Appendix

Wetland Offset Policy

Wetlands provide a wealth of public goods[1]. The conservation of wetlands, however, also presents substantial opportunity costs to private landowners who would otherwise develop the land. Wetland degradation has been regulated federally since 1973, starting with the Clean Water Act (CWA). Section 404 of the CWA requires permits to develop wetlands under the "no net loss" principle: that is, unavoidable impacts to wetland resources must be offset by restoration, enhancement, or preservation (USACE and EPA, 2008). In the early days of Section 404, compliance was mandated onsite (Salzman and Ruhl, 2006), which drew criticism for undue burden on the landowner as well as lack of oversight and regulation of actual ecological effectiveness and success (Sunding and Zilberman, 2002). Currently, developers can comply with CWA regulation through several mechanisms: 1) Permittee-Responsible-Mitigation, where the developer themselves undertakes a restoration project; 2) In-lieu Fee Mitigation, where a fee is paid to a fund for a future restoration project, or; 3) Mitigation banking, where credits are purchased from a bank that has carried out a large-scale restoration project in anticipation of degradation in the same watershed or "service area" (Levrel et al., 2017). Mitigation banking as an institution has rapidly gained popularity as the most flexible option of complying with the "no net loss" objective. For banks, mitigation activities usually involve restoring fallowed farmland to a more wild state, which is then managed and maintained in perpetuity (Erwin, 2009).

An intermediary regulator outlines the exchange value between restored and existing wetlands, which have a minimum 1:1 acreage exchange rate but are often evaluated further using criteria on ecological functionality[2]. Hydrologic boundaries and potential flood storage are often among the criteria used, but direct downstream flood protection benefits (i.e., number of households protected) are typically not considered in this system.

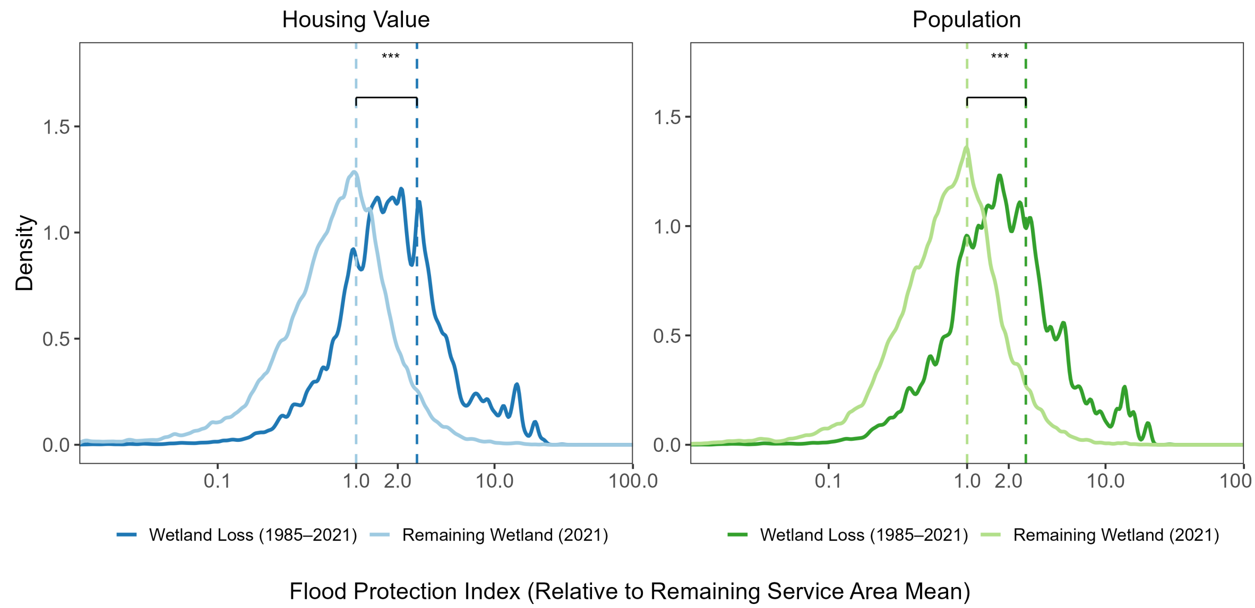
[1] Though they make up just 6% of the Earth's surface, they contribute a crucial array of ecosystem services: biodiversity, carbon sequestration, nutrient cycling, aesthetics, and more (Gulbin et al., 2019) that can be challenging to evaluate and price. Studies estimate that 54–57% and potentially even up to 87% of wetlands have been lost globally since the 1700s (Gulbin et al., 2019).

[2] For example, Florida uses "uniform mitigation assessment method" (UMAM) scores to define specific trading ratios across a variety of wetland ecosystem types.

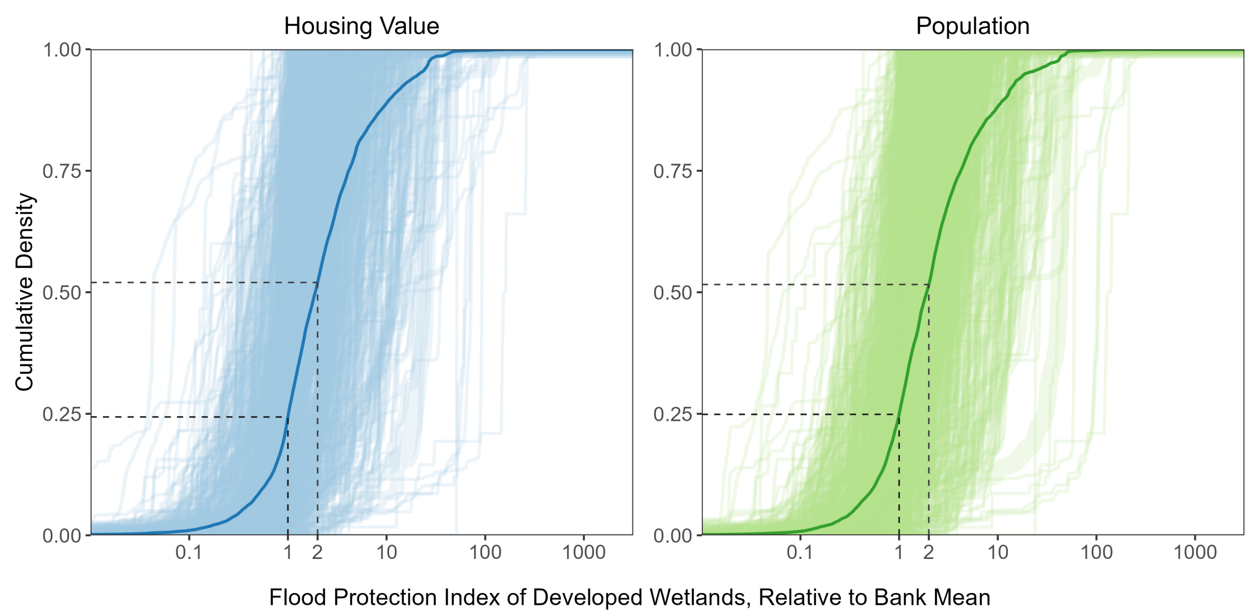
Prior to a bank's establishment, it must go through an environmental review, outline specific restoration plans, and provide a timeline for carrying them out. Regulators assign a total number of credits to the project based on wetland functionality over time. Banks are then placed under conservation easement, preventing any future development on that site and allowing for long-term ecosystem recovery. Because banks serve as alternatives to on-site conservation, the land involved must be placed under a permanent conservation easement, preventing any future development or alternative uses. Furthermore, credits are released incrementally as the bank hits key restoration milestones (USACE and EPA, 2008).

Housing Value and Population

For robustness, we repeat our analysis using two alternative measures of downstream exposure: total housing value and population. We apply the same directional distance decay weighting methodology, replacing housing units with total housing value and population. The patterns remain consistent: wetlands lost to development are disproportionately located in areas with higher downstream exposure, whether measured by population or housing value. In both panels of Figure S-1b, the average cumulative distribution curve lies to the right of the reference line at 1.0, indicating that lost wetlands tend to have flood protection values well above the mean for restored bank wetlands. Similarly, when comparing housing value and population index distributions of developed wetlands compared with wetlands remaining in present day, the pattern follows Figure 2 in the main text.



(a)



(b)

Figure S-1: (a) Probability density functions of normalized flood protection indexes for lost (1985–2021, red) and remaining (2021, blue) wetlands across mitigation markets (n = 915). Distributions are shown for two alternate flood protection indexes using housing value and population data as proxies for flood protection benefits. (b) Cumulative distribution functions of developed wetland flood protection indexes, normalized by the respective bank means, across all service areas (n = 695). Thicker lines indicate markets with greater total wetland loss.

1 Land Value Analysis

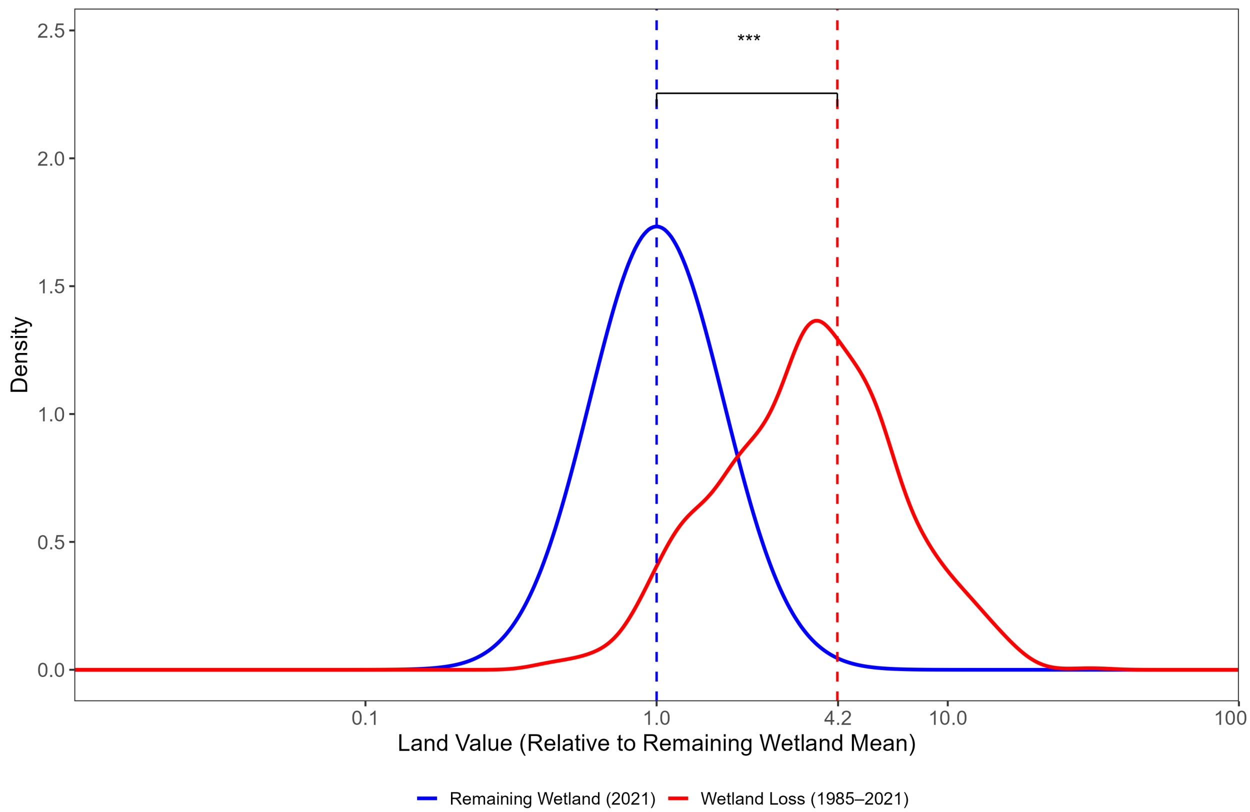


Figure S-2: Probability distribution function for normalized land values (Nolte, 2020) of lost (1985 - 2021, red) and remaining (2021, blue) wetlands in mitigation markets (n = 915). Values on the x-axis are expressed as ratios to the mean land value for the corresponding service area (1 = service-area mean). The three stars represent a p-value of < 0.001 in a two-tailed t-test.

Case Studies

Top Ten Highest Wetland Loss Value Service Areas

We identified the ten service areas the most downstream housing units of lost wetlands. All but one (Katy Prairie Stream), cluster in Southern Florida.

Bank / Area	Sum	Mean	Max
Service Areas			
FP&L Everglades Phase II MB	192,274,418,184	24,634.567	472,971
Poa Boy MB	156,256,959,705	81,913.627	302,071
Loxahatchee MB	147,470,839,515	35,630.305	472,971
Big Cypress MB Phase VI	129,623,989,635	25,213.931	122,679
Big Cypress MB Phase I-V	129,621,443,360	25,217.606	122,679
Panther Island MB – Expansion	129,240,514,671	25,165.396	122,679
Panther Island MB	128,990,113,342	25,136.187	122,679
Katy Prairie Stream	125,240,019,034	81,244.235	462,163
St Johns MB	121,540,093,306	92,853.476	302,071
Florida Wetlandsbank at Pembroke Pines MB	50,514,038,970	21,428.852	472,971
Crosby Island Marsh MB	45,528,876,319	75,576.886	199,468
Little Pine Island MB	39,503,913,338	48,314.260	124,040
Banks			
FP&L Everglades Phase II MB	29,693,056,779	310,376.059	472,208
Loxahatchee MB	2,317,028,665	390,137.846	404,998
Panther Island MB	636,504,971	63,472.773	64,862
Florida Wetlandsbank at Pembroke Pines MB	406,041,491	283,746.674	290,381
Panther Island MB – Expansion	386,103,642	63,988.008	65,448
Crosby Island Marsh MB	311,094,870	105,206.246	105,826
Little Pine Island MB	158,040,467	22,746.181	23,198
St Johns MB	93,947,271	48,854.535	63,645
Katy Prairie Stream	6,643,953	100,665.950	102,918
Big Cypress MB Phase I-V	4,300,164	2,795.945	3,144
Big Cypress MB Phase VI	1,753,888	2,549.255	3,103
Poa Boy MB	1,503,035	39,553.542	40,914
Loss Areas			
FP&L Everglades Phase II MB	29,692,066,694	310,391.665	472,208
Loxahatchee MB	17,216,747,392	341,649.582	472,208
Florida Wetlandsbank at Pembroke Pines MB	13,582,088,005	368,407.736	472,208
Panther Island MB	10,424,054,222	75,427.856	122,572
Big Cypress MB Phase I-V	10,423,989,308	75,427.932	122,572
Big Cypress MB Phase VI	10,423,989,308	75,427.932	122,572
Panther Island MB – Expansion	10,423,860,514	75,428.091	122,572
Katy Prairie Stream	7,325,699,734	158,048.364	462,169
Little Pine Island MB	4,892,911,662	67,695.726	124,650
Crosby Island Marsh MB	4,720,622,486	118,183.974	199,444
Poa Boy MB	4,373,018,293	141,750.998	293,784
St Johns MB	4,256,186,386	122,593.075	293,784

Table S-1: Housing units summary for South Florida wetland areas. Values represent downstream housing unit exposure across three categories: service areas, bank footprints, and areas of wetland loss (1985–2021).

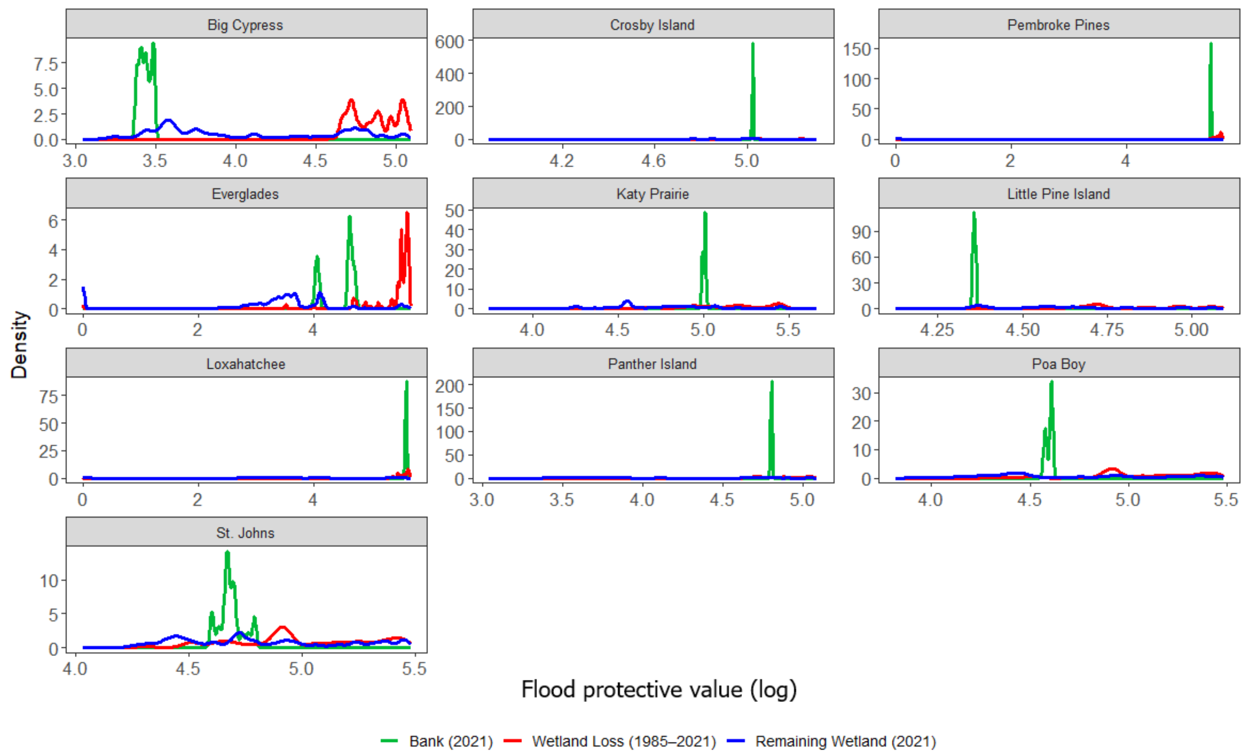


Figure S-3: Probability distribution functions of flood protective value (measured in terms of downstream housing units) for the top 10 service areas with the highest lost wetland value.

	Comparison	Mean Loss	Mean Group	t-stat	df	Region
Loxahatchee MB	bank	341,653	390,138	-0.17	34.9	S Florida
	service area	341,653	36,138	0.34***	721.1	
Little Pine Island MB	bank	67,653	22,746	0.44*	13.9	S Florida
	service area	67,653	48,099	0.21†	51.5	
Panther Island MB	bank	75,428	63,666	0.15	12.6	S Florida
	service area	75,428	25,211	0.26*	58.2	
Florida Wetlands Bank at Pembroke Pines	bank	368,394	283,747	0.20*	107.1	S Florida
	service area	368,394	21,588	0.45***	312.4	
Big Cypress MB	bank	75,428	2,720	0.34**	54.1	S Florida
	service area	75,428	25,211	0.26*	59.7	
Crosby Island Marsh MB	bank	118,184	105,206	0.09	14.7	S Florida
	service area	118,184	75,722	0.23*	90.0	
St Johns MB	bank	122,593	48,855	0.22	25.5	S Florida
	service area	122,593	92,789	0.05	145.6	
Katy Prairie Stream	bank	158,048	100,666	0.02	757.7	S Texas
	service area	158,048	81,245	0.19**	190.3	
Poa Boy MB	bank	141,751	39,554	0.05†	728.3	S Florida
	service area	141,751	81,913	0.10	98.1	
FP L Everglades MB	bank	311,201	11,215	0.70†	3.1	S Florida
	service area	311,201	24,072	0.36***	709.8	

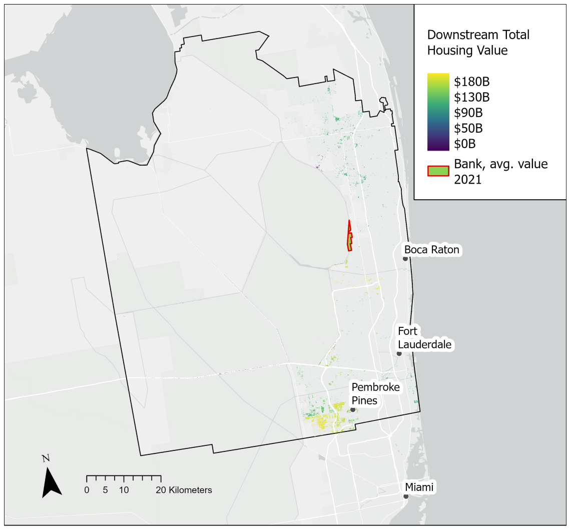
Table S-2: Characteristics of wetland markets with largest lost flood-protective value (measured in terms of downstream housing units) 1985-2021. T-statistics are based on the Dutilleul T-Test (Dutilleul et al., 1993), correcting for spatial autocorrelation. One, two and three stars indicate significance values of 0.05, 0.01, and 0.001 respectively, based on a one-tailed hypothesis test that the developed wetland flood-protection value is higher than either the bank or remaining undeveloped area value. † denotes marginal significance at the 0.1 level.

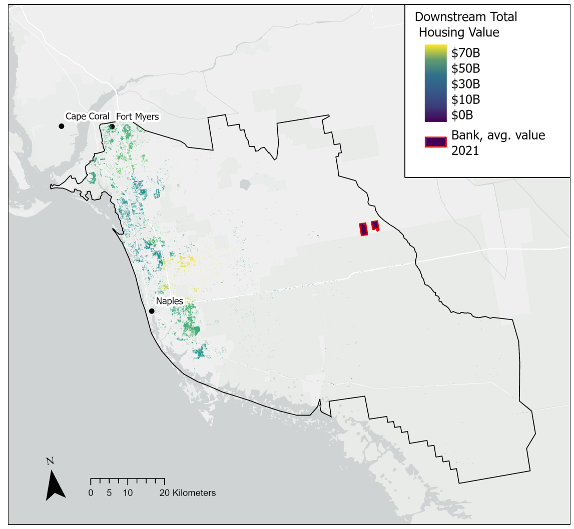
Bank	Comparison	Mean Loss	Mean Group	t-stat	df
Loxahatchee MB	bank	135,267,200,000	143,828,100,000	-0.08	30.6
	service area	135,267,200,000	14,086,210,000	0.37***	547.1
Little Pine Island MB	bank	31,153,320,000	13,011,230,000	0.48*	13.1
	service area	31,153,320,000	21,042,300,000	0.26*	38.6
Panther Island MB	bank	39,356,780,000	36,307,930,000	0.09	17.4
	service area	39,356,780,000	14,413,410,000	0.23*	60.2
Florida Wetlands Bank at Pembroke Pines MB	bank	145,046,300,000	114,968,500,000	0.19*	106.4
	service area	145,046,300,000	8,407,103,000	0.46***	269.7
Big Cypress MB	bank	39,356,870,000	412,557,800	0.41***	183.1
	service area	39,356,870,000	14,413,370,000	0.23*	61.0
Crosby Island Marsh MB	bank	29,115,350,000	24,901,240,000	0.13	16.4
	service area	29,115,350,000	18,728,670,000	0.23*	86.2
St Johns MB	bank	32,782,770,000	10,870,950,000	0.29*	34.7
	service area	32,782,770,000	23,932,200,000	0.08	128.1
Katy Prairie Stream	bank	34,239,600,000	21,014,250,000	0.03	717.8
	service area	34,239,600,000	18,310,380,000	0.13*	215.8
Poa Boy MB	bank	36,597,860,000	8,484,106,000	0.06*	1,204.5
	service area	36,597,860,000	19,761,290,000	0.10	116.0
FP L Everglades MB	bank	129,832,500,000	6,038,667,000	0.74†	2.7
	service area	129,832,500,000	10,612,590,000	0.38***	585.2

Table S-3: One-tailed t-test comparison of downstream flood protective value (measured in terms of total housing value) between lost wetlands and bank / service area

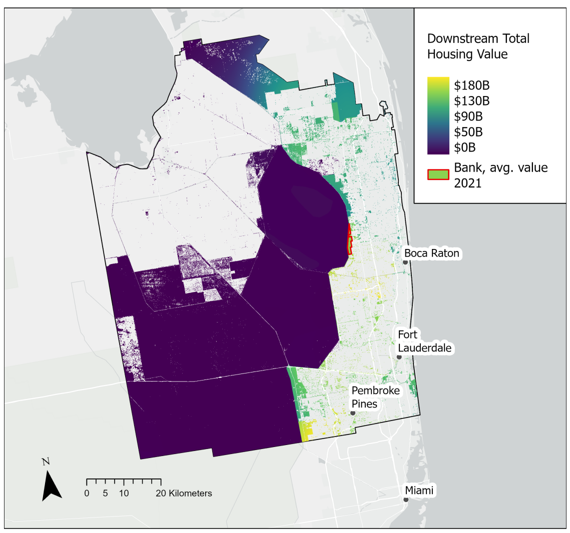
Bank	Comparison	Mean Loss	Mean Group	t-stat	df
Loxahatchee MB	bank	674,141	720,551	-0.08	27.3
	service area	674,141	73,395	0.36***	526.1
Little Pine Island MB	bank	89,351	25,024	0.41†	13.1
	service area	89,351	65,545	0.15†	73.2
Panther Island MB	bank	97,915	82,074	0.12	13.2
	service area	97,915	32,644	0.26*	71.2
Florida Wetlands Bank at Pembroke Pines MB	bank	729,895	539,585	0.19*	91.5
	service area	729,895	42,724	0.47***	285.8
Big Cypress MB	bank	97,916	6,574	0.27*	55.4
	service area	97,916	32,644	0.26*	67.0
Crosby Island Marsh MB	bank	296,139	275,137	0.06	15.6
	service area	296,139	187,421	0.24*	86.0
St Johns MB	bank	276,175	112,714	0.19	31.4
	service area	276,175	207,182	0.05	151.0
Katy Prairie Stream	bank	402,128	264,934	0.03	613.3
	service area	402,128	201,311	0.22**	154.0
Poa Boy MB	bank	325,518	89,674	0.05†	820.8
	service area	325,518	190,079	0.09	101.7
FP L Everglades MB	bank	628,525	17,888	0.69	2.9
	service area	628,525	52,740	0.38***	550.8

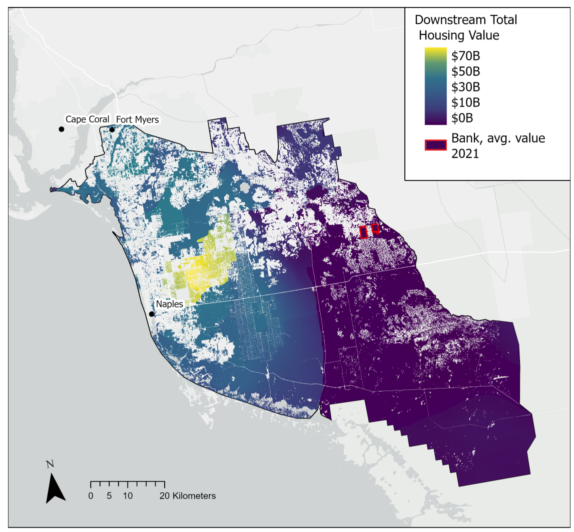
Table S-4: One-tailed t-test comparison of downstream flood protective value (measured in terms of population) between lost wetlands and bank / service area



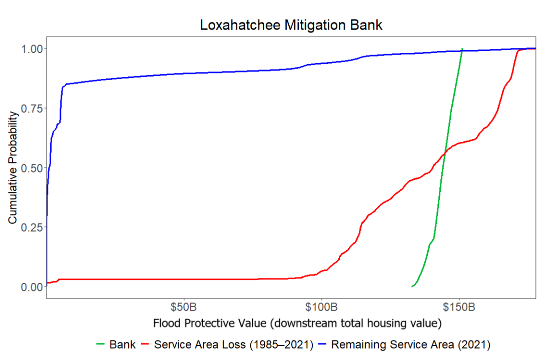


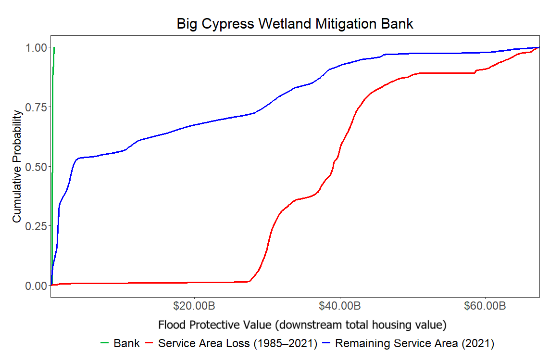
(a) **(d)**





(b) **(e)**





(c) **(f)**

Figure S-4: Comparison of two mitigation bank service areas. Loxahatchee Mitigation Bank (a - c) and Big Cypress MB (d - f). (a, d) Downstream total housing value of wetland cells converted to development, 1985–2021. (b, e) Downstream total housing value of remaining wetland cells in 2021. (c, f) Empirical cumulative distribution functions comparing (a) and (b). Raster resolution: 30 m.

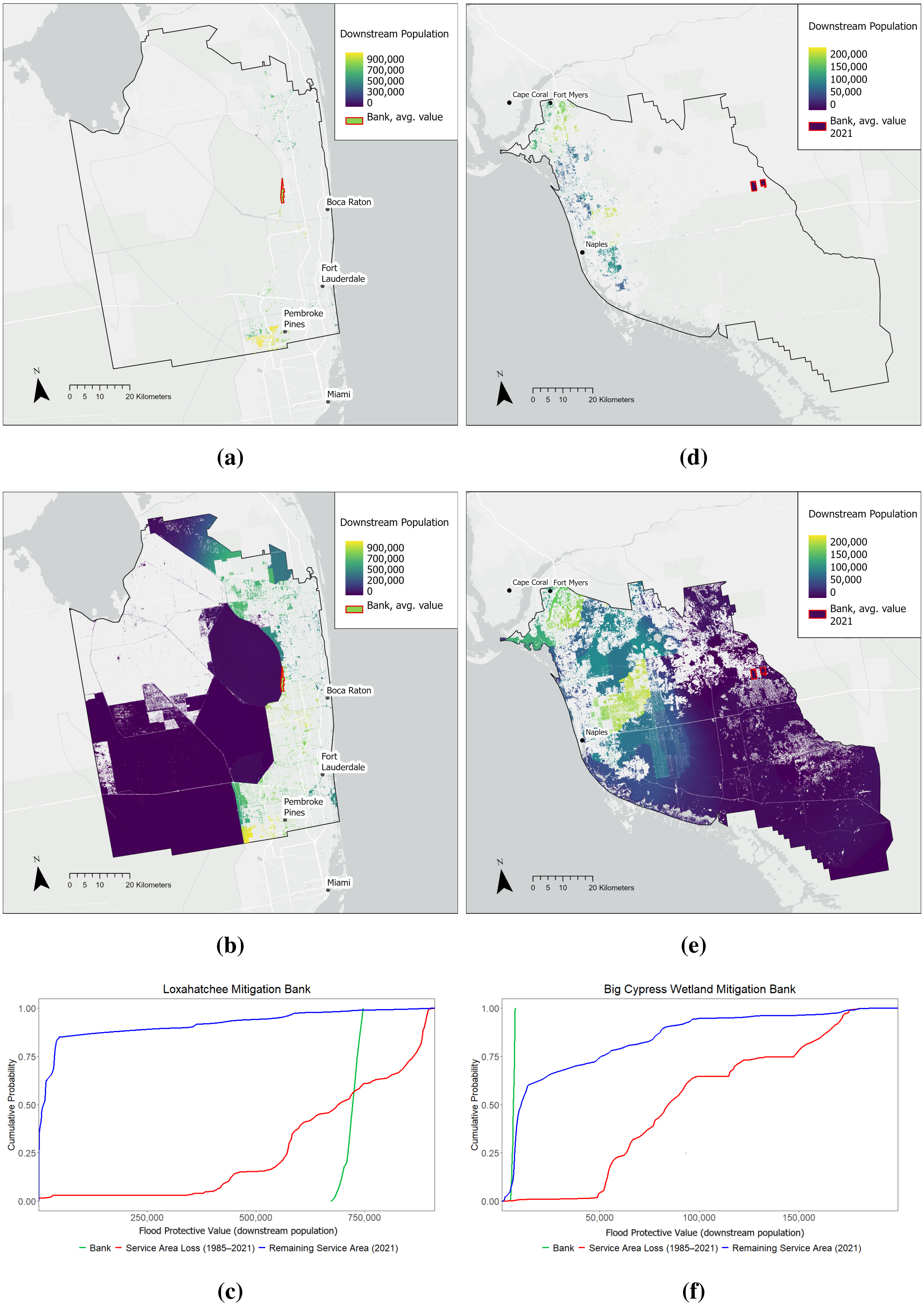


Figure S-5: Comparison of two mitigation bank service areas. Loxahatchee Mitigation Bank (a - c) and Big Cypress MB (d - f). (a, d) Downstream population of wetland cells converted to development, 1985–2021. (b, e) Downstream population of remaining wetland cells in 2021. (c, f) Empirical cumulative distribution functions comparing (a) and (b). Raster resolution: 30 m.

Downstream exposure is substantially and statistically significantly higher for lost wetlands or remaining service area wetlands than for those restored in the Big Cypress mitigation bank. (Table S-3, Table S-4). Loxahatchee Mitigation Bank shows a different pattern. While lost wetlands still protected more people and property than those remaining, the bank wetlands in this case provide similar flood protection value to the lost wetlands (though not statistically significant). However, lost wetlands are notably higher value than remaining wetlands for housing value and population ($p > 0.001$) (Table S-3).

The service area of Loxahatchee MB contained lost wetland cells with the second-highest total downstream housing unit exposure. The bank with the highest lost wetland cell value (Everglades MB), is positioned on the southern coast of Florida and may have different flood protection benefits due to hurricane-related storm surge.

State Trends in Lost Wetland Value

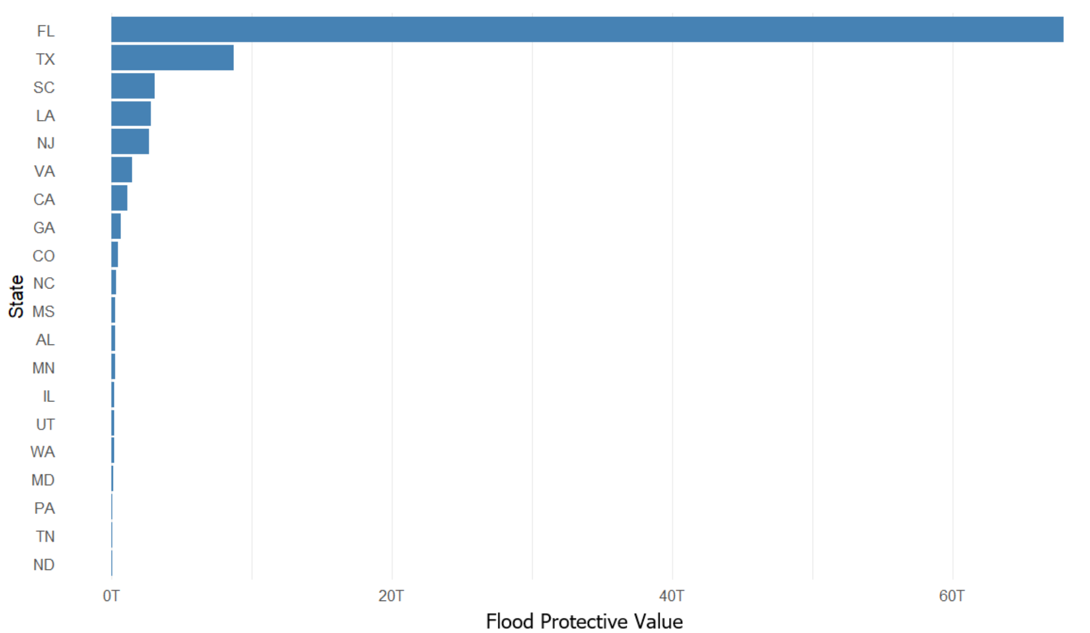


Figure S-6: Total flood-protective value (measured in terms of downstream housing units) of wetlands converted to development by state, 1985-2021.

Florida far outweighs all other states in terms of lost wetland flood protective value. This is potentially driven by higher rates of development. The rest of the top states also cluster in the Southeast.

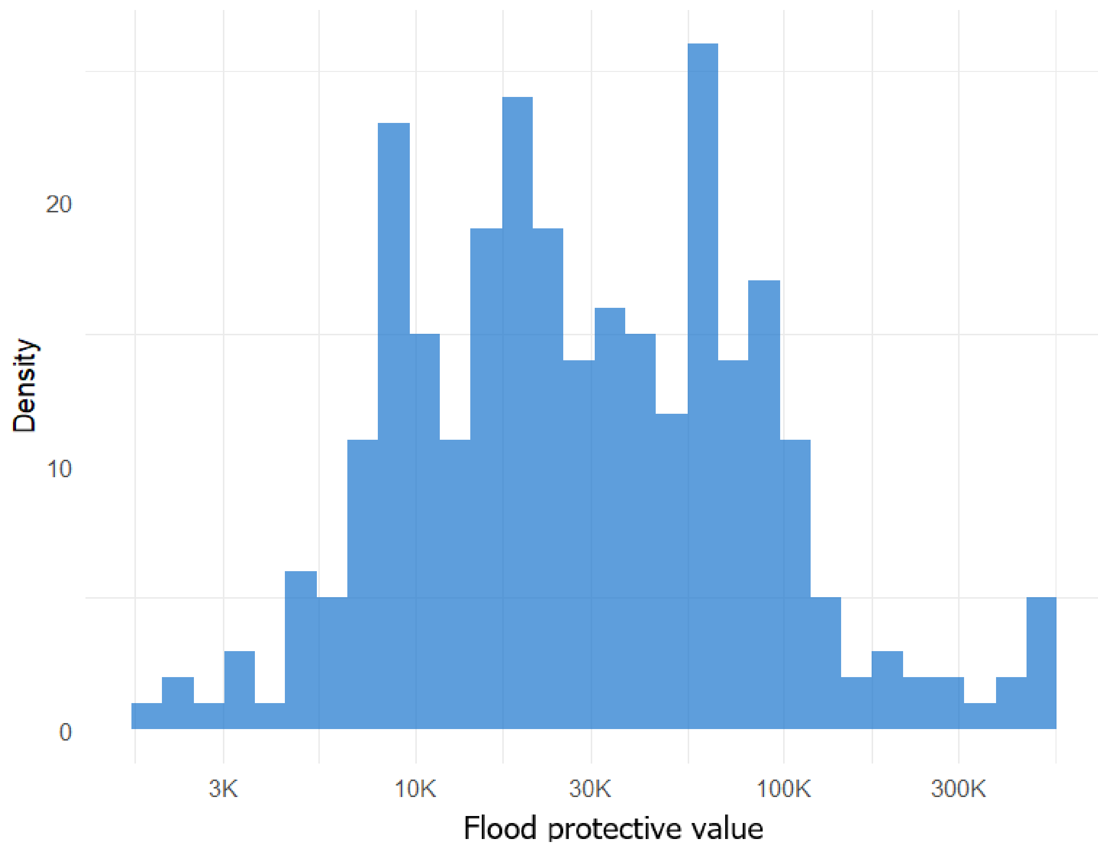


Figure S-7: Log mean flood protective value (measured in terms of downstream housing units) for 288 banks within a 40km buffer from CONUS coastline.

We isolate 288 mitigation banks that intersect a 40km coastal buffer to tease out whether coastal banks (which often have few to none downstream census tracts) have systematically lower flood protection value based on our function, which quantifies value unrelated to storm surge. These coastal banks may be undervalued with our metric as they may protect communities from hurricane-related damages.

Distance Decay Interpolation

For each 30m wetland cell w, we assign a flood protection weight $f(d)$ based on its upstream distance d (in kilometers) from a downstream census tract centroid. We define a piecewise function with d values at 0, 10, 20, 30, and 40km:

$$f(d) = \begin{cases} 0.25, & d = 0 \\ 1, & d = 10 \text{ or } d = 30 \\ 0.75, & d = 20 \\ 0, & d \geq 40 \end{cases}$$

For all other values of d, we apply linear interpolation between the nearest defined points. For any two known distances d_1 and d_2, with known weights $f(d_1)$ and $f(d_2)$, the interpolated value at a distance $d \in (d_1, d_2)$ is given by:

$$f(d) = f(d_1) + \left(\frac{d - d_1}{d_2 - d_1}\right) \cdot [f(d_2) - f(d_1)]$$

For example, a wetland pixel 15km upstream from a census tract centroid would receive a weight of:

$$f(15) = 1 + \left(\frac{15 - 10}{20 - 10}\right) \cdot (0.75 - 1) = 0.875$$

—

Mitigation Ratios

We valued losses and gains in wetland area at a $1:1$ credit ratio, following the U.S. Army Corps of Engineers' compensatory-mitigation rule, which specifies that in the absence of a functional assessment, "a minimum one-to-one acreage or linear-foot compensation ratio must be used" to offset authorized impacts to waters of the United States (USACE and EPA, 2008). This baseline reflects the rule's core objective of "no net loss" . While our analysis adopts the regulatory default for clarity and comparability, we acknowledge that the actual number of credits required can depart from $1:1$ when site-specific factors warrant.

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