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Private Value of Mangrove Coastal Protection Benefits

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Traditional risk industry catastrophe models show that coastal mangrove forests provide tangible economic flood protection benefits, particularly in Florida, where flood risk exposure is very high. However, these models do not account for all benefits to home values and can miss how much private markets actually value mangroves and therefore may be willing to pay for their protection and restoration. We use an asset pricing framework to assess the private market value of mangroves for storm protection across seven Florida counties. First, we model flood impacts for four storm return periods with and without mangroves using catastrophe risk models under current conditions and with climate change. Second, we translate these simulated damage paths into the present value of mangroves for housing values using a standard asset pricing model. Third, we replace estimates from the catastrophe models with housing market-based valuations of mangrove protection from storms in the same asset pricing framework. We find that the value of mangroves' flood-protection benefits to residential property values in the seven Florida counties is $14B across these seven counties under current conditions, $17B with climate change, and up to $18B using market-based valuations. The estimates vary markedly by county. Most notably, using market-based valuations our estimates are high for Pinellas (>$6B) and Manatee ($0.5B) counties even though the overall storm protection from mangroves to properties is relatively low in these counties. The benefits imply that residential real estate stakeholders have an incentive to contribute to financing of protection and restoration of these habitats.

valuing ecosystem services | flood damages | mangroves

Significance

Ecosystem benefits are rarely valued quantitatively. Despite substantial benefits accruing to individuals and businesses, private investment in habitat conservation and restoration is limited. Mangrove forests have been shown in risk industry models to avert potential storm damages in Florida, which has more than 1/3 of all US national flood insurance program policies. Market-based approaches show that mangroves also affect housing valuations, and these values grow with climate change. These coastal protection benefits for Florida add up to $14-18 billion across 7 counties when asset pricing models are used to account for reduction in uncertainty and variable discount rate. However, they vary substantially across counties. These estimates are key for decisions on how to finance mangrove protection and restoration.

Coastal flood risks are growing worldwide, driven by rising seas, intensifying storms, expanding coastal populations and built infrastructure. At the same time, the habitats that serve as first lines of coastal defense such as wetlands (mangroves, marshes) and reefs (coral, oyster, rocky) face severe degradation from these same pressures of development and climate change. In this study we focus on mangrove ecosystems. Global mangroves declined by roughly 4% between 1996 and 2010, with losses exceeding 30% in some nations (1). Recent observations indicate that mangrove loss and degradation rates have slowed since about 2010 globally, and there have been some regrowth and restoration successes (2). However, this recovery is more challenged in populated areas where both development and impacts of cyclones are key threats to mangroves and their associated services (3).

Mangrove forests effectively reduce the impacts of waves, storm surges, and shoreline erosion (4–6). In coastal areas of Florida, which contains over 90% of the mangroves in the U.S., they reduce flooding across vast areas (Figure 1). A growing body of research has quantified the value of mangroves for reducing storm damages (7–12). Most studies advance hydrodynamic and catastrophe risk modeling approaches from the engineering and insurance industries to simulate flooding under a range of storm conditions and to quantify losses avoided by the presence of mangrove forests.

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All authors jointly conceived the project and performed research. GH and TL created the conceptual asset pricing framework for mangrove valuation. MB, BR, DG, and BC modeled flood damages. BC, DG, and TL conducted all calculations. GH and MB led the drafting of main manuscript, TL led the drafting of supplementary materials with all authors contributing to both.

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According to these models (we will refer to them as risk-based), mangroves averted an estimated $725 million in damages during Hurricane Irma, representing a 14% savings and $4.1 billion (30% in savings) during Hurricane Ian (13). In Collier County, mangroves reduce average annual losses from storm surge by approximately $67 million per year (13). These models have informed national wealth accounting, with the World Bank's Changing Wealth of Nations program incorporating mangrove flood protection services as a component of natural capital in national balance sheets (14). Across all nations with mangroves, the estimated present value of flood reduction benefits from mangroves now exceeds $855 billion (1).

We believe that these estimates present a lower bound on how markets may value the benefits of flood protection provided by mangroves. First, most of these estimates only rely on expected future damages. However, mangrove flood protection may also reduce the dispersion of potential losses across different storm severity and across geographies, which market participants also value. This variance-reduction benefit can be quantified by using a convex utility function that accounts for risk aversion. Second, most estimates rely on the fixed discount rate assumption, which makes them very sensitive to the chosen discount factor, while not incorporating the fact that in bad states of nature, e.g. in the aftermath of the storms, markets may value protection more than in the good ones. This can be captured in the asset pricing framework that uses stochastic discount factor, which lets the discount rate respond to flood events and, therefore, more accurately measure the present value of future losses (15–17). Both enhancements raise the resulting present value of mangroves relative to traditional approaches.

A more recent approach applies hedonic regression to coastal real estate markets, estimating the extent to which mangrove flood protection is capitalized into property values. Analyzing more than a million housing transactions in Zillow's ZTRAX database across coastal Florida counties, Liu et al. (18) demonstrate that proximity to mangroves significantly moderates the price effects of heavy hurricane seasons: properties closer to mangroves experience substantially smaller price declines in the years following a heavy hurricane season than properties located farther away from mangroves. These results reveal that private housing markets capitalize the storm protection services of mangroves into property values, representing a novel and important signal of the economic significance of nature-based defenses. Yet, this market-based measure has not yet been compared with the risk-based, nor have these results been used to assess the aggregate magnitude of this capitalized value across Florida coastal counties. Further, the effects of climate change on the value of mangroves for risk reduction have not been considered. Additionally, Liu et al. (18) report the conditional market value of mangroves for housing values stabilizing after storms; here we compute an unconditional value of mangrove protection based on future storm probability forecasts.

This study advances previous understanding of the value of mangrove protection benefits by using an asset-pricing framework to derive and compare two valuations, both within the same framework but differing in their loss input: a risk-based (catastrophic) estimate, which draws on catastrophe-risk modeling of avoided flood damages (8, 11, 13), and a market-based (hedonic) estimate, which draws on housing-market responses to storms. This analysis provides a more comprehensive account of the total economic contribution of Florida's mangroves to coastal flood risk reduction. We further examine how projected climate change through sea level rise and storm intensification will alter the value of mangrove protection. Finally, we discuss how these combined valuations can support financing mechanisms for risk reduction, adaptation, mangrove conservation, and restoration.

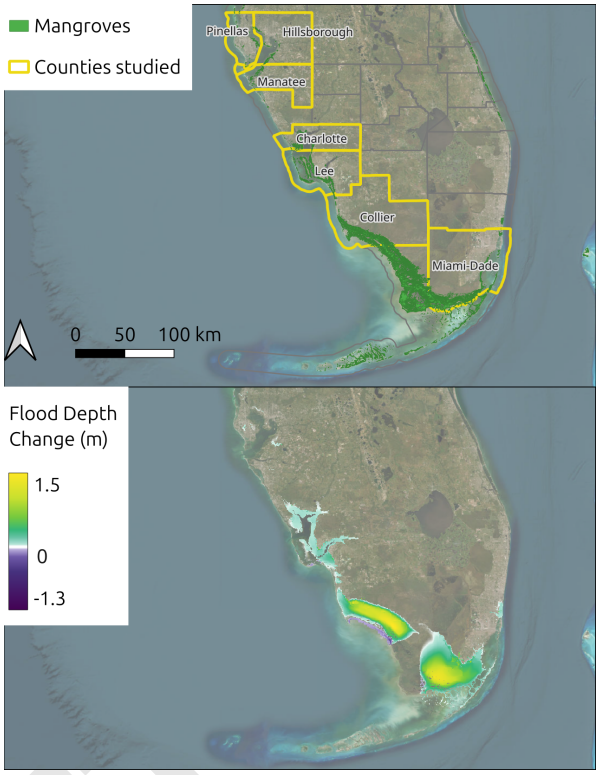


Fig. 1. Area of study, mangroves, and flood depth. Seven counties used in the study (top) and change in flood depth in meters from removing mangroves during a one-in-fifty year storm event (bottom). Flood maps are modeled with the numerical model SFINCS (Super-Fast INundation of CoastS), using a composite of high-resolution federal elevation datasets (USGS 3DEP, NOAA CUDEM, and others) merged to 10 m resolution. See Methods and Supplementary Information for details. Monroe County is excluded: insufficient housing data could be matched to mangrove-proximity data to estimate a hedonic response in Liu et al. (18), and its mainland is predominantly public conservation land.

The analysis is conducted in three steps. First, we develop a modeling framework for housing prices following a standard asset pricing model. We calibrate the model using risk-based calculations of direct damages across different storm strengths, considering scenarios with and without mangroves and under present and future climate, for each county in Florida. Using 1,000 simulations of the storm frequency through 2100, we calculate expected net present value of private properties. By comparing these estimates for scenarios with and without mangrove protection, we derive present value of mangrove protection in terms of property values. These are the Risk-based Asset Pricing (RAP) estimates. Second, we translate the empirical estimates of housing market response to 100-year storms from Liu et al. (18) into market pricing-based losses in storm years. We then replace risk-based damages in model calibration with these market pricing-based losses to produce the present value of mangrove

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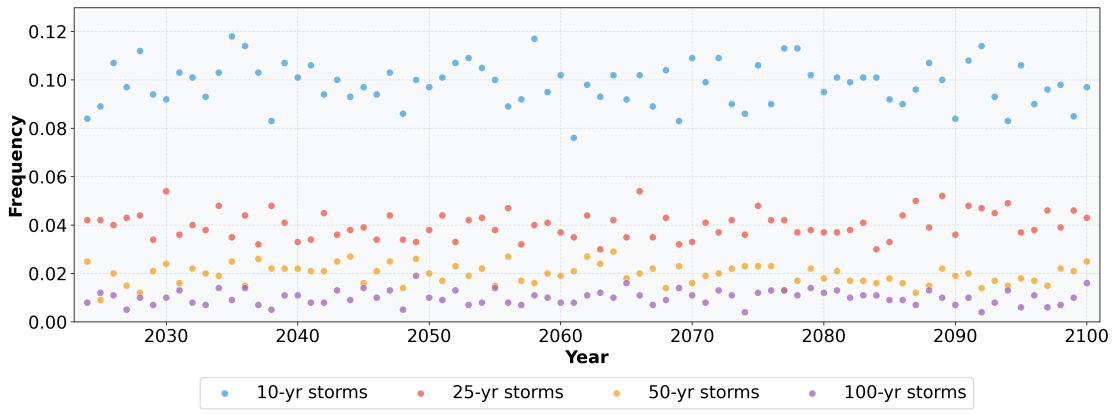


Fig. 2. Simulated storm occurrence frequencies. Reported are annual storm occurrence frequencies across 1,000 Monte Carlo simulations, by return period (RP). Each year, storm occurrence is drawn independently for each of the four return periods from a Bernoulli distribution with annual exceedance probability of 10%, 4%, 2%, and 1% for the 10-, 25-, 50-, and 100-year storms, respectively; the realized frequencies fluctuate around these targets. A single year can experience multiple storm types, but at most one storm of each type. These frequencies are identical in the baseline and climate-change scenarios: we hold the storm return-period probabilities fixed and model climate change through changes in flood depth and extent (from the future hydrodynamic flood maps) rather than through storm frequency. Additional details are in the Supplementary Information.

protection as reflected in hedonic property prices. These are Market-based Asset Pricing (MAP) estimates. In contrast with RAP, MAP estimates reflect total damage effects (including direct structure damages from flood and wind as well as any other losses from flooding), non-pecuniary flood costs, as well as beliefs and learning about effects of storms and mangrove protection. Third, we aggregate all our per-property estimates to county level using detailed calculations of exact individual properties that are subject to flooding in each scenario and their values.

Two approaches to valuing mangrove protection impacts on property values

We value mangrove protection in two ways, both within a single asset-pricing framework and differing only in the loss input: risk-based asset pricing (catastrophic), which uses modeled flood damages, and market-based asset pricing (hedonic), which uses observed housing-price responses to storms. Both are used in the same asset pricing model, delivering RAP and MAP estimates. The two differ not in whose value they capture — both are private-value measures — but in the empirical basis of the loss input: the risk-based estimate uses a modeled, *ex ante* expectation of future damages, in the expected-damage tradition (19), whereas the market-based estimate is calibrated from *ex post* realized property-price responses to past storms (18). Because property prices are forward-looking, this *ex post* calibration still recovers a forward-looking valuation.

A standard rational expectations property price model with a constant relative risk aversion utility function (CRRA) can be used to express a pricing kernel m_t, which can be used to price any asset, it is also known as a Stochastic Discount Factor (SDF) in the finance literature. The price of a representative property is then an expected present discounted value of the housing services δ provided by the property. The pricing kernel adjusts to shocks to consumption that occur due to storms. In addition, a property value is reduced by storm damages ξ_h in every period the storm occurs, $s_t = 1$.

$$H_t = \mathbb{E}_t \left[\sum_{j=1}^{\infty} (1+\delta)^j \left(\prod_{k=1}^{j} m_{t+k} \left(1 - s_{t+k}\, \xi_h\right) \right) \right] (1 - s_t \xi_h). \quad [1]$$

Mangroves reduce storm damages, so that

$$\xi_h^m = \xi_h (1 - a(d, w)), \quad [2]$$

where ξ_h is disaster damage without mangroves (mangroves of width 0), $0 < a(d,w) < 1$ is the mangrove adaptation benefit for mangroves of width w meters located d kilometers from the property, with $\partial a/\partial d < 0$ and $\partial a/\partial w > 0$. By construction $\xi_h^m < \xi_h$ if mangroves are present.

With mangrove protection, the property value is increased to

$$H_t^m = \mathbb{E}_t \left[\sum_{j=1}^{\infty} (1+\delta)^j \left(\prod_{k=1}^{j} m_{t+k} \left(1 - s_{t+k}\, \xi_h^m\right) \right) \right] (1 - s_t \xi_h^m). \quad [3]$$

Thus, the value of mangrove protection for a representative property can be expressed as a share of its value:

$$V_t^m = (H_t^m - H_t)/H_t. \quad [4]$$

We simulate 1,000 Monte Carlo paths from year 2024 through 2100 at annual frequency. Each path draws independent storm realizations based on return period (RP) probabilities: 10% for RP10, 4% for RP25, 2% for RP50, and 1% for RP100 events. Frequency of each storm occurring in a given year across simulations is shown in Figure 2. In the climate change scenario, we factor in sea level rise and more severe storm conditions through the hydrodynamic flood maps and a scenario-based increase in the damaging flood levels. Specifically, we scale up the flood levels for each RP using future (2050s) flood hazard maps. Full details on storm probability assumptions and climate forcing are provided in the Supplementary Information.

Property damage ratios ξ_h vary by county, storm severity, scenario, and protection by mangroves (Figure 3). These risk-based damage estimates for Florida counties are obtained by combining flood hazard maps with building

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exposure data and FEMA Hazus damage functions (20–25). The flood maps are determined through a flood numerical model using present-day extreme sea level data and climate change scenarios. We use these values to compute the net present value of housing (Equation 1) for each county and scenario for the cases with and without mangrove protection. This exercise gives us an estimate of the economic value of avoided damages due to mangrove protection per property, V^m, our set of RAP estimates.

The hedonic approach relies on the reaction of residential properties' market prices to 100-year storms analyzed in Liu et al. (18). From this analysis, we obtain the response of property prices to a hurricane that passed through their county, $\partial H_t^{data}/\partial s_t^{100}$ and $\partial H_t^{m\,data}/\partial s_t^{100}$, which we measure as a percentage change in the price of a given property from the sale prior to the storm to the sale following the storm, adjusted by the trends in Florida's overall housing price index and other confounders. From these, we can use our model to infer the hedonic equivalent of property-damage loss parameters. The pooled statewide estimates are $\hat{\xi}_h^{100} = 0.074$ (without mangroves) and $\hat{\xi}_h^{m\,100} = 0.015$ (with mangroves), which we scale proportionately for less severe storms for the other three return periods. We use county-specific hedonic estimates for Hillsborough, Manatee, Miami-Dade, and Pinellas, and the pooled statewide estimate for Charlotte, Collier, and Lee (additional discussion in Supplementary Information). It is not surprising that these hedonic loss ratio estimates from Liu et al. (18) are substantially lower than the structural ones in Figure 3, because property values (the denominator) reflect more than just the value of structure and include the value of land, amenities, and other property attributes.

Using our storm paths simulations, and $\hat{\xi}_h^{100}$ and $\hat{\xi}_h^{m\,100}$, we recompute present value of properties with and without mangrove protection. These reflect market perception of not only avoided structural damages from storms, but also any indirect damages associated with temporary or permanent relocation, effects on employment, effects on public infrastructure, as well as any perceived value of ecosystem loss due to storms, expectations about future protection value, or changes in the insurance policy availability and cost. The hedonic coefficient $\hat{\xi}_h$ therefore captures the composite market response to a hurricane, encompassing channels beyond direct structural damage. We note that attributing the observed post-hurricane price differential to the year of the storm is a simplifying assumption. In practice, transaction price differences may reflect these changes over several years following the storm (18). We repeat the calculation using these market-based losses, which gives MAP values, $\hat{V}_t^m$.

Results

For each property, we report RAP estimates (V^m) and MAP estimates ($\hat{V}_t^m$) converted to dollars using the mean property value in each county (Figure 4 A,B). The RAP value of mangrove protection varies spatially: with the smallest benefits in Manatee and some of the greatest in Collier and Miami-Dade counties. The MAP estimates are more compressed and are not highly correlated with RAP estimates. Per-property benefits range from a few hundred dollars to $103,000 using RAP measures and

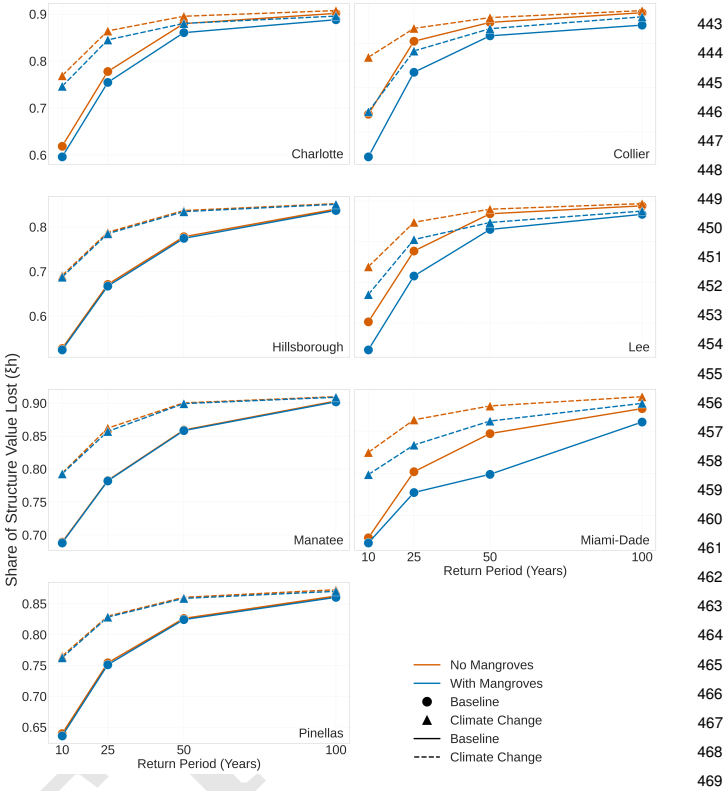


Fig. 3. Direct loss parameter. Losses are calculated per structure affected by flooding in each scenario. The unweighted average loss ratio is computed for each county and scenario. For scenarios with mangrove protection, the loss parameter is multiplied by the mangrove-driven reduction in flood probability (the ratio of buildings flooded with mangroves to those flooded without); see Methods for details. The structure value-weighted version is reported in the Supplementary Information.

from $23,000 to $117,000 for MAP measures. The effect of climate change on the RAP value of mangroves is heterogeneous across counties (Figure 4B versus 4C): the value rises in Collier, Miami-Dade, and Manatee, but declines in Lee, Charlotte, Pinellas, and Hillsborough, where mangrove effectiveness saturates as base flood levels overtop these and other coastal defenses. MAP values vary by county because they use the county-specific loss parameters from Liu et al. (18) where available: they equal 6.9% of property value where the pooled statewide estimate applies (Charlotte, Collier, and Lee) and range from 4.5% in Manatee and 4.6% in Miami-Dade to 20% in Pinellas.

We aggregate these per-property estimates of mangrove value to the county level, only aggregating the value of houses that are at risk of flooding in each scenario (Figure 4D–F). MAP estimates vary from $0.5B (Manatee) to $6.05B (Pinellas county), while RAP estimates vary from roughly $19M (Manatee) to $4.69B (Lee county). The share of houses subject to flooding varies greatly across counties, so per-property and county-aggregate values need not align. Counties where a large share of properties are exposed to flooding — Lee County in particular — rank higher in aggregate mangrove value than their per-property values alone would imply with either RAP or MAP estimates.

To put these dollar values in context, we also measure them as a share of total housing value in each county. RAP mangrove values are highest for Collier county, at 7.6% of total housing value (and 5.5% in Lee). MAP

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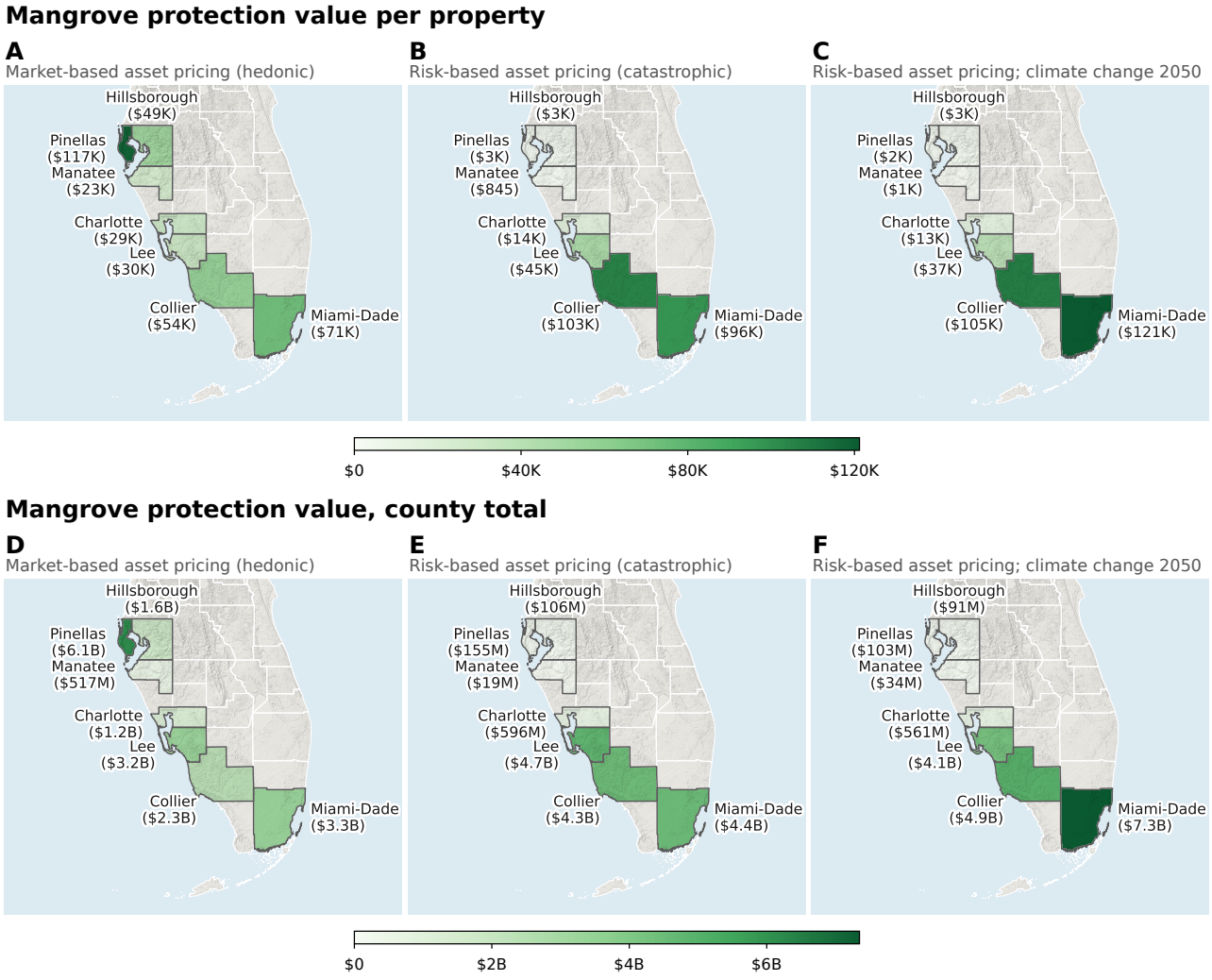


Fig. 4. Asset-pricing valuation of mangroves in seven Florida counties. The benefits of mangroves for housing value are valued per property (**A**–**C**) and summed county-wide (**D**–**F**). Values in **A** and **D** are based on market-based asset pricing (hedonic); values in **B** and **E** are based on risk-based asset pricing (catastrophic); and values in **C** and **F** incorporate the effects of climate change to 2050 on catastrophic asset pricing. See Methods for details.

values are distributed differently across counties, reaching 7.3% of housing value in Pinellas and 4.7% in Charlotte. Even in Miami-Dade county, where housing values are very high, the mangrove protection value is 1.9% of total housing value when hedonic pricing parameters are used (these numbers are reported in Supplementary Information). When combined across all counties, for the state of Florida we find the value of mangrove protection to residential homeowners is $14.32B in risk-based value in the baseline scenario, $17.15B if climate change is factored in. When we use hedonic loss estimates, the value is $18.08B. While these totals appear close in magnitude, they mask substantial heterogeneity across counties.

Discussion

We presented two estimates of the coastal protection benefits of mangroves, both within an asset-pricing framework: a risk-based valuation (catastrophic) that uses modeled flood damages (RAP estimates), and a market-based (hedonic) valuation that uses observed housing-price responses to storms (MAP estimates). At the state level the two are comparable in magnitude—$14–17B for the risk-based estimate versus $18B for the market-based estimate—but they diverge markedly across counties. The RAP value of mangroves increases with climate change in the most exposed counties and in aggregate, though it remains below the MAP value statewide. The value of these protection benefits also has a different geographic pattern for MAP relative to RAP.

Flood protection is just one of the services provided by mangroves. Mangroves also provide habitat for coastal fauna and flora (26), help prevent coastal erosion (27), provide protection from wind damages (8, 28, 29), and sequester carbon (30, 31). Where flood protection benefits to property are high, they often dwarf these other economic values in dollar terms. Nonetheless future inclusion of these values can affect the total value of mangrove benefits and its spatial variation.

Our comparison contrasts current mangrove extent with a counterfactual of no mangroves. This counterfactual is a necessary analytical device for valuing the protection provided by mangroves currently in place; it is not a projection of future mangrove distribution. The distribution of wetlands in Florida can be dynamic as mangroves

encroach and retreat into marsh habitats. The mangrove northern distribution is limited mainly by freezing but even the likelihood of freezing in Florida is dynamic with climate change (32, 33). Across both baseline and climate-change scenarios we hold mangrove extent fixed at present-day coverage; the climate-change scenario varies the flood hazard (sea-level rise and storm intensity), not the mangrove footprint. However for both marshes and mangroves the primary driver of distribution change and degradation is human, primarily through coastal development (3). Given the high degree of uncertainty about these future changes, we did not include them in our simulations.

Importance of quantifying private benefits of ecosystem services. It is critical to mobilize private investment to manage habitats to reduce coastal risk. Despite the obvious public need for risk reduction and conservation, the funding required far exceeds the resources available to public and nonprofit risk managers and nonprofit organizations (34). Quantifying climate adaptation benefits of ecosystems such as mangrove forests is an important step towards determining their overall value and designing financial instruments for their protection and restoration for two reasons. First, even though mangroves' per-storm effectiveness diminishes as sea levels rise, climate change raises the exposure and expected losses that adaptation mitigates, so the value of adaptation benefits rises over time — an attractive feature for financializing such benefits. Second, climate adaptation benefits many parties, yet its value accruing to specific private institutions — households, developers, insurers, and banks — has not so far been quantified, even though standard financial valuation methods are well suited to the task.

Our analysis covers almost all of Florida where mangroves provide significant coastal protection benefits to people and property, and thus provides a strong if conservative estimate of the total state-wide benefits in terms of the net present value of mangroves to homeowners, managers, insurers, developers, and other residential real estate stakeholders. The potential for participation of these stakeholders in funding mangrove protection and restoration is therefore quantified and can serve as a basis for the state's conservation policies, as well as potential for public-private partnerships in conservation efforts. For instance, our estimates show that private sector investment in mangrove conservation is much more likely in Charlotte, Collier, and Lee counties. In these counties, per-property private value of mangroves is high and the share of properties protected by mangroves is high. Local governments in these counties could seek up to \$1.2B, \$2.29B, and \$3.2B, respectively—the county-aggregated MAP values in Figure 4D—in private contributions towards conservation efforts, since these reflect the market value of such efforts (which may be above or below RAP values). In contrast, in Manatee county private benefits are low under both measures, so private-sector contribution is less likely. Pinellas is a notable case: its RAP benefit is modest, yet it has the largest MAP value in the state, reflecting that market prices may capitalize perceived protection beyond modeled structural damages.

There are three important considerations for these policy implications. First, mangrove expansion is not without tradeoffs: where mangroves expand, they can do so at the expense of salt marsh habitats and the distinct ecosystem services they provide (33). Second, coastal property values are partly shaped by subsidized federal flood insurance and related regulatory distortions (35, 36). This concern is mitigated by the fact that these distortions are concentrated in high-risk flood zones, whereas hedonic estimates in Liu et al. (18) are identified from medium-flood-risk properties least exposed to them. Third, in this study we only focus on the benefits of mangroves for flood protection, not including many co-benefits (such as their carbon capture potential (30) and other ecosystem services) and not incorporating costs of their protection and restoration. Thus, our analysis should not be interpreted as a complete cost-benefit analysis.

Contributions to the literature on ecosystem valuation and housing market response to climate shocks. There is a growing body of literature on the value of reefs, dunes and wetlands natural infrastructure, but the vast majority of existing valuations are framed in terms of avoided flood damages to exposed populations and built infrastructure. These estimates are essential for informing management priorities and climate finance mechanisms, but they do not quantify specific private economic benefits accruing to individual landowners, households, and the real estate sector whose assets lie within the protective zone of mangrove ecosystems. Quantifying these benefits would allow private financial institutions and individuals to incorporate mangrove benefits into private investment and risk management decisions (37, 38). Where previous studies calculate total regional protection value, this study calculates how mangrove proximity affects individual homeowner cash flows and wealth through a forward-looking asset pricing model. This reframing shifts the question from "How much damage do mangroves prevent?" to "How much should private market participants pay for that protection?", directly addressing how economic agents value nature-based adaptation.

With respect to the literature that calculates the value of avoided damages thanks to mangrove protection (8, 9, 39), the most direct comparison can be made between our results and those in Narayan et al. (13), which shows that mangroves reduce average annual loss by 67M USD per year in Collier County. Using the same assumptions of 5% discount rate and 2.5% consumption growth rate, the present value of this loss reduction is 0.9B USD. Our corresponding RAP estimate for Collier is substantially larger, over \$4.3B (Figure 4E) for two main reasons: first, we not only calculate average losses with and without mangroves, we also factor in reduction in loss dispersion that mangroves provide, by using a stochastic model with the convex utility function that incorporates dislike of uncertainty; second, the use of stochastic discount factor, with the same base risk-free rate of 5% and consumption growth of 2.5%, magnifies the benefit of damage reduction in the aftermath of storms, because it puts higher value on each unit of consumption in distressed states. Using MAP estimates, we get a value of the same order of magnitude as RAP but over 40% lower (2.29B, Figure 4D), suggesting that market agents underprice flood protection value of mangroves in Collier county. While the approach in Narayan et al. (13) is appropriate for measuring costs and benefits of public investments and for pricing insurance

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instruments, our approach is useful in quantifying the value of mangroves to private institutions participating in the real estate market.

We rely on the estimated housing market reaction to hurricanes as a function of distance to mangroves in Liu et al. (18). While estimates in Liu et al. (18) provide hedonic value of mangroves conditional on the arrival of a 100-year storm, in this paper we use a forward-looking model to evaluate the unconditional present value of mangroves, allowing for a variety of storms in the future. We use benchmark estimates from Liu et al. (18) to calibrate the housing loss parameter (ξ_h) conditional on the storm in our model (Equation 1). Liu et al. (18) is the first analysis of the value of mangroves as flood adaptation that relies on housing market values, however, it builds on a body of the literature that analyzed the effects of storms on housing and other markets as well as the value of ecosystems (40–45).

We also contribute to the finance literature that examines climate risk pricing in housing markets (46–48). Our comparison of MAP and RAP estimates reveals geographic differences in how markets price disaster risk: when MAP valuations exceed RAP valuations, households internalize protection's insurance properties; when MAP valuations fall short of RAP, policy intervention may be warranted. This dual-valuation framework connects natural infrastructure valuation to broader debates on climate risk pricing in asset markets (46, 49).

Limitations. We do not explicitly include hard infrastructure such as seawalls, bulkheads, or hybrid configurations such as living shorelines—which can themselves affect flood exposure and property values (50–53)—in our spatial analyses because these data are not publicly available (if at all). Some of these structures such as high berms and dikes can be implicitly captured as changes in elevation in topographic data. We also do not include flood protection of other ecosystems, such as coastal marshes, which may be substantial (37). Moreover, our counterfactual removes mangroves without substituting alternative protection. In practice, some flood reduction could be achieved through engineered defenses such as seawalls and dikes (53). Some of these alternative measures may have lower implementation costs than mangrove restoration, although they are unlikely to have as many important co-benefits (23).

MAP mangrove value estimates incorporate all possible storm-protection effects of mangroves, not just those limited to the loss of structure value due to flooding. These may include reduction in the loss of life (28), loss of public infrastructure and utilities, loss of business, and loss of location-based amenity values. Moreover, these estimates can also include additional mangrove adaptation benefits, such as protection from the wind (54). All these considerations should lead to MAP values exceeding RAP. However, MAP values also reflect beliefs of market participants about climate change and related risks to properties, and the protection values of mangroves. For example, under-appreciating future climate-related damages will lead to underpricing of the protection value of mangroves. Thus, while we measure the difference between MAP and RAP values, we are not able to attribute the differences to a specific mechanism.

Our asset pricing model relies on the assumption of rational expectations, which means that markets correctly evaluate the moments of storm arrival distribution and the expected losses. This is a standard assumption for the benchmark scenario. However, it becomes less straightforward for the climate change scenarios, since there is no certainty about the climate change path and market participants' perceptions of climate risks are heterogeneous and may respond to the storms (41, 42). Moreover, by assuming a CRRA utility function, which is standard in the literature, we do not allow for loss aversion, ambiguity aversion, probability weighting, or any other deviations from standard rational expectations framework. Including these refinements is likely to increase all simulated housing values, as higher weight is typically put on losses in these models (and we only model losses), but the effect on the value of mangroves is generally ambiguous.

Materials and Methods

Here we provide a summary of research methods. Please refer to the Supplementary Information for details.

Data Sources. Our analysis is focused on seven counties in Florida: Charlotte, Collier, Hillsborough, Lee, Manatee, Miami-Dade, and Pinellas. These seven counties cover almost all of Florida where mangroves provide significant coastal protection benefits to people and property. We do not include St. Johns and Monroe counties in our analyses as mangrove habitats are dynamic in St. Johns and there was not sufficient transaction data in Monroe for the market analysis in Liu et al. (18). We integrate multiple geospatial and hazard datasets to quantify coastal flood risk and the protective benefits of mangroves. Inputs include mangrove extent, coastal elevation and nearshore bathymetry, land cover, and ocean water levels and wave conditions (from historical reanalyses, synthetic events, and mid-century projections). These layers are combined with building footprints and building-level attributes and values (updated to 2025 dollars) to compute 10-m resolution flood maps and building-level damages following FEMA Hazus guidelines. Full data descriptions and citations are provided in the Supplementary Information.

Modeling and calibrating property prices. We model property prices using a standard approach that relies on constant relative risk aversion (CRRA) utility function with risk aversion parameter γ and discount factor β. This utility function implies a stochastic discount factor m which serves as a pricing kernel for property prices.

$$m_{t+1} = \beta\,(1+g_c)^{-\gamma}(1-s_{t+1}\xi_c)^{-\gamma}, \qquad [5]$$

where g_c is annual consumption growth rate in the absence of disruption by storms and ξ_c is a drop in consumption due to storm $s \in \{0,1\}$. See Supplementary Information for derivations.

We calibrate pricing kernel parameters as standard in the asset pricing literature: $\gamma = 2$ and $\beta = 0.95$ (55). We set $g_c = 0.025$ above the ∼2% mean consumption growth in standard national calibrations (15), reflecting that Florida's consumption growth and coastal real estate appreciation consistently outpace national averages. For consumption shocks, we set $\xi_c = [0.01, 0.02, 0.04, 0.08]$ for return periods of 10, 25, 50, and 100 years, respectively. These conservative values are informed by empirical evidence from major hurricanes showing household consumption declines ranging from 1% for moderate storms to 7–11% for severe events in developing economies (56, 57) and 3–5% in advanced economies with comprehensive insurance (58). See Supplementary Information for detailed calibration methodology. The consumption shock ξ_c represents a single-period decline in the storm year, after which consumption resumes trend growth from the reduced level. These values are conservative for Florida, where insurance market disruptions have left many households with high deductibles or no coverage. Mangroves only affect structural flood damages (ξ_h), not consumption shocks (ξ_c). Consumption shocks capture factors including income disruption, displacement costs, and broader economic impacts that are independent of flood protection.

Property price can be represented by recursive equation

$$H_t = \mathbb{E}_t\left[m_{t+1}\,(1+\delta)(1-s_{t+1}\,\xi_h)\,H_{t+1}\right](1-s_t\xi_h), \qquad [6]$$

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which when collapsed leads to Equation 1. δ is the stream of housing services provided by the property. We calibrate this value using rental yield, a standard approach in housing literature (15), setting $\delta = 0.07$ based on Florida market data (see Supplementary Information for detailed calibration). ξ_h, our key parameter of property damage due to storm, is discussed below.

Flood Modeling and direct damages. High resolution flood modeling provides flood extent and inland water depths for different mangrove and climate scenarios. Flood maps are modeled with the numerical model SFINCS (Super-Fast INundation of CoastS) (59), a reduced-physics model that resolves coastal and inland inundation. The model is forced with spatially variable water-level time series from the combined action of storm surge, astronomical tides, and wave induced set-up. The dataset described in Muis et al. (60) is the basis for the description of the storms. The shape is estimated following Dullaart et al. (61) while the maximum water level for each return period is extracted from COAST-RP (62) for the current climate. Bathymetry and elevation data for the flood model are obtained from a composite of federal products, prioritizing accuracy and horizontal granularity for each location. Native resolutions range from 1 m to ∼450 m: USGS 3DEP lidar (1 m, land; 63), NOAA CUDEM (≈ 3 m, nearshore topobathymetry; 64), the 2008 National Elevation Dataset (≈ 3 m, land gap fill; 65), NOAA BlueTopo (∼4–16 m, offshore; 66), and ETOPO 2022 (≈450 m, deep-offshore gap fill only; 67). All sources are merged onto a common 10 m grid in NAD83 UTM zone 17N (EPSG:26917), using average resampling for sources finer than 10 m and bilinear interpolation for coarser sources.

Mangroves are represented in the flood model through a roughness coefficient (e.g., (8)). Surface roughness is specified as spatially varying Manning coefficients in the model and is derived from the 30 m USGS National Land Cover Database (NLCD, 68) and Kalyanapu et al. (69). Mangrove extent from 2020 Global Mangrove Watch data (GMW, 70) is overlaid with Manning coefficient $n = 0.14$ (71); offshore areas beyond NLCD coverage are assigned open-water roughness ($n = 0.025$); and mangrove degradation is represented through a reduction of the 'healthy' mangrove roughness, assuming that most areas with mangrove loss would become water.

Flood damages are calculated by combining the flood hazard maps with building exposure and vulnerability curves. Building exposure is drawn from the National Structure Inventory (NSI) (72), combined with footprints from Microsoft Open Buildings (73); NSI 2021 values were updated to 2025 prices using a cumulative price ratio of 1.19 (74). For each building, we compute direct flood damage with a FEMA depth–damage (vulnerability) function that maps flood depth to a structural loss ratio. The functions are taken from the FEMA Flood Assessment Structure Tool (FAST), updated with Hazus 7.0 curves (20, 22, 75), and one is selected per building according to its occupancy type, foundation type, and number of stories (Supplementary Information, Fig. S1). We apply the selected function to the maximum water depth at the building to obtain a percent damage, which we multiply by the total building value to give the dollar loss, repeated across all buildings and flood scenarios.

From these flood maps, we compute property damages. The analysis is conducted at the county level by simulating damages for a representative property and aggregating calculated protection values county-wide. The model is calibrated using damage ratios calculated as the arithmetic mean of damage-to-value ratios across flooded properties: $\xi_h = (1/N)\sum_i (damage_i/value_i)$. This equal-weighting approach treats each property equally, appropriate for representative property simulations. We track the share of each county's properties subject to flooding in each scenario. Supplementary Information presents results using damage ratios weighted by structure value as a robustness check. Finally, to reflect that mangroves can reduce both flood severity and the likelihood of flooding, we apply an extensive-margin adjustment in mangrove scenarios by scaling the structural damage ratio by the ratio of flooded buildings in the "with mangroves" versus "without mangroves" scenarios.

Climate change scenario. The impact of climate change on coastal flood hazard is incorporated directly into the hydrodynamic flood modeling through two distinct physical mechanisms: baseline sea level rise (SLR) and climate-driven changes in storm-surge dynamics. First, regional mean sea level rise projections from the IPCC Sixth Assessment Report (AR6) are incorporated into the baseline water levels used in the simulations (76). Second, to account for changes in storminess and meteorological forcing, we adjust maximum storm-surge levels using the ensemble mean of the future projections of Muis et al. (60). These surge projections are derived from the Global Tide and Surge Model (GTSM) forced with a high-resolution Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model ensemble (HighResMIP), directly capturing climate-driven shifts in wind and atmospheric-pressure extremes. We use results from the SSP5-8.5 emissions scenario as this is the only scenario for which sea level and wave projections are available for the same Global Climate Models. However the differences among emissions scenarios in SLR, extreme sea levels and waves are minor by mid century (77–79), e.g., the difference in SLR across all emissions scenarios is only a few centimeters by mid century. It is only after mid-century when the impacts of emissions scenarios begin to diverge.

By integrating updated baseline sea levels and dynamically projected peak surge levels directly into the hydrodynamic flood model, the resulting future hazard maps account simultaneously for deeper inundation depths and altered extreme water level distributions. Storm probabilities are therefore evaluated directly against these updated future flood maps, without applying any separate frequency post-adjustment, ensuring that no climate-change impact is double-counted.

Linking the model to hedonic estimates. In the data we observe the ratio of property prices in the storm year t_0 relative to prior year $H_{t_0}^{data}/H_{t_0-1}^{data}$. Assuming infinite (i.e. sufficiently long) horizon for asset pricing, the storms are independent and identically distributed (i.i.d.), and expectations are fully rational, we can show that $H_{t_0}^{data}/H_{t_0-1}^{data} = 1 - \hat{\xi}_h$ (See Supplementary Information for derivations). The hedonic estimates in Liu et al. (18) identify the market's repricing of mangrove protection following 100-year storms and do not separately identify responses to smaller storms. We therefore anchor each county's directly estimated $\hat{\xi}_h^{100}$ and extrapolate to shorter return periods with a linear-in-return-period rule,

$$\hat{\xi}_h(\mathrm{RP}) = \frac{\mathrm{RP}}{100}\,\hat{\xi}_h^{100}, \qquad [7]$$

so that the market-implied loss ratio equals 0.50, 0.25, and 0.10 of the 100-year value for 50-, 25-, and 10-year storms, respectively. This scaling approach produces conservative estimates, as shown in the Supplementary Information. We then repeat the model simulation with $\hat{\xi}_h$ values replacing those of ξ_h. We repeat this analysis for properties protected by mangroves, replacing ξ_h^m with $\hat{\xi}_h^m$.

We obtain estimates for the market impact of the mangroves from Liu et al. (18). Note that the estimates are based on repeated sales of properties that are outside the FEMA-designated high-risk flood zones (the Special Flood Hazard Areas), and therefore these prices are less likely to be distorted by regulation and federal insurance (35, 44). While the publication reports average estimates for the state of Florida, unpublished intermediate results are available at county level. However, for some counties these estimates are not reliable due to insufficient variation given all controls included in the regression. That said, even if imprecise, county-level estimates are more appropriate for our analysis. We replace overall average with county-level estimates for Hillsborough, Manatee, Miami-Dade, and Pinellas counties, while applying overall average to Charlotte, Collier, and Lee, for which county-level estimates are too noisy. Compared to state-wide averages, the effects are slightly larger for Hillsborough county, slightly smaller for Manatee and Miami-Dade, and are substantially larger for Pinellas county.

Aggregation. Our baseline calculations focus on a representative property for each county. To compute the aggregate value of mangrove protection for a county, we multiply the relative protection value V^m by the total structural value of the county's "at-risk" housing stock. We define this at-risk stock as the total value of properties that would flood during a 100-year return period (RP100) event in the scenario without mangroves (i.e., the 1% annual chance floodplain). Holding this exposure base constant across all scenarios isolates the marginal protective effect of mangroves (captured by V^m) from changes in the definition of baseline exposure. We repeat this aggregation for each county, for the no-climate-change and climate-change scenarios, and for the MAP estimates. To place these values in context, we also report aggregate mangrove protection value as a share of total residential property value in each county, with detailed results reported in Supplemental Information.

Data, Materials, and Software Availability. All calibration inputs as well as codes are available on GitHub mangrove-asset-pricing.

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