Putting a Price on Adaptation: A Generalizable Framework for Valuing the Benefits of Climate Adaptation*

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Abstract

Public agencies and local governments increasingly use benefit-cost analysis (BCA) to decide which climate adaptation projects to fund. Standard BCA models value adaptation almost entirely through avoided direct physical damage evaluated at expected values. This approach risks underestimating benefits along two dimensions: spillovers from direct damages and reduction in uncertainty of the damage distribution. We develop a general, hazard-agnostic framework that (i) organizes losses into a common ledger of assets, loss channels, and stakeholders, with explicit rules against double counting; (ii) assigns each loss channel a valuation method that can be implemented with public data in any U.S. jurisdiction in order to evaluate spillover effects; (iii) converts hazard-model output into a full annual loss distribution rather than a single expected value; and (iv) values the reduction in risk itself through an option-price measure that reflects both avoided expected losses and a reduction in uncertainty borne by those who cannot diversify the loss. The framework can also accommodate co-benefits and dis-benefits of adaptation, time-varying hazard, and distributional weights. We pilot the framework with physics-based storm-flood scenarios from the CoSMoS-Adapt model in Santa Cruz County, California, evaluating damage-reduction benefits of dune restoration, submerged reefs, and seawalls. In this pilot, our framework increases estimated benefits by a factor of three to five relative to standard BCA models.

Keywords: climate adaptation; cost-benefit analysis; flood risk; risk aversion; option price; nature-based solutions; sea-level rise.
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1 Introduction

Adaptation spending needs are rising rapidly, and scarce adaptation funds are usually allocated based on benefit-cost analysis (BCA) ranking. In the United States, eligibility for FEMA hazard-mitigation funding requires a benefit-cost ratio (BCR) of at least one, and federal water-resources projects are ranked by net economic benefits. This makes the *measurement of benefits* the main margin on which adaptation projects succeed or fail. Yet in practice benefits are usually measured as avoided direct physical damage to buildings and contents, derived from depth-damage curves and evaluated at their expected value (Meyer et al. 2013; Federal Emergency Management Agency 2024b). This convention omits categories of loss that are quantitatively important, such as business interruption, displacement, supply-chain disruption, damage to public infrastructure, and the loss of non-market services from natural assets (Hallegatte and Przyluski 2010; Botzen et al. 2019). Moreover, by relying on expected values, standard methodologies assume that society is indifferent to the variance of losses. That assumption is hard to defend when losses fall on households, small firms, and local governments that are under-insured and cannot diversify them (Kind et al. 2017; Hallegatte et al. 2017; Markhvida et al. 2020).

This paper provides a general framework for putting dollar values on the benefits of adaptation projects, designed to be implemented with publicly available data across hazards, places, and project types. We pilot it on coastal storm flooding in California, where physics-based hazard modeling is unusually rich, but the framework is not specific to coasts: the same ledger, valuation methods, and risk adjustment apply to riverine and pluvial flooding, extreme heat, and wildfire. One issue that we do not address in this framework is distribution effects of direct-damage based models. Since damages tend to be larger for higher market value properties, they tend to skew estimated towards more well-to-do communities, while social costs are higher and capacity to self-adapt is lower in low-income areas. Distributional weights introduced by FEMA in 2024 can be applied within our framework (Section 2.5), but they are unlikely to fully bridge the adaptation gap on their own. Our pilot study, however, is not suffering from the adaptation gap bias, because we apply our analysis to compare various adaptation options for a given community, rather than to produce rankings across communities.

The framework has four building blocks. First, a *loss ledger* that enumerates exposed assets, the channels through which a hazard event imposes losses on them (physical damage, lost use during repair, displacement, supply-chain spillovers, non-market services, health), and the stakeholders who bear each loss, together with explicit accounting-stance and double-counting rules. The connection to stakeholders can be used to determine whether a given loss can be insured, but it can also help quantify private sector contribution to adaptation projects funded through private-public partnerships. Second, a *valuation library* that assigns each asset-channel pair a method—depth-damage functions for structures, hedonic rent imputation for displacement, rent-to-revenue ratios for business interruption, input-output linkages for spillovers, benefit transfer for recreation and ecosystem services, and engineering unit costs for public infrastructure. Third, a procedure for turning a set of modeled hazard scenarios into a *full annual loss distribution*, using a Pareto

curve fitted to return-period losses. This is an important step because modeling hazard scenarios is computationally expensive. Fourth, a *risk-adjusted benefit measure* implemented using probability Value-at-Risk measures as well as Certainty Equivalent using CRRA or CARA utility functions, the approaches most commonly used in the finance literature and by financial sector practitioners.

Our contribution, therefore, is in bridging the gap between engineering and economics literature on the value of climate adaptation. A large engineering and natural-hazards literature estimates avoided damages from coastal defenses and nature-based solutions (Hinkel et al. 2014; Narayan et al. 2016; Beck et al. 2018; Reguero et al. 2018), and integrated assessment models such as CIAM compute optimal coastal adaptation at scale (Diaz 2016; Lincke and Hinkel 2018). These studies generally value adaptation through expected avoided direct damage. The economics literature, in turn, has long established that the benefit of loss reduction under uncertainty is an option value rather than an expected surplus (Graham 1981), that the risk premium on public projects vanishes only when risk can be diversified or hedged (Arrow and Lind 1970), and that risk aversion and income differences can change flood-protection rankings substantially (Kind et al. 2017). Few applied adaptation BCAs implement these insights, partly because the information needed is rarely assembled. We show how to transform standard hazard-model output into an economically sound framework, and how much it matters quantitatively in our pilot application.

The pilot was conducted for California's Fifth Climate Change Assessment and is expanded in this paper. We combine CoSMoS-Adapt flood simulations (Barnard et al. 2014, 2019) with a building-level inventory and our valuation library for Santa Cruz County (including the cities of Santa Cruz and Capitola). We conduct simulations for various sea-level and wave conditions and for three time horizons: through 2025, 2055, and 2085. We evaluate three adaptation measures: dune restoration, submerged (rocky) reefs, and seawalls. Three findings stand out. First, losses beyond direct structural damage are large: for the 100-year storm in Santa Cruz county, adding non-structural and indirect losses roughly triples the loss estimate. Conventional BCAs therefore understate benefits substantially even without accounting for uncertainty reduction. Uncertainty reduction further increases these benefits: owners would pay 11–36% more than the reduction in expected damage for the risk reduction that adaptation delivers. Second, seawalls produce the largest avoided damages, but restored dunes deliver the highest benefit-cost ratios because of their much lower production and maintenance costs. Third, cost-effectiveness varies sharply within the site: benefits are concentrated in two of ten study units, dunes pass a benefit-cost test only at the Santa Cruz Boardwalk, and seawalls only at Boardwalk and in Capitola. Spatial targeting therefore matters as much as the choice of measure.

The rest of the paper proceeds as follows. Section 2 sets out the welfare framework. Section 3 presents the loss ledger and the valuation library. Section 4 shows how the framework generalizes beyond coastal flooding. Section 5 describes the California pilot, and Section 6 reports its results for Santa Cruz. Section 7 discusses limitations and extensions, and Section 8 concludes.

2 A Welfare Framework for Valuing Adaptation

2.1 Setup

Consider a study region containing exposed assets $k = 1, \ldots, K$, each owned or used by one or more stakeholders $g \in \mathcal{G}$ (owner-occupiers, landlords, tenants, businesses, workers, local government, visitors). The region can implement an adaptation option $a \in \mathcal{A}$, with $a = 0$ denoting the status quo. A hazard model, exogenous to this framework, maps a hazard event e and option a into a local intensity $h_{kt}(e, a)$ at each asset in year t. The monetized loss from event e is

$$L_t(e, a) = \sum_{k=1}^{K} \sum_{c \in \mathcal{C}} \ell_{kc}\big(h_{kt}(e, a)\big), \tag{1}$$

where c indexes *loss channels*: physical damage to structures and contents, lost use during repair (rent or business revenue), displacement and relocation, supply-chain spillovers, loss of non-market services, damage to public infrastructure, and health. Section 3 specifies $\ell_{kc}(\cdot)$ for each asset class and channel.

The total value of option a in year t has three parts: the change in the loss distribution it induces, any co-benefits or dis-benefits it creates independently of hazard events (e.g., recreational and habitat value of a restored dune, or loss of beach area caused by a seawall), and its cost. We treat each in turn.

2.2 Expected Annual Damage from a Small Number of Modeled Events

Hazard models are expensive to run, so losses are typically observed for only a few return periods $T_1 < T_2 < \cdots < T_n$, with annual exceedance probabilities $p_i = 1/T_i$ and losses $D_i = L(e_i, a)$. The conventional estimator of expected annual damage (EAD) integrates the loss-exceedance curve by the trapezoidal rule (Reguero et al. 2018):

$$\mathrm{EAD}^{\mathrm{trap}} = \sum_{i=0}^{n-1} \frac{D_i + D_{i+1}}{2} \, (p_i - p_{i+1}), \tag{2}$$

where we add a 2-year event with zero damage ($T_0 = 2$, $p_0 = 0.5$, $D_0 = 0$) and do not extrapolate beyond the rarest modeled event.

Equation (2) provides no information on dispersion. We therefore also fit a Pareto curve to the modeled points. Let W denote the value of the assets whose owners bear the loss, and X the annual loss as a share of W. Each modeled event gives one point (x_i, p_i), where $x_i = D_i/W$ and $p_i = 1/T_i$ is the annual probability of a loss at least that large. As in equation (2), years milder than the 2-year event bring no loss, and we fit the curve from the 2-year event's annual probability of one half onward:

$$\Pr(X > x) = \frac{1}{2}\left(\frac{x_m}{x}\right)^{\alpha}, \qquad x_m \le x \le 1, \tag{3}$$

where $\alpha > 0$ is the tail index and x_m is the loss of the 2-year event. Losses cannot exceed the value of the exposed assets, so $\Pr(X > x) = 0$ for $x > 1$. Taking logs gives a straight line, $\ln p_i = \ln \frac{1}{2} + \alpha \ln x_m - \alpha \ln x_i$, which we fit by ordinary least squares. Figure 5 illustrates the fit. The fitted distribution provides a smooth interpolation over the loss support and delivers the *probability value-at-risk*,

$$\text{pVaR}(\tau) = \Pr(X > \tau) = \frac{1}{2}\left(\frac{x_m}{\tau}\right)^{\alpha}, \tag{4}$$

the annual probability that losses exceed a materiality threshold τ, a statistic that is intuitive to decision-makers and that we report alongside EAD. Evaluated under no adaptation and under adaptation, equation (4) gives p_N and p_A, the annual probabilities of losing a share τ or more.

The expected annual benefit of option a in year t is the reduction in EAD, $\Delta\text{EAD}_a(t) = \text{EAD}_0(t) - \text{EAD}_a(t)$, but it is not a full benefit in that it does not reflect reduction in uncertainty.

2.3 Valuing Uncertainty Reduction: Option Price and Risk Premium

Expected-value BCA treats a project that lowers the variance of losses but not their mean as worthless. When losses fall on agents who cannot fully insure or diversify them, the relevant welfare measure is the *option price*: the maximum certain annual payment an agent would make for the project, before knowing which events will occur (Graham 1981). For an agent with wealth W, utility $u(\cdot)$, and exposure to annual loss L_a, the option price OP_a solves

$$\mathbb{E}\big[u(W - L_a - OP_a)\big] = \mathbb{E}\big[u(W - L_0)\big], \;\; L_0 > L_a. \tag{5}$$

Define the certainty-equivalent loss ℓ_a^{CE} by $u(W - \ell_a^{CE}) = \mathbb{E}[u(W - L_a)]$, and the risk premium $\pi_a = \ell_a^{CE} - \text{EAD}_a \geq 0$. With constant absolute risk aversion utility function, the option price is exactly the difference in certainty-equivalent losses; more generally, to first order in OP_a/W,

$$OP_a \;\approx\; \ell_0^{CE} - \ell_a^{CE} \;=\; \underbrace{\big(\text{EAD}_0 - \text{EAD}_a\big)}_{\text{avoided expected loss}} + \underbrace{\big(\pi_0 - \pi_a\big)}_{\text{avoided risk premium}}. \tag{6}$$

Equation (6) is the central object of the framework. Conventional BCA measures only the first term. The second term is positive whenever adaptation compresses the loss distribution, and it is largest for measures that truncate the tail—which is why the ranking of measures can change once uncertainty reduction is priced.

Annual flood outcomes We implement equation (6) in two ways, and both use the same definition of flood risk. Let $x_5, x_{20}, x_{50}, x_{100}$ denote the losses, as shares of W, caused by the 5-, 20-, 50- and 100-year storms under no adaptation. Each year, one of five outcomes $k \in \{0, 5, 20, 50, 100\}$ occurs: no damaging flood ($x_0 = 0$), or a loss of x_k. An adaptation measure lowers the probability of the x_k loss reaching them. Under adaptation scenario s, outcome k has the probability $\pi_{s,k}$, which follows from the fitted Pareto curve of that scenario (Table 1).

The probability of each outcome is the difference between two values of the pVaR. For example, under no adaptation, a loss at least as large as that of the 5 year storm occurs with a probability $1/5$ and one at least as large as a 20 year storm with probability $1/20$. The first probability already includes the second because every year with a 20 year storm also has a loss at least as large as that of the 5 year storm. To avoid double counting these years the probability that the loss in a year reaches that of a 5 year storm but not a 20 year storm is then $1/5 - 1/20 = 0.15$. Using $1/T$ directly for every outcome would count the same years several times: a 100 year storm would appear in all four storm outcomes and the probabilities would sum to more than one.

An adaptation measure lowers $\text{pVaR}(x_k)$ at every loss level which moves the probability away from the damaging outcomes and toward the outcome with no damage. Because the outcomes start at the loss of the 5-year storm under no adaptation, the willingness to pay below is the willingness to pay to reduce the chance of a storm that damages at least as much as the 5-, 20-, 50- or 100-year storm under no adaptation, that is, to reduce tail risk.

Table 1: Annual flood outcomes

Outcome	No adaptation	Scenario s
No damaging flood	$1 - 1/5 = 0.80$	$1 - \text{pVaR}_s(x_5)$
Loss of x_5	$1/5 - 1/20 = 0.15$	$\text{pVaR}_s(x_5) - \text{pVaR}_s(x_{20})$
Loss of x_{20}	$1/20 - 1/50 = 0.03$	$\text{pVaR}_s(x_{20}) - \text{pVaR}_s(x_{50})$
Loss of x_{50}	$1/50 - 1/100 = 0.01$	$\text{pVaR}_s(x_{50}) - \text{pVaR}_s(x_{100})$
Loss of x_{100} or more	$1/100 = 0.01$	$\text{pVaR}_s(x_{100})$

Note: Entries are annual probabilities. pVaR_s is equation (4) evaluated on the fitted Pareto curve of scenario s. x_k is the loss from the corresponding storm under no adaptation as a share of W.

Arrow–Pratt (mean-variance) implementation For losses that are small relative to wealth, $\pi_a \approx \frac{1}{2} A \operatorname{Var}(L_a)$, where $A = -u''/u'$ is the coefficient of absolute risk aversion. With constant relative risk aversion γ, $A = \gamma/W$, so $\pi_a \approx \gamma/2W \operatorname{Var}(L_a)$. This requires only the mean and variance of losses, which we take from the five outcomes. We calibrate $\gamma \in \{2, 3\}$, consistent with estimates from labor supply and insurance choices (Chetty 2006). Written with X, the loss as a share of W, equal to x_k with probability $\pi_{s,k}$, the willingness to pay for an adaptation measure is

$$\text{WTP} = W\left[(\mathbb{E}_N[X] - \mathbb{E}_A[X]) + \tfrac{1}{2} A\left(\text{Var}_N(X) - \text{Var}_A(X)\right)\right], \tag{7}$$

where the coefficient A on the variance of the loss share plays the role of γ. Adaptation measures raise WTP both by lowering expected losses and by reducing the variance of losses.

CRRA implementation This approach uses a constant relative risk aversion (CRRA) utility function:

$$u(x) = \begin{cases} \dfrac{x^{1-\gamma}}{1-\gamma}, & \gamma \neq 1, \\ \ln(x), & \gamma = 1, \end{cases} \tag{8}$$

where x is wealth subject to flood losses and γ is the coefficient of relative risk aversion. Under no adaptation, a loss of x_k occurs with probability $\pi_{N,k}$. Under adaptation, the probability of each loss of x_k or more falls, giving probabilities $\pi_{A,k}$. The corresponding utilities are

$$\mathbb{E}[u(W_N)] = \sum_{k=0}^{4} \pi_{N,k}\, u\big((1-x_k)W\big), \tag{9}$$

$$\mathbb{E}[u(W_A)] = \sum_{k=0}^{4} \pi_{A,k}\, u\big((1-x_k)W\big). \tag{10}$$

With a single catastrophic loss, these expressions reduce to a comparison of p_N and p_A for one loss level; using all four storms lets smaller floods count as well. Certainty equivalents are

$$CE_s = \begin{cases} \left[\sum_k \pi_{s,k}\big((1-x_k)W\big)^{1-\gamma}\right]^{\frac{1}{1-\gamma}}, & \gamma \neq 1, \\ \prod_k \big((1-x_k)W\big)^{\pi_{s,k}}, & \gamma = 1, \end{cases} \qquad s \in \{N, A\}, \tag{11}$$

and willingness to pay for the adaptation measure is the difference in certainty equivalents:

$$\text{WTP} = CE_A - CE_N. \tag{12}$$

A risk-neutral owner ($\gamma = 0$ or $A = 0$) is willing to pay exactly the reduction in expected loss. The amount by which WTP of a risk averse owner exceeds this is the avoided risk premium in equation (6). We calibrate $\gamma \in \{2, 3\}$, consistent with estimates from labor supply and insurance choices (Chetty 2006), and report $A \in \{2, 4\}$ as a sensitivity check. Here W is the wealth of the agent bearing the loss. In the pilot, we use the value of the structures and contents of the buildings that bear the loss as a stand-in for their owners' wealth (Section 6.2).

Whose risk premium? The risk premium is a private cost of bearing undiversified risk. If a loss is spread across many taxpayers or held by well-diversified insurers and investors, its social risk premium approaches zero (Arrow and Lind 1970). We therefore apply the risk adjustment only to the undiversified share of each loss channel and treat insured and diversified losses at expected value. In the pilot, the risk adjustment applies to physical damage to structures and contents, which owners bear directly. Lost rent and business revenue can be insured through loss-of-rents and business-interruption cover and unemployment benefits, and supply-chain losses are spread across many firms. We therefore assume these losses to be diversified, and so our WTP measures serve as a lower bound for how much owners would pay to reduce risk. The ledger in

Section 3 records the bearer of each loss for this purpose. As a market-based benchmark, catastrophe reinsurance and catastrophe bonds have historically been priced at several times expected losses (Froot 2001), so the premium households implicitly pay to transfer flood risk provides an upper bound on π for the insured share. Where flood insurance take-up is low, as in most of coastal California, the undiversified share is large.

2.4 Horizon, Discounting, and Costs

Sea-level rise makes hazard, and therefore benefits, time-varying. Each adaptation project is likely to have a finite service horizon H. We observe $\text{EAD}_a(t)$ for $t \in \{2025, 2055, 2085\}$ and interpolate linearly between these years. The present value of benefits over horizon H is

$$PV_a^B = \sum_{t=0}^{H-1} \frac{\Delta\text{EAD}_a(t) + \Delta\pi_a(t) + E_a(t)}{(1+r)^t}, \tag{13}$$

where $t = 0$ is the first year of operation, which is not discounted, and $E_a(t)$ are non-hazard co-benefits ($E_a < 0$ for dis-benefits, such as the loss of beach area in front of a seawall; Section 3.7). Costs are $C_a = I_a + \sum_{t=0}^{H-1} M_a(t)/(1+r)^t - R_a/(1+r)^H$, with up-front investment I_a, maintenance $M_a(t)$, and residual value R_a. Decision metrics are

$$\text{BCR}_a = PV_a^B / C_a, \qquad \text{NPV}_a = PV_a^B - C_a, \tag{14}$$

and the *break-even cost*, PV_a^B itself, is the largest investment for which $\text{BCR}_a = 1$. The break-even cost is useful because it can be reported before engineering designs and cost estimates are available.

2.5 Distributional Weights

Equation (6) captures differences in the *ability to bear* risk, but not differences in the social value of a dollar across income groups. The framework therefore allows each stakeholder's benefits to be weighted by $\omega_g = (\bar{y}/y_g)^\eta$, where y_g is the income of group g, $\bar{y}$ is national median income, and η is the elasticity of marginal utility of income. FEMA's 2024 interim methodology applied this weight to building replacement values with $\eta = 1.4$ at the census-tract level, bounded between 1 and 3.7 (Federal Emergency Management Agency 2024a). Because the status of distributional weights in federal guidance changed in 2025, we report weighted results only as a sensitivity analysis and use the unweighted results as our main estimates. The same weights can be combined with the risk premium, as proposed by Kind et al. (2017).

3 The Loss Ledger and Valuation Library

3.1 Accounting Rules

Adding up losses across many assets and channels risks double counting and mixing welfare losses with transfers. The framework imposes four rules.

(i) Declare the accounting stance. Losses are measured from the perspective of the region's residents, firms, and governments. Some regional losses—for example, tourist spending that shifts to a neighboring beach—are transfers from a state or national perspective. We flag such items and report them separately so that users with a national stance (as in federal BCA) can exclude them.

(ii) Separate stocks from flows. Physical damage is a loss of capital stock, valued at repair or replacement cost; lost use (rent, business earnings, recreation) is a flow, valued for the duration of the disruption. Both are counted, but the flow must not be one already capitalized into the stock value used for damage.

(iii) Count value added, not revenue. A closed business also stops buying intermediate inputs, so its social loss is lost value added (wages and profits), not lost revenue. The pilot reports lost revenue, which is an upper bound on lost value added; converting it with industry value-added shares from the BEA input-output accounts is a direct extension.

(iv) Treat input-output spillovers as a bounded channel. Simple input-output multipliers assume no substitution, spare capacity, or inventory, and therefore overstate indirect losses from localized, short disruptions; dynamic models with adaptive behavior find much smaller—though sometimes non-trivial—losses (Rose 2004; Hallegatte 2008). We report supply-chain spillovers as a separate line, computed as an upper bound, so that they can be excluded from a conservative BCR.

3.2 Asset Classes, Loss Channels, and Methods

Table 2 summarizes the ledger. Rows are asset classes that appear in essentially any developed coastal or riverine floodplain; columns list the loss channels, who bears them, and the method we use to quantify them. Assets not quantified in the Santa Cruz pilot—beaches, parks, roads, agriculture, ports, utilities, wharves, military installations, historic and cultural sites, and wetlands—are included so the table can serve as a checklist for other applications.

Table 2: Loss ledger: asset classes, loss channels, bearers, and valuation methods

Asset class	Loss channels	Main bearers	Valuation method (data)
Residential structures	Structure and contents; lost rent during repair; tenant relocation	Owners, landlords, tenants, insurers	Depth-damage functions (Hazus/FAST, NSI); hedonic rent model (listings); 50% substantial-damage rule triggers displacement
Commercial and industrial structures	Structure and contents; business interruption; supply-chain spillovers	Owners, businesses, workers, trading partners	Depth-damage and restoration-time functions (Hazus); structure value × rent-to-price ratio ÷ rent-to-revenue ratio; I-O ratios (BEA)
Beaches and dunes	Recreation; amenity; ecosystem services; storm buffer	Visitors, residents, public	Benefit transfer per acre; hedonic amenity premium; beach-area change from shoreline model
Parks, open space	Amenity; recreation	Residents, visitors	Hedonic property-value model (CPAD)
Roads, bridges	Repair; travel delay and detours	Governments, commuters, freight	Unit repair costs per lane-mile (FHWA); value of time × detour hours
Agriculture	Crop, livestock, and income loss; land and equipment	Farmers, farmworkers	Per-acre values and net cash flow (Census of Agriculture), by crop type
Utilities, ports, wharves	Asset damage; service interruption	Utilities, boatowners, ratepayers, port users	Replacement cost; outage costs
Wetlands, reefs	Ecosystem services; protection	Public	Benefit transfer; avoided damage (conservation value)
People	Mortality, injury; displacement; mental health	Residents, workers	VSL and morbidity values; displacement costs

Notes: The Santa Cruz results quantify residential, commercial and industrial structures. Road repair costs are computed but roads lie outside the adaptation study units. Banks, insurers, and credit unions are not listed as separate stakeholders because they are exposed through nearly all private assets; they matter for the risk-bearing split in Section 2.3. A more detailed stakeholder map is in the Online Appendix.

3.3 Residential Structures

Direct damage follows FEMA's Hazus flood methodology (Federal Emergency Management Agency 2024b). Structure and content values and occupancy come from the National Structure Inventory (NSI; U.S. Army Corps of Engineers 2022), and depth-damage functions from FEMA's Flood Assessment Structure Tool (Federal Emergency Management Agency 2022) map inundation depth to the damaged share of each value by occupancy type. A building whose damage equals or exceeds 50% of its pre-flood structure value is "substantially damaged" under FEMA rules and must be vacated.[1] Every damaged residential building adds two flow losses. The landlord loses rent during repair, with repair duration taken from Hazus recovery-time tables by occupancy type and flood depth. If the building is substantially damaged, the tenant also pays a one-time relocation cost, set at 1.5 months' rent to reflect typical security deposits. Rents are imputed from a hedonic model,

$$\text{Rent}_j = \alpha + \beta_P \,\text{Price}_j + \beta_A \,\text{Area}_j + \varepsilon_j, \tag{15}$$

[1] https://www.fema.gov/fact-sheet/substantial-damage-quick-guide

estimated on rental listings in Santa Cruz, where Price_j is the asking price and Area_j the floor area of listing j. The coefficients are applied to the structure value and floor area of damaged units in the NSI. The approach transfers to any U.S. location with NSI coverage and listings data.

3.4 Commercial Structures, Business Interruption, and Supply Chain Effects

Commercial and industrial structure and content damage is computed as above. In addition, we compute lost revenue due to business interruption. We estimate monthly rent for each commercial or industrial building as its structure value times a rent-to-price ratio, and impute revenue by dividing rent by an industry rent-to-revenue (occupancy-cost) ratio (Appendix Table 16). Lost revenue equals imputed monthly revenue times the closure duration implied by flood depth (Hazus restoration-time tables).

Supply-chain spillovers use the BEA supply-use tables. For a building in industry i with lost revenue X_{ij}, we compute a downstream ratio δ_i (intermediate inputs purchased by i over i's gross output) and an upstream ratio v_i (output of i used as intermediate input by other industries over i's gross output), and bound the spillover by $X_{ij}(\delta_i + v_i)$. This is an upper bound and is reported separately.

3.5 Natural Assets: Beaches, Dunes, and Open Space

Natural assets generate three kinds of value that adaptation can affect: use value to visitors (recreation), amenity value to nearby residents, and ecosystem services. We measure recreation and ecosystem values per acre by relying on California studies (King et al. 2009; Pendleton et al. 2011). We compute amenity value using a hedonic model of property prices on proximity to protected open space (from the California Protected Areas Database),

$$\ln P_j = \alpha + \boldsymbol{\beta}_1' \mathbf{S}_j + \beta_2 \,\text{Proximity}_j + \varepsilon_j. \tag{16}$$

To avoid double counting, hedonic amenity values are attributed to residents and benefit-transfer recreation values only to visitors.

3.6 Public Infrastructure and Agriculture

Roads are valued at engineering repair costs per lane-mile, choosing resurfacing or reconstruction by inundation depth (Federal Highway Administration 2015). Detour and delay costs can be added using value-of-time guidance but are excluded from the pilot because of the uncertainty in rerouting, which at the first pass appears non-material in our pilot study areas. Agricultural losses combine per-acre land and building values, equipment values, and annual net cash flow from the Census of Agriculture, adjusted for whether flooding destroys an annual or perennial crop. In the pilot study area there are no sizable livestock operations, thus value of livestock losses is not included.

3.7 Co-Benefits and Dis-Benefits of Adaptation Measures

Adaptation measures change the landscape even in years without floods. Restored dunes and reefs add habitat and recreational value; seawalls fix the shoreline, so that as sea level rises the beach in front of them narrows and eventually disappears ("passive erosion"; Griggs 2005). Because beach value per acre is large relative to many structures, this dis-benefit can be first-order for armoring projects. The framework includes these in $E_a(t)$ in equation (13), valuing the change in beach and dune area $\Delta A_a(t)$ at the per-acre recreation and ecosystem value v: $E_a(t) = v\,\Delta A_a(t)$.

3.8 Health and Mortality

The ledger includes mortality and morbidity, valued with the value of a statistical life and of morbidity, but we report them separately from the monetized property and income ledger for two reasons. First, flood mortality in the California study regions is low, and the numbers are highly sensitive to the VSL chosen (Viscusi and Aldy 2003). Second, when health losses are monetized and non-pecuniary losses are not fully counted (for example, non-pecuniary losses from displacement), putting a large VSL-based number beside an incomplete property ledger distorts the comparison between categories. For heat and wildfire smoke, where health is the dominant channel, this issue becomes more important.

4 Beyond Coastal Flooding: Generalizing the Framework

Nothing in Sections 2–3 is specific to coastal flooding. Applying the framework to another hazard requires three substitutions: a hazard model that produces intensity fields $h_k(e, a, t)$ for a set of return periods or scenarios, with and without the adaptation option; the loss channels that matter for that hazard; and the corresponding damage response functions. The loss-distribution machinery (equations 3–4), the option-price decomposition (equation 6), discounting, co-benefits, and distributional weights carry over unchanged. Table 3 gives the mapping for the hazards most often targeted by U.S. adaptation funding.

Table 3: Applying the framework to other climate hazards

Hazard	Hazard model output	Dominant loss channels	Valuation methods	Example adaptation
Coastal flooding (pilot)	Depth and duration by return period (CoSMoS-Adapt)	Structures, business interruption, displacement, beaches, roads	Depth-damage; hedonic rent; rent-to-revenue; I-O; benefit transfer	Seawalls, dunes, reefs, managed retreat
Riverine / pluvial flooding	Depth and velocity by return period (HEC-RAS, FEMA flood maps)	Structures, business interruption, agriculture, roads, utilities	Same as coastal; crop-calendar adjustments, livestock losses	Levees, floodplain restoration, green stormwater infrastructure
Extreme heat	Temperature and heat-index distribution by scenario	Mortality, morbidity, labor productivity, energy demand	Dose-response for mortality (Carleton et al. 2022); labor supply (Graff Zivin and Neidell 2014); VSL	Urban tree canopy, cool roofs, cooling centers
Wildfire and smoke	Burn probability and intensity; $PM_{2.5}$ exposure	Mortality, health (smoke), structures, business interruption, ecosystems	Structure loss functions; $PM_{2.5}$ dose-response and VSL; I-O	Fuel treatment, defensible space, home hardening

Two differences across hazards deserve emphasis. First, for heat and smoke the health channel dominates, so the treatment of mortality valuation (Section 3.8) is central rather than peripheral. Second, the relevant "event" may be a season rather than a storm, but the framework only requires an annual loss distribution, which can be built from seasonal simulations.

5 Pilot Application: Coastal Storm Flooding in California

In our pilot, we use $H = 30$ years, matching typical adaptation-pathway planning cycles. Our central discount rate is a real 2%, consistent with current estimates of the social rate of time preference, the 2023 revision of Circular A-94, and the rate used by EPA for the social cost of carbon (Office of Management and Budget 2023; U.S. Environmental Protection Agency 2023). We also report 3% and 7%. The 7% rate matters for practice because, since April 2025, federal guidance has reverted to the 1992 Circular A-94 and FEMA requires 7% for hazard-mitigation eligibility (Office of Management and Budget 1992; Association of State Floodplain Managers 2025). It is, however, hard to justify as a social rate of time preference when long-term real Treasury yields are near 2%. Because adaptation benefits rise over time due to climate change, BCRs are sensitive to both the rate and the horizon. A longer horizon with declining discount rates (Arrow et al. 2013; Drupp et al. 2018) would favor measures with low depreciation rates and growing benefits, such as dunes. We report the horizon at which each measure breaks even as an additional robustness metric.

5.1 Study Sites

We implement the framework as the economic component of a pilot for California's Fifth Climate Change Assessment. The pilot covers three coastal regions chosen to span the state's main coastal settings. This paper reports results for Santa Cruz County (Figure 1). Santa Cruz County (the cities of Santa Cruz and Capitola and unincorporated county) has dense residential and commercial development behind beaches and existing armoring, with varied geomorphology.



Figure 1: Study site: Santa Cruz County, California.

5.2 Hazard Scenarios

Flood hazard comes from CoSMoS-Adapt, an extension of the USGS Coastal Storm Modeling System (Barnard et al. 2014, 2019) designed to evaluate specific adaptation projects. Extreme-value analysis of a downscaled California wave dataset gives offshore wave and water-level conditions for storms with 5-, 20-, 50-, and 100-year return periods (Appendix Table 17). Future conditions add sea-level rise from the state's 2024 guidance (California Ocean Protection Council 2024) and non-stationary changes in extreme waves from CMIP6 projections. The storms are simulated with 2-D XBeach models at resolutions of 2–20 m, both in a hydrodynamic mode and in a morphodynamic mode that lets the beach and dunes erode during the storm. For 2055 and 2085 horizons, the model topography is updated with long-term shoreline change from CoSMoS-COAST (Vitousek et al. 2017). The output is a flood-depth raster for every combination of epoch (2025, 2055, 2085), return period, and adaptation scenario. Our results use the morphodynamic runs, with topography updated for long-term shoreline change in 2055 and 2085.

The model was benchmarked against the January 2023 and December 2024 "bomb swell" events in Santa Cruz. Both produced offshore waves of about 6 m but very different flooding, because the 2023 event coincided with high tide and the 2024 event with low tide. The contrast illustrates why damage must be modeled from the joint distribution of waves and water levels rather than from wave height alone.

5.3 Adaptation Scenarios

The adaptation options are representative of projects proposed in California adaptation plans, such as the City of Santa Cruz's Resilient Coast program. Each measure is placed in reaches that are at high risk in the no-adaptation baseline and that meet typology-specific suitability criteria.

- *Seawalls and rock armoring* are placed along the existing non-erodible back-beach line, with crest height set to the local 50-year 99th-percentile water level plus 0.5 m.
- *Dune restoration* uses a standard cross-section (2 m above the existing berm, 6 m crest, 12 m base) placed 16 m seaward of the back-beach line. Dunes are erodible in the morphodynamic runs.
- *Submerged reefs* have a uniform 1.5 m crest above the seabed, 10 m crest width, and 15 m base, and are placed just seaward of the mapped wave-breaking zone of the 50-year storm.
- *Beach recharge (nourishment)* restores the shoreline to its 2025 position in future epochs. It was modeled in Santa Cruz but is not included in the benefit-cost results below.

Benefits and costs are evaluated for "adaptation study units," the shoreline sections that a single project would protect, rather than for the whole coastline. Santa Cruz has eleven study units, from Seabright to New Brighton. Ten enter the benefit-cost analysis; Sunny Cove is excluded because its total damage from the 50-year storm in 2025, without adaptation, is below $0.5 million. Dunes are not placed at Pleasure Point, reefs not at Sunny Cove, and seawalls not at Seabright and Sunny Cove.

5.4 Implementation of the Valuation Library

For real estate, we augement the National Structure Inventory (structure and content values, occupancy, foundation type, stories, and residents and workers, including those aged 65 and over) with Microsoft building footprints. Structures missing from the NSI but visible in 2025 satellite imagery are assigned values from the nearest NSI point within 50 m. Where several NSI points fall in one footprint, as in mixed-use buildings or condominiums, each is assigned the footprint's average flood depth and evaluated with its own damage function. NSI values (2021 prices) are converted to 2025 dollars with a CPI-U factor of 1.19. Flood rasters for each scenario and return period are intersected with the inventory, and the channels in Table 2 are computed building by building. The pilot quantifies lost rent for all damaged residential buildings and lost revenue for

all damaged commercial and industrial buildings. The Santa Cruz results cover buildings only: road damage is computed but lies outside the adaptation study units, and beaches and agriculture are not yet valued. Parameter values are in Table 4, and details are in Appendix A.

Table 4: Pilot parameter values by asset class (2025 USD)

Asset class	Key parameters	Sources
Residential	NSI structure and content values; hedonic rent model (92 Santa Cruz listings); relocation = 1.5 × monthly rent if substantially damaged	NSI; FEMA FAST; Zillow listings
Commercial and industrial	Monthly rent = structure value × rent-to-price ratio (8.61% a year commercial, 7.38% industrial); rent-to-revenue ratios 7.5% (commercial) and 4% (industrial); I-O ratios δ_i, v_i	LoopNet; broker sources (Table 16); BEA supply-use tables
Valuation library (not in the Santa Cruz results)		
Beaches	\$89,452 per acre per year (recreation \$59,233 + ecosystem \$1,619 in 2010 USD, ×1.47)	King et al. (2009)
Roads	Resurfacing \$2.7M/mile; reconstruction \$9.5M/mile (4 lanes)	Federal Highway Administration (2015)
Agriculture	Land and buildings \$38,401/acre; net cash flow \$654/acre/yr (2022 USD)	2022 Census of Agriculture

5.5 Adaptation Costs

Unit costs come from engineering and planning studies, are converted to 2025 dollars (Appendix Table 18), and are applied to the length and cross-section of each project. Table 5 reports the full cost library, including measures not modeled in the pilot, so that it can be applied more broadly.

Table 5: Unit costs of adaptation measures (2025 USD)

Measure	Cost per unit	Source
Modeled in pilot		
Seawall	\$11,150 per linear ft at 1.52 m (5 ft) to \$40,000 at 4.57 m (15 ft), ×1.06 to 2025 dollars (\$38,776–\$139,108 per m), interpolated by wall height	(Heberger et al. 2009; King et al. 2009)
Dune restoration	\$5,000 per linear ft (upper bound of NOAA range), ×1.25 to 2025 dollars (\$20,505 per m)	NOAA Office for Coastal Management (2020)
Submerged (rocky) reef	\$2,000 per linear ft, ×1.39 to 2025 dollars (\$9,121 per m)	Rella and Miller (2014); University of New South Wales Water Research Laboratory (2013)
All three measures: maintenance 5% of construction cost per year over 30 years		
Cost library (not modeled in pilot)		
Beach nourishment	\$1.64M per mile + \$548,375 per mile per year; \$14.70 per m^3	Colgan et al. (2020); King et al. (2009)
Levees	New: \$2,820 per linear ft; raising existing: \$996 per linear ft	Heberger et al. (2009)
Groins	150-ft groin: \$1.81M–\$3.04M initial + \$11,562 per year	Colgan et al. (2020)
Managed retreat	\$5.6M–\$26M per mile	Colgan et al. (2020)

Seawalls Per-foot costs are interpolated linearly by wall height between \$11,150 per foot at 1.52 m (5 ft) and \$40,000 per foot at 4.57 m (15 ft), and converted to 2025 dollars with a factor of 1.06. Walls lower or higher than this range are costed at its nearest end. In the pilot, maintenance is 5% of construction cost per year for all three measures. The pilot omits the long-run loss of beach in front of walls, which would lower seawall BCRs (Section 3.7).

Dune restoration NLSP levee schedules for earthen embankments with 3:1 slopes imply only about \$651 per meter of dune at 2 m height, well below NOAA's \$2,000–\$5,000 per linear foot for installation plus \$100–\$500 per foot per year for maintenance, which includes design, engineering, materials, and equipment (NOAA Office for Coastal Management 2020). We use the top of the NOAA range, \$5,000 per foot, converted to 2025 dollars with a factor of 1.25 (\$20,505 per meter). Dune BCRs are therefore conservative. The pilot does not include the cost of rebuilding dunes after storm erosion.

Submerged reefs Rock for the 11.25 m^2 design section costs about \$351 per meter in 2025 dollars at \$97 per ton (Rella and Miller 2014). Engineered submerged breakwaters cost \$1,500–\$5,000 per meter (University of New South Wales Water Research Laboratory 2013). The pilot uses \$2,000 per linear foot, converted to 2025 dollars with a factor of 1.39 (\$9,121 per meter).

6 Pilot Results: Santa Cruz

We build up the benefits of adaptation in layers. We start with direct physical damage, the benefit that standard BCA measures (Section 6.1). We then add what owners would pay to reduce the risk of severe storms (Sections 6.2 and 6.3), and finally the losses that storms impose beyond the buildings themselves (Section 6.4). Section 6.5 compares each layer with the costs of the measures.

6.1 Direct Damages and Their Reduction by Adaptation

Without adaptation, direct expected annual damage to structures and contents in Santa Cruz is $44.4 million per year in 2025, rising to $52.5 million in 2055 and $72.6 million in 2085 (Table 6; Figures 2–3). Most of the increase comes after 2055. Risk is highly concentrated. The Santa Cruz Beach Boardwalk area accounts for $20.3 million and Capitola for $16.6 million of present-day direct EAD. For the 100-year storm, direct damage of $233 million rises to $328 million by 2085.

Table 6: Direct expected annual damage and benefits by adaptation measure, Santa Cruz ($ millions per year, 2025 USD)

	2025	2055	2085
Panel A. Direct expected annual damage			
No adaptation	44.4	52.5	72.6
Dune	36.6	43.7	65.2
Reef	42.6	51.7	70.9
Seawall	8.0	10.0	31.6
Panel B. Direct expected annual benefit (ΔEAD)			
Dune	8.0	9.5	8.3
Reef	1.8	1.0	1.8
Seawall	36.4	42.5	41.1
Panel C. Share of no-adaptation direct damage avoided (%)			
Dune	18	18	11
Reef	4	2	3
Seawall	82	81	57

Note: Direct damage is damage to structures and contents. EAD from equation (2). Benefits are computed for each study unit in which the measure is placed and summed.

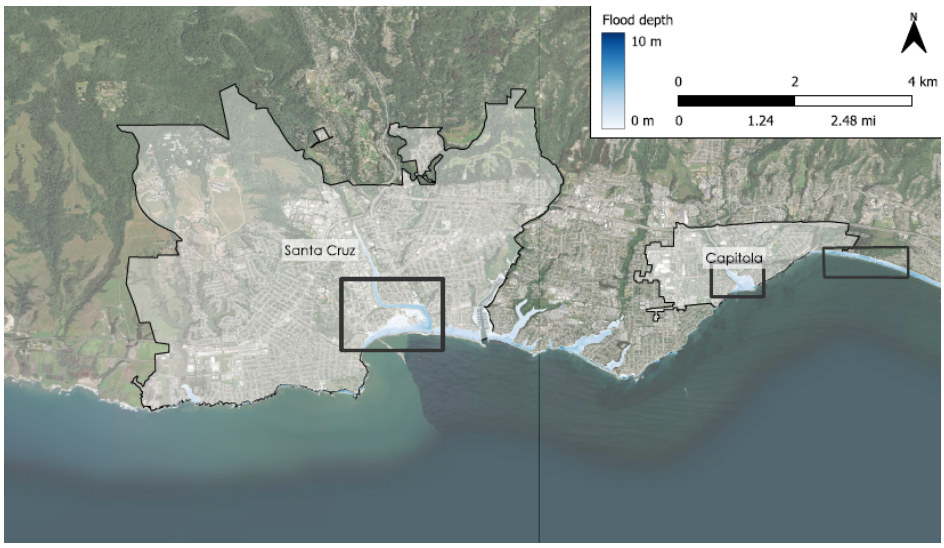


Figure 2: Present-day flood hazard (100-year return period), Santa Cruz, no adaptation.

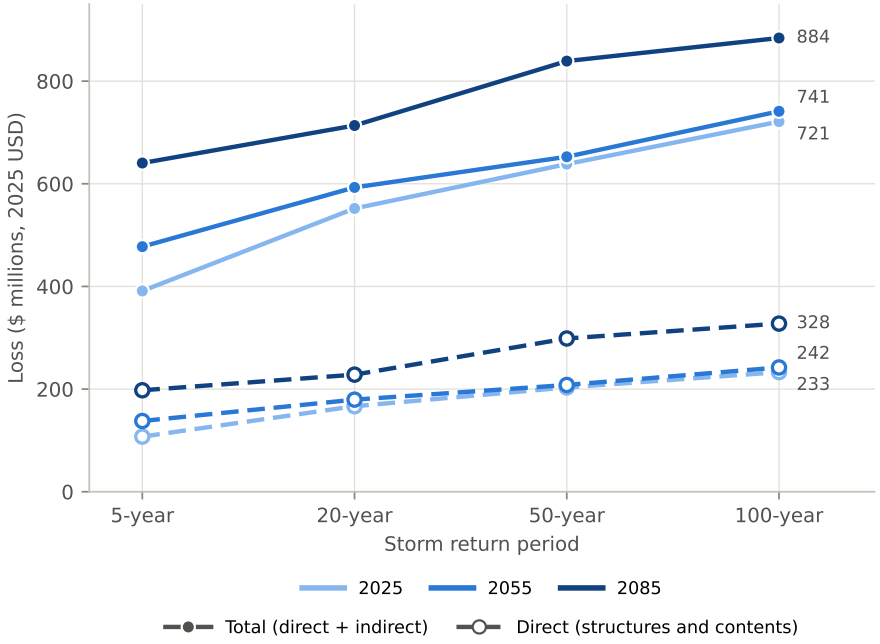


Figure 3: Losses by return period in 2025, 2055, and 2085, Santa Cruz, no adaptation ($ millions, 2025 USD). Solid lines show total losses (direct and indirect); dashed lines show direct damage to structures and contents.

Seawalls deliver the largest avoided damages (Figure 4). They cut direct EAD by 82% in 2025 (from $44.4 million to $8.0 million). Their protection erodes as fixed-height structures are overtopped more often: for the 100-year storm, seawalls reduce direct damage by 52% today but by only 27% in 2085, and residual direct EAD behind them rises nearly fourfold, from $8.0 million to $31.6 million.

Dunes reduce direct EAD by 18% in 2025. Higher water levels increasingly overtop dunes: avoided direct EAD stays between $8 million and $9.5 million per year, and the reduction in the 100-year loss falls from 3% to 1%. Submerged reefs reduce present-day direct EAD by about 4%, because breaking waves offshore does less to reduce flooding than a barrier at the shoreline. The report notes that reef benefits from reduced long-term erosion are not yet captured. These benefits could be added through the beach-area channel in Section 3.7.

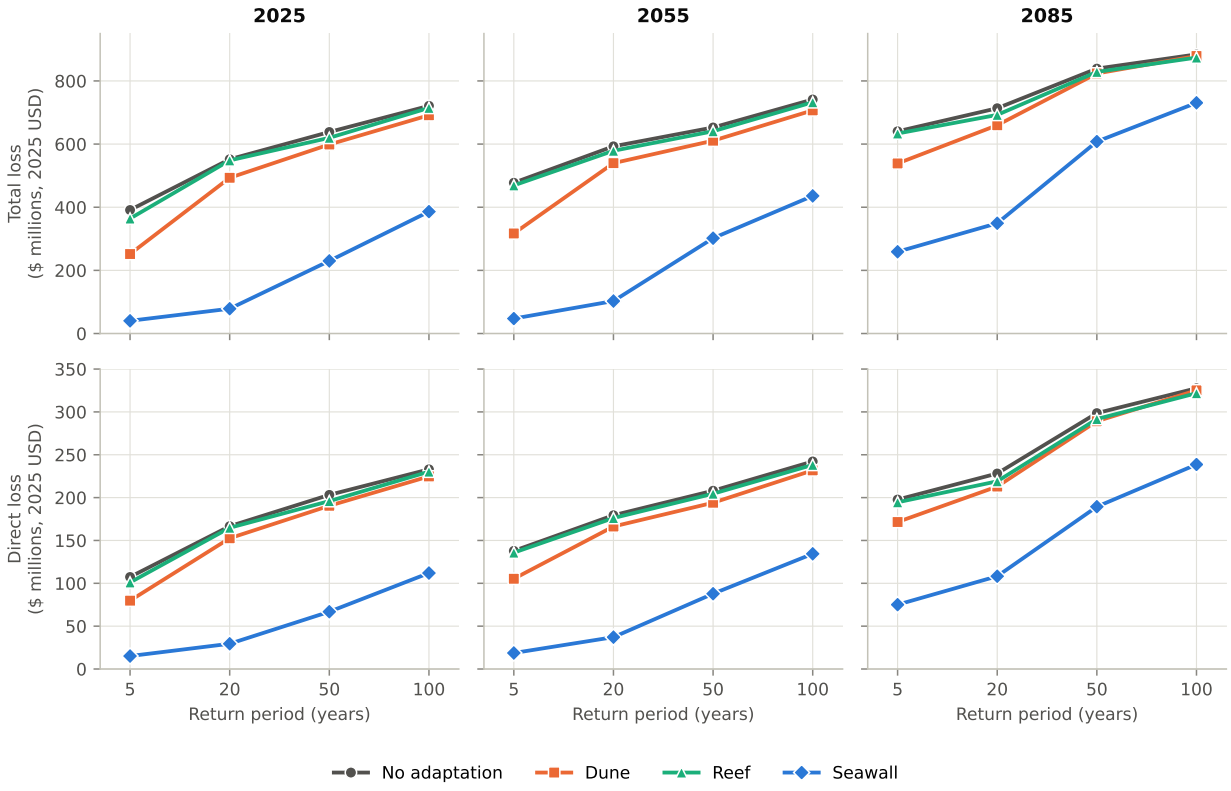


Figure 4: Losses by return period under each adaptation option, Santa Cruz, 2025, 2055, and 2085 ($ millions, 2025 USD). Top: total losses (direct and indirect). Bottom: direct damage to structures and contents.

6.2 Willingness to Pay for Risk Reduction

The benefits in Table 6 are expected values and therefore assume that affected individuals are indifferent between a certain loss and an uncertain loss with the same mean. We now relax this assumption using the loss distributions and the willingness to pay derived in Sections 2.2 and 2.3. We consider the owners of the 588 buildings in the ten study units damaged by at least one storm under no adaptation, and ask how much they would be willing to pay to reduce the probability of a severe storm damaging their properties. W is the value of these buildings, structures and contents, $706 million in 2025 dollars, and losses are their physical damage as a share of W.

Figure 5 shows the fitted Pareto curves. The dashed lines mark the loss levels $x_5, \ldots, x_{100}$

caused by the four storms under no adaptation. With no adaptation, the 100-year storm damages about a third of the value of the affected buildings at 2025 and 2055 sea levels and 46% by 2085. Each adaptation curve lies below the no-adaptation curve at these loss levels, so every measure lowers the probability of every loss.

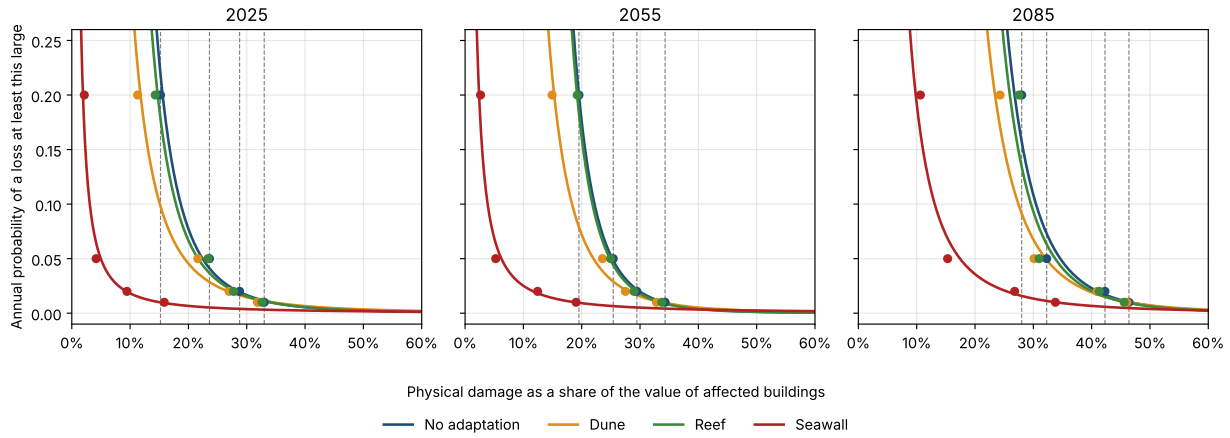


Figure 5: Fitted Pareto Loss Distributions, Santa Cruz

Note: Dots show the 5-, 20-, 50- and 100-year storms. Loss is physical damage as a share of the value of affected buildings, and probability is one over the return period. Lines show the fitted Pareto curves (equation (3)), which start at an annual probability of one half; the vertical axis is cut at 0.25. Dashed lines mark the losses $x_5, \ldots, x_{100}$ under no adaptation.

Table 7 shows this for a loss as large as that of the 50-year and 100-year storm. Seawalls lower the annual probability the most, to 0.4% for a 50-year storm and 0.3% for a 100-year storm at 2025 sea level and to 0.6% for a 50-year storm and 0.46% for a 100-year storm by 2085. Dunes and reefs lower it only marginally, especially for a 100-year storm.

Table 7: Annual Probability of a Loss at Least as Large as the 50- and 100-Year Storms' (pVaR, %)

	Loss $\geq x_{50}$			Loss $\geq x_{100}$		
	2025	2055	2085	2025	2055	2085
No adaptation	1.93	2.17	1.70	1.15	0.96	1.03
Dune	1.64	1.65	1.49	1.12	0.93	0.99
Reef	1.80	1.98	1.51	1.10	0.87	0.93
Seawall	0.39	0.52	0.58	0.32	0.42	0.46

Note: $\text{pVaR}_s(x_{50})$ and $\text{pVaR}_s(x_{100})$ from equation (4). Each row gives its corresponding p_A.

Table 8 reports the resulting willingness to pay. The first column is the WTP of a risk-neutral owner, equal to the reduction in expected tail damage; the other columns add risk aversion. The risk-neutral WTP differs from the direct benefit in Table 6 because it counts only losses at least as large as the 5-year storm's under no adaptation, each valued at the bottom of its range. In

2025, owners would pay $29.8 million per year for the risk reduction a seawall delivers under CRRA preferences with $\gamma = 2$, 17% more than the $25.4 million reduction in expected tail damage. Accounting for risk aversion raises WTP by 11–36% with $\gamma = 2$ and 16–58% with $\gamma = 3$, and by 10–26% and 20–52% under mean-variance preferences with $A = 2$ and $A = 4$.

Table 8: Willingness to Pay for Risk Reduction, Santa Cruz ($ millions per year)

		Risk	CRRA		Mean-variance	
Strategy	Year	neutral	$\gamma = 2$	$\gamma = 3$	$A = 2$	$A = 4$
Dune	2025	13.9	15.6 (12%)	16.4 (18%)	15.4 (11%)	16.9 (22%)
	2055	17.6	20.6 (17%)	22.2 (26%)	20.2 (15%)	22.8 (30%)
	2085	13.9	17.8 (28%)	19.8 (43%)	17.0 (22%)	20.1 (45%)
Reef	2025	4.7	5.2 (11%)	5.5 (16%)	5.2 (10%)	5.7 (20%)
	2055	2.5	2.9 (17%)	3.2 (25%)	2.9 (14%)	3.2 (29%)
	2085	5.0	6.5 (29%)	7.2 (44%)	6.2 (22%)	7.3 (45%)
Seawall	2025	25.4	29.8 (17%)	32.3 (27%)	29.0 (14%)	32.7 (29%)
	2055	28.6	34.6 (21%)	38.1 (33%)	33.5 (17%)	38.5 (35%)
	2085	30.8	41.7 (36%)	48.5 (58%)	38.8 (26%)	46.8 (52%)

Note: Risk-neutral WTP equals the reduction in expected physical tail damage, from losses at least as large as the 5-year storm's under no adaptation. Percentages in parentheses give the increase over risk-neutral WTP.

The premium grows as sea levels rise, because the losses being avoided become a larger share of the buildings' value. It is largest for seawalls, which lower the probability of large losses the most, and reaches 36–58% under CRRA preferences by 2085.

6.3 Direct Damages and the Tail Risk Premium

Table 9 adds the risk premium to direct damages, using CRRA preferences with $\gamma = 2$. Without adaptation, owners bear a tail risk premium of $5.0 million per year in 2025 on top of $44.4 million of expected direct damage. By 2085 the premium reaches $13.4 million: it grows by 169%, against 64% for expected direct damage, because the losses being avoided become a larger share of the buildings' value. Adaptation removes part of this premium. The avoided tail risk premium adds 12–27% to the direct benefits of seawalls, 21–47% to those of dunes, and 29–79% to the small direct benefits of reefs, with the largest additions by 2085.

Table 9: Direct damage and the tail risk premium, Santa Cruz ($ millions per year, 2025 USD)

		2025	2055	2085
Panel A. No adaptation				
	Direct EAD	44.4	52.5	72.6
	Tail risk premium	5.0	6.9	13.4
	Direct EAD + tail risk premium	49.4	59.4	86.0
Panel B. Expected annual benefit				
Dune	Direct	8.0	9.5	8.3
	+ Avoided tail risk premium	9.7	12.5	12.2
Reef	Direct	1.8	1.0	1.8
	+ Avoided tail risk premium	2.3	1.4	3.3
Seawall	Direct	36.4	42.5	41.1
	+ Avoided tail risk premium	40.9	48.6	52.0

Note: Rows in Panel B are cumulative. The tail risk premium is the certainty-equivalent loss minus the expected loss over the five outcomes in Table 1, with CRRA utility, $\gamma = 2$ and $W = \$706$ million. The avoided tail risk premium is the CRRA ($\gamma = 2$) WTP minus the risk-neutral WTP in Table 8.

6.4 Lost Rent, Business Revenue, and Supply-Chain Costs

Storms do damage not only to structures and contents. They also force tenants to relocate, cost landlords rent and businesses revenue while buildings are repaired, and spread losses to suppliers and customers. Adding these channels raises expected annual damage without adaptation from $44.4 million to $154.1 million in 2025, and to $229.5 million by 2085 (Table 10). Lost rent and business revenue is the largest component, 44% of the total in 2025. For the 100-year storm, total losses are $721 million in 2025, roughly three times direct damage, and $884 million by 2085.

Table 10: Expected annual damage without adaptation, Santa Cruz ($ millions per year, 2025 USD)

	Physical	Tail risk premium	Lost rent and revenue	Supply chain	Total EAD	Total EAD + tail risk premium
2025	44.4	5.0	67.6	42.1	154.1	159.1
2055	52.5	6.9	77.4	47.6	177.6	184.4
2085	72.6	13.4	97.7	59.2	229.5	242.9
Change	+64%	+169%	+45%	+41%	+49%	+53%

Note: EAD from equation (2). Total EAD is physical damage plus lost rent and revenue plus supply-chain costs. Lost rent includes tenant relocation costs. Supply-chain costs are lost revenue multiplied by industry-specific input–output multipliers. Change is from 2025 to 2085. The tail risk premium applies to physical damage only, as in Table 9.

Indirect losses raise the benefits of every measure (Table 11). Avoided damages rise from $8.0 million to $37.9 million per year for dunes and from $36.4 million to $131.4 million for seawalls in

2025. With the avoided tail risk premium, total benefits are three to five times the direct benefits that standard BCA counts.

We do not apply a risk premium to these indirect losses. Lost rent and business revenue can be insured through loss-of-rents and business-interruption cover and unemployment benefits, and supply-chain losses are spread across many firms and their customers, so we assume these losses to be diversified and their social risk premium approaches zero (Arrow and Lind 1970). We keep them at their expected value, and the risk premia in Tables 10 and 11 are therefore a lower bound.

Table 11: Expected annual damage and benefits by adaptation measure, Santa Cruz ($ millions per year, 2025 USD)

		2025	2055	2085
Panel A. Expected annual damage				
No adaptation		154.1	177.6	229.5
Dune		116.5	135.6	201.5
Reef		147.2	174.1	225.8
Seawall		22.7	28.1	105.5
Panel B. Expected annual benefit				
Dune	Direct	8.0	9.5	8.3
	+ Avoided tail risk premium	9.7	12.5	12.2
	+ Lost rent, revenue and supply chain	39.6	46.4	33.1
Reef	Direct	1.8	1.0	1.8
	+ Avoided tail risk premium	2.3	1.4	3.3
	+ Lost rent, revenue and supply chain	7.4	4.0	5.3
Seawall	Direct	36.4	42.5	41.1
	+ Avoided tail risk premium	40.9	48.6	52.0
	+ Lost rent, revenue and supply chain	135.8	155.9	135.0
Panel C. Share of no-adaptation damage avoided (%)				
Dune		25	24	13
Reef		4	2	2
Seawall		85	84	54

Note: Rows in Panel B are cumulative: each adds one component to the row above. The last row equals EAD without adaptation minus EAD with the measure, plus the avoided tail risk premium. Benefits are computed for each study unit and summed. The avoided tail risk premium is computed as in Table 9. Panel C uses EAD only.

6.5 Present Values, Break-Even Costs, and Benefit-Cost Ratios

Table 12 reports the present value of expected avoided damage over 30 years in Santa Cruz. This is also the break-even cost: the most that could be spent on each measure before BCR falls below one. At our central 2% rate, seawalls avoid $3.0–3.2 billion in damages, dunes $0.9 billion, and reefs $0.1–0.2 billion. At 7%, the figures are 42% lower. Letting benefits follow the projected EAD

path raises dune and seawall present values by about 6% and lowers reef present values by a fifth, because reef benefits fall after 2025.

Table 12: Present value of expected avoided damage over 30 years, Santa Cruz (break-even cost; $ millions, 2025 USD)

	Constant 2025 benefit			Time-varying benefit		
	$r = 2\%$	$r = 3\%$	$r = 7\%$	$r = 2\%$	$r = 3\%$	$r = 7\%$
Dune	865	764	503	919	810	526
Reef	157	139	91	125	112	77
Seawall	3,002	2,653	1,745	3,184	2,805	1,824

Note: Computed from Table 11 (EAD only). "Constant" applies the 2025 benefit in every year, with the first year undiscounted (annuity factors 22.84, 20.19, and 13.28 at 2%, 3%, and 7%). "Time-varying" interpolates benefits linearly between 2025 and 2055. Excludes the risk premium and co-benefits.

Figure 6 shows the distribution of present values across adaptation study units, and Figure 7 the site-level BCRs. Although dunes avoid less damage, their BCRs are higher than those of seawalls because of their much lower unit costs. The site-level dune BCR is 3.4 in 2025 and 3.9 in 2055, and falls to 2.6 by 2085 as higher water levels overtop dunes. Seawall BCRs are 2.5–3.0. Reefs pass the test only at present sea levels, with a BCR of 1.2 in 2025, and fall to about 0.6 thereafter. These results use a 7% discount rate and conservative dune costs, and they ignore passive erosion in front of seawalls. Correcting these assumptions would widen the gap between dunes and seawalls.

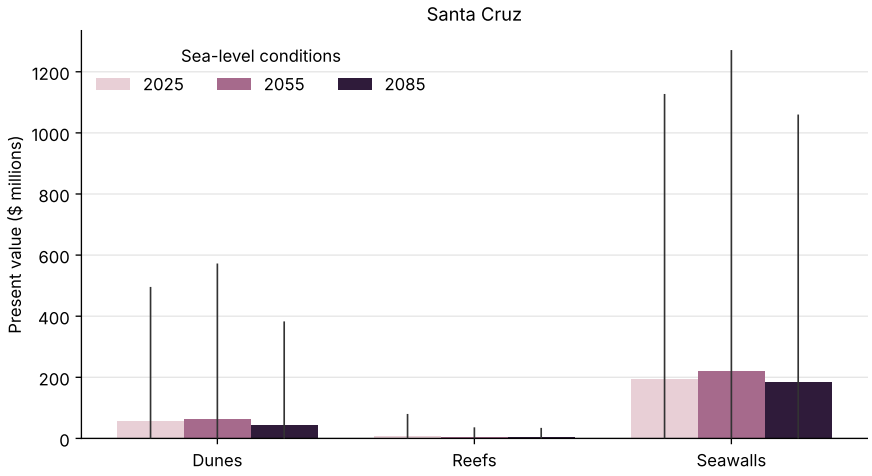


Figure 6: Present value of avoided damages per adaptation study unit, by measure and period, Santa Cruz ($r = 7\%$, 30 years, constant benefits). Bars are means across the study units where the measure is placed; whiskers show the range.

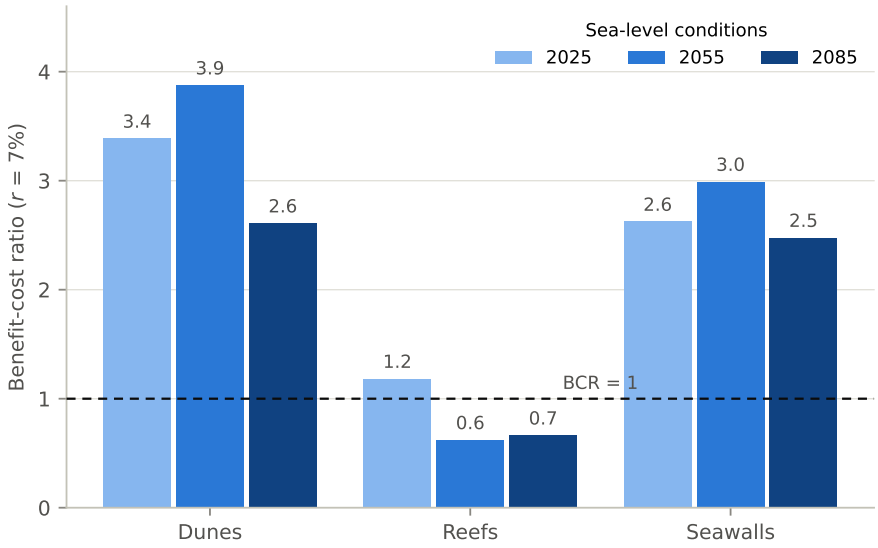


Figure 7: Benefit-cost ratios by measure and period, Santa Cruz ($r = 7\%$, 30 years). Each bar is the total present value of avoided damage across the study units where the measure is placed, divided by its total cost. The dashed line marks BCR $= 1$.

Table 13 shows how each layer of benefits changes the decision. Valued on direct damage alone, no measure passes a benefit-cost test at 7%: BCRs are 0.7–0.9 for dunes and seawalls and 0.2–0.3 for reefs. Adding the avoided tail risk premium raises them by 12–29% in 2025 and by 27–79% in 2085, enough to lift dunes and seawalls to about one in 2055 and 2085. Adding lost rent, business revenue and supply-chain costs lifts BCRs to three to five times their direct-damage values, and dunes and seawalls then pass in every period.

Table 13: Benefit-cost ratios by layer of benefits, Santa Cruz ($r = 7\%$)

Measure	Year	Direct	+ Avoided tail risk premium	+ Lost rent, revenue and supply chain
Dune	2025	0.71	0.87	3.54
	2055	0.85	1.12	4.15
	2085	0.74	1.09	2.96
Reef	2025	0.31	0.40	1.27
	2055	0.18	0.25	0.69
	2085	0.32	0.57	0.91
Seawall	2025	0.73	0.82	2.71
	2055	0.85	0.97	3.11
	2085	0.82	1.04	2.70

Note: Columns are cumulative and follow Panel B of Table 11. Benefits of each period are held constant over 30 years; costs include construction and maintenance. The avoided tail risk premium uses CRRA utility with $\gamma = 2$. Without it, the BCRs in the last column are 3.39, 3.88 and 2.61 for dunes, 1.18, 0.62 and 0.66 for reefs, and 2.62, 2.99 and 2.48 for seawalls (Figure 7).

Averages hide large differences along the coast (Table 14). Benefits are concentrated in two study units. Dunes pass a benefit-cost test only at the Boardwalk, where their BCR is 9–13. Seawalls pass at the Boardwalk and Capitola, and reefs at the same two units. Elsewhere BCRs are well below one for all three measures, so armoring and nature-based measures pass in some study units and fail in most others.

Table 14: Benefit-cost ratios by study unit, Santa Cruz ($r = 7\%$)

	Dune			Reef			Seawall		
Study unit	2025	2055	2085	2025	2055	2085	2025	2055	2085
Boardwalk	**11.39**	**13.15**	**8.80**	**4.94**	**2.24**	**2.13**	**7.59**	**8.56**	**7.14**
Capitola	0.51	0.00	0.00	**1.41**	**1.39**	**1.47**	**3.40**	**3.96**	**2.95**
Moran Lake	0.03	0.00	0.00	0.11	0.03	0.08	0.49	0.49	0.87
New Brighton West	0.00	0.00	0.00	0.02	0.00	0.01	0.28	0.35	0.37
New Brighton East	0.00	0.00	0.00	0.00	0.00	0.55	0.23	0.26	0.30
Pleasure Point	–	–	–	0.01	0.02	0.23	0.13	0.13	0.19
Corcoran	0.10	0.09	0.07	0.00	0.09	0.11	0.07	0.07	0.39
Blacks Beach	0.08	0.20	0.00	0.03	0.00	0.00	0.06	0.12	0.02
Twin Lakes	0.02	0.00	0.13	0.03	0.03	0.04	0.01	0.00	0.05
Seabright	0.00	0.04	0.00	0.00	0.08	0.20	–	–	–

Note: EAD-based BCRs, without the risk premium. Bold entries exceed 1. A dash means the measure is not placed in the unit. Sunny Cove is excluded because its 2025 50-year damages are below $0.5 million.

7 Discussion: Limitations and Extensions

Dynamic and general-equilibrium effects Our benefits are partial-equilibrium, one-period losses. Two dynamic channels are omitted. First, disasters can have persistent effects on local output and growth (Hsiang and Jina 2014), so avoided damages understate benefits. Second, adaptation spending itself displaces other investment, public or private. For publicly funded projects this opportunity cost can be approximated by multiplying costs by the marginal cost of public funds (Dahlby 2008), or by comparing projects on their marginal value of public funds (Hendren and Sprung-Keyser 2020); quantitative macro models of adaptation make the same point in general equilibrium (Fried 2022). Both adjustments are straightforward extensions of equation (14).

Stochastic discount factor Our analysis (so far) does not account for the fact that financial value of losses is likely to be higher in the years with heavy storms that lead to substantial damages. In such years, marginal utility of consumption increases and therefore utility value of the losses is higher. This change can be implemented by replacing the present value calculations that use constant discount rate with an asset pricing model.

Non-pecuniary losses The ledger monetizes property, income, and some non-market services, but not the stress, health effects, and disruption of displacement, which studies of household well-being find can be as large as asset losses for poorer households (Hallegatte et al. 2017; Markhvida et al. 2020). Our estimates are therefore conservative for measures that prevent displacement. By the same logic, we report mortality separately rather than adding VSL-based values to an otherwise incomplete ledger (Section 3.8).

Belief heterogeneity and capitalization If flood risk is not fully priced into coastal property values (Bernstein et al. 2019; Bakkensen and Barrage 2022; Gourevitch et al. 2023), hedonic values will change as information improves. This affects the amenity component of benefits and, through property-tax bases, local governments' ability to bear risk.

Transferability The pilot uses national data sources (NSI, Hazus/FAST, BEA) for most channels, which makes it replicable across U.S. jurisdictions. The locally collected inputs—rental listings and commercial rent ratios—are the main barrier to scaling. They can be replaced by national rent indices and meta-analytic benefit-transfer functions at some cost in precision.

8 Conclusion

We develop a framework for valuing the benefits of climate adaptation that is general across hazards and implementable with public data. It rests on four elements: a loss ledger with explicit accounting rules, a valuation library matched to that ledger, a closed-form loss distribution built

from a few hazard-model runs, and an option-price benefit measure that separates avoided expected losses from the avoided risk premium. The California pilot shows that the elements that conventional BCA omits are quantitatively important. Losses beyond direct structural damage are large, restored dunes, which look modest in avoided damage, have the highest benefit-cost ratios, and benefits change with sea-level rise in ways that differ sharply across measures and study units. Pricing the reduction in tail risk adds 12–47% to the direct benefits of dunes and seawalls, with the largest additions as sea levels rise.

Three implications follow for practice. First, agencies can report the break-even cost and the option-price decomposition alongside the conventional BCR at little additional cost, because both follow from hazard runs that are already required. Second, the choice between gray and green adaptation depends on site characteristics—the composition of exposed assets, the wave climate, and the rate of hazard growth—so evaluation at the reach level matters more than general rules about which measure is better. Third, since the risk premium is borne by those who cannot diversify, the social value of adaptation is highest where insurance coverage and fiscal capacity are lowest, which links adaptation appraisal to insurance and adaptation-finance design (Reguero et al. 2020; Kousky 2019).

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Appendix A Valuation Details for the Pilot

A.1 Residential Real Estate

Every damaged residential building loses rent for the repair period. If a building is substantially damaged (structure damage above 50% of structure value), the tenant also pays a one-time relocation cost of 1.5 months' rent, reflecting typical security deposits. Monthly rents are imputed with the hedonic model in equation (15), estimated on 100 Zillow rental listings in Santa Cruz (Table 15). Regressors are the asking price and floor area. Predicted rents are applied to the structure value and floor area of damaged units in the NSI inventory.

Table 15: Hedonic rent regression, Santa Cruz

	Monthly rent ($)
Intercept	1,848.2
Asking price ($)	0.000745
Floor area (sq. ft.)	1.126
Observations	92
R^2	0.76

Note: Ordinary least squares on Zillow rental listings.

A.2 Commercial Real Estate

Business interruption is computed for all commercial and industrial buildings. Monthly rent is structure value times an annual rent-to-price ratio of 8.61% for commercial and 7.38% for industrial buildings, divided by 12. Monthly revenue is rent divided by a rent-to-revenue ratio of 7.5% for commercial and 4% for industrial buildings, within the ranges in Table 16. Lost revenue is monthly revenue times the closure duration in months, which follows Hazus depth-restoration tables by occupancy type.[2]

Table 16: Rent-to-revenue (occupancy-cost) ratios by industry

Source	Industry	Ratio	Reference
Occupier	Retail	5–10%	https://www.occupier.com/blog/lease-to-rent-revenue-ratio
	Office	4–7%	
	Industrial	3–5%	
	Restaurants	6–10%	
Commercial One Brokers	Retail	5–10%	https://commercialonebrokers.com/percentage-of-business-income-spent-on-rent
	Restaurants	6–10%	
	Law firms	15%	
inmall	Fashion retail	8–12%	https://inmall.io/occupancy-cost-ratio-calculator
	Grocery stores	3–5%	
	Restaurants	6–10%	
	Specialty retail	8–15%	

[2]FEMA Hazus Flood Technical Manual: https://www.fema.gov/sites/default/files/documents/fema_hazus-flood-model-technical-manual-5-1.pdf

Supply-chain spillovers use the BEA supply-use tables. Each NSI occupancy type is matched to a BEA industry i, and for that industry:

$$\delta_i = \frac{\text{Intermediate inputs used by industry } i}{\text{Gross output of industry } i}, \tag{A.1}$$

$$v_i = \frac{\text{Output of industry } i \text{ used as intermediate input}}{\text{Gross output of industry } i}. \tag{A.2}$$

The upper bound on spillover losses for building j in industry i with lost revenue X_{ij} is $X_{ij}(\delta_i + v_i)$, so total loss is at most $X_{ij}(1 + \delta_i + v_i)$. Hotels, dormitories and nursing homes (NSI types RES4–RES6) are treated the same way, with lost rent in place of lost revenue.

A.3 Natural Assets

Parks and open space are classified with the California Protected Areas Database, and their amenity value is estimated with equation (16). For beaches, King et al. (2009) value recreation at Ocean Beach, San Francisco, at $3.4 million per year (2010 USD) for 57.4 acres, or $59,233 per acre, and ecosystem services at $1,619 per acre. The total of $60,852 per acre per year (2010 USD) becomes $89,452 in 2025 dollars (factor 1.47).

A.4 Agricultural Land

The 2022 Census of Agriculture for California gives land and building values of $38,401 per acre and annual net cash flow of $50,980 per farm, or about $654 per acre for the average 78-acre farm. Lost profits are applied to inundated farmland, adjusted for annual versus perennial crops and the timing of flooding. Livestock is excluded because densities in the study areas are negligible (fewer than 0.5 cattle per acre).

A.5 Roads

Following Federal Highway Administration (2015) for small urbanized areas, resurfacing costs $485,000 and reconstruction $1,704,000 per lane-mile (2012 USD). With four lanes and a 2012–2025 factor of 1.40, this gives $2.72 million per mile for resurfacing and $9.54 million per mile for reconstruction. As a cross-check, Knutson et al. (2021) estimate recurring repair costs of $33,230 and $153,400 per mile per year under 0.5 m and 1.0 m of permanent inundation.

Appendix B Boundary Conditions and Conversion Factors

Table 17: Offshore storm boundary conditions by return period, Santa Cruz

RP (yr)	H_s (m)	T_p (s)	Dir (°N)	WL (m)
5	6.75	19.20	238	1.297
20	8.06	21.23	238	1.372
50	8.92	22.53	238	1.410
100	9.58	23.48	238	1.437

Note: H_s = significant wave height; T_p = peak period; Dir = mean wave direction; WL = still water level (NAVD88); RP = return period. Present-day (2025) conditions.

Table 18: Price-level conversion factors to 2025 U.S. dollars (CPI-U)

Base year	**Factor**
2000	1.88
2010	1.47
2012	1.40
2014	1.35
2020	1.23
2021	1.19
2022	1.12

Appendix C Stakeholder Map (Online Appendix)

Table 19 lists stakeholders by asset type. It is the checklist used to assign loss bearers in the ledger and to identify which losses are diversified (Section 2.3).

Table 19: Coastal assets and their stakeholders

Asset	**Stakeholders**
Roads, highways, bridges, transit, bike paths	Federal and state agencies; commuters; emergency services; workers and employers who lose access; recreation users
Restaurants, cafes, shops	Owners (independent, franchise, corporate); employees; customers; suppliers and service providers
Hotels	Owners; employees; long- and short-term guests
Wharves and boardwalks	Tenant businesses and employees; boat, tour, and ferry operators; event organizers; Coastal Commission; marine researchers; wildlife
Beaches	State Parks; Coastal Commission; visitors; beachfront and vacation-home owners; adjacent businesses; recreation businesses; universities
Parks, open space, green belts	Park agencies; residents and visitors; event and recreation businesses; farmers; utilities using rights of way; wildlife
Residential properties	Owner-occupiers; landlords; tenants
Utilities (water, wastewater, stormwater, energy, desalination)	Utilities and public-works departments; ratepayers, including hospitals, schools, and emergency services; regulators
Ports, harbors, docks, aquaculture	Port authorities; shipping, fishing, and recreational boating; seafood processors and distributors; U.S. Coast Guard and Navy
Seawalls, revetments, breakwaters	Protected property owners; local governments; construction and dredging firms
Agriculture and ranches	Owners and operators; farmworkers; input suppliers; consumers
Wetlands, estuaries, marine protected areas; cultural and tribal lands; historic buildings; military	Public; tribes; resource agencies; Department of Defense

Note: Banks, credit unions, and insurers are exposed through nearly all private assets and are not listed separately.