On the **Economics of Coastal Adaptation Solutions** in an Uncertain World

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The economics of adaptation to climate change relies heavily on our ability to compare the benefits of adaptation options (ranging from changes in policy to implementing specific projects) with their costs. Since these benefits are derived from damages avoided by any such adaptation, they are critically dependent on the specification of a baseline. In Yohe, et al. (1995) and (1996), for example, estimates of the economic cost to the developed coastline of the United States from sea level rise were provided for two baselines. The first presumed that efficient coastal real estate markets would use *perfect foresight* to internalize impending inundation from rising seas and depreciate the economic value of any structure that would not be protected to zero just as the waters arrived. In the perfect foresight case, therefore, economic damage attributable to sea level rise included only estimates of the value of land that was not protected. These estimates were, in fact, calibrated in terms of the value of inland land because the same efficient market would transfer the location premium of the lost coastal property to adjacent (and more elevated) lots.

While the perfect foresight scenario was anchored squarely on the long economic tradition of working from an efficiency benchmark, it was not as realistic as its *no-foresight* alternative. In this baseline, property owners would maintain their properties until the bitter end (not because they would not anticipate rising seas, but because they could not imagine that government would not protect their holdings). Here, economic damage attributable to sea level rise included the value of abandoned structure that would appreciate over time even as the seas rose. It should be no surprise that narrowly applied adaptation decisions (to protect property or not depending upon whether the discounted cost of protect were lower or higher than the economic damages that would be avoided, for example) were different in many locations across the two baselines. On the whole, therefore, more resources were devoted to protecting property when underlying market inefficiently refused to internalize risk (because adaptation had higher economic value). It followed that estimates of the economic cost of rising seas including the cost of adaptation were significantly higher.

These early results also informed the economics of mitigation, to some degree, because that literature relies heavily on estimates that include adaptation costs and the economic value of residual damages that cannot be avoided. It follows that estimates of the economic value of mitigation, and therefore potentially the level of mitigation that some decision-makers might find palatable, also depend critically on the specification of the adaptation baseline. This, of course, is one of the reasons why it is so important to incorporate adaptation into large scale integrated assessment models.

The current exercise paper reinforces this point in an environment that superimposes stochastic coastal storm events on two alternative sea level rise scenarios. It reports estimates of the value of adaptation to rising sea and associated changes in the character of major coastal storms against two baselines.[1] In the first, decisions are made under assumptions of perfect economic efficiency that are supported by the availability of actuarially fair insurance. Indeed, providing this insurance will proposed as a *policy response* to potential increases in damages associated with coastal storms that can be associated with sea level rise, and its value with and without other adaptations will be evaluated. In the second, perhaps more realistic assumptions about how fundamental market imperfections might significantly impair society's ability to spread risk sustain an exploration of comparable valuations in a "second-best" world in which the policy response has not been implemented.

One *engineering response* (designed for an urban area) and one *environmentally benign response* (designed to exercise natural defenses for a suburban area with coastal marshland) are considered along both baselines (i.e., with and without the *policy response*). It turns out that the metric by which the relative values of these adaptations should be measured will, indeed, depend fundamentally on whether or not the *policy response* is in place. In either case, though, value comparisons are tracked not only in terms of differences in the annual values of various adaptation strategies, but also in terms of potential difference in their optimal timing along observed and/or anticipated sea level rise trajectories.

Section 1 underscores the role of adaptation in responding efficiently to a generic externality problem that includes mitigation as part of the response portfolio; that is, we see why characterizing economic efficiency in either sphere depends critically on achieving efficiency in the other. Section 2 demonstrates why efficiency on the adaptation side of the ledger depends,

[1] It is important to emphasize from the start that changes in the intensity and frequency of coastal storms included in this analysis do not depend on any direct causation from climate change. Their character, from the perspective of a local decision-maker who is worried about how best to respond to the associated risk, will change simply because, for instance, the current 50-year storm anomaly superimposed upon seas that are .3 meters higher in 2055 might look like the current 75-year storm – or the current 100-year storm in some locations.

in circumstances that are marked by persistent inter-annual uncertainty, on the provision of actuarially fair insurance coverage to spread risk. That is, we see why individuals fully insure (i.e., adapt completely) in an uncertain situation involving the potential for economic loss when they have access to such insurance; and we therefore see why providing fair insurance can be proposed as a potentially attractive *policy response*. Given this ability to spread risk effectively, we will see, in particular, that individuals (and by extension communities and other layers of public and/or private jurisdiction) can achieve levels of expected welfare that are as high as possible by fully insuring against losses driven by inter-annual variability along specific climate change scenarios.

Section 3 argues that the results from the first two sections mean that the value of adaptation interventions designed to diminish exposure and/or sensitivity to climate risk (driven by coastal storms and dynamic sea level rise, for example) can be measured either in terms of changes in expected outcomes (assuming that the *policy response* sustains the efficiency baseline because decision-makers take advantage of actuarially fair insurance) or changes in certainty equivalents (along second-best baselines in which the *policy response* has not be implemented). The value of any such intervention will be demonstrably larger in the later case since aversion to risk must then be taken into account. It follows that certain adaptations (in the coastal domain, for example, vegetation preservation, engineering projects, etc) that might not be economically justifiable at some point in time given the availability of perfect insurance markets could produce benefits in excess of costs in the absence of such availability.

Section 3 also includes a thorough illustration of how this theory can be applied to coastal adaptation decisions for one year and one adaptation. Section 4 subsequently reports analogous results for two adaptation options designed for two locations in the Boston area (with and without the insurance policy option) in five year increments through the year 2100 with and without the insurance-based *policy response* in place. Both the illustration in Section 3 and the specific analyses in Section 4 draw heavily from earlier simulation work that is described in Kirshen, et al. (2008). Those simulations allowed us to report estimates of the economic value of alternative adaptation options over time against both baselines. In the *engineering response* case, it also becomes clear that the selection of the baseline (i.e., the implementation of the *policy response* that could actually influence the time at which that adaptation might best be implemented. A final section will also offer some discussion of more general thoughts about context, content, and implication.

1. The Role of Economic Efficiency in Defining the Economic Baseline for Adaptation and Mitigation.

Cropper and Oates (1992; pp 678-682) offer perhaps the simplest context within which to discover the critical role played by adaptation in defining the efficiency baseline against which the value of mitigation would be measured in a first-best world. Their model begins with a production function for some positively valued good given by:

$$X = X\,[L_X, E, Q(E)]$$

where L_X represents labor allocated from a fixed supply $\boldsymbol{L}$ to the production X, E represents the emission of some pollutant, and Q(E) represents the level of ambient pollution created by E.[2] The decision-maker's objective function mimics society's positive valuation of X and negative valuation of exposure to pollution; that is, utility depends positively on the consumption of X and negatively on exposure to pollution after abatement activities are undertaken. Notationally, then, utility is given by:

$$U = U\{X, F[L_E,Q(E)]\}$$

where $F[L_E,Q(E)]$ indicates the level of pollution to which individuals are exposed; note that this exposure depends on the level of pollution, Q(E), and the result of devoting L_E to abatement activity.[3] The decision-maker's problem is to therefore maximize

$$U\{X\,[L_X, E, Q(E)], F[L_E,Q(E)]\}$$

with respect to L_X, L_E, and E subject to a scarcity constraint that limits the supply of labor to $\boldsymbol{L}$; i.e., $L_X + L_E \leq \boldsymbol{L}$.

First-order conditions for this relatively straightforward constrained optimization problem require that

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[2] It is important to note that $\{\partial X/\partial L_X\} > 0$, $\{\partial X/\partial E\} > 0$ and $\{\partial X/\partial Q\} < 0$; that is, the marginal products of labor and emissions are positive, but the marginal product of pollution is negative. In expressing emissions as an input to the production process, the model obscures without loss of generality the link between a commonly viewed input like energy and the emissions involved in its employment. Moreover, higher emissions produce higher levels of pollution, so $\{dQ/dE\} > 0$.

[3] It is also important to note that $\{\partial U/\partial X\} > 0$ and $\{\partial U/\partial F\} < 0$ while $\{\partial F/\partial L_E\} < 0$ and $\{\partial F/\partial Q\} > 0$. In words, the marginal utility of X is positive, the marginal utility of exposure to pollution is negative, the marginal product of labor in *abating* exposure (i.e., in *reducing* exposure) is positive while the marginal product of pollution in creating residual exposure is positive.

L_X: $\{\partial U/\partial X\}\cdot\{\partial X/\partial L_X\} = \lambda$;

L_E: $\{\partial U/\partial F\}\cdot\{\partial F/\partial L_E\} = \lambda$;

E: $\{\partial U/\partial X\}\cdot\{\partial X/\partial E\} + \{\partial U/\partial X\}\cdot\{\partial X/\partial Q\}\cdot\{dQ/dE\} + \{\partial U/\partial F\}\cdot\{\partial F/\partial Q\}\cdot\{dQ/dE\} = 0$;

λ: $\boldsymbol{L} - L_X - L_E = 0$.

The first two conditions combine directly to show that:

$$\{\partial U/\partial X\}\cdot\{\partial X/\partial L_X\} = \{\partial U/\partial Q\}\cdot\{\partial F/\partial L_E\} = \lambda; \qquad (1)$$

i.e., scarce labor should be allocated between production and abatement activities so that the marginal utility value of labor in production is equal to the marginal utility value of labor in abatement. The parameter λ is the constraint multiplier in the constrained optimization; in the solution, it represents the marginal utility value of labor. Equation (1) thereby makes it clear that the value of the last (marginal) unit of labor available is the same regardless of whether it is allocated to producing X or abating exposure. Equation (1) also makes it clear that that *efficient adaptation (abatement activity) must be part of the baseline against which efficiency in limiting emissions should be measured.*

The third condition characterizes this efficiency. It is most effectively discussed and interpreted after a little rearranging:

$$\{\partial U/\partial X\}\cdot\{\partial X/\partial E\} = -\,[\{\partial U/\partial X\}\cdot\{\partial X/\partial Q\}\cdot\{dQ/dE\} + \{\partial U/\partial F\}\cdot\{\partial F/\partial E\}\}\cdot\{dQ/dE\}] \quad (2).$$

In words, emissions should be allowed up to the point where the marginal utility value (generated by their role in the production of the positively valued good X) equals the *negative* of the sum of the marginal value (expressed in terms of utility) of the harm that they do in production and the direct marginal disutility that they create by exposing the population to residual pollution.

Much has been made of the condition represented in equation (2). It shows, for example, that the economically efficient level of emissions is not zero unless one of the sources of harm begins at a very high level (a level at which the harm caused by the first unit of emissions even given strenuous abatement is greater than its initial value in producing X). For present purposes, however, it is more important to recognize that equation (2) is only part of a series of simultaneous equations. Indeed, efficient emissions identified there must be supported by the efficient labor allocation characterized in equation (1). Put another way, and consistent with a long tradition in economics, the efficiency baseline against which emissions are to be judged (and thus mitigation effort against unregulated emissions is to be judged) depends critically on the efficient provision of abatement (adaptation) activity.[4]

2. A Full-insurance Result – the Efficiency Baseline under Uncertainty.

Having established the critical role played by efficiency in defining a baseline in a deterministic model, we now add uncertainty and risk to the calculus. One of the simplest models that nonetheless captures the essential characteristics of this added complication can be derived from Rothschild and Stiglitz (1976).[5] Consider, to that end, a decision-maker motivated to maximize expected utility in the face of an uncertain future. Let her utility function be given by $U = U(w)$, where w represents wealth and let $\boldsymbol{\pi}$ represent the probability of sustaining some loss L against an initial wealth denoted by W. Assume, as well, that the probability of avoiding this loss is $(1-\boldsymbol{\pi})$. The expected outcome across these two "states of nature" (given that the likelihood of retaining W is $(1-\boldsymbol{\pi}) \cdot 100\%$ while the likelihood of enjoying only $[W - L]$ is $\boldsymbol{\pi} \cdot 100\%$) is simply

$$E\{\text{outcome}\} = (1-\boldsymbol{\pi}) \cdot W + \boldsymbol{\pi} \cdot [W - L] = [W - \boldsymbol{\pi}L] \equiv \hat{w}.$$

The expected loss, in other words, is $\boldsymbol{\pi}L$, but our decision-maker would be willing to pay even more to eliminate any chance of the loss if she were even a little averse to risk (i.e., her utility had some concavity so that $\{d^2U/dw^2\} < 0$ while $\{dU/dw\} > 0$. To be more specific, the certainty equivalent wealth for our decision-maker facing this risky situation is implicitly defined as w_{CE} such that

$$U(w_{CE}) = (1-\boldsymbol{\pi}) \cdot U(W) + \boldsymbol{\pi} \cdot U(W - L),$$

and the extra "risk premium" that she would be willing to pay is simply

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4 Even a casual review of an intermediate microeconomics textbook like Mansfield and Yohe (2003) can reveal evidence of this tradition. The widespread use of perfect competition as a benchmark against which the cost of economic distortion is calculated, the definition of the substitution effect and the corresponding specification of compensated demand curves against which willingness to pay and willingness to accept are calculated (and compared with changes in ordinary consumer surplus), and the definition of "diversifiable risk" and its omission from the calculation of risk premia for risky investments, all come to mind as beginning members of a very long list of examples.

5 A brief but nonetheless thorough description of the underlying construct described here can be found on pages 220-223 in Kolstad (2009)

$$RP \equiv \hat{w} - w_{CE}.$$

To her, therefore, the economic cost of having to face the $\boldsymbol{\pi} \cdot 100\%$ chance of loosing L relative to her initial wealth W is

$$C(\boldsymbol{\pi}) = W - \hat{w} - RP = W - w_{CE}.$$

It is important to note that w_{CE} (and RP, for that matter) depends on the concavity of the utility function (i.e., the degree of risk aversion). It is perhaps more important to realize that the cost of the risky situation depends directly on w_{CE}. It follows that value of any intervention (adaptation) that changes either the dimension of the loss or its likelihood should be calculated as the difference in the resulting certainty equivalents – also a measure that depends on risk aversion.[6]

It turns out, however, that this comparison of certainty equivalents does not necessarily satisfy the efficiency standard that can be inferred from Section 1. To see why, suppose that our decision maker could purchase insurance coverage against her potential loss. Suppose, more specifically, that PR is the price per dollar of this available coverage and let C denote amount of coverage she might purchase. Our decision-maker's problem is now to choose the coverage that maximizes expected utility given by

$$\boldsymbol{\pi} \cdot U\{W - L - C \cdot PR + C\} + (1 - \boldsymbol{\pi}) \cdot U\{W - C \cdot PR\}.$$

The appropriate first order condition for this unconstrained optimization problem is simply

$$\boldsymbol{\pi} \cdot (1 - PR)\, U'\{bad\} - (1 - \boldsymbol{\pi}) \cdot PR\, U'\{good\} = 0$$

where

> $U'\{bad\}$ simply denotes [dU/dW] evaluated in the bad state of nature when the loss occurs; i.e., $\{bad\} = W - L - C^* \cdot PR + C^*$ with C^* representing the selected coverage and

[6] To be explicit, suppose some adaptation reduced the loss to L' and/or its likelihood to $\boldsymbol{\pi}'$. This new situation would sustain a new certainty equivalent, denoted w_{CE}'. Since $w_{CE}' > w_{CE}$, the value of adaptation would be $\{w_{CE}' - w_{CE}\} > 0$. It is this value that should be compared to the expense involved in implementing the adaptation to decide whether or not it is worth the effort.

U′{good} similarly denotes [dU/dW] evaluated in the good state of nature when the loss does not occur but the bill for insurance coverage C* must still be paid; i.e., {good} = W – C* · PR.

It follows that C* solves:

$$U'\{bad\} / U'\{good\} = \{(1 - \boldsymbol{\pi}) \cdot PR\} / \{\boldsymbol{\pi} \cdot (1 - PR)\}. \qquad (3)$$

Now assume that the supply side of a risk-neutral insurance market is regulated (either by competition or by government intervention) so that it offers actuarially fair coverage. More precisely, assume that offering insurance coverage across a wide range of customers produces an expected return of zero so that the expected value of income in the good state of nature for the (risk neutral) insurance company equals the expected value of outflow in the bad state of nature.[7] In this simple model, therefore, actuarial fairness implies that :

$$\{(1 - \boldsymbol{\pi}) \cdot PR \cdot C\} = \{\boldsymbol{\pi} \cdot (C - C \cdot PR)\} = \{\boldsymbol{\pi} \cdot C \cdot (1 - PR)\}.$$

The left-hand side of this equation is expected income from our decision-maker in the good state of nature; the middle and right sides represent expected outflow in the bad state of nature. Set equal to each other across the extremes of the equation, they mean that expected profits are equal to zero. After some algebra, they also mean that

$$PR = \boldsymbol{\pi},$$

and that

$$\{(1 - \boldsymbol{\pi}) \cdot PR\} / \{\boldsymbol{\pi} \cdot (1 - PR)\} = 1.$$

Inserting this condition back into the decision-makers equilibrium condition from equation (3), we have that

[7] Insurance companies still make money, but not directly from their customers. Instead, they make money by investing the premiums that they take in (inflows of revenue that accrue at the beginning of a year, for example) before they have to make payments to cover the claims of their customers (outflows that are staggered over the following 12 months).

$$U'\{bad\} = U'\{good\}$$

It must be true, as a result, that the outcome in the good state of nature matches the outcome in the bad state of nature. Mathematically, then

$$W - L - C^* \cdot PR + C^* = W - C^* \cdot PR; \qquad (4)$$

but this could only happen if $C^* = L$.

It follows from equation (4) that our decision-maker would choose to be fully insured against the loss L if she were able to purchase insurance from a competitive (i.e., maximally efficient) market – a condition for characterizing the efficiency standard depicted in Section 1. Satisfying that standard would therefore mean that

$$\{bad\} = W - L - C^* \cdot PR + C^* = W - L \cdot PR = W - \boldsymbol{\pi} \cdot L \text{ and}$$
$$\{good\} = W - C^* \cdot PR.\ W - L \cdot PR = W - \boldsymbol{\pi} \cdot L.$$

More importantly, since {bad} = {good} after the efficient level of insurance coverage has been purchased,

$$\hat{w} = w_{CE}$$

because

$$RP = 0.$$

As a result, the comparison of certainty equivalents required to evaluate the value of an adaptation that changes either the dimension of the loss or its likelihood should, if conducted along the efficiency baseline, be calculated as the difference in the resulting expected outcomes – a measure that *does not* depend on risk aversion.

3. The Value of Insurance in Climate Adaptation.

The lessons of Sections 1 and 2 combine to support the conclusion that efficient insurance should be part of the adaptation baseline in cases where climate impacts are uncertain or part of dynamic and stochastic processes. Responding to increased risks born of coastal storms superimposed upon futures that involve uncertain sea level rise certainly fit the bill in this regard; and we now know that computing the economic value of coastal adaptation in terms of expected damages avoided presumes either risk neutrality across decision-makers or the availability of actuarially fair insurance coverage against potential losses. Since neither presumption is particularly attractive, however, we are left with a dilemma. We can estimate the relative values of alternative adaptation options against an artificial baseline that does not fit reality; the advantage here is that differences in expected outcomes are the appropriate measures of economic value. Alternatively, we can compute those relative values in against a "second-best" baseline that is more realistic; the disadvantage here is that differences in certainty equivalents are now the appropriate measures of economic value.

The remainder of this paper explores this choice in the context of various adaptation options that have been analyzed for two coastal regions in the Boston area; Figure 1 shows their locations. To be more specific, we use comparisons of the economic value of these adaptations to evaluate the "So what?" question – i.e., what difference does it make to use one set of measures in lieu of another? Put another way, these comparisons provide estimates of the value of providing actuarially fair insurance as part of alternative adaptation portfolios, and they will demonstrate the degree to which the value of insurance depends on decision-makers' aversion to risk. The present section will illustrate exactly how for a GREEN adaptation option (an *environmentally benign* response) that Kirshen, et al. (2008) viewed as potentially appropriate for a suburban area of the located along the coastline north of Boston (Zone 3 in Figure 1).[8]

[8] The GREEN adaptation employs a nonstructural, environmentally benign or green accommodation that elevates or wet flood-proofs all residential development in the floodplain and wet flood proofs all industrial and commercial development; it therefore allows a degree of migration of coastal marshes, and this helps preserve their abilities to offer protection from storm surges. In a stricter version of current FEMA regulations, the 'GREEN' scenario requires that all growth in the current 100 and 500 year floodplains be totally flood-proofed at the time of construction and we again assume that flood-proofing new residential, commercial, and industrial structures only nominally adds to the cost of construction. It also requires that current residential development in the present and 100 and 500 year floodplains be flood-proofed upon sale of the structure assuming a 15-year turnover rate. The retrofitting of those structures already present in the floodplain is assumed to be 80 percent effective; that is, when a retrofitted building is flooded, damages to buildings and contents are reduced to 20 percent of the damages without flood-proofing. In the 100-year floodplain homes are retrofitted by elevating them at a cost of approximately $17,000 per home. In the area outside the 100-year floodplain, wet flood-proofing is used at a cost of $3500 per home. Both costs were was from tables in FEMA (1998) for a home with a 90 square meter footprint and frame construction set on a basement/crawlspace. Elevation prevents flooding of the living spaces of the home; wet flood-proofing allows floodwaters to enter the home, but prevents damage to the structure and its contents. The cost of commercial and industrial flood-proofing was assumed to be 10 percent of the commercial and industrial damages that would otherwise be incurred; this is the approximate ratio between the cost of residential flood-proofing and residential damages incurred. Flood-proofing of industrial and commercial properties is implemented after they are flooded. This is an

Figure 2 displays economic damages with and without implementing GREEN in the year 2055 in Zone 3 in two sets of cumulative distribution functions. The points displayed there are the result of simulating 100 plausible and equally likely storm experiences for the region in that year based on statistical techniques that superimpose historical storm patterns along two alternative sea level scenarios: one that reaches 0.6 meters by 2100 and a second that reaches 1.0 meter over the same time period. In 2055, therefore, sea level is roughly 0.3 and 0.5 meters higher than today, respectively. Expected damages with and without GREEN adaptation (the without case is dubbed RIO for "ride it out") amount to $8.52 and $11.22 million (2000$), respectively, along the 0.6 meter scenario; and they climb to $18.76 and $27.19 million for the 1 meter scenario. In this example, therefore, GREEN adaptation would allow the community to avoid $2.70 (= $11.22 - $8.52) million in expected damages in 2055 if the 0.6 meter sea level rise scenario were to materialize; and it would expect to avoid $8.43 (= $27.19 - $18.76) million in expected damages in the same year if sea level were on track to rise by a full 1 meter through the year 2100.

We now turn to consider the calculation of certainty equivalents to handle the "second-best" world where efficient insurance is not available. Constant (but not necessarily zero) relative aversion to risk is easily brought to bear by assuming a utility function for the decision-maker of the form:

$$U(w) = \{[w^{(1-\rho)}] / (1-\rho)\} \text{ for } \rho \geq 0 \text{ but } \rho \neq 1 \qquad (5)$$

and where (w) again represents wealth or some economic outcome that is uncertain. In this formulation, ρ explicitly reflects the degree of constant relative risk aversion – a parameter that simply specifies the curvature of this utility function at any level of wealth. That is,

$$RRA \equiv - \{U''(w) \cdot w\}/\{U'(w)\} = \rho.$$ [9]

It is, finally, important to note that the functional form depicted in equation (5) converges to

$$U(w) = \ln(w)$$

"Accommodation" SLR response. As in the case of the RIO scenario, streets will be frequently flooded in the future; these damages were not considered in this scenario.

[9] In recording this definition, U'(w) and U"(w) represent the first and second derivatives of U(w), respectively.

when $\rho \rightarrow 0$.

Now let E{U(w)} be the probabilistically weighted mean of utility across a comprehensive range of possible outcomes. It follows that the corresponding certainty equivalent w_{CE} can be given by

$$w_{CE} = \{(1-\rho) \cdot E[U(w)]\}^{1/(1-\rho)} \quad (6a)$$

for $\rho \geq 0$ and $\rho \neq 1$. Moreover,

$$w_{CE} = \exp\{E[U(w)]\} \quad (6b)$$

for $\rho = 1$.

Equations (6) can now be used to calculate the corresponding value of the GREEN option in 2055 for various levels of risk aversion; the results are displayed in Figure 3. Based on economic aggregates tracked across OECD countries over 30 years, Anthoff, et al. (2009) reported that 0 to 3 is a reasonable range for RRA.[10] When RRA = 0, of course, $\hat{w} = w_{CE}$; this is the actuarially fair insurance baseline otherwise interpreted as the policy-based alternative. The Anthoff, et al. (2009) range straddles (with a larger variance) the mean of 1.49 estimated by Evans and Sezer (2004) and (2005) using a different approach that focused on the behaviors of actual decision-makers. Panel A in Figure 3 portrays the economic value of damages avoided for the two sea level rise scenarios. The vertical distance between the mean and the certainty equivalent value estimates accounts for the risk premium – an amount that clearly grows as aversion to risk increases. Panel B meanwhile shows how the difference between value estimates based on certainty equivalents (i.e., no insurance available) and alternative estimates based on mean outcomes (i.e., actuarially fair insurance available) climbs as aversion to risk becomes larger. These schedules can therefore be interpreted as the value of insurance. While it is interesting to note that they are not very different *across the two sea level rise scenarios* (for this adaptation in this year in this location), the value of insurance climbs significantly in both cases as RRA climbs.

[10] It is perhaps important to note, in light of the divergence in valuation estimates as RRA climbs toward 3, that Heal (2009) works with a range for what he calls IRRA (Index of Relative Risk Aversion) that extends to an upper limit of 6.

4. The Relative Value of Adaptation over Time and the Timing of a Response.

Having established the theoretical unpinning of this analysis, we now turn to a more complete portrait of how the future might unfold in two specific regions near Boston. As indicated above, one *policy response* (making actuarially fair insurance against the stochastic annual consequences of dynamic climate variability that is contingent on climate change) and two adaptations (an *environmentally benign response* designed for a suburban region and for which ongoing and persistent expenditure would be required and one *engineering response* for an urban region for which a large expense at a time to be determined by decision-makers and downstream maintenance/operational cost would be incurred) will be considered. To be clear, the two adaptations would be options for two different regions – the first in Zone 3 in Figure 1 and the second Zone 2 in Figure 1. Both will nonetheless be evaluated with and without the insurance program (the *policy response* that could be implemented in both and perhaps all locations); and so the implications of implementing that policy on evaluating each adaptation will be explored.

Distributions of damages associated with stochastic storm events across 100 random runs and absent any adaptation in Zones 2and 3 are displayed in Figure 4 for selected years between 2010 and 2090. Notice that the scales of potential damage from coastal storms contingent on two different sea level rise scenarios are the same for the urban region (Zone 2) while the potential damages corresponding to the same sea level futures are significantly different across the two sea level rise future for the suburban district (Zone 3).

4.1. Adaptation in the Suburban Region (Zone 3).

Kirshen, et al (2008) concluded that investing in natural defenses and flood-proofing structures might be an attractive adaptation in Zone 3 because their persistent and on-going expense would be dominated by the value of economic of property and economic activity that would be protected; this is the *environmentally benign response.*. Panel A of Figure 5 confirms their conclusion for the 1 meter scenario. For every year portrayed (and all other years not depicted), the net economic value of adaptation (damage avoided net of adaptation cost) is positive. Notice, though, that this value grows with relative risk aversion in every year. Since RRA = 0 corresponds to case in which the *insurance policy response* is in place, it is clear from Panel A that enacting such a policy that would actually reduce the value of adaptation. Why? Because it would eliminate the additional cost attributable to rising seas that would otherwise be produced by stochastic manifestations of climate change (storm surges, etc…) in any particular year.

This reduction in value is irrelevant, of course (since all values for all years are positive) unless scarce public resources could be allocated to alternative programs with potentially higher returns. Indeed, lower values for relative risk aversion consistently mean that the net value of the adaptation to climate risk smaller; and so implementing the insurance-based *policy response* would make it more likely that policy-makers would be able to afford these attractive alternatives even if they were designed to respond to stresses that were not related to climate change. Panel B of Figure 5 tells the same story for the 0.6 meter scenario on a slightly different scale. Scale matters, of course, when opportunity cost *vis à vis* other public investments are on the table.

4.2. Adaptation in the Urban Region (Zone 2).

The *engineering response* considered by Kirshen, et al (2008) for an urban area (Zone 2 in Figure 1) provides a different context within which to consider the value of the policy option. Here, the adaptation option must be viewed as a long-term investment for which significant up-front expense would be required and for which persistent maintenance costs would be incurred over a long period of time. Of course, such an investment would produce a long-term stream of benefits calibrated in terms of damages avoided, and so discounting the future is an essential element in the decision process. More specifically, decision-makers at any point at time should evaluate the present value of undertaking investment in adaptation; and so it should be anticipated that this investment might become more attractive as the future unfolds (because benefits appear on the nearer-term horizon as time passes) even if discounted benefits did not exceed discounted costs in the near term.

The two panels of Figure 6 cast this time dependence in terms of correlations of the internal rate of return (IRR) of the adaptation investment along 5-year increments (between 2010 and the middle of this century) and for alternative values for relative risk aversion.[11] Again, RRA = 0 implies conducting these calculations under the assumption that the insurance-based *policy response* had been implemented. Leaving aside for the moment the question of determining a benchmark interest rate, Figure 6 is ripe with content.

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[11] The internal rate of return (IRR) simply represents the discount rate for which the present value of the investment is precisely equal to zero. It follows immediately from this definition that projects for which the IRR is less than the applicable interest rate should not be pursued; conversely, projects for which the IRR is greater than the applicable interest rate are attractive (and should be pursued in the absence of a budget constraint).

Notice, for example, that all of the contours climb with RRA for both of the sea level scenarios (except for high values of RRA in mid-century). This means that the economic cost of uncertainty (unless it were eliminated by the *policy response*) adds to the value of investment in this adaptation in any year. Put another way, the absence of the insurance-based *policy response* (cases in which RRA > 0) adds to the IRR of this adaptation investment to an extent that depends on decision-makers' aversion to risk. It follows that investment in this adaptation could be profitable earlier (than in the presence of the insurance program option) to a degree that depends on risk aversion. Figure 6 indicates the value of such an insurance program in the positive slope of the IRR contours (steeper for high RRA along the 0.6 meter scenario but persistent along the 1 meter scenario). Conversely, and perhaps more importantly, implementing the insurance-based *policy response* would, by virtue of making RRA = 0 applicable, delay profitable investment in adaptation and would therefore "buy some time". Not an infinite amount of time, to be sure, but some time that would be extended if the lower sea level future turned out to be reality.

It remains only to discuss the interest rate against which the IRR for various public investments, like this adaptation project, should be compared. In this context, though, the enormous debate among economists that has focused attention on time preference, attitudes toward risk, and attitudes toward inequality is less important than the character of the adaptation investment (see, e.g., Nordhaus (2007), Stern (2008), Stern and Taylor (2007), Anthoff, et al. (2009)). Arrow and Lind (1970) and Ogura and Yohe (1977) followed Samuelson (1964) and Vichrey (1964) to show that downstream returns to a public investment project can, on *efficiency grounds alone,* be discounted a sub-market rate of interest in the context of a system that taxes the return to private capital (e.g., a tax system that taxes corporate profits). All that is required is that the public investment complement private capital (in the strict sense of increasing its marginal productivity. The idea behind this result is that the corporate profits tax discourages private investment and that the consequences of this distortion can be ameliorated by public investment that increases the productivity of private capital and therefore works in the opposite direction to encourage investment.

While quantitative estimates of the productivity spillovers of BYWO protection have not been performed, it should be clear at least intuitive that this sort of investment would, most likely, complement private capital. It follows that, for example, a 5% real threshold for private investment might translate into something on the order of 2% or 3% for BYWO adaptation investment. This simple argument favors BYWO in absolute terms, to be sure; but it is also clear from Figure 6 that it also favors moving the implementation date forward and thereby amplifies the positive effect of increased risk aversion in the absence of an insurance program.

To see this, notice from Panel A of Figure 6, for example, that the BYWO investment would become attractive for a 5% return threshold (based on standard returns in private capital markets) in 2020 without insurance and RRA > 2.5 along the 1 meter scenario; under the *policy response,* if insurance would be available and RRA = 0 would apply and the trigger date would lie some time between 2025 and 2030. If BYWO were seen to complement private capital, though, a 3% threshold could easily be more appropriate as standard against which to compare IRR. This would make immediate implementation an attractive option with high RRA; and, in fact, 2015 would not be too soon to invest in BYWO even given the *policy response.* Panel B can support comparable and parallel insights for the slower sea level rise scenario, although the dates are farther in the future because the seas are rising more slowly. The 5% threshold would, in particular, lead to anticipating undertaking BYWO in 2050 if insurance were available (again, when RRA = 0), and no sooner than 2040 even with no insurance and high RRA. The 3% threshold supported by complementarity would, meanwhile, see BYWO turning attractive 10 years earlier with insurance (shortly after 2040) and without insurance (as early as 2030 with high RRA).

5. Discussion

The first fundamentally qualitative lesson to be drawn from this work is the obvious but frequently ignored insight that baseline matters. That might not have been obvious in Section 1 where the efficiency criteria of a first-best world were described and employed to show that the relative values of adaptive and mitigative responses to a negative externality are inexorably linked with one another. To be more specific, Section 1 demonstrated that the marginal value of the last unit of effort in mitigating exposure to an external stress (like sea level rise driven by rising global mean temperatures) must equal the marginal value of the last unit of effort devoted to reducing sensitivity to the manifestations of that stress (like damages created by storm surges whose severities climb as the sea rise).

Motivated by this demonstration that we need to formalize efficient adaptation, Section 2 demonstrated that the provision actuarially fair insurance coverage for damages associated with coastal storms would be an essential component of efficient adaptation in the face of sea level rise. The key there was to recognize that the character of damage associated with the stochastic incidence of coastal storms would change with rising seas. It followed that the consequences of an external stress like sea level rise in any period in any location would be characterized not only in terms of expected economic damages driven by the long term trend, but also in terms of distributions of annual damages around those means that would also change over time. Section 2 showed that the provision of actuarially fair insurance would allow researchers and decision-makers to characterize economic damages associated with sea level rise in terms of expected damage (because people or societies would choose to fully insure against stochastic storm damage). Absent such insurance, however, added social cost generated by uncertainty about exactly which storm incidence would materialize with any given sea level rise in any given year had to be included in the calculation; and while expected damage calculations do not depend on aversion to risk, this added cost component certainly does.

Section 3 combined these two theoretical results to calculate the value of a specific adaptation in a suburban coastal zone north of Boston in 2055 along two different baselines. Welfare was expressed mathematically so that relative aversion to risk of decision-makers could be characterized by a single parameter (denoted RRA and technically the curvature of the welfare function). When RRA = 0, the decision-maker is risk-neutral so that variation in possible damages attributed to sea level rise but driven by stochastic storm events does not matter. When RRA > 0, variability driven by storm events reduces expected welfare and so this additional cost must to taken into account in calculating both damages attributable to sea level rise and the value of adaptation. It was important to note, though, that efficient application of actuarially fair insurance would replicate the RRA = 0 case regardless of individuals' aversion to risk. They would, by purchasing full coverage against all risk in their own best interest, guarantee that they would experience the expected level of damage regardless of which storm-future appeared.

The first baseline in Section 3 was therefore motivated by Section 2; it assumed that an adaptation policy which provides actuarially fair insurance coverage had been implemented (and efficiently exploited) so that both the cost of sea level rise and the value of adaptation could be calibrated in terms of expected damages; this characterized the *policy response* option to sea level rise. More specifically, the value of adaptation against this *policy response* baseline was the difference between expected damages without adaptation and the sum of expected residual damages with adaptation and the cost of that adaptation. In the second baseline (a second-best and perhaps more realistic alternative in which the insurance-based *policy response* was not implemented, not available, or not exploited) both the cost of sea level rise and the value of adaptation had to be calibrated in terms of certainty equivalents (hypothetical certain outcomes for which utility would be exactly equal to expected utility across damages from a simulated range of storm events over the course of one year). Relative risk aversion matters in these calculations. Indeed, damages attributed to sea level rise were seen to be larger (as long as RRA > 0) as were estimates of the value of adaptation. Moreover, both grew as society or its decision-makers become more averse to risk.

Section 4 confirmed this finding for an *environmentally benign response* – an adaptation designed for the suburban zone referenced in Section 3 and an *engineering response*designed to protect an urban community in Boston along two sea level rise scenarios (one reached 60 centimeters by 2100 and the other reached 100 centimeters over the same time period). The first adaptation involved persistent expenditure over time, but the values of adaptation were always positive (though not monotonic in time). In every case, damages attributed to sea level rise and the value of this adaptation rose with relative risk aversion. Put another way, damages and the value of adaptation were smallest in the first-best world where the *policy response* made actuarially fair insurance was available. The rate at which they climbed with RRA was, of course, an indication of the sensitivity of the value of the insurance-based *policy response* to aversion to risk.

The second adaptation involved undertaking an enormous public investment at some point in time followed by annual maintenance and operating expense thereafter. The decision rule therefore involved determining when the present value of benefits (reductions in damages calibrated as differences in expected values assuming the insurance-based *policy response* and as differences in certainty equivalents otherwise) exceeded the present value of costs. Again, damages attributed to sea level rise and the value of this adaptation rose with relative risk aversion for both sea level rise scenarios. Put another way, damages and the value of adaptation were still smallest in the first-best *policy response* world where actuarially fair insurance was available case. For this *engineering response,* the value of insurance was best illustrated by the rate at which the internal rate of return (IRR) of this public investment in adaptation rose with risk aversion. From a practical perspective, it was even more revealing to observe that the date for which the adaptation would be achieve an IRR greater than the threshold interest rate (and therefore the date at which it would first be implemented) moved farther into the future as RRA fell (and moved farthest into the future in first best *policy response* world). Put another way, efficient amelioration of sensitivity through insurance bought the society some time before it would have to undertake a big public investment project.

In conclusion, consideration of engineering and a programmatic adaptation to sea level rise with associated changes in coastal storm damage offers several more general hypotheses for similar cases in which the manifestations of climate change cause economic damage that is stochastically correlated with long-term trends. First of all, *the choice of a baseline against which to gage the values of various responses to external stress is not simply an academic issue*. Difference in baseline, which can be framed in terms of whether or not certain policies had been implemented, can easily change the values of all sorts of adaptation and influence their timing. Secondly, *the value of adaptation can be expressed in terms of differences in expected outcomes damages (with and without the adaptation) only if the effected community has access to efficient risk-spreading mechanisms (like actuarially fair insurance) or reflects risk neutrality in its decision-making based on other available institutional structures.* Otherwise*, increases in decision-makers' aversion to risk increase the economic value of adaptations that reduce expected damages and diminish the variance of their inter-annual variability.* Finally, *for engineering and other adaptations that involve significant up-front expense followed by ongoing operational cost,, increases in decision-makers' aversion increase the value of adaptation and therefore move the date of economically efficient implementation closer to the present.*

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Figure 1: Location of the Boston Study Areas. Source: Figure 1 on page 455 in Kirshen, et al. (2008).

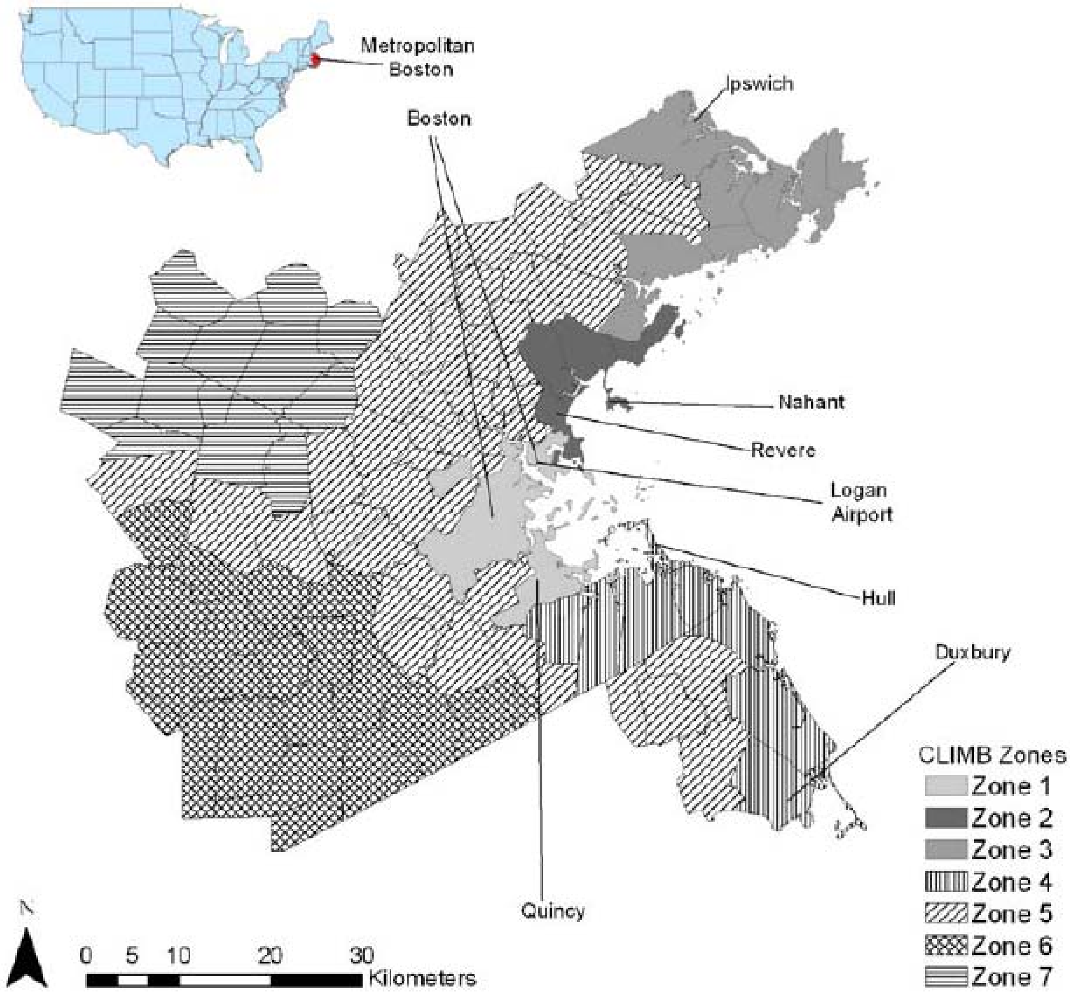
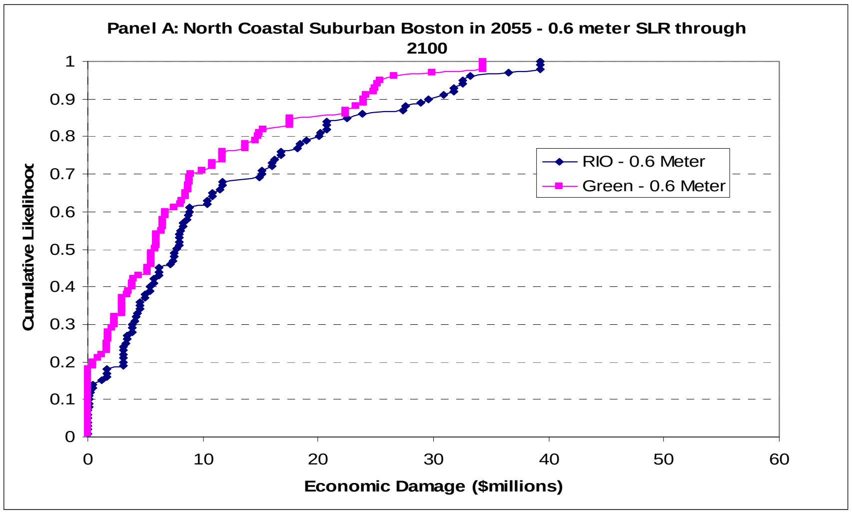
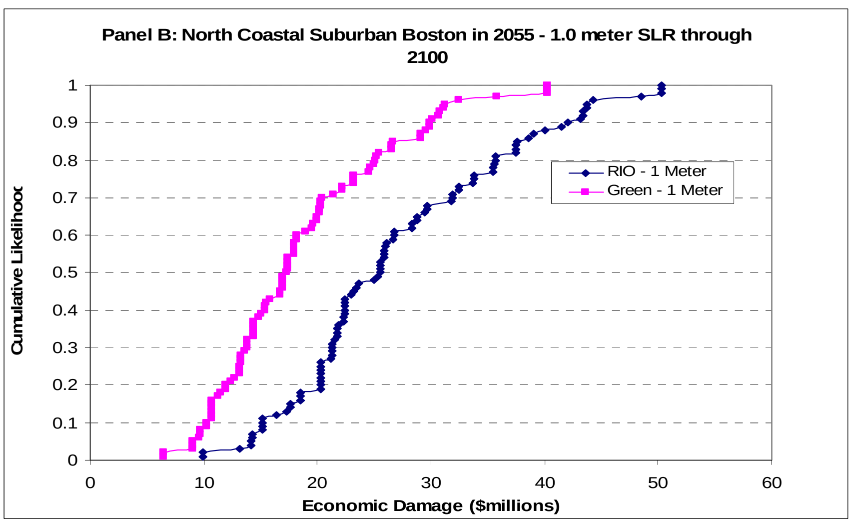


Fig. 1 Seven CLIMB zones: zone 1 = South Coastal Urban, zone 2 = North Coastal Urban, zone 3 = North Coastal Suburban, zone 4 = South Coastal Suburban, zone 5 = Developed Suburbs, zone 6 = Developing Suburbs South, zone 7 = Developing Suburbs North

Figure 2: Cumulative distributions of economic damage for 100 alternative manifestations of stochastic storm behavior in 2055. Panel A displays damages with and with GREEN adaptation along the 0.6 meter sea level rise scenario; Panel B does the same for the 1.0 meter scenario.

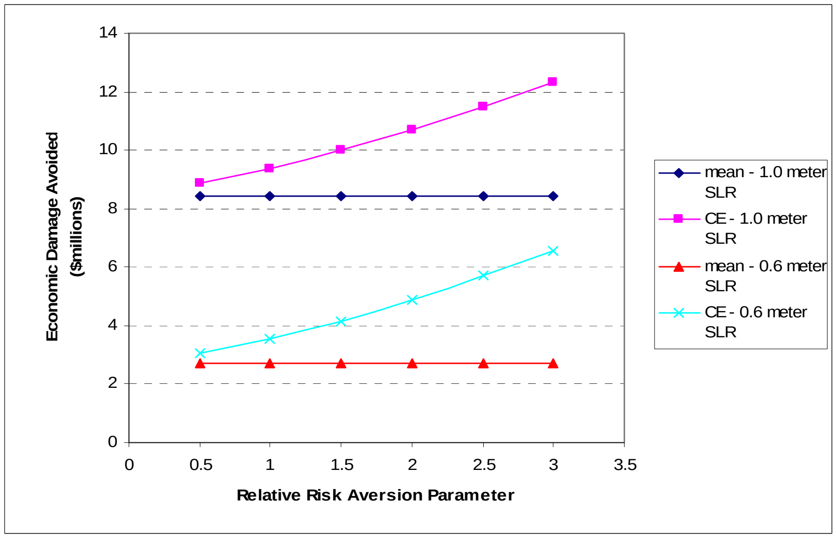


Panel A

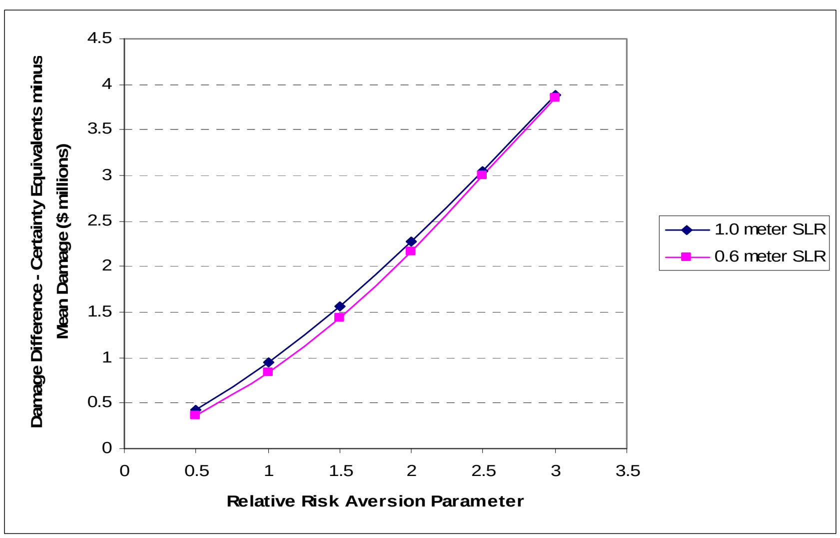


Panel B

Figure 3: Alternative portraits of the value of GREEN adaptation. Panel A displays estimates of economic damages avoided by GREEN adaptation measured in terms of mean outcome and certainty equivalents. Panel B shows the difference between the certainty equivalent and mean outcome calculations; i.e., it shows the value of making efficient insurance coverage available.

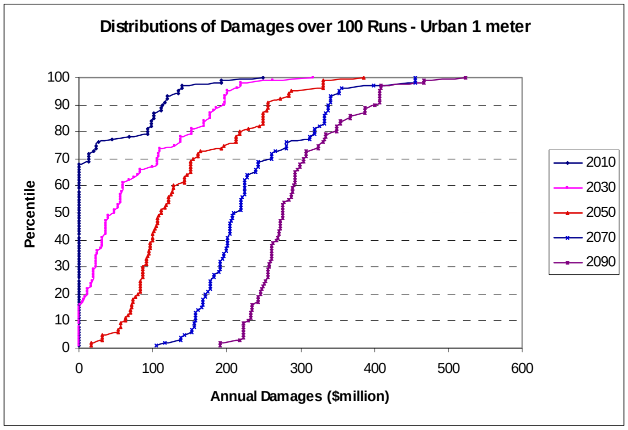


Panel A

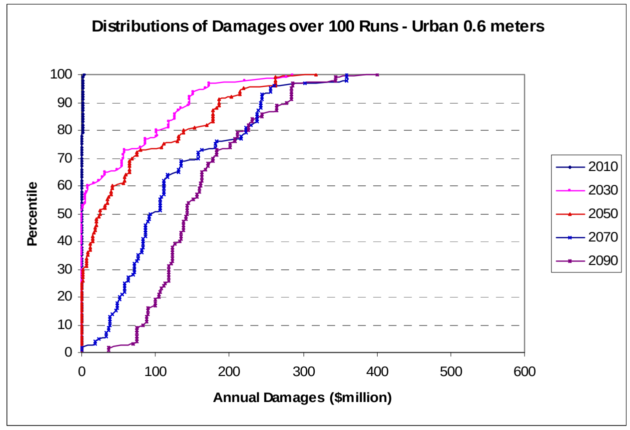


Panel B

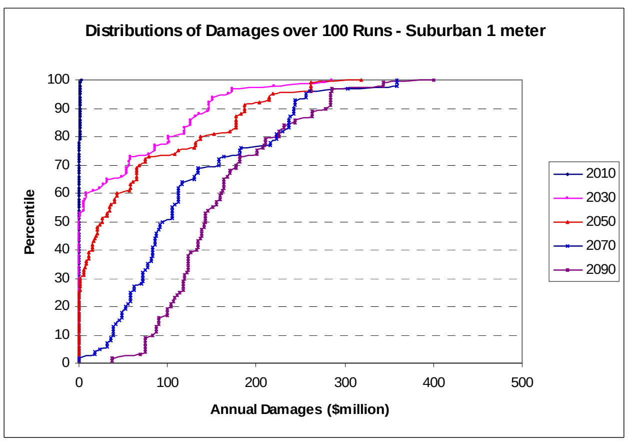
Figure 4: Distributions of Economic Damage across 100 Runs for Two Sea Level Rise Scenarios. Panels A and B indicate economic damages from coastal flooding in selected years for the urban area in Boston (Zone 2 in Figure 1) for 1.0 and 0.6 meter sea level rise scenarios, respectively. Panels C and D do the same for a suburban area located north of Boston (Zone 3 in Figure 1).



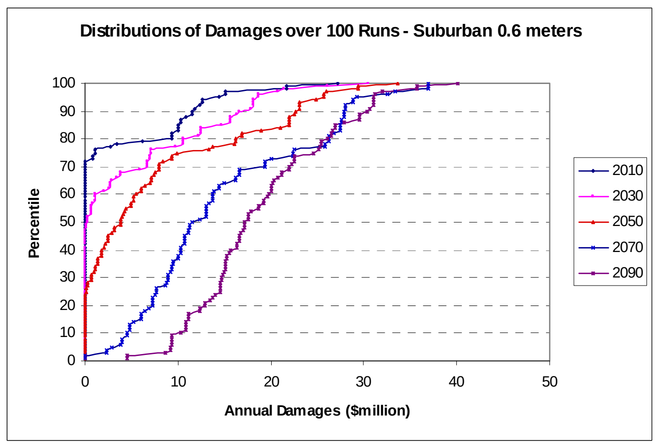
Panel A



Panel B

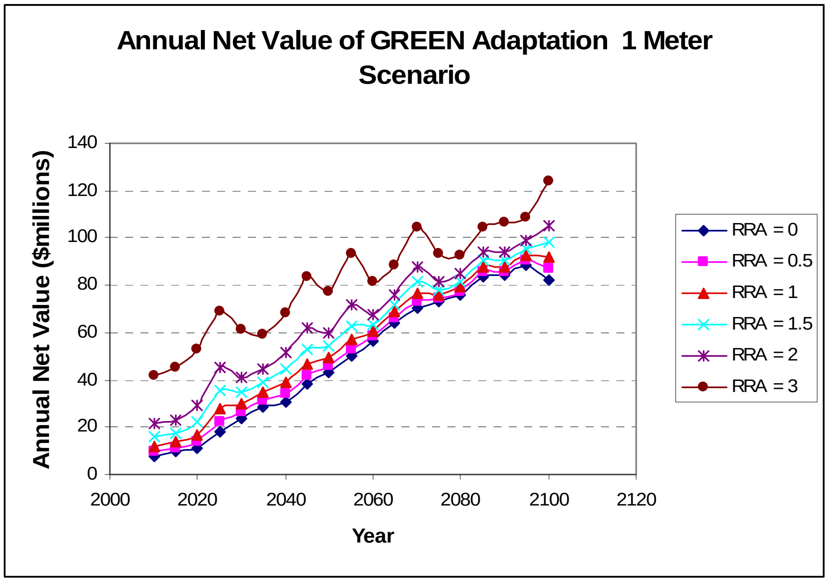


Panel C

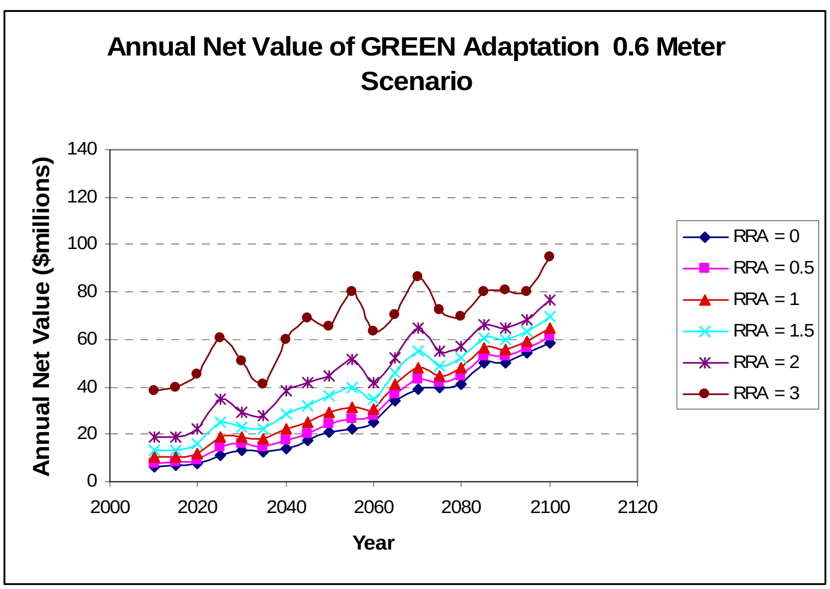


Panel D

Figure 5: Damages and/or Net Damages plus Adaptation Cost in the Suburban Region over Time for Different Specifications of Relative Risk Aversion (Note: RRA = 0 corresponds to risk neutrality and so is the appropriate measure given the under the insurance provision policy). Panel A indicates the sum of residual damages plus adaptation cost along the 1 meter sea level rise scenario for alternative values of relative risk aversion. Panel B does the same for the 0.6 meter scenario.

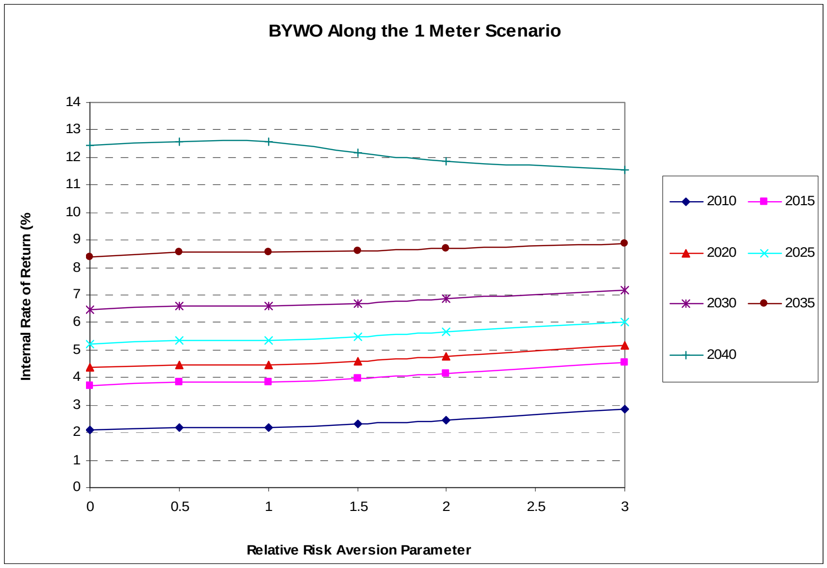


Panel A

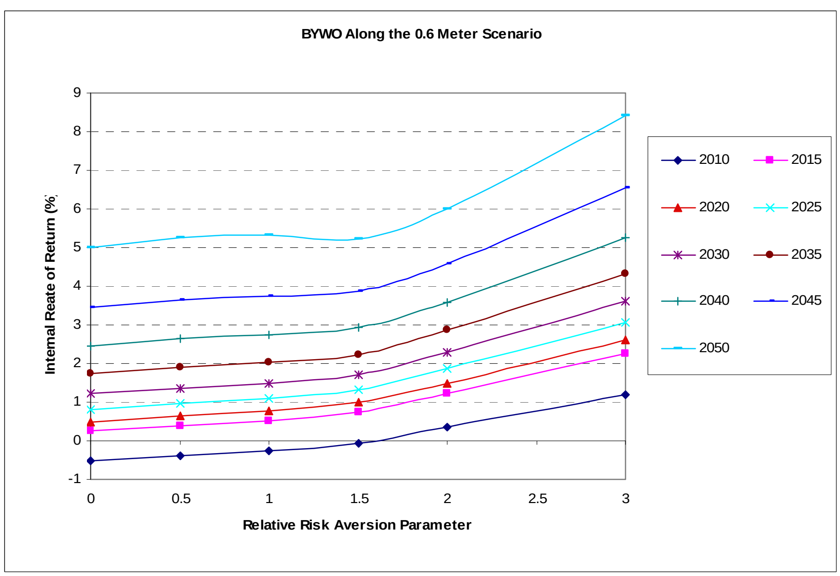


Panel B

Figure 6: Internal Rates of Return for the BYWO Adaptation for Different Years. Panel A indicates the internal rate of return for the BYWO option evaluated at different points in time for different values of risk aversion along the 1 meter sea level rise scenario. Panel B does the same along the 0.6 meter sea level trajectory. In both cases, RRA = 0 indicates the internal rate of return if the insurance policy were implemented.



Panel A



Panel B