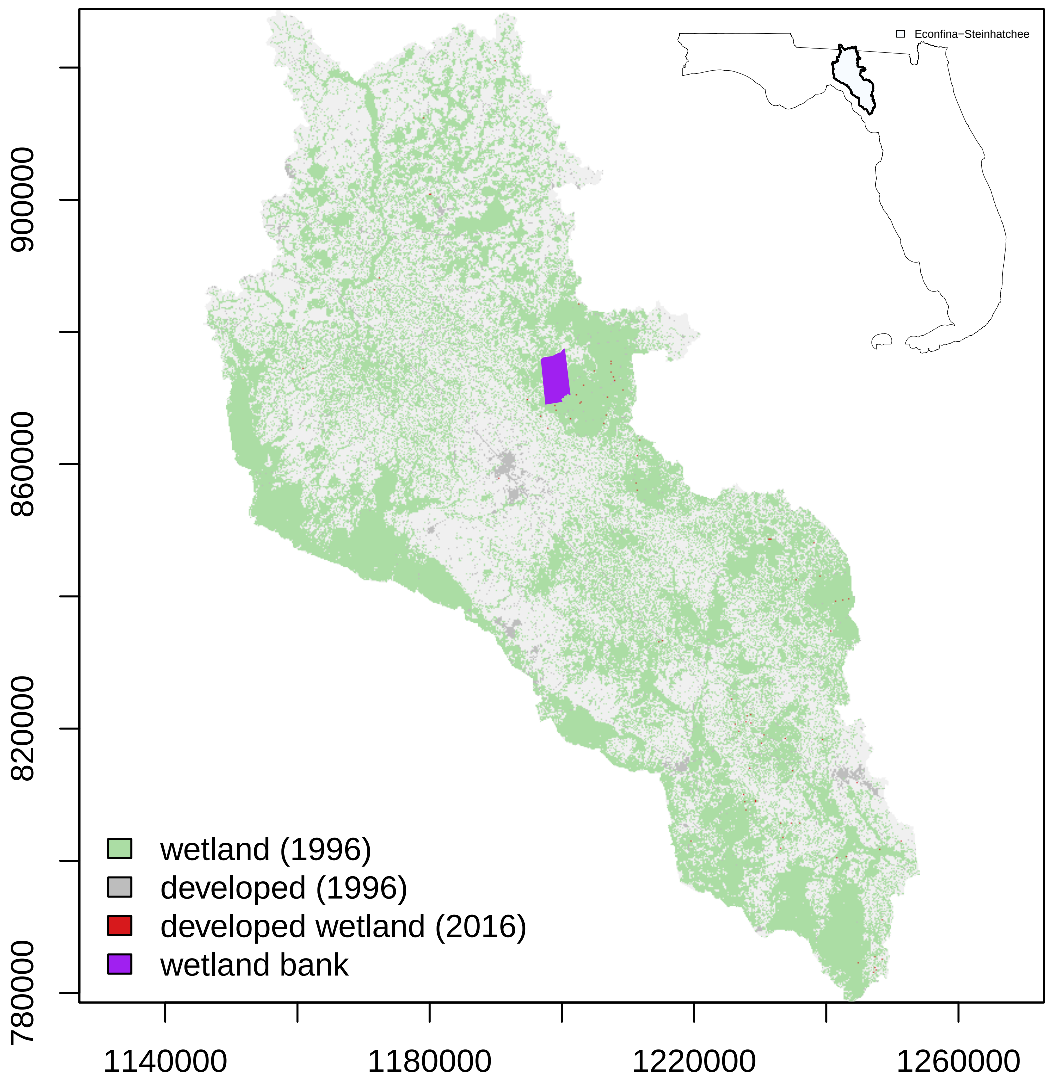

Figure A4.24. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

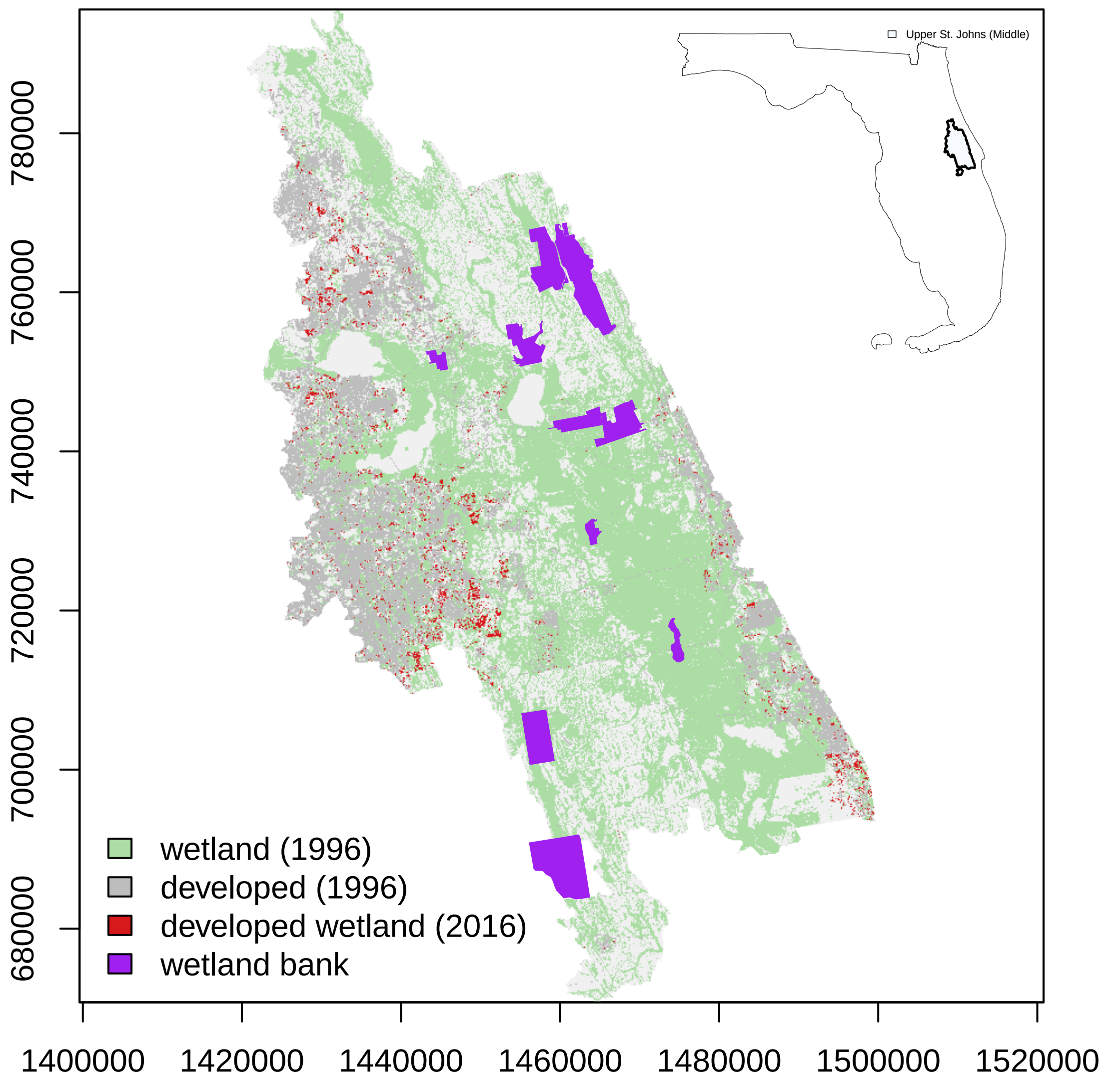

Figure A4.25. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

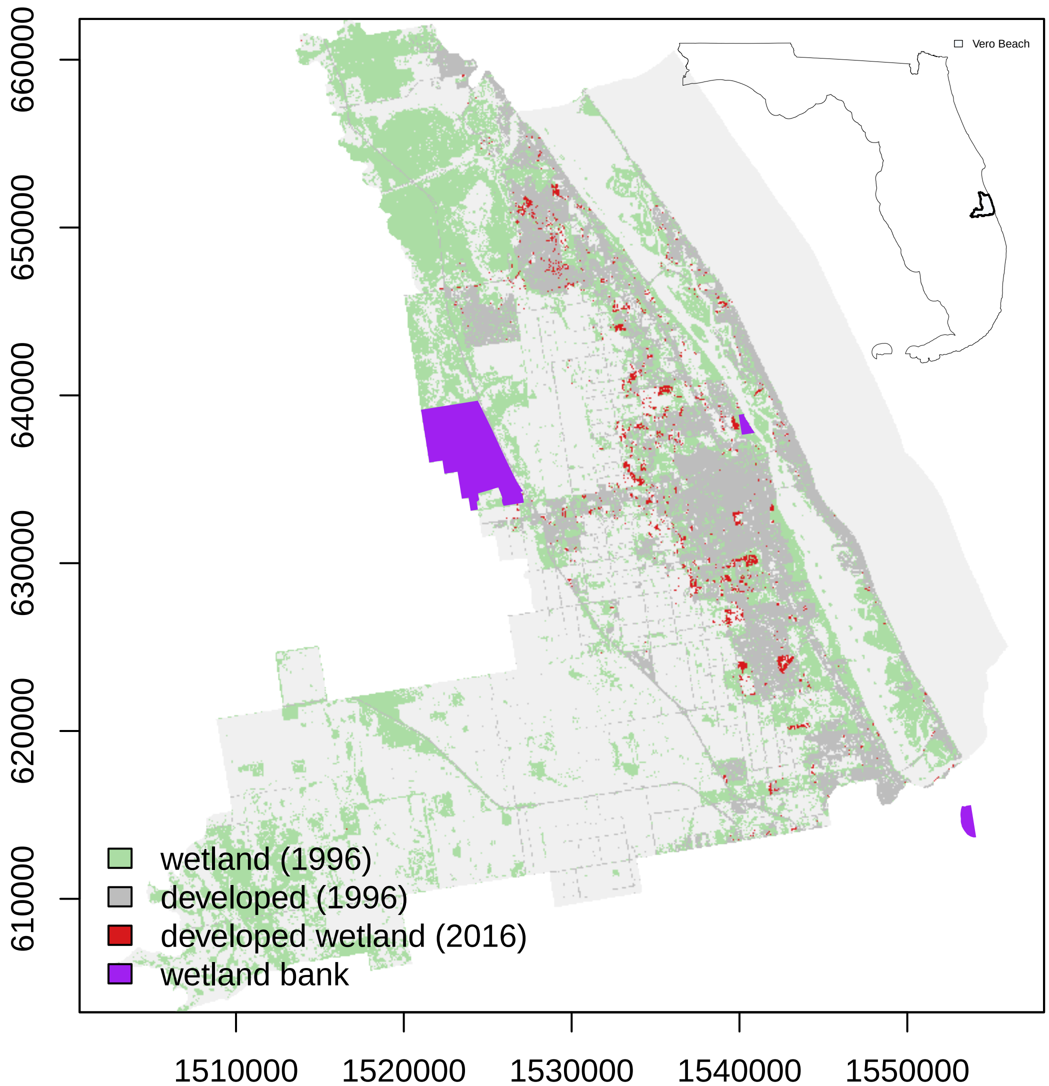

Figure A4.26. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

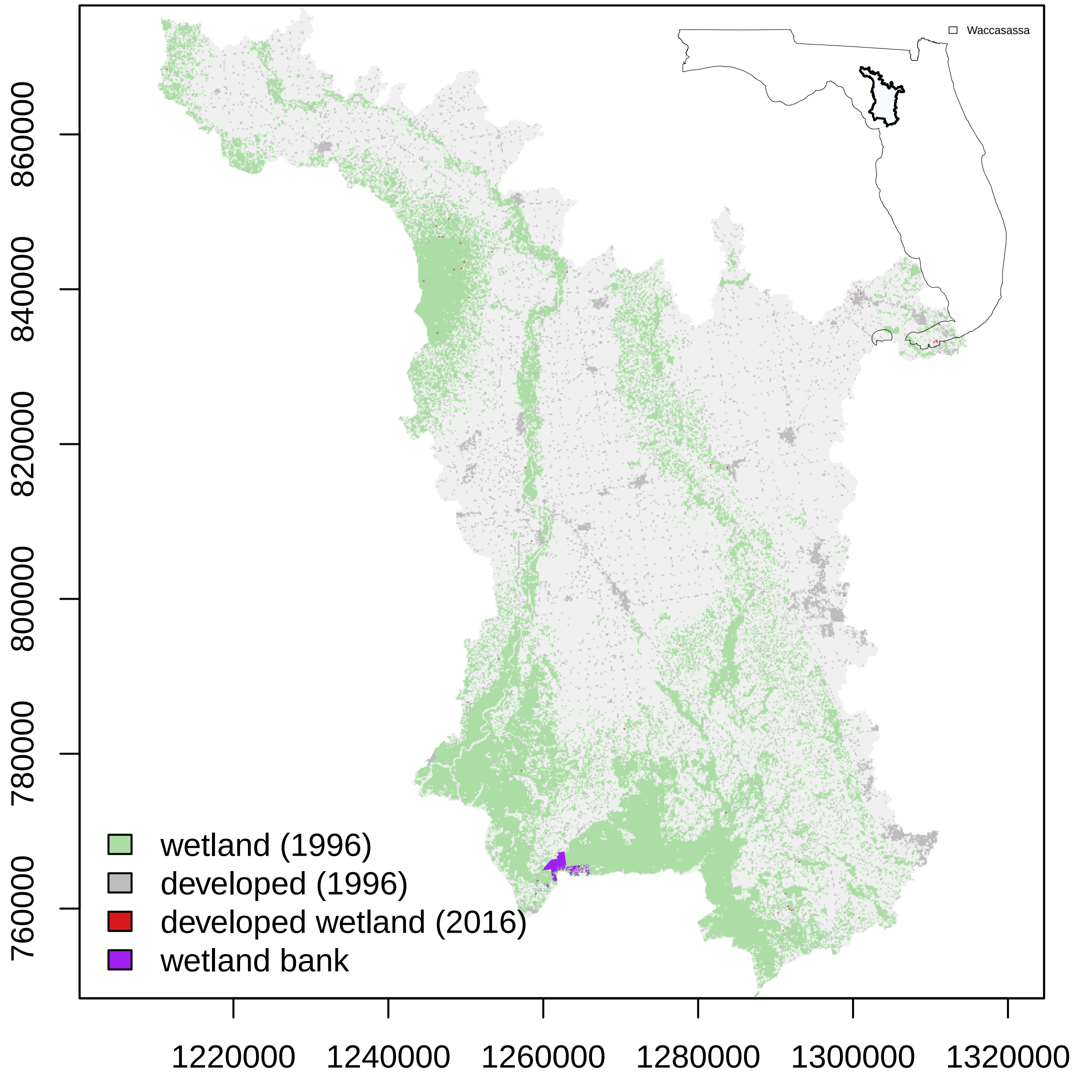

Figure A4.27. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

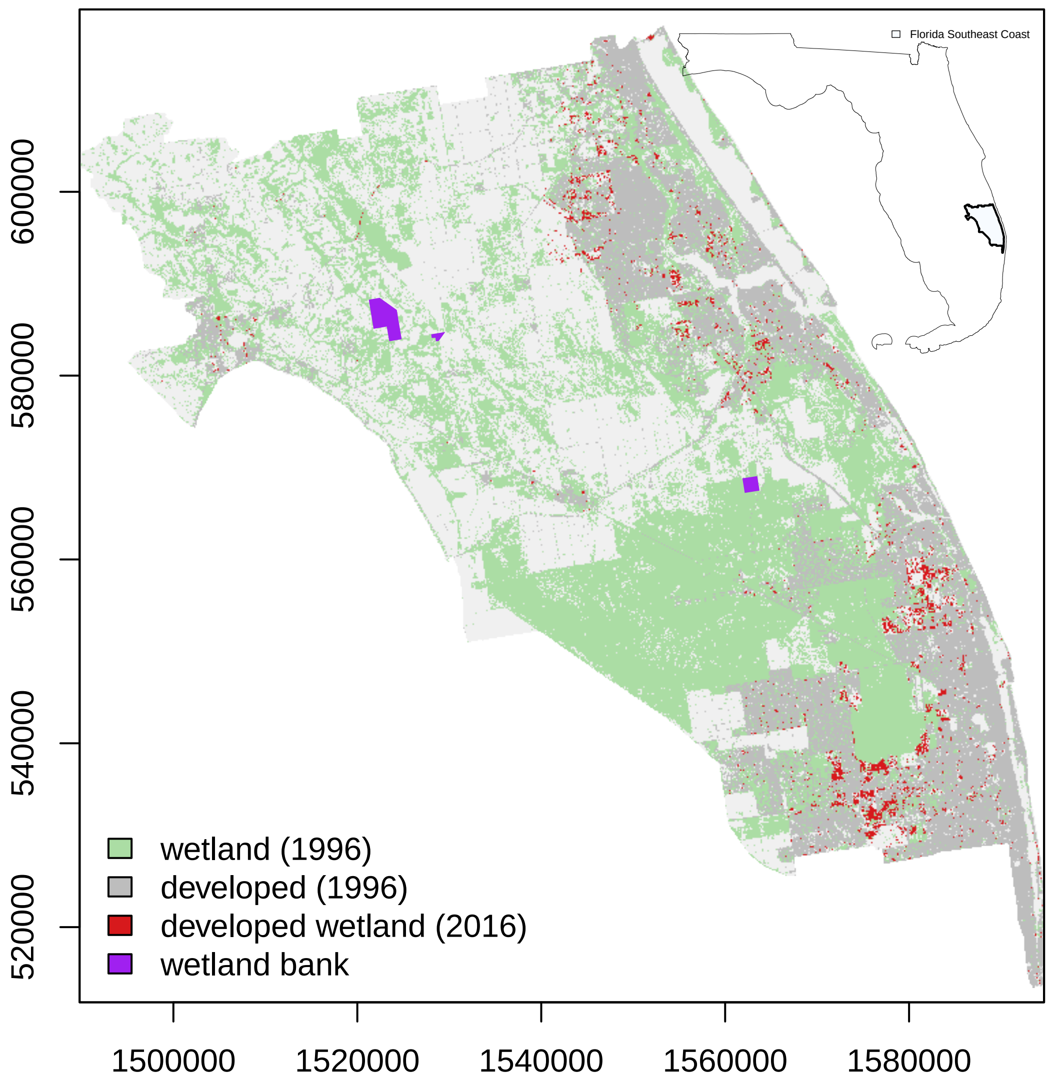

Figure A4.28. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

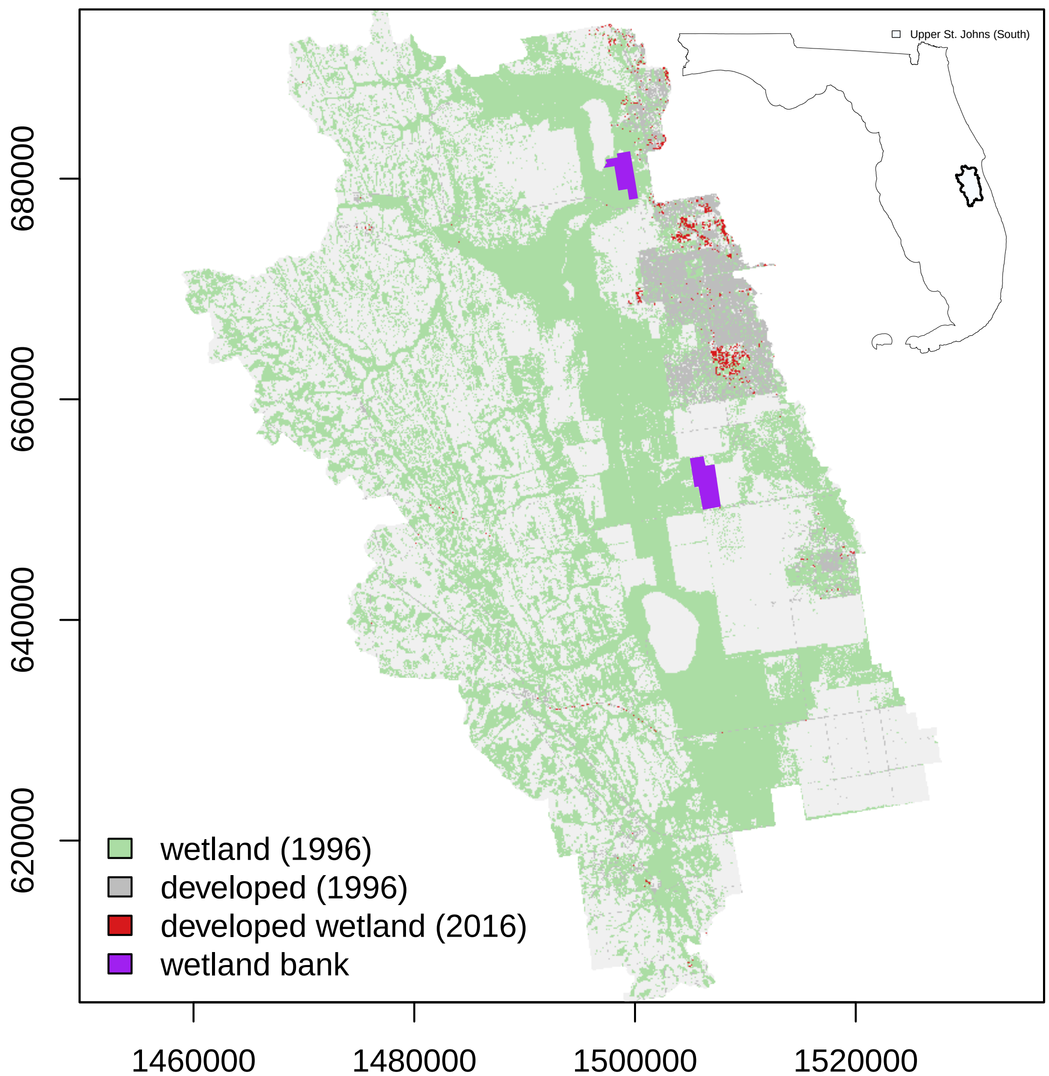

Figure A4.29. Market-Level Wetland Development and Banks

Pixel-level land use for initial wetlands (green) and initial developed land in 1996 (grey), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

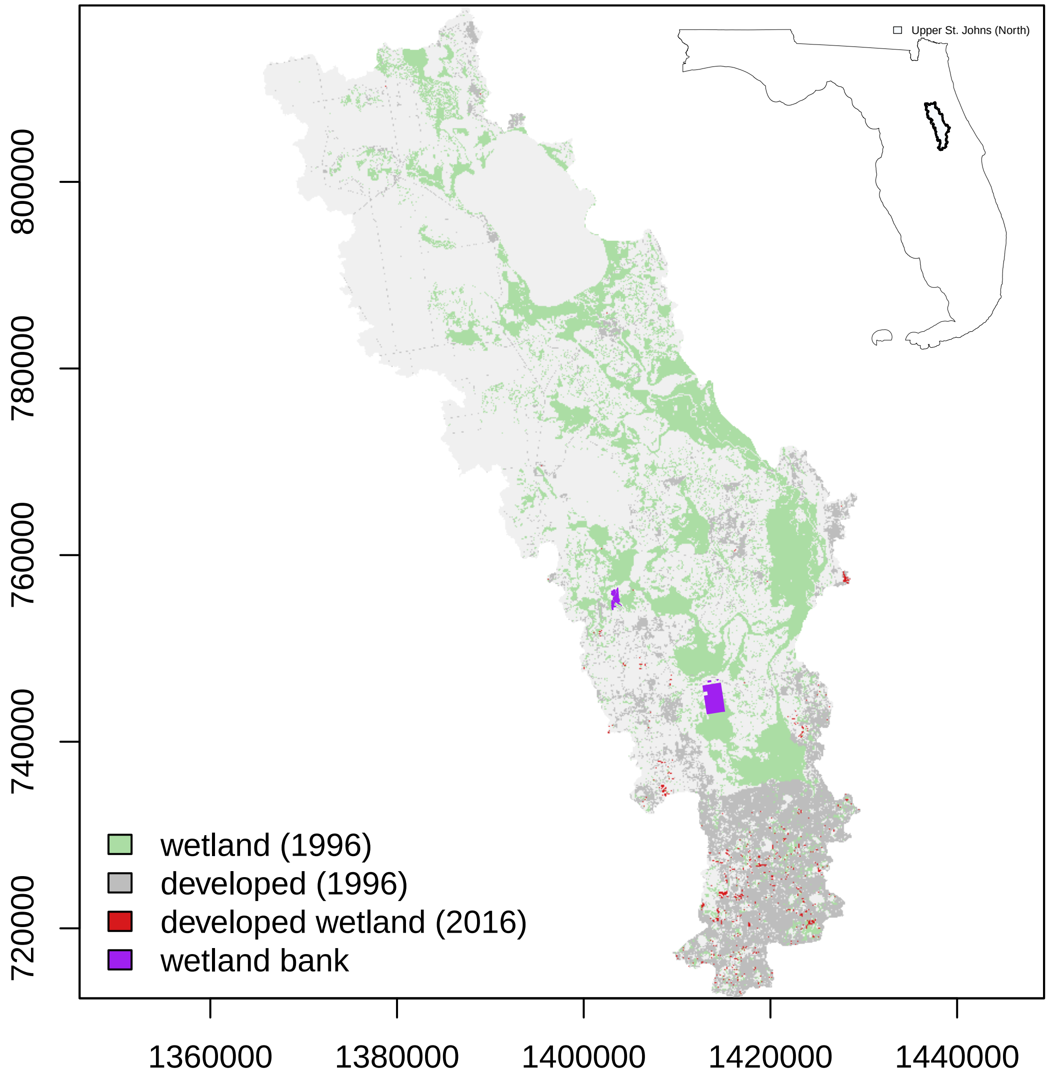

FIGURE A4.30. MARKET-LEVEL WETLAND DEVELOPMENT AND BANKS

Pixel-level land use for initial wetlands (**green**) and initial developed land in 1996 (**grey**), new development on wetlands from 1996–2016 (**red**), and wetland banks (**blue**) established by 2018.

Source. Author's calculations using NOAA C-CAP data, USGS (2013) hydrological regions, and Florida wetland mitigation bank contracts described in Appendix A.

B Details of data construction

We build four main datasets for our analysis:

1. watershed-by-period panel for five-year periods between 1996–2016, used to estimate demand
2. market-by-year panel from 1995–2020, used to estimate supply
3. firm-by-year panel from 1995–2020, used to estimate supply
4. watershed-level long difference from 1990–2020, used to estimate flood protection functions

Let us explain each in turn.

B.1 Watershed panel (used to estimate demand)

B.1.1 Initial land use

We use the CCAP data described in A.7 to track watershed-level wetlands, developed land, and highly-developed land at baseline and over time.

All initial values are calculated from the first CCAP map in 1996.

1/ We calculate the area of each HUC12 as the sum of pixels. A pixel is 900m^2 (900/4047 acres).

2/ We intersect each HUC12 with land ownership boundaries from 1995 (Appendix A.8) to partition each HUC12 into public and private land.

For each HUC12,

2a/ We calculate the area of public and private land.

2b/ We calculate the area of public wetland as the number of wetland pixels on public land.

2c/ We calculate the area of private wetland as the number of wetland pixels on private land.

2d/ We calculate the area of all wetlands as the number of wetland pixels in the HUC12.

3/ We calculate developed land and highly-developed land for each HUC12.

In addition to baseline land cover (1996), we build land cover stocks (1996, 2001, 2006, 2011, 2016) using the same steps.

B.1.2 Conditional choice probabilities

For each HUC12, and for each period 1996–2001, 2001–6, 2006–11, and 2011–16, we also use CCAP data calculate within-pixel transitions of interest for our analysis.

We define four transition types:

1. wetland to developed
2. other to developed
3. wetland to other
4. developed to not developed

The last, developed to not developed, never occurs in the data.

For each watershed-period, we calculate the total number of pixels experiencing each type of transition.

For each watershed-period, we then define the conditional choice probability by dividing the number of conversions in each transition type by the total area of private wetland at the start of the period obtained in B.1.1. For example, the conditional choice probability of developing a private wetland from 1996–2001 in watershed h is the share of 1996 wetland pixels in watershed h that are converted to development in 2001.

B.1.3 Watershed offset prices

We use the transaction-level offset prices (Appendix A.2) to construct average prices for each watershed-period.

Each transaction is matched to a wetland bank.

We construct a one-to-many match of watersheds to banks by constructing for each watershed the set of banks whose service area polygons overlap with that watershed. We also construct one-to-one matches of watersheds to markets and banks to markets.

For each watershed-period, we calculate the average price per offset observed for banks whose service area contain that watershed during that period.

For remaining watershed-periods without prices, we look for the average offset price for transactions observed in that watershed's market during the five-year period, using the algorithm that matches watersheds to markets discussed below in B.2.1.

B.1.4 Watershed price instruments

We follow the same approach used to construct watershed-period-level offset prices in B.1.3 to build watershed-period-level price instruments from bank-level data.

Sunk capacity instruments

For the own historical capacity instrument, we calculate the average licensed capacity over banks that entered prior to that start of the period whose service area contain that watershed during that period.

Hausman instruments

For the Hausman historical capacity instrument, we calculate the average licensed capacity over banks that entered prior to that start of the period who operate in the same water management district as the watershed but whose service areas do not contain the watershed.

For the Hausman price instrument, we calculate the average price over the period observed for banks who operate in the same water management district as the watershed but are matched to different markets and whose service areas do not contain the watershed.

Conservation land instruments

For the public conservation land instrument, we add public wetland acres in 1996 to the acres in each HUC12 bought under Florida Forever and/or Preservation 2000 between 1995–2000 as described in Appendix A.8 during the period, i.e., from 1995–2000 for the first period, 2001–2005 for the second period, et cetera. We construct the leave-out instrument for each h by summing this measure of public conservation land over all other HUC12s $h' \neq h$ in the same market as h.

B.1.5 Watershed demographics

For each watershed-period, we construct demographic values from the annual demographic and home price data introduced in Sections A.9.1–A.9.2. This requires matching zip codes to watersheds.

Spatial interpolation

For quantities (population and number of housing units), we allocate to watersheds in proportion to the zip code's overlap with that watershed. This ensures that population and housing unit aggregates will sum to the Florida total.

For prices (median income, median home price, average home price), we obtain values for watersheds by calculating the weighted average value over all zip codes with observed data that intersect with the watershed, weighted by area intersected.

Temporal aggregation

We calculate values for each watershed-period by averaging the annual watershed time series over each period. Baseline values are constructed from 1995 and lagged values from the five-year period prior to the observed period (and from 1995 for the first period, 1996–2001).

B.1.6 Water management district

We match watershed to water management districts using the first four digits of the watershed's HUC12 code and the matching of HUC4s to water management districts from Appendix A.6.

B.1.7 Flood risk controls

We intersect block-level flood risk maps (Appendix A.12) with watershed polygons to calculate the percentage of the watershed's area contained in storm surge and 100-year flood zones, respectively.

B.2 Market-by-year panel (used to estimate supply)

We use the market-by-year (30×26) panel to estimate entry policy functions and build aggregate market-level demand curves for the forward-simulation.

B.2.1 Market definition algorithm

We observe the service area for each bank, which we use to construct a partition of Florida watersheds into markets. Service areas largely coincide with USGS (2013) 8-digit hydrologic unit or subbasin (HUC8) regions:

1. Every bank is matched to the HUC8 that contains the most of its service area.
   - 23 bank service areas (22.3%) have at least 90% of their area in a single HUC8 and also cover at least 90% of that HUC8's area.
   - 83 bank service areas (80.6%) have at least two-thirds of their area in a single HUC8.
   - coincide perfectly with a single HUC8.
2. Some bank service areas do not cover their entire principal HUC8 area.
   - 51 bank service areas (49.5%) cover less than half of their principal HUC8 area.

   Typically, service areas do not cover the entire HUC8 because some parts of that HUC8 are not served by any bank (e.g., Oklawaha, Kissimmee).

   In two HUC8s, different banks in the same principal HUC8 operate primarily in different parts of the HUC8 with limited overlap. We split

   - Lower St. John's into Lower St. John's (North) and Lower St. John's (South)
   - Upper St. John's into Upper St. John's (North), Upper St. John's (Middle), and Upper St. John's (South)
3. Some bank service areas extend beyond one HUC8.
   - 20 bank service areas (19.4%) have more than one-third of their area in another HUC8.

There are three cases:

A. Banks that cover all of more than one HUC8 already defined as a market. We merge St. Mary's and Nassau into one market.

B. Banks that cover some, but not all, of another HUC8, already defined as a market:

- Cape Canaveral, Lower St. John's (North), Lower St. John's (South), St. Andrew – St. Joseph Bays, and Upper St. John's (South).

We assign these banks to their principal HUC8.

C. Bank service areas that cover some, but not all, of another HUC8, not defined as markets (i.e., without any native banks). We add the relevant HUC12s not in the principal HUC8, but who are included in bank service area(s) assigned to that HUC8, to the market. This extends

- Crystal-Pithlachascotee, Kissimmee, Big Cypress Swamp, St. Andrew – St. Joseph Bays, Pensacola Bay, Charlotte Harbor, Econfina-Steinhatchee, and Sarasota Bay

beyond their limit. The most common situation here is an inland bank service area extended to cover a subset of a coastal HUC8s (smaller than the principal [inland] HUC8s) that is not otherwise covered by existing mitigation banks.

B.2.2 Market states

We build public and private wetland stocks, as well as developed and highly-developed land extent, for 1996, 2001, 2006, 2011, and 2016 following the procedure used for the watershed-level panel (Appendix B.1.1), summing over all HUC12s contained within each market.

We calculate the within-pixel total area of other land converted into development as in Appendix B.1.1, converting the five-year values to annual values by dividing by five.

We extend these states to 1995–2020 by linearly interpolating across missing years.

We obtain average market-level flood risk by averaging the flood risk variables over all HUC12s contained within the market.

We obtain other states (number of firms, number of entrants, number of incumbents, annual offsets produced, annual offsets sold, cumulative offsets produced, cumulative offsets sold, offset balances) from the firm-by-year panel discussed in Appendix B.3.

B.3 Firm-by-year panel (used to estimate supply)

We build a bank-by-year balanced panel from 1995–2020.

We obtain the entry year and total production potential from the bank contracts discussed in A.1.1.

For each bank-year, we calculate cumulative annual production, cumulative annual sales, and offset balances or reserves (the difference between cumulative production and cumulative sales) from the ledger assembled in A.1.2.

For a small number of banks, we fix some apparent measurement error in production, where some early observed balances exceed historically observed production; in these cases, we add surplus balances to the banks' initial production year

A small number of banks also have negative production recorded on the ledger (six banks, 1-2 times per bank); we reduce the prior year's production by that amount.

B.4 Watershed long difference (used to estimate flood protection)

B.4.1 Initial land use and CCPs

We follow the same procedure as in Sections B.1.1 and B.1.2 to build initial land cover and total development on wetlands, constructing long transition probabilities from 1996–2016.

To obtain total development on wetlands for each watershed attributed to offset markets, we sum development on wetlands occurring in periods where the watershed's market had at least one wetland bank at the start of the period.

B.4.2 Wetland banking activity

We include the total area of land committed to wetland banks from 1995–2018 in our flood protection regressions.

Most bank sites (60 of 107) are contained within a single watershed and nearly all banks (102 of 107) have more than half of their area within a single watershed.

For wetland bank sites that cover more than one watershed, we attribute the area of the bank site that intersects that watershed to that watershed.

B.4.3 Flood insurance claims

Spatial interpolation

For each flood claim introduced in Appendix A.10, we observe its latitude and longitude (to one decimal place), census tract (2010), and zip code tabulation area (ZCTA5).

We identify each flood claim with a "claim area," i.e., a polygon corresponding to its approximate location, by intersecting a one-decimal-place latitude-longitude grid with census tracts and zip codes to build a partition of Florida of about 22,000 separate polygons.

We then assign each flood claim to watersheds in proportion to the claim area's overlap with that watershed.

For robustness, we consider results that use only the latitude-longitude-by-census-tract grid, as well as a binary match that assigns flood claims that overlap with more than one HUC12 to the HUC12 that contains the largest share of that claim's area.

Temporal aggregation

For each watershed, we sum annual flood claims for each year, first for structures built up to 1995, then for structures built after 1995, then for all structures.

We deflate each to current (2020 USD) prices using the price index defined in A.13.

We then construct annual average watershed-level claims for the periods used in the analysis: 1991–1995 (benchmark pre-period), 2016–2020 (benchmark post-period), 1985–1994 (robustness pre-period), 2011–2020 (robustness post-period).

B.4.4 Flood insurance policies

Spatial interpolation

For each flood insurance policy introduced in Appendix A.11, we observe latitude and longitude (to one decimal place) and zip code (ZCTA5) but—unlike claims—not census tract. We repeat the interpolation algorithm in B.4.3.

B.4.5 Flood risk

We use the watershed-level measures of flood risk from B.1.7.

B.4.6 Hydrological network extension

In Table A5, we run some specifications with neighboring watershed values, where neighbors are defined with respect to the hydrological network topology (A.5).

We use the flow matrices from Appendix A.5. Upstream values correspond to the inflow matrix multiplied by the vector of watershed values. Downstream values correspond to the outflow matrix multiplied by the vector of watershed values.

For each watershed, we calculate total wetlands developed 1996–2016, area committed to wetland banks 1996–2016, and total area of watersheds upstream and downstream.

B.5 Overlapping federal jurisdiction

Our analysis abstracts from trade in federal offsets under §404 of the Clean Water Act; here, we elaborate on the discussion in footnote 5 to describe in more detail how state and federal wetland regulation interacts in Florida.

As described in the main text, our conversations with experts indicate two salient differences between Florida regulations and federal regulations: (i) the definition of wetlands and (ii) the jurisdictional nature of those wetlands. On (i), the state of Florida has a broader definition of wetlands (Florida requires evidence of two of the following: wetland vegetation, wetland hydrology, and hydric soils; the federal government requires evidence of all three). On (ii), the jurisdictional nature of those wetlands, all Florida wetlands fall under state jurisdiction, while only wetlands defined as waters of the United States fall under federal jurisdiction.

Given that we abstract from trade in federal offsets, the primary concerns are that, on the supply side, wetland banks have additional payoffs due to federal credit sales, and on the demand side, some developers face additional federal regulation in some periods and not others. Most, but perhaps not all, of these shocks will be absorbed by our time period and water management district fixed and our controls for local watershed characteristics.

Several facts indicate this approximation will not create problems for our analysis.

First, legally, courts have been clear that state governments retain authority to regulate all wetlands in their state, whether or not the federal government also has additional regulatory authority under Section 404 of the Clean Water Act (Fumero *et al.*, 2020). The resulting predictability and durability of the state offset program has made it significantly more influential than shifting federal guidelines.

Second, while most Florida wetland banks also receive some federal offset credits, Florida wetland banks must first satisfy the state offset program requirements before applying for federal credits, and our conversations with experts indicate that federal credits are awarded by EPA/Corps regardless of the jurisdictional status of the bank's new wetlands (Green, 2023). ("[T]he changes in federal jurisdiction with the various Supreme Court decisions (Rapanos and now Sackett) and the way various administrations have implemented EPA regulations (NWPR) . . . has not affected mitigation banks in Florida to my knowledge," Green, 2023).

Third, empirically, overlapping federal requirements, where they apply, appear to be minimal relative to Florida state requirements. Banks sell fewer federal offsets at much lower prices than state offsets, reflecting the fact that federal credits are easily obtained by existing state banks (as federal credits are awarded regardless of federal jurisdictional status) but are demanded by fewer wetland developers (those with federal wetlands).

Table A7 compiles federal offset prices from our data, and the ledger of all federal offsets traded in Florida. It shows that federal wetland offsets comprise 18% of all Florida wetland offsets traded (by estimated market value) from 2006–2018.

These facts lead us to consider changes in federal regulation in Florida as not central to the incentives to restore or develop Florida wetlands. Indeed, recognizing this redundancy, the EPA transferred authority to manage the §404 program to Florida in 2020 to streamline permitting (FDEP, 2023).

We emphasize this conclusion is specific to Florida. Outside of Florida, we view the investigation of shifting federal jurisdiction over wetlands on wetland bank industry dynamics as an interesting area for future research. In such places, the changing probability of regulatory scrutiny over time could affect wetland bank payoffs and the economics of wetland offsets (see, e.g., the recent economic analysis of the regulatory uncertainty created by air pollution standards in Gowrisankaran *et al.*, 2023).

C Estimation details

C.1 Details of wetland acre-to-offset ratios

Both demand and flood risks are estimated using land cover data, but entry costs and market outcomes are denominated in offsets.

We combine land cover changes from 1996–2016 with observed offset production and sales from 1995–2016 to approximate ratios of wetland development acreage to offsets for each water management district. This gives us $\tilde{\upsilon}_h$ that is common to all h in a water management district.

Table A2 reports this data and resulting ratio estimates.

C.2 Details of demand curve estimation

Here, we describe some details of some calculations in Table 3.

Regression details

Functional forms for covariates in the regressions are natural logs for median income, population, and other development (with the inverse hyperbolic cosine used for population and other development to allow for zeros), percent area for development, high development as a fraction of overall development, flood zone A, and flood zone V. Instruments are quadratic polynomials.

Consumer surplus calculation

See C.5.1.

C.3 Details of dynamic estimation algorithm

Here, we specify the details of the dynamic estimator underlying the results in Table 4.

Step I

The model is simulated at an annual resolution from 1995–2050.

The simulation runs over $m \in \{1, 2, \ldots, M\}$ with $M = 30$ markets (hydrological regions with observed entry) and all local watersheds h contained in these regions.

The initial conditions for each m and h are the extent of wetland, the extent of developed land, and the initial population and median income, observed at baseline (1996).

We fix the annual discount factor to $\beta = 0.95$.

Production

Each entrant's lifetime offset production or wetland value, $\tilde{\upsilon}_f$, is drawn from the conditional empirical distribution of capacities of wetland mitigation banks in our data, conditioned on water management district and the number of incumbents. The production function $\mathcal{B}$ issues offsets over the first ten years of production, i.e., $\mathcal{B}(\tau, x_{ft}) = \tilde{\upsilon}_f/10$ for $\tau \leq 10$ and $\mathcal{B}(\tau, x_{ft}) = 0$ for all $\tau > 10$.

Entry and trade

Entry policy functions are estimated using a probit model with period fixed effects (indicators for $t < 2001$, $t < 2006$, and $t < 2011$), water management district fixed effects, the number of incumbents, and indicator for markets without incumbents, and the natural logarithms of private wetlands, public wetlands, median income, population, and total incumbents' offset reserves in the market (with asinh() for balances).

The endogenous market state transitions are the set of incumbents and their ages and offset balances; the wetlands, developed land, and home prices for each local watershed; and the total stock of wetlands, total area of developed land, and average home price in each market.

Our data requires that we estimate local demand over five-year intervals. We assume banks commit to trades over a five-year period.

Trading functions are built from the polynomial approximation described in the main text and using the bounds implied by offset balances and the equilibrium conditions constructed using aggregate market demand elasticities.

Exogenous demand states

The exogenous local demand shifters are (a) median income, (b) population, and (c) other contemporaneous development on non-wetlands.

For each local watershed, the evolution of other development is estimated as a function of the share of developed land, water sub-basin (HUC8) fixed effects, and period fixed effects (indicators for $t < 2001$, $t < 2006$, and $t < 2011$). The evolution of the natural logarithm of the demographic variables are specified as an AR(1) process with a common intercept.

To forward-simulate local demand shifters, we calculate the expected component of the next period's state from the current state and the estimated persistence coefficients, then draw a shock from the empirical distribution of residuals of these regressions to obtain the next period's state.

Step II

To estimate costs using the value function (17), we invert $\phi_t(s_t, x_{ft}) = G_t(z|x_{ft})$ at $z = V(0, 1, s_t|x_{ft})$ to obtain the conditional entry cost distribution $G_t(\cdot|x_{ft})$. Specifically, we assume that $G_t(\cdot|x_{ft})$ is Gaussian, so that we can obtain the entry costs via

$$\Phi^{-1}(\phi_t(s_t, x_{ft})) = \frac{1}{\sigma(x_{ft})}\left[V(0, 1, s_t|x_{ft}) - \mu(x_{ft})\right].$$

Specifically, we regress $V = V(0, 1, s_t|x_{ft})$ on $x = x_{ft}$, $\Phi^{-1}(\phi_t(s_t, x_{ft}))$, and their interaction. In practice, we take as (s_t, x_{ft}) water management district fixed effects and indicators for a market with zero incumbents, one incumbents, and more than one incumbent. This regression gives us coefficients $(\beta_x, \beta_{\phi x}, \beta_\phi)$, which allows us to use the identity

$$\hat{V} = \beta_x' x + \left(\sum \beta_{\phi x}' x + \beta_\phi\right)\Phi^{-1}(\phi_t(s_t, x_{ft})) = \mu(x) + \sigma(x)\Phi^{-1}(\phi_t(s_t, x_{ft}))$$

to approximate $\mu(x)$ with $\beta_x' x$ and $\sigma(x)$ with $\sum \beta_{\phi x}' x + \beta_\phi$.

To obtain realized entry costs $\hat{\kappa}_{ft}$ for each bank f that entered at t with value function $\hat{V}_{ft}$, i.e., expected costs conditional on entry, we integrate $G(\cdot|x_{ft})$ over $(-\infty, \hat{V}_{ft})$. We implement this numerically by drawing 10^6 times from the unconditional cost distribution $\kappa_{ft} \sim \mathcal{N}(\mu(x_{ft}), \sigma(x_{ft}))$ and calculating the average cost over draws such that $\kappa_{ft} < \hat{V}_{ft}$.

To construct the annual rates of return on capital reported in Table 4, we take markups and solve for the average annual return that would realize the full value in 10 years.

C.4 Details of marginal flood damage calculations

Here, we describe some of the derived values reported in Tables 5–A8 and Tables A3–A5.

For marginal damages per acre reported in Table 5 and Table A8, we calculate the derivative of predicted annual damages from the coefficient estimates in Table 5, $D_h(Q_h; \hat{\zeta}, \hat{\gamma}, \hat{\rho})$, numerically around $[Q_h - \frac{1}{2}\Delta, Q_h + \frac{1}{2}\Delta]$ for $\Delta = 1$ acre as $\hat{D}_h'(Q_h; \hat{\zeta}, \hat{\gamma}, \hat{\rho}) = D_h(Q_h + \frac{1}{2}\Delta; \hat{\zeta}, \hat{\gamma}, \hat{\rho}) - D_h(Q_h - \frac{1}{2}\Delta; \hat{\zeta}, \hat{\gamma}, \hat{\rho})$. We then multiply this value by $\sum_{t=0}^{\infty}(1+r)^{-t}$ to obtain the NPDV permanent damages for $r = 0.05$ (baseline) as well as $r = 0.03$ and $r = 0.07$ (Table 6, rows 13–14).

For marginal damages per offset (Table A8, column 2), we multiply each $D_h'(Q_h; \hat{\zeta}, \hat{\gamma}, \hat{\rho})$ by $\tilde{\upsilon}_h$.

For marginal damages per acre with hydrological network spillovers (Table A5), we calculate the derivative of predicted annual damages from the coefficient estimates numerically around $[Q_h - \frac{1}{2}\Delta, Q_h + \frac{1}{2}\Delta]$ for $\Delta = 1$ acre as $\hat{D}'_h(Q_h; \hat{\zeta}, \hat{\gamma}, \hat{\rho}) = \sum_{h'} D_{h'}(Q_h + \frac{1}{2}\Delta; \hat{\zeta}, \hat{\gamma}, \hat{\rho}) - \sum_{h'} D_{h'}(Q_h - \frac{1}{2}\Delta; \hat{\zeta}, \hat{\gamma}, \hat{\rho})$, because Q_h can now affect damages in HUC12s $h' \neq h$ through the hydrological network.

C.5 Details of welfare calculations

Here, we describe some of the details of the calculations that underly the results presented in Table 6.

C.5.1 Aggregate consumer surplus

To calculate watershed-level consumer surplus using the estimates $(\hat{\theta}, \hat{\xi}_h)$, we use the closed-form expected consumer surplus from Small and Rosen (1981), which in our model is

$$\sum_t \sum_h \tilde{\upsilon}_h W_{ht} \frac{1}{\tilde{\upsilon}_h \hat{\theta}_P} \ln \Big(1 + \exp\{\hat{\theta}' X_{ht} - \tilde{\upsilon}_h \hat{\theta}_P P_t + \hat{\xi}_{ht}\}\Big) \tag{A1}$$

dividing by $\tilde{\upsilon}_h \hat{\theta}_P$ to express values in 2020 USD.

Average expected parcel utility reports $\frac{1}{\hat{\theta}_P} \ln \Big(1 + \exp\{\hat{\theta}' X_{ht} - \tilde{\upsilon}_h \hat{\theta}_P P_t + \xi_{ht}\}\Big)$ and measures the expected utility of an acre of private wetland under the distribution of observed offset market prices relative to the outside option.

Evaluating (A1) over all watersheds requires prices, but some local watersheds do not have observed prices in our estimation. To evaluate (A1), we infer these unobserved prices by calculating the predicted price for each watershed that fits observed choice probabilities in each period to construct an average offset price for each period, which we use for watersheds missing prices. An alternative is to use the simulated prices from our dynamic estimator; we do not find significant differences between these two approaches' consequences for consumer welfare.

C.5.2 Aggregate costs and producer surplus

To construct the aggregate marginal producer prices function in Figure 4B, we order bank sales by descending simulated value per offset sold, i.e., $\hat{\upsilon}_{f_1} \equiv \hat{V}_{f_1}/\hat{q}_{f_1} > \hat{V}_{f_2}/\hat{q}_{f_2} > \dots$, then define $V'(Q) = \max_{f_k}\{\hat{\upsilon}_{f_k} : Q \leq \sum_{f \leq f_k} \hat{q}_f\}$.

To construct the aggregate marginal entry cost function in Figure 4B, we use the same order over banks and define $C'(Q) = \sum_f \hat{\kappa}_{ft} \mathbf{1}(f_k \in \arg\max\{\hat{\upsilon}_{f_k} : Q \leq \sum_{f \leq f_k} \hat{q}_f\})$.

Aggregate costs used for total private gains from trade and counterfactuals involving Q offsets sold overall are then calculated as

$$C(Q) = \int_0^Q C'(q) dq \tag{A2}$$

and aggregate producer surplus as

$$\Pi(Q) = \int_0^Q \left[V'(q) - C'(q)\right] dq, \tag{A3}$$

using numerical integration.

C.5.3 Aggregate flood damages

For total flood damages, we integrate $D'_h(\cdot; \hat{\zeta}, \hat{\gamma}, \hat{\rho})$ over $[1, Q_h]$, where Q_h are observed wetlands developed from 1996–2016. For watersheds with some wetland development that occurs prior to trade, $Q_h^{\text{pre}} \leq Q_h$, we scale total damages by $y_h = (Q_h - Q_h^{\text{pre}})/Q_h$. Total damages then equal

$$\sum_h y_h \int_1^{Q_h} D_h'(q; \hat{\zeta}, \hat{\gamma}, \hat{\rho}) dq \tag{A4}$$

For total damages under the counterfactual tax designs, we calculate (A4) for $\{Q_h^{\text{cf}}\}_h$.

C.6 Details of counterfactuals

Here, we describe some of the details of the counterfactuals presented in Table 6.

C.6.1 Value of offset markets

Wetlands developed under the market correspond to all wetlands developed in watershed-periods with trade. Wetland offsets are a weighted average of acres of wetlands developed with weights $\tilde{v}_h$ from the water management district trading ratios discussed in C.1.

Total developer value equals total consumer surplus calculated from (A1) plus producer surplus plus total producer costs. The alternative definition, total consumer surplus plus the market value of all offsets purchased, gives a similar, though not identical, number because the observed market value of all offsets purchased relies on the price interpolation discussed in C.5.1 while the producer surplus uses the price simulations from the dynamic estimator.

Producer surplus and supply costs and producer surplus or observed trade are obtained from (A3) and (A2) at the total volume of trade under the market.

Private gains from trade equal the sum of consumer surplus and producer surplus.

Welfare defined as private gains from trade net total flood damages.

C.6.2 Pigouvian counterfactual

Pigouvian taxes constructed with C.4 and a 5% discount rate to value future flood protection.

Counterfactual consumer surplus obtained by evaluating (A1) at the counterfactual vector of prices (observed prices plus Pigouvian taxes).

Total bank costs calculated by integrating the cost function under the total counterfactual volume traded, i.e., with (A2).

Producer surplus defined as the market value of trades under the counterfactual net of the total costs.

Tax revenue calculated as the sum of wetland development that occurs under the counterfactual weighted by the vector of per-offset Pigouvian taxes.

Private gains from trade equal the sum of consumer surplus, producer surplus, and tax revenue.

C.6.3 Uniform tax counterfactual

Counterfactual consumer surplus, producer surplus, and costs obtained for each candidate tax identically as in C.6.2 and a 5% discount rate to value future flood protection. We run a grid search over \$500/offset intervals to find the tax that maximizes welfare (consumer surplus added to producer surplus and tax revenue net of damages). The objective function appears globally concave, with an interior solution at $\tau^* = \$30{,}000$/offset.

D Supplement—C-CAP Regional Land Cover Classification Scheme

No pixels were unclassified for our study area. The definitions from NOAA are below:

D.1 Developed land

- Developed, High Intensity (2) – contains significant land area and is covered by concrete, asphalt, and other constructed materials. Vegetation, if present, occupies less than 20 percent of the landscape. Constructed materials account for 80 to 100 percent of the total cover. This class includes heavily built-up urban centers and large constructed surfaces in suburban and rural areas with a variety of land uses.
- Developed, Medium Intensity (3) – contains areas with a mixture of constructed materials and vegetation or other cover. Constructed materials account for 50 to 79 percent of total area. This class commonly includes multi- and single-family housing areas, especially in suburban neighborhoods, but may include all types of land use.
- Developed, Low Intensity (4) – contains areas with a mixture of constructed materials and substantial amounts of vegetation or other cover. Constructed materials account for 21 to 49 percent of total area. This subclass commonly includes single-family housing areas, especially in rural neighborhoods, but may include all types of land use.
- Developed, Open Space (5) – contains areas with a mixture of some constructed materials, but mostly managed grasses or low-lying vegetation planted in developed areas for recreation, erosion control, or aesthetic purposes. These areas are maintained by human activity such as fertilization and irrigation, are distinguished by enhanced biomass productivity, and can be recognized through vegetative indices based on spectral characteristics. Constructed surfaces account for less than 20 percent of total land cover.

D.2 Agricultural land

- Cultivated Crops (6) – contains areas intensely managed for the production of annual crops. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.
- Pasture/Hay (7) – contains areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle and not tilled. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.
- Grassland/Herbaceous (8) – contains areas dominated by grammanoid or herbaceous vegetation, generally greater than 80 percent of total vegetation. These areas are not subject to intensive management such as tilling but can be utilized for grazing.

D.3 Forest land

- Deciduous Forest (9) – contains areas dominated by trees generally greater than 5 meters tall and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.
- Evergreen Forest (10) – contains areas dominated by trees generally greater than 5 meters tall and greater than 20 percent of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.
- Mixed Forest (11) – contains areas dominated by trees generally greater than 5 meters tall, and greater than 20 percent of total vegetation cover. Neither deciduous nor evergreen species are greater than 75 percent of total tree cover. Both coniferous and broad-leaved evergreens are included in this category.

- Scrub/Shrub (12) – contains areas dominated by shrubs less than 5 meters tall with shrub canopy typically greater than 20 percent of total vegetation. This class includes tree shrubs, young trees in an early successional stage, or trees stunted from environmental conditions.

D.4 Barren land

- Unconsolidated Shore (19) – includes material such as silt, sand, or gravel that is subject to inundation and redistribution due to the action of water. Substrates lack vegetation except for pioneering plants that become established during brief periods when growing conditions are favorable.
- Barren Land (20) – contains areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earth material. Generally, vegetation accounts for less than 10 percent of total cover.
- Tundra (24) – is categorized as a treeless region beyond the latitudinal limit of the boreal forest in pole-ward regions and above the elevation range of the boreal forest in high mountains. In the United States, tundra occurs primarily in Alaska.
- Perennial Ice/Snow (25) – includes areas characterized by a perennial cover of ice and/or snow, generally greater than 25 percent of total cover.

D.5 Freshwater (palustrine) wetlands

- Palustrine Forested Wetland (13) – includes tidal and nontidal wetlands dominated by woody vegetation greater than or equal to 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is below 0.5 percent. Total vegetation coverage is greater than 20 percent.
- Palustrine Scrub/Shrub Wetland (14) – includes tidal and nontidal wetlands dominated by woody vegetation less than 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is below 0.5 percent. Total vegetation coverage is greater than 20 percent. Species present could be true shrubs, young trees and shrubs, or trees that are small or stunted due to environmental conditions.
- Palustrine Emergent Wetland (Persistent) (15) – includes tidal and nontidal wetlands dominated by persistent emergent vascular plants, emergent mosses or lichens, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is below 0.5 percent. Total vegetation cover is greater than 80 percent. Plants generally remain standing until the next growing season.

D.6 Saltwater (estuarine) wetlands

- Estuarine Forested Wetland (16) – includes tidal wetlands dominated by woody vegetation greater than or equal to 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent. Total vegetation coverage is greater than 20 percent.
- Estuarine Scrub/Shrub Wetland (17) – includes tidal wetlands dominated by woody vegetation less than 5 meters in height, and all such wetlands that occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent. Total vegetation coverage is greater than 20 percent.
- Estuarine Emergent Wetland (18) – Includes all tidal wetlands dominated by erect, rooted, herbaceous hydrophytes (excluding mosses and lichens). These wetlands occur in tidal areas in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent and are present for most of the growing season in most years. Total vegetation cover is greater than 80 percent. Perennial plants usually dominate these wetlands.

D.7 Water and submerged lands

- Open Water (21) – includes areas of open water, generally with less than 25 percent cover of vegetation or soil.
- Palustrine Aquatic Bed (22) – includes tidal and nontidal wetlands and deepwater habitats in which salinity due to ocean-derived salts is below 0.5 percent and which are dominated by plants that grow and form a continuous cover principally on or at the surface of the water. These include algal mats, detached floating mats, and rooted vascular plant assemblages. Total vegetation cover is greater than 80 percent.
- Estuarine Aquatic Bed (23) – includes tidal wetlands and deepwater habitats in which salinity due to ocean-derived salts is equal to or greater than 0.5 percent and which are dominated by plants that grow and form a continuous cover principally on or at the surface of the water. These include algal mats, kelp beds, and rooted vascular plant assemblages. Total vegetation cover is greater than 80 percent.