

November 2016

The Economics of Adaptation to Climate Change in Coasts and Oceans: Literature Review, Policy Implications and Research Agenda

Charles S. Colgan
Middlebury Institute of International Studies at Monterey

Follow this and additional works at: <https://cbe.miis.edu/joce>



Part of the [Behavioral Economics Commons](#), [Emergency and Disaster Management Commons](#), [Environmental Policy Commons](#), [Finance Commons](#), [Physical and Environmental Geography Commons](#), [Policy Design, Analysis, and Evaluation Commons](#), and the [Regional Economics Commons](#)

Recommended Citation

Colgan, Charles S. (2016) "The Economics of Adaptation to Climate Change in Coasts and Oceans: Literature Review, Policy Implications and Research Agenda," *Journal of Ocean and Coastal Economics*: Vol. 3: Iss. 2, Article 1.

DOI: <https://doi.org/10.15351/2373-8456.1067>

This Review is brought to you for free and open access by Digital Commons @ Center for the Blue Economy. It has been accepted for inclusion in *Journal of Ocean and Coastal Economics* by an authorized editor of Digital Commons @ Center for the Blue Economy. For more information, please contact ccolgan@miis.edu.

1. INTRODUCTION

Discussions about climate change have undergone a subtle but critical change in language. Today one speaks of “mitigation” of climate change and of “adaptation to the effects” of climate change.¹ These terms imply that climate change is no longer something that can be entirely avoided or prevented; the choices now are about reducing the extent of possible damages and adjusting to the damages already likely to occur whatever future reductions in climate change occur.

While no part of the earth will escape the effects of climate change, the world’s oceans and coasts present a unique set of challenges. Most of the heat generated by climate change is absorbed by the oceans, partly because the oceans cover three quarters of the planet, and partly because of water’s capacity to absorb and hold heat. Warming oceans will expand and may erase major areas of the world’s shorelines. Warmer oceans will redistribute fish species, which will impact industries and communities, to which will be added the effects of fundamental changes in ocean chemistry as seawater absorbs more and more carbon. (Intergovernmental Panel on Climate Change 2014)

Adaptation to the effects of climate change has emerged as a major issue for those addressing issues related to oceans and coasts, and many of the questions being examined are economic. Attention to sea level rise is frequently spurred by depictions of the millions or billions of dollars of property and infrastructure at risk. Those engaged in developing adaptation strategies confront questions of how to deploy limited resources for adaptation in the context of deep uncertainty about when and to what extent adaptation will be needed.

There are many studies of the economic effects of climate change. Examples in the U.S. include studies sponsored by the public sector (Melillo, Richmond, and Yohe 2014) and the private sector (Gordon 2014) But there have been few reviews of the economics of adaptation. Kahn undertakes such a review including

¹ There is a significant amount of linguistic confusion in the literature about the terms mitigation and adaptation. “Mitigation” is a term that has long been used in the literature on natural hazards such as flooding and earthquakes to refer to steps meant to reduce damages from these hazards. In this meaning, “mitigation” and “adaptation” are functionally equivalent. In the climate change literature, “mitigation” is most commonly used to refer to steps, such as use of renewable energy sources, which reduce the extent of climate change. “Adaptation” refers to steps to reduce damages or to reorganize economic activities to adjust to the consequences of climate change, such as shifting fishing effort between species.

discussions of climate effects on agriculture and food prices as well as individual adaptation to periods of excessive heat. (Kahn 2016) His review does include a discussion of sea level rise but in the larger context of how individuals and organizations will assess the risks of damage to their property, and how this will shape their decisions to invest in shoreline property. He points out that because both the timing and magnitude of risk are unknown, it is difficult to apply standard economic models to these cases. He identifies alternate models that might be used for investment decisions, without concluding which is most appropriate.

There are many coastal areas that are already explicitly developing adaptation strategies. In the United States, areas such as Miami, Florida (Wdowinski et al. 2016) and the lower Chesapeake Bay (Eggleston and Pope 2013) are already dealing with sea level rise effects and trying to find cost effective solutions to a crisis that is already happening. In the northeastern United States where Hurricane Sandy struck in 2012, significant public and private resources are being devoted to developing plans to deal with the recurrence of such storms. California has already issued guidance to communities for sea level rise planning, with a focus on land use. (California Coastal Commission 2015) In Europe, where dealing with climate change issues does not confront the peculiar politics at work in the United States, adaptation to sea level rise is well underway. (Tol, Klein, and Nicholls 2008; Hinkel et al. 2010)

At the same time, there are numerous low-lying coastal areas where adaptation is not a question of rebuilding existing structures or building protective barriers but the continued existence of shore land suitable for habitation. This is already a well-known problem in small island nations in the Indian Ocean (The Seychelles National Climate Change Committee 2009) and the Pacific (Ives 2016), but it is also an imminent problem for communities in Alaska (Mooney 2015) and Louisiana (Beller and Charles 2016). Adaptation that requires complete retreat from islands and shore lines is no longer a theoretical possibility but must be actively factored into the options of many areas if not for immediate action than very possibly within the lifetime of current residents of such areas.

These examples indicate that sea level rise and its effects are not a matter of the distant future. Most places are not yet seeing these effects. Nonetheless, decisions are being made throughout the world about where and what to build, rebuild or expand in coastal areas. New residential and commercial development

is going in to places that will, well within the economic life of the structures, be subject to recurrent flooding from storms and/or constant “nuisance flooding” with daily tidal shifts. Infrastructure, including roads, energy facilities, water and sewer facilities along with other critical infrastructure such as hospitals, are also being built or rebuilt with little regard to the threats from sea level rise. Adaptation is an issue for today, whatever the climate and sea level rise models say about changes over this century.

There is, therefore, some urgency in finding ways to deploy limited resources in the most effective manner possible. In this paper, I review the current state of the application of economics to the formulation of adaptation strategies for oceans and coasts with focusing on four questions:

- How can economics help confront the profound uncertainty that shapes all decisions regarding climate change? This is a particularly critical issue because the dominant use of economics in adaptation thinking will likely be benefit-cost analysis, which, in its standard form assumes certain characteristics of the future which simply will not hold in a world with a nonstationary climate.
- How should adaptation be paid for? This would seem at first glance to be a question for much more advanced stages of planning once options are identified and evaluated. But the willingness of decision makers to undertake actions that could be very costly in the near term relative to highly uncertain benefits in the distant future will largely depend on an acceptance that resources for adaptation can be found. An understanding of the rapidly evolving landscape of adaptation finance and its possibilities will be an important catalyst for action.
- What are the socioeconomic values at risk from climate change? To date, most socioeconomic studies designed to spur adaptive actions have focused on likely damages to property. But economic vulnerability extends well beyond the loss of individual buildings to the entire functioning of local and regional economies and these effects have barely been considered.
- Can market mechanisms be used to make adaptation more efficient? Market based tools such as carbon taxes or cap and trade

emissions regulations have become the most commonly suggested and used approaches to encouraging emissions reductions. Is there a similar role for market-based approaches to choosing adaptation strategies?

2. A BRIEF INTRODUCTION TO COASTAL ADAPTATION

While “mitigation” of climate change through reduction in greenhouse gas emissions is relatively straightforward as to the objective, if not the means, “adaptation” is a more complex concept. This widely cited definition leaves a great many questions unanswered: To what changes are we supposed to adapt? How big will those changes be? When will they occur? What responses should be considered? On what basis will we chose the response? Where will the resources to respond be found?

The IPCC defines adaptation as “adjustments in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities”. (Intergovernmental Panel on Climate Change 2008) This definition clearly does not supply all the necessary answers, but it does bound the outcomes of adaptation as “moderating harm”. Adaptation cannot eliminate all the harm that is possible, but it can reduce it to an extent to be defined.

There are other possible definitions, however. Pelling defines adaptation as “the process through which an actor is able to reflect upon and enact change in those practices and underlying institutions that generate root and proximate causes of risk, frame capacity to cope and further rounds of adaptation to climate change”. (Pelling 2011) This is a far more ambitious vision than that of the IPCC, with goals set beyond minimizing harm to transformation of society’s characteristics that created the risks of climate change in the first place.

For purposes of this analysis, adaptation will be defined in terms much closer to that of the IPCC and to the concept of minimizing harm, leaving to another discussion the issue of broader societal changes as an outcome of adaptation. The focus on minimizing harm is also a focus primarily on those choices to which decision makers will most likely devote attention, at least over the next several decades.

The climate related change that will be the principal focus of analysis is sea level rise and consequent risks from both chronic and disaster related

flooding. Climate change related effects on ocean thermal and chemistry characteristics are considered to the extent they affect coastal communities. From this definition of the changes to be considered also flows the issue of vulnerability to be considered as those affecting the populations and economies of coastal areas.

Adaptation in this sense is closely related to the concept of resilience, which is generally defined as the ability to absorb a shock and return to the original pre-shock condition. Resilience is the operating framework for a number of public organizations such as NOAA² as well as private organizations such as the Coastal Resilience network.³ Resilience is a function of both capacity, meaning the institutions and processes needed to make adaptive/resilient decisions and the decisions that are made. This merging of capacity and outcomes implies that over time the decisions that are made reinforce capacity and resilient outcomes grow in likelihood as a combination of growing capacity and choices made.

The strategies leading to resilience affecting coastal communities are generally grouped in three categories:

- Structural adaptation, or the modification of the built environment to minimize the effects of flooding; elevating buildings or other structures is a common example.
- Creation of barriers, such as sea walls or tidal barriers or other engineered armoring of shorelines to prevent flood waters reaching critical assets. Barriers also include the use of natural barriers such as coral reefs or beaches to ameliorate flood damage potential.
- Retreat, or the shifting of economic assets away from the shoreline and out of the flood zone so that the risks are eliminated.

This paper focuses on questions of the use of economic theory and analysis to choose whether, when, and which of these strategies to employ. Relevant decisions are assumed to be in the local regions where impacts will primarily occur, though decisions made at national or larger regional levels play important roles. The assessment is relatively agnostic among these three choices as the best solutions are extremely dependent on local circumstances. (Ruckelshaus et al. 2016) There is an underlying assumption that adaptation choices will focus on

² <http://oceanservice.noaa.gov/facts/resilience.html>

³ <http://coastalresilience.org/>

the first two of these alternatives in most places before considering retreat, but the focus in the paper is on the long term and over time all of these options are in play.

2.1 Making Rational Decisions Despite the Profound Uncertainty of Climate Change and its Effects

The basic problem for economists is that climate change undercuts several bedrock theoretical principles, particularly in welfare economics, that economists have considered necessary for understanding the world. One of these is the way to make decisions when outcomes are primarily the outcome of stochastic processes. The other is how to make decisions when the consequences of those decisions may occur primarily beyond the lifespan of those who make the decision. Mixed into these discussions are questions about whether current individuals' welfare is the appropriate metric for evaluating choices for individuals in the future. Climate change is not the only challenge to these basic principles, but it is one where finding the appropriate answers is particularly critical because of the magnitude of the stakes in the decisions to be guided by economic analysis.

The problem of making decisions in a world where outcomes cannot be reliably known is one of the oldest problems in economics (Heal and Millner, 2014).

The problem was addressed as long ago as 1921 by Frank Knight who distinguished between risk, where probabilities could be defined, and uncertainty, where they could not (Knight 1921). The development of the concept of expected present value, or risk adjusted present value, by Von Neumann and Morgenstern appeared to provide a solution to the problem in a way that fully preserved the ability to develop quantitative models that could provide unique solutions given the inputs (J. Von Neumann and Morgenstern 1944). In fact, this is the approach that is taken with many of the integrated climate change assessment models that have been developed, which integrate climate, physical process, and economic effects models to try to predict economic consequences. These include the FUND, DICE, and PAGE models (J. Weyant, 2014).

The problem for climate change is that there are a number of reasons why it is extraordinarily difficult to translate uncertainty into risk in the Knight sense, a characteristic described as "deep uncertainty" (Lempert 2014). Others have

characterized it as a problem of “fat tails”, meaning that the ends of a probability distribution may be more likely and of larger consequence than implied by the “normal” curve. (Pindyck 2011; Nordhaus 2011) Climate change is considered a problem where either no probability can be meaningfully assigned or where the greatest-and worst threats- are at the extremes of (unknown) probability distributions, and thus are essentially useless for current decision making.

The challenge in climate change, and associated effects like sea level rise, is not that there is a single “uncertainty” but that the situation with which decisions makers must struggle are the cumulative effects of many uncertainties including: how much climate change will occur, how much and how effective mitigation efforts will be, the pace and structure of demographic and economic change in vulnerable areas, and technological uncertainties that will affect both the extent of change and the possibility of adaptation for reducing damages. With these uncertainties, how can the economist’s principal tool for evaluation of choices, benefit-cost analysis, be used?

A summary of these various issues is contained in the “dismal theorem” (M. L. Weitzman 2011). This holds that the extent of damages from climate change may be so catastrophic, even if of small likelihood of occurring, that the only rational choice is to devote virtually all output in the economy to preventing such outcomes. The probability distribution has a “fat” tail because of the magnitude of the possible changes, and the slope of the probability density function no longer conforms to the usual assumptions so the discount rate becomes infinite. Since neither an infinite discount rate nor devotion of all output to preventing damages from climate change is possible, benefit-cost analysis becomes essentially useless.

The dismal theorem, and the entire debate about the applicability of economics to the climate change context, has its origins in the debate over the Stern Review, a study commissioned by the Government of the United Kingdom to investigate the economic case for action to reduce greenhouse gases (GHG). (Stern 2007) That seminal study concluded that drastic action to reduce GHG emissions was justified by the size of the threat. A major source of controversy about the *Report* was the use of a very low discount rate that significantly increased benefits to be realized in the distant future relative to present costs. A large number of comments on the Stern Report questioned the use of very low discount rates and the approach taken in the benefit-cost analysis of the Report (M. Weitzman 2007; J. P. Weyant 2008; Mendelsohn 2008)

The debate about discount rates and the use of benefit-cost analysis has been primarily focused on efforts to reduce GHG emissions, but the questions involved are equally applicable to the strategies to respond to sea level rise. The dismal adaptation corollary is that since the worst outcome is complete elimination of current shore uses, all resources should be devoted to adapting to the worst possible outcome. But this is not, in fact how sea level rise planning has been taking place.

Rather, sea level rise has been modeled explicitly to provide visualizations of possible consequences. Examples include the NOAA Sea Level Rise Viewer⁴ and the estimates of the real estate data firm Zillow.⁵ The sea level rise viewers have the advantage of providing visual clues as to the possible consequences of sea level rise at specific places and under defined assumptions (for example which IPCC scenario to use) but the apparent precision of these models hides the deep uncertainty about what degree of sea level rise/flooding should actually be defined as the management goal for adaptation actions. The viewers provide no guidance about what to do in response to the predictions, when actions should be taken, and how these actions can be financed. We are left with the same problems of how to deal with multiple uncertainties and the same set of questions about how to deal with probabilities and discount rates.

These apparent difficulties with the standard approaches to economic analysis have led to suggestions that noneconomic approaches be used to make decisions about how to deal with climate change. These have included applications of decision analysis, such as maximin analysis and robust decision-making (Kunreuther et al. 2013), as well as variations on multicriteria analysis (Hallegatte et al. 2011; Khazai et al. 2013; Toman 2014)

These approaches have the advantage of avoiding many of the thorny issues involved in monetizing costs and benefits, as well as the problems of the social rate of time preference. But these virtues come at exactly the price that benefit-cost analysis addresses: how we do we know what we are getting in return for the resources we must give up, and thus the issue circles back again towards the dismal theorem.

⁴ <https://coast.noaa.gov/slr/>

⁵ <http://www.zillow.com/research/climate-change-underwater-homes-12890/>

Perhaps the answer is to simply ignore the implications of the dismal theorem and simply proceed to conduct benefit-cost analyses. Benefit-cost is required as a condition for getting funding for adaptation from some government agencies such as the Federal Emergency Management Agency (FEMA) when seeking adaptation assistance money. (FEMA 2009) Benefit-cost analysis has also been used as a screening tool to examine a range of adaptation alternatives to identify the most effective approaches for a given situation. (Economics of Climate Adaptation Working Group 2009)

These project-level applications of benefit-cost analysis are quite important because they offer the opportunity to define and even expand the range of options for adaptation. A good example of this is the concept of “natural” or “green infrastructure”, which is the use of natural features such as shorelines, wetlands, coral reefs, and mangrove forests as protective structures. A growing body of studies demonstrates the technical feasibility of using natural infrastructure (Narayan et al. 2016; Shepard, Crain, and Beck 2011; Beck and Lange 2016) for protection of shoreline properties and economic evaluations are demonstrating their cost competitiveness. The paper by King is part of a growing body of literature that uses benefit-cost analysis to show that nature-based approaches to protecting coastal properties against sea level rise effects are very likely to be either competitive or superior to engineered armoring approaches such as seawalls (Newkirk et al. 2016; ENVIRON International Corporation 2015).

Benefit-cost analysis can and will continue to play its traditional role in project and program evaluation, both *ex ante* and *ex post*. (Li, Mullan, and Helgeson, 2014), but the big questions about how to handle the uncertainties surrounding sea level rise and other effects remain. Each adaptation project evaluation will contain explicit or implicit assumptions about the extent and timing of sea level rise, which are in turn driven by assumptions about the degree of climate change. Analysts may take refuge in scenarios by choosing some combination of the IPCC scenarios and their sea level rise consequences then conducting analysis using “low”, “middle”, and “high” scenarios. This makes uncertainty visible and appears to reduce the scope of the problem, but still does not resolve the issue. If a project passes the benefit-cost test at the low scenario but not the middle scenario, what conclusion should be drawn?

What then lies between benefit-cost analyses based on “best guesses” and the dismal theorem? A possible answer lies in conceiving of adaptation, at least for

those places not confronting immediate existential crises, as a sequence of decisions taken with progressively increasing information. The focus would be on helping decision-makers find a way to resolve uncertainty for their purposes rather than specifying an exact procedure to be used by everyone. Such a process would be grounded in five elements: (1) traditional benefit-cost models to define and narrow available options; (2) recognition of the problem from the decision maker's perspective by incorporation of the insights of psychologists and others who have studied the way people respond to risk and uncertainty; (3) the application of statistical methods better suited to handling uncertainty to provide some, but not definitive guidance; (4) stakeholder processes where the perceptions of risks can be shaped for those who actually must make the decisions rather than for the analysts who must only arrive at a theoretically and empirically elegant solution; and (5) a continuing set of decisions in which the information from the first four elements permits choices between actions that should be taken in the present or postponed, and for those actions that are judged to be postponable, the specification of the information that will be needed to move the action from future to present. This process requires explicit choices by those involved in the decision process about how they will deal with uncertainty at each stage and, over time, the range of uncertainty can be reduced as new information becomes available.

This approach implies a shift in focus from economic analysis that seeks the "optimum" adaptation strategy to economic analysis that supports a process of risk assessment and judgments grounded in the best available information, including economic information over a continuing set of decision points.

This shift in perspective is critical because a large body of literature has shown that people's perceptions of risk and uncertainty—and their choices in risky situations—are shaped by a variety of factors that are largely unconnected to the economist's preferred tool of expected (probability adjusted) values. The seminal work by Kahneman and Tversky showed that people are biased against losses rather than the possibility of gains, and that the way in which a risk is described (framed) and the sources of the description have more to do with the choices made than any measurements of either probability or outcomes. (Kahneman and Tversky 1979; Kahneman and Tversky 2000) Extended research into different aspects of risk perception and communication has offered a number of insights about how people actually respond to risk, including risk aversion, the

endowment effect, anchoring to recent events, and the extent of control that people feel that they have (Ropeik 2010).

This literature is too large to explore all the possible ramifications, but three key findings provide some guidance for the adaptation problem. (1) People are risk averse—they are more worried about losses than gains. (2) The degree of control that people believe they have over risks affects whether they see risks as high or low. (3) People are less likely to act to reduce risks perceived to be remote in time or space. Taken together, these biases mean that adaptation decisions that would cost money today relative to remote risks where actions taken will still have uncertain outcomes would tend to be avoided or at the least postponed, but a clear sense that decisions will make a real difference in risks may encourage steps to assess the options. That assessment can then address risk aversion and remoteness.

The processes to support adaptation should allow people to see both the risks of action and inaction; risk aversion cuts both ways. The availability of options for adaptation and funding resources (as discussed below) provides a measure of control. This will be the primary role of the kinds of benefit-cost analyses noted above. Finally, the focus on acting on what should be done in the near term while still addressing the long term places the decisions in a manageable context.

Information about probabilities is still needed, whether through statistical analysis of historical data or the results of modeled futures is helpful, even if expressed only on a qualitative scale of “highly unlikely” to “highly likely”. Exact probabilities cannot be known but risk aversion means that people need some sense of the range of probabilities. In the climate change context, where historically derived frequentist based probabilities such as those used to calculate risks for flood insurance are decreasingly relevant, there are two possible approaches. One is to simulate probability distributions that do not yet exist through mechanisms such as Monte Carlo models (The Rhodium Group 2014). The alternative is to use Bayesian models that explicitly account for the risks of both action and inaction and which can do not rely on a specific historic pattern to be useful (though history can still be a part of the process) For these reasons, they are increasingly being used in situations with “deep uncertainty” (Cyert and DeGroot 1997) as well as in applications related to climate change (Zorrilla et al. 2010; Gutierrez, Plant, and Thieler 2011).

A further element in bounding uncertainty is the use of scenarios, which will likely be used in addition to any statistical analysis if for no other reason than that scenarios are already integral to the IPCC analysis, which sets out multiple possible futures based on assumptions about the extent to which mitigation effects will be effective (Intergovernmental Panel on Climate Change 2014). IPCC scenarios tend to drive almost all climate change related planning simply because they are the most widely vetted and distributed. But scenario based planning is also a commonly used approach for long term problems. It is highly flexible in the types of information it can use but also simplifies the communication problem and allows stakeholders a major voice in setting the terms that will define the decision problem (Myers and Kitsuse 2000).

But a word of caution is in order about scenario planning. Scenarios will be part of many processes, but they are methods of information integration, not information generation. There are many different approaches to the construction of scenarios (Amer, Daim, and Jetter 2013). Some processes seek only descriptive scenarios (this is what the world might look like) and others seek normative scenarios (this is what the world should look like). There are multiple methodologies for combining and simplifying large amounts of quantitative data (including forecasts), each of which introduce their own biases into the resulting scenarios. In any scenario process, there is a debate about the right number of scenarios to be examined. Two is generally considered too few, five or more are too many, which leaves three or four. Three scenarios inevitably attract attention to the middle scenario, while four require that two dimensions be identified to create the matrix.

The final element in a revised economic approach is to recognize that the key probabilities are those of the decision makers and those who must concur with the decisions (the stakeholders) to decide which actions are most appropriate. There is evidence that rigorous group processes are capable of shaping risk perceptions and adaptive strategies that combine analysis of probabilities with the perspectives of individuals (Susskind et al. 2015). The key to success to help non-experts to assess the uncertainty of climate change and formulate adaptation plans is to allow the group participants to define the levels of risk that they will use for the planning process. This is a recognition that it is the perceptions of risk are the key to motivating action, but also that better measurements of risk can influence those perceptions when introduced in a structured process.

This approach resembles the iterative approach to benefit-cost analysis suggested by The Economics of Climate Adaptation Working Group (ECAWG), but extends that proposal by adding the risk perception, and stakeholder process elements. ECAWG proposes a simple rule: conduct a benefit-cost analysis of alternatives, and identify those that are cost effective (have a benefit-cost ratio greater than one). Then deploy those options determined to be cost effective and leave the rest of the risk to insurance and reinsurance (Economics of Climate Adaptation Working Group 2009). The ECAWG benefit-cost analyses of major adaptation options were conducted using scenarios as way of addressing uncertainty and conducted their benefit-cost analyses with a twenty-year time frame. The results depend on choosing the scenario that best conforms to actual climate change effects. The adaptation options they assessed may have useful lives well beyond the twenty years for which they conducted the analysis, and thus the options may or may not be cost effective over longer periods.

3. WHERE IS THE MONEY GOING TO COME FROM?

The discussion in the previous section noted that a sense of control was an essential part of effectively confronting issues with high levels of uncertainty. While the many options for climate change in the IPCC scenarios (and associated sea level rise models) certainly reduce a sense of control, the factor that is perhaps most daunting to those who must make adaptation decisions is a sense that the needed resources needed are simply unavailable now and perhaps in the future. If there is no money, what can we do? The question of financing adaptation is thus not an issue to be decided once a plan has been formulated; it is a precursor to whether planning takes place at all.

For some this may not seem like an economic question at all; in a sense it is a purely political question posed in terms of simply generating the political will to make the necessary investments (McKibben 2016). But Weitzman's dismal theorem reminds us that no matter what the level of will, resources are still limited and no single source of funds is ever likely to be enough. The funding for coastal adaptation will, indeed, come from a complex mix of existing, emerging, and new sources of finance that will require as much creativity as the engineering of adaptation options themselves. Some options will require changes in current

institutions or creation of new institutions, but these are barriers that can be overcome.

Infrastructure to shield shorelines against erosion has historically been financed either by the public, through standard financing (e.g. road budgets or natural hazard disaster funding), or the private sector when property owners build to protect their individual properties. But a combination of forces has expanded the sources and types of funding available and this expansion will likely continue. These forces are driven by:

1. The sheer size of damages from natural hazards, which has greatly increased, partly due to climate change but mostly due to the steady increase of human uses in hazard prone areas.
2. The pressures on public budgets resulting from the Great Recession of 2007-2009 and its aftermath.
3. The development of new approaches to climate change adaptation, particularly the nature-based or “green” infrastructure concepts that were noted in the benefit-cost studies discussed earlier.

The increasingly complex array of financing options can be usefully depicted with a relatively simple framework such as that presented in Figure 1. The framework’s structure derives from distinguishing who pays for adaptation and who benefits from it using a standard public goods/private goods framework. Pure public goods are non-excludable in production (once produced the benefits are widely available) and non-rival in consumption (one person’s consumption does not diminish anyone else’s consumption); pure private goods are both excludable and rival. Because of non-excludability and non-rivalry, public goods cannot be paid for in proportion to the amount consumed as private goods can. The division is not so clear because many goods are mixes of benefits with mixed levels of excludability and rivalry, but the distinction is still helpful for illustrative purposes.

	Public Pays	Private Sector Pays
Public Benefits	<p>I</p> <p>Benefits are purely public</p> <p>Cannot be meaningfully divided among users to allocate costs</p> <p>Options</p> <ul style="list-style-type: none"> • General Tax Revenues • General Obligation Bonds • Specialized Consumption Tax • Post-disaster recovery funding 	<p>II</p> <p>Private funds provide benefits greater than the private funder realizes</p> <ul style="list-style-type: none"> • Impact Investing • Green Bonds <p>Private organization created to share benefits among organization members/funders</p> <ul style="list-style-type: none"> • Hazard Assessment Districts • Tax Increment Financing Districts • Water/Sewer • Stormwater <p>Debt Versions</p> <ul style="list-style-type: none"> • Revenue Bonds • Moral Obligation Bonds
Private Sector Benefits	<p>III</p> <p>Publicly subsidized private expenditures</p> <ul style="list-style-type: none"> • Tax Subsidies • Income Tax Credits • Property Tax Credits • Valuation adjustments 	<p>IV</p> <p>Private charges for service in proportion to private benefits</p> <ul style="list-style-type: none"> • Goods/Service Charges • Insurance/Reinsurance • Catastrophe Bonds • Resilience Bonds

Figure 1. Financing matrix

4. DISCUSSION OF FINANCING MATRIX QUADRANTS

Quadrant I: Public Benefits, Public Funding

This is the classic public goods situation, where funding comes from general tax sources, either present period (appropriations) or as debt (bonds). This general purpose revenue and expenditure source is what many officials look to when the subject of funding comes up, because appropriations, grants, loans, etc. are all part of the normal structure of government spending. But it is precisely this source that is most under stress from other demands.

Quadrant I could contain major public appropriations programs for adaptation like general public infrastructure in the U.S., but in fact, while some European countries have devoted general revenues to adaptation (the Netherlands has effectively been doing so for decades), such funding is not available in the U.S. Rather, the largest source of Quadrant I funding for dealing with the effects of sea level rise related flooding in the U.S. is post-disaster recovery funding. These are the appropriations made to cover losses to public and private property following a disaster that are over and above insurance payments. Such post-disaster funding is now common in the U.S. and occurs in other countries as well. (Jackson 2013; The Council of the European Union 2002) It is an issue for general public goods financing in Quadrant I because this source always serves as the ultimate backstop for all recovery funding, and it is the first line of defense for most publicly owned property, which is essentially self-insured.

In fact, the U.S. National Flood Insurance Program was never designed to cover catastrophic losses. Premiums and coverages were designed for predictable floods and in what was thought to be the extremely rare event of a flood beyond the 100-year level, the flood insurance funds from which claims were to be paid would be supplemented with appropriations. What has happened since the 1970s, and particularly over the last decade with Katrina, Sandy, and other record floods is that the “reinsurance” (the money “borrowed” from general revenues to pay claims) now dwarfs the actual insurance to the point where it is uneconomic to ever repay the “debt” with premiums (Michel-Kerjan 2010). Technically classified as generally available public expenditures, post-disaster funding is considered a problem of public budgeting like many others, but it should perhaps be better considered as the ultimate reinsurance for coastal areas and thus is connected to the funding discussed in Quadrant IV, as discussed below.

A major issue with post disaster funding is the distinction between the uses of such funds to restore lost properties and the use of such funds to reduce future damages (that is to adapt to future risks). In some places, such as the United

States, the policy is that recovery funding is to be used only for the purposes of replacing what was lost, not for upgrading infrastructure making other adaptive changes. This policy is designed to stretch recovery resources as much as possible, but it has the effect of limiting the flow of funds to adaptive measures at precisely the time that it would be least expensive to deploy them because the expenditures are now incremental to the recovery efforts.

A special case of public goods funding is the levying of general taxes dedicated to specific purposes. For example, many U.S. local jurisdictions (cities and counties) levy a special sales tax within a jurisdiction and use the revenues to support specific purposes, such as transportation improvements or the construction and operation of civic/convention centers. This is a variation on the strategy identified in Quadrant II of creating special purpose districts. The difference is that in Quadrant I, the revenues for the special purpose come from all or a subset of general taxpayers, while in Quadrant II the revenues come from those who most directly benefit.

Quadrant II: Public Benefits, Private Funding

“Impact investing” is one of the most important areas of innovation in finance over the last decade. (J.P. Morgan Global Research and The Rockefeller Foundation 2010). In impact investing, private funds are pooled to purchase a debt instrument which will be repaid at a market or near-market rate, but which will fund projects that have general benefits beyond those realized by either the bond buyer or seller. Impact investing has been used in a variety of fields including health and social services, but the most relevant version for current purposes is the category of “Green Bonds” or, when applied to ocean-related uses “Blue Bonds” (The World Bank; World Economic Forum, 2013).

“Green bonds” are a general category of debt used for environmentally related purposes. Perhaps the major current use is for “climate bonds”, which are used primarily to pay for greenhouse gas (GHG) mitigation efforts, such as renewable energy or energy efficiency projects. In the most common type of climate bonds the “impact” is a certified reduction in emissions, with the reduction being measured in physical and/or economic terms. Independent certifying agencies have arisen to perform the audits of project effectiveness. Such bonds, with their accompanying non-financial metrics, have begun to be proposed for adaptation projects, but this is still at an early stage and the development of impact metrics

for adaptation projects has not proceeded at nearly the pace that it has with respect to energy and GHG mitigation. The development of such metrics for measuring the effectiveness of sea level rise adaptation projects such as natural infrastructure will determine the extent to which “impact investing” becomes a source of funding.

A second approach in this quadrant is the creation of special purpose districts, where taxes or fees are charged to the residents of the district and the resulting revenues are used for the general benefit of the district’s residents. Water and sewer fees are one of the oldest arrangements of this type, and this principle has evolved into the creation of stormwater districts to fund the additional infrastructure needed to manage high volume water flows during storms. Stormwater districts are, to all intents and purposes, an adaptation strategy related to climate change, although not all stormwater infrastructure or financing is explicitly sized to manage climate change-related effects (Colgan, Kartez, and Sheils 2016).

Other examples of this approach are the levee districts that support maintenance of flood control infrastructure in the lower Mississippi valley, California, and Florida. The capital cost of constructing levees is usually born by the U.S. Army Corps of Engineers, but operating and maintenance costs are a local responsibility. Local funding often comes from surcharges on the property tax in the protected areas, but when these are inadequate, levee boards have tried a wide variety of ways to fund operating costs, from leasing levee space for cell phone towers to taking contributions from casinos (Miller 2012).

Another variation is the use of tax increment financing. This approach is a version of the special purpose district, where the increment from the development of new real property is set aside and used for specific purposes. (Dye and Merriman 2006) Tax increment financing is used for a wide number of purposes, from building infrastructure directly related to a project whose property tax increment is captured to rebating a portion of the tax increment directly to the project sponsor as an incentive. Tax increment financing could be used to fund shoreline protection or to pay for adaptive building modifications for new shoreline developments or, in some cases, existing development.

These variations on the theme of regional or community level organized, collected, and used financing represent one of the largest opportunities for

securing the needed financing for adaptation. The approach builds on existing financing models and has the major advantage of being an approach that enhances the local/regional control over the way in which adaptation is carried out. Communities can, in the right circumstances, design not only the technical, engineering, and policy approaches to adaptation but the financing mechanisms as well.

Quadrant III: Public Payment, Private Benefits

This is the general category of public subsidies to private beneficiaries and is in a sense the obverse of Quadrant I. From the public budget perspective, funding in Quadrant I and Quadrant III are equivalent; resources are expended or revenues foregone. But Quadrant III targets the resources to those with a specific tax nexus, most likely in terms of income or property values. It is a good example of the mixed nature of funding and benefits, because such subsidies are usually justified, however loosely, as having some broader public purpose, but the primary benefits tend to accrue to a narrow group.

There are many variations in how tax subsidies can be made available (credits, deductions, exclusions, depreciation allowances, etc.). Tax subsidies are generally only useful in jurisdictions with sophisticated tax systems.

Quadrant IV: Private Payments, Private Benefits

As with Quadrant I, this is a common funding approach. Individual property owners have been taking steps to protect their property against shoreline erosion for centuries. But the heart of financing in this part of the framework is insurance, which is technically a private payment to cover a risk. In some ways, insurance is the economic “ground zero” for climate change, since it is insurance, whether provided by private industry, public programs, or the ultimate insurance of special public expenditures for disaster recovery (discussed in Quadrant I) where the costs of sea level rise in coastal regions will be most visible. Flood insurance (including special post disaster funding) is the largest single pool of funding dedicated to the problems of flooding and sea level rise; finding the appropriate role for these funds in adaptation is perhaps the major funding challenge.

There are traditional insurance issues of coverage and pricing that must be addressed. How much should insurance cover from flood damages, whether from

catastrophic flooding or nuisance flooding (frequent low level flooding of streets and properties)? Should insurance pay to reduce future risks or merely to recover what is lost? What price should be charged for insurance and should the insurance be mandatory or voluntary? There are also distributional issues about the relative responsibilities of public and private insurance: Does the common practice of appropriating emergency funds to recover from flood disasters create a moral hazard problem for flooding or reduce the incentive for the purchase of insurance? For insurers, both public and private, there are choices to be made about how much of their capital and payouts should be used to reduce future risks and what strategy should be used to reduce such risks?

These issues are complicated by the structure of insurance, which is provided in a two-tier system⁶. The first tier is the insurance purchased directly on properties either from private insurance companies or from government programs. The second tier is reinsurance, which is insurance purchased by first tier providers against especially large claims. There is a combination of private and public institutions involved in both tiers, with the precise mix determined by national policies. Flood insurance is provided entirely by the private property and casualty insurance industry in most European countries, but it is provided by the public sector in the U.S. through the National Flood Insurance Program (NFIP). Reinsurance is provided primarily by the private sector for privately provided primary insurance and the government provides it for publicly provided primary insurance. The public sector also provides both primary and reinsurance for publicly owned property—that is the public sector effectively self-insures.

The same questions that are raised concerning primary insurance above also apply to reinsurance. What role can reinsurance play in reducing future risks by funding, directly (through specific investments) or indirectly (through reduced fees passed on to consumers) adaptive measures?

In addition to using public disaster recovery appropriations for adaptation in addition to recovery as discussed above, there are two possible sources of adaptation funds from the insurance markets. One is from the pooling of savings in the primary markets, the other from the flexibility created by innovations in reinsurance.

⁶ There is a third level called retrocession, which is essentially reinsurance for the reinsurers. Most of the same issues applying to reinsurance apply to retrocession, so it is not included in detail here.

5. POOLING SAVINGS

The National Flood Insurance Program and the Federal Emergency Management Agency do take two important steps towards encouraging adaptation. One is a grants program that provides funds to communities to invest in adaptive infrastructure, when such investments pass a benefit-cost test (see above). The second is the Community Rating System, which offers discounts on flood insurance premiums in communities that undertake specific types of steps to reduce risks, such as limiting rebuilding in flood areas (National Flood Insurance Program 2006). The CRS is a good example of the kind of economic incentives for adaptation that may be needed, but participation by communities remains low and the adequacy of the incentives given increasing risks is open to question. Moreover, the CRS and the infrastructure programs address community level adaptation actions, not individual property actions. Nothing prevents communities from pooling the savings on flood insurance premiums to invest in further adaptation measures, but such pooling of savings has not yet occurred.

6. REINSURANCE

Insurance is possible because risks can be measured with sufficient confidence that capital can be attracted to provide recompense for losses while still creating a return to capital through other investments. But insurance companies also live with the risks of losses at the tail ends of the probability curves on which they rely for their “normal” businesses. At these “catastrophic tails”, primary insurers do not have adequate capital to pay policyholders. To cover these risks, insurance companies purchase backup or reinsurance.

As insurance for the largest catastrophes reinsurance is generating much interest in considering climate change risk management. It is the reinsurers who are left to cover the losses from tropical and extra tropical cyclones and other weather events that were once extraordinary but will become ordinary. Reinsurance is a highly specialized industry and providing reinsurance is highly skilled work. Deciding what to cover and at what price when the risks at hand occur relatively infrequently is one of the most difficult challenges in managing risks. As it has evolved, reinsurance accomplishes this task through a complex network of relationships among the individuals who work for the reinsurance firms and the individuals who work for the insurance firms who purchase their

services. This network of experts in regular contact with one another allows reinsurers to decide how much of a given risk (hurricane damages, for example) the reinsurer will cover and at what price they will provide coverage to the primary insurer (Jarzabkowski, Bednarek, and Spee 2015). These relationships among individuals are cultivated and maintained over extended periods and it is the confidence in the relationships that permits pricing decisions to be made. Because so much depends on individual relationships, the number of reinsurance firms is quite small.

But this traditional relationship-based reinsurance industry is undergoing significant change brought about by two different trends. The first is that reinsurers are becoming more and more reliant on computer based integrated assessment models to assess risks. These models combine information on hazard-causing phenomena, such as flooding, with economic information about the magnitude of values at risk. They supplement relationship-based information and the traditional approach but at the same time the formal economic and related meteorological and hydrological analysis opens the door for assessing risks to a larger circle than the traditional reinsurance specialists.

The other major change in reinsurance might be described as the “securitization” of reinsurance through the development of a new class of financial instruments called catastrophe bonds. (Swiss Re 2012; Alvarez 2015) Catastrophe bonds are a means to create reinsurance for a short period in a specific area. The bond is issued through a “special purpose vehicle” (SPV) under the laws of countries such as the Bahamas or Grand Cayman Islands. The SPV becomes essentially a temporary reinsurance company created for one specific set of hazards in one specific place. The bond issuer creates and sells a bond that will pay the purchaser of the bond a fixed repayment and return over the life of the bond (usually three years). Under the terms of the bonds, if a specified set of events with specific parameters occur during the life of the bond, such as a hurricane that damages more than \$X million in property, then the proceeds of the bond, which are held in trust until maturity, are liquidated and the funds used to pay the reinsurance claims. Essentially, the seller of the bond is betting that the catastrophe will not occur and they will be repaid the face amount plus interest. The bond seller is effectively acting as an insurance company collecting the equivalent of premiums but having to pay out if the catastrophe occurs.

Catastrophe bonds have several advantages, of which the most important is that they attract additional capital into the pool of reinsurance funds, without having to establish new reinsurance companies or rely on recreating the network of expert relationships on which reinsurance depends. The availability of the formal risk models noted above is essential to this process because the risk modelers' results are available to anyone who purchases them. The fundamental mechanism for attracting this additional capital is the ability of catastrophe bonds to create a well-defined and narrow portion of the total risk, and a market in which purchasers of the bonds may assess the portion of the risk they are asked to bear relative to other similar investment opportunities. Catastrophe bonds have been described as performing a transformation in financial markets for reinsurance like the securitization of mortgage lending over the past twenty years. (Jarzabkowski, Bednarek, and Spee 2015)

The new capital flowing into the insurance process from catastrophe bonds is a possible target for use in financing adaptation. The parties to the catastrophe bond have a mutual interest in avoiding the conditions requiring the bond be used to pay claims and, to the extent those conditions are defined by damage size parameters, both have an interest in using some of the bond proceeds to invest in damage-reducing adaptations. In fact, this idea has been developed into a proposal for "resilience bonds" (Vajhala and Rhodes 2015). Resilience bonds represent a direct connection from insurer to adaptation action, though such bonds have not yet been shown to be marketable.

However, the resilience bond approach is not the only way that reinsurers can reduce their risks. The traditional method of diversifying the risk portfolio may be more attractive in many cases. Instead of investing in physical projects, catastrophe bonds can be tailored to cover a smaller part of the risk, leaving others to cover the rest. Resilience bonds provide new options for attracting capital to adaptation but they will operate in competition with risk reduction through diversification strategies and their ultimate role is not clear.

Before leaving the discussion of insurance, it is important to note that there are a number of distortions in the flood insurance market through the under-insured and the over-insured, that limit the possible roles of insurance in supporting adaptation, particularly in the U.S. Public flood insurance in the U.S. is not charging premiums sufficient to cover damages let alone further risk

reduction.⁷ Efforts to make insurance accessible by keeping premiums low transfer the risk from the insured to the insurance program and ultimately onto the public treasury, while efforts to recover costs for the insurance program move public insurance into the same premium territory as private insurance. (Committee on Risk-Based Methods for Insurance Premiums 2015) These problems exist even before the effects of sea level rise are factored in. The National Flood Insurance Program still plans for and prices for the 100-year flood (a 1% per year probability of flooding), the same as when the program was established fifty years ago.

Even with the mispricing, there are still many uninsured properties, which are properties that have no flood insurance and do not have sufficient assets to self-insure. Even worse are those properties that are located outside currently defined hazard zones, but are also located inside emergent hazard zones created by sea level rise. In many parts of the world properties in near shore areas that should be covered by flood insurance because of changing threats from sea level rise are not even currently eligible to buy the insurance, and thus are provided no insurance price signals to take adaptive actions.

At the same time, there is also a significant problem of the over-insured, exemplified by what the National Flood Insurance Program defines as repetitive loss properties (King 2005), which are defined as one or more flood insurance claims payments that each exceeded \$5,000, with at least two of those payments occurring in a 10-year period, and with the total claims paid exceeding \$20,000; or two or more flood insurance claims payments that together exceeded the value of the property. Such properties are generally not charged actuarially accurate premiums, thus placing additional stress on the insurance pool to the point where the entire existence of public flood insurance is called into question. (Mcguire, Goodman, and Wright 2015) The over-insured also represent the clearest example of moral hazard where insurance-based incentives for risk reduction are almost eliminated.

⁷ The extent to which flood insurance is unworkable in private markets is largely a function of policy choices. European countries such as the U.K. and Germany make flood insurance mandatory within standard homeowner policies, thus spreading the risk and reducing premiums. The U.S. chose not to mandate flood insurance because insurance is traditionally regulated at the state level rather than the national level. Create a new national program at the federal level avoided conflicts with the states but left the federal government with the problems associated with a voluntary insurance pool.

The scale of funding needs for adaptation is indeed daunting and there are no grant programs immediately and easily available to pay those costs. But a careful arrangement of existing possible sources will greatly increase the pool of resources available. This arrangement can tentatively be characterized as follows:

1. Use general tax revenues to fund the largest projects with the greatest benefits, such as proposals to build tidal barriers across the entrance to New York Harbor like the barriers on the Thames and in the Netherlands.
2. Encourage the formation of local financing districts using fees, taxes and tax increments, insurance savings, and other funding streams flowing from the benefits of reduced flood risks.
3. Tap the growing “green bonds” market by establishing certifiable standards for risk reduction impacts that could attract bond buyers interested in the adaptation side of climate change finance.
4. Funds for disaster responses should always pay for both recovery and reduced risks. This is especially true of general public revenues used for disaster recovery but could also be true of catastrophe bonds and other insurance payments. Every disaster is an opportunity to reduce risks and no opportunity should be missed to do so.
5. Flood insurance, public or private, should be managed and priced to encourage risk reducing adaptation actions whenever possible. Revised building codes that mandate risk reducing adaptation should be funded through reduced insurance costs.

This discussion of financing as part of developing adaptation strategies began by noting that finance is essential to provide a sense of control over the problem. That control lies primarily in communities planning for adaptation to be aware of their options under elements 2 and 3 in the above list and to incorporate those in their planning. Elements 1 and 4 will require actions above the community level but will be essential to developing effective adaptation strategies.

7. VULNERABILITY AND RESPONSES OF REGIONS AND INDUSTRIES

A major theme in the climate change economics literature and in economic studies of coastal and oceans effects is measuring the dimensions of economic vulnerability. In general, these vulnerability studies have provided very good information about the stakes involved in sea level rise and have been successful in raising awareness, but there are two very large gaps in the literature: First, almost all studies have examined the possible effects of climate change in the *late* 21st century on the economy and population of the *early* 21st century. Coupled forecasts of climate change with forecasts of economic and demographic change are notably lacking. And because little attention has been paid to linking the forces driving socioeconomic change to climate change, even less attention is being paid to how economic forces will shape the changes in local, regional, and national economies that follow the effects that climate change will have on coasts and oceans. This results in the second major gap: the tendency in vulnerability studies to focus on comparative statics rather than the dynamic changes in local and regional economies after events such as major floods.

Economic vulnerability assessments with specific attention to the consequences of sea level rise have been done at both the national and regional levels, with regions defined very broadly and very narrowly. The most common metric of vulnerability is property losses (Gordon 2014; Yoskowitz, Gibeaut, and McKenzie 2009) and public infrastructure losses (J. E. Neumann et al. 2003; ICLEI 2013). Property damage vulnerability studies have become so common that they are being reported in the press. (Brady 2016) Social vulnerability, defined as impacts on populations with particular characteristics, such as low income, immigrant, the elderly, and disabled are also frequently assessed. (Cutter, Boruff, and Shirley 2003; ICLEI 2013) There have also been studies vulnerabilities of particular ocean economy sectors. (Jepson and Colburn 2013)

There have been some macroeconomic models that have translated property losses into reductions in capital stock and business interruptions (Jorgenson et al. 2004) into losses in productivity that affect economy-wide output (The Rhodium Group 2014). But vulnerability studies need to be at the regional and local levels to inform decision-making where adaptation decisions will be made. There is a fairly large literature on the economic impacts of flooding disasters conducted on an *ex post* basis (Colgan and Adkins 2006; Mu and Chen 2016), but there do not appear to be many studies translating this understanding of the historical record into projections of possible future changes. There are also studies that have set out

to assess vulnerability on regional economic functioning by looking at possible employment impacts (Colgan and Merrill 2008) or by creating multivariate indicator series to create a more complete picture than single metrics (Khazai et al. 2013; Song et al. 2016).

A common theme to many of these studies is that the vulnerability metrics chosen are relatively easy to locate geographically. Property tax records, the locations of public infrastructure, and detailed Census records are all generally available at sufficient geographic detail that they can be matched using Geographic Information Systems (GIS) to the outputs of various forms of hydrographic/climate models. GIS analysis makes it possible to closely match the distribution of possible flooding/inundation impacts to estimate total potential property losses, population affected, or infrastructure facilities disrupted.⁸

The current regional economic vulnerability studies are very valuable in raising awareness of the effects of sea level rise, but are still addressing only a part of the issue. A high priority should be integrating demographic and economic forecasts into the integrated sea level rise models so that the time periods of projected sea level rise and its effects are at least in the same decade. Long range economic and demographic forecasting is obviously subject to a high degree of forecast error, but these types of forecasts are undertaken all the time for infrastructure planning (particularly transportation) as well as for long-term land use plans. In many cases, such forecasts already exist for these larger purposes and are available at detailed enough geographies (census tracts or transportation analysis zones) to match the geographic detail of flooding/inundation modeling. If they are otherwise available, there are several options to construct such models (REMI, REDYN) using standard regional models.

Forecasts are also essential to introduce explicit consideration of the key economic and demographic forces shaping vulnerability. For example, many parts

⁸ The availability of detailed geo-located data clearly facilitates the development of economic vulnerability analyses, but such data is not always available, particularly in the case of low income countries. In many cases, it is necessary to build vulnerability analyses from the top down rather than the bottom up. Disaggregation of economic data is a standard practice, which will be needed in many cases where forecasted conditions are used in the vulnerability analysis as discussed below. The simplest disaggregations use a combination of geographic and population criteria, such as the global 1km grid GDP data created by the United Nations Environment Program (Global Change and Vulnerability Unit 2012)

of the U.S. coast currently house a disproportionately older population because they are centers for retirement and because of overall aging of the U.S. population. But the demographic profile of these areas in 50 years will almost certainly be different because of restructuring of national and regional populations as the baby boom generation gives way to its successors. Another example is that many communities are located in what are currently the transition zones between urban and rural economies; by the end of the century, many such communities may be entirely urban (if outward spreading of urban space continues) or may remain transitional or even become more rural if urban space recentralizes. The differences in possible vulnerability for these communities are quite significant depending on how urban space evolves.

The longer-term dynamics of regional change are an essential part of the story, but many coastal areas are also characterized by the short-term dynamics of seasonality. It is not uncommon for coastal areas that are popular tourist destinations to see populations grow in high season by a factor of five or more and for economic activity to triple or even quadruple. Such seasonal variations clearly alter the economic values at stake in assessing vulnerability, yet most economic and population data used in vulnerability studies is either annual average data or measured at only point in the year (often in the low season precisely to avoid the effects of seasonal growth). Seasonal variations in population and economy are essential to vulnerability studies in many areas.

The addition of a dynamic perspective on regional economies to better understand how future economies may be vulnerable to future threats should also be coupled to a better understanding of how economies will respond to those threats. Relatively little has been done to consider this aspect of adaptation, but if the previous sections are correct that adaptation will be a long term iterative process then the ability to forecast each iteration of the economy, however imperfectly, will be an essential element in strategy formulation.

The Khazai et al. study gets close to the kind of regional impact analysis that is needed, with the inclusion of an industrial vulnerability index, which includes such impact-causing factors related to flooding as labor availability, supply chains, and dependency on water and electric power. The paper applies the industrial vulnerability index, together with guides measuring regional dependency, and social fragmentation to the German state of Baden-Wuerttemberg. The approach in this paper begins to focus on the dynamics of

regional change and of industrial impact, though it does so still within a comparative statics model of vulnerability.

But there are still major weaknesses to be addressed. The Khazai et al. industrial index is constructed entirely for goods-producing industries, including selected manufacturing and construction industries. This ignores the fact that the urban areas where economic vulnerability from sea level rise is most acute are predominantly non-manufacturing regions. Nor is there much focus on ocean related industries in the literature, such as coastal tourism and recreation or marine transportation, although impact studies on ports available (Hallegatte et al. 2011; Lempert, Srivier, and Keller 2012).

The idea of economic vulnerability as a function of the structure of the local/regional economy has also not been explored from the perspective of local clusters that may be disproportionately at risk. Clusters are complex networks of relationships among businesses and other institutions within the region whose cumulative effect is to confer competitive advantages through external economies of scale (Porter 1998). Disruption of clusters or economic base industries may lead to significant shifts of activity outside the region if the locations of existing firms become untenable because of persistent flooding disasters.

Ocean-dependent activities provide a good example of vulnerability extending beyond sea level rise to include effects on the ocean such as changes in ocean temperatures, as oceans absorb the greatest share of atmospheric warming, and ocean acidification, as the extra carbon dioxide in the atmosphere changes the chemistry of the oceans. The major threats from these changes will be to fisheries and to ecosystems such as coral reefs, which are critical habitat in their own right and, in many areas, a key resource for both fishing and tourism industries (Cooley and Doney 2009; Kroeker, Micheli, and Gambi 2013; Kleypas and Yates 2009). There are already significant concerns about fishing communities in Alaska. (Himes-Cornell and Kasperski 2015), and the National Marine Fisheries Service has conducted a survey of fishing communities' vulnerability to climate change (Jepson and Colburn 2013). Similar threats to tourism and recreation related communities have not been examined.

While the focus in this paper has primarily been on sea level rise and flooding, particularly from catastrophic events, the vulnerability of fishing communities from changes in thermal regimes and chemistry represents a different set of

challenges for economists than the issues related to sea level rise that requires a moment's reflection. Thermal and chemical changes will be more gradual than catastrophic, with subtle ecosystem changes transforming fisheries over relatively long period. These trends will give more time for adaptation plans to be formulated and implemented, but will also mean that catalytic events that focus attention on the problems will be less likely.

Changes in the ecosystem will reduce the abundance of some commercially important species to the point where they are no longer economically viable. An example is the lobster fishery in southern New England, which has declined from a stock of over 50 million U.S. short tons (45.36 million metric tons) to less than 10 million U.S. short tons (9.1 million metric tons), primarily due to warming waters (Atlantic States Marine Fisheries Commission 2015). In such cases the fishing industry may shift to fishing for other species. This is not an uncommon change; as fishing has dropped due to regulation to prevent overfishing, shifts to other species have become common. This experience needs to be examined as an example of how climate-induced shifts in ocean ecosystems and fisheries may change the fishing industry.

But simply shifting fishing effort may not be an option, or it may not be an option for sufficient numbers of fish harvesters, to maintain communities, particularly in fishing-dependent communities. The transition of communities and economies dependent on single resource bases will become increasingly common in fishing communities, but such transitions have already occurred in regional economies dependent on mining, agriculture, and forests. These are among the most difficult changes in regional economics and economic development and thus define a different type of economic vulnerability (Wu, Barkley, and Weber 2008).

The current approach to economic vulnerability studies serves well to raise awareness of the stakes at issue in failing to either prevent further climate change or reduce the damages from climate change that has already occurred. But economics has barely begun the equally important tasks of understanding how local and regional economies are changing, how those changes will affect future vulnerabilities, and how the responses to the effects of climate change will reshape those local and regional economies. Comparative statics analyses will not serve the dynamic, iterative adaptive processes discussed here. Moreover, economic vulnerability studies become the foundation for benefit-cost analyses based on expected losses avoided through adaptation measures. If we are

evaluating a project to protect a \$10 million property today, the possibility that there will be five more such properties in thirty years' time needs to be considered. If it is not, beneficial adaptation options could be rejected as too costly. In this case, our limited knowledge today would result in seriously *underestimating* the future benefits of adaptive measures.

8. THE ECONOMICS OF COASTAL MANAGEMENT UNDER SEA LEVEL RISE

Adaptation emerges from the discussion so far as an iterative, flexible process where choices are made over time based on continually improving information and resources expanding to meet needs. These are the characteristics that have allowed economists' advocacy of market or market-like approaches to dominate policy choices about GHG reductions. Can the same characteristics of flexibility and iterative improvements guide the choices of specific adaptation strategies? The answer will depend on whether climate change and sea level rise present an opportunity to evolve the approaches to coastal management that have evolved based on the approaches to environmental management that were dominant in the 1970s.

Coasts have long been recognized as unique assets. The competition among human uses and between human uses and ecosystems gave rise to the movement for coastal zone management in the late 1960s and early 1970s. The United States and many other developed countries were the first to develop and implement CZM programs, and today most countries have some version of a CZM program following support for the concept in various UN agreements (Cicin-Sain and Knecht 1998). For the most part, CZM programs follow largely traditional land use and environmental regulatory approaches, allowing real estate markets to perform basic allocation of space to users, subject to review by at least one level of regulatory review. This is a system that generally works well, but if sea level rise ultimately reshapes shorelines and coastal regions at anywhere near even some of the relatively modest projections of one meter or so (to say nothing of projections of five meters or more), then there is a serious question whether traditional approaches to coastal management can keep up with the possible changes.

Regulatory programs can be effective, but they can also be time consuming and expensive to plan and implement. Rapid adjustments within regulatory programs are difficult. The question arises, therefore, whether some of the virtues of markets might be adapted to coastal management purposes to create systems which can achieve the purposes of balanced uses of the coasts with more flexible, incentive-oriented approaches. This is, of course, a point that economists have been making for more than 40 years (Kneese and Schulze 1975), and there is now substantial experience with such market approaches to environmental policy as emissions trading (Tietenberg 2006).

The key concepts to considering how market mechanisms might facilitate better coastal management are ecosystems services and natural capital. Ecosystem services and natural capital have become a major focus of attention, particularly in the international environmental and development spheres because of efforts by global institutions such as the United Nations and the World Bank to explicitly incorporate concepts of sustainability into development aid programs. The European Union has also made a major commitment to building measurement of ecosystem services into policy making, and has partnered with the United Nations to put out the first major standards for incorporation of ecosystem services into standard measures of economic performance (Weber 2011).

Several projects are actively examining how to value ecosystem services and how to use this information in policymaking. These include Natural Capital Project⁹ is one of many efforts seeking to transform valuation information based on flows of services into capital stock values; the Economics of Ecosystems and Biodiversity, or TEEB (Sukhdev et al. 2010), the World Bank's Global Partnership for Wealth Accounting and Valuation of Ecosystem Services or WAVES (WAVES Partnership 2016), and the European Environmental Agency's efforts to create a Common International Classification of Ecosystem Services, or CICES (European Commission et al. 2013).

The CICES ecosystem services classification, reflecting general usage, designates provisioning, regulating, and cultural service types. Regulating services include flood protection and mitigation and markets for such services could promote investment in natural infrastructure.

⁹ www.naturalcapitalproject.org

Markets for ecosystem services are a concept that is under active development, for example in the Australian State of Victoria (Victorian Government 2011). The development of market allocation process for ecosystem services has touched on a wide variety of resources, including urban open space (Doyle and BenDor 2009), wetlands and watershed protection areas (Bonn et al. 2014) and agriculture (Ribaud et al. 2010), but the principles being applied and experience gained may be transferred to coastal areas. The discussion above about the role of ecosystem services as possibly contributing to coastal protection in the face of sea level rise points to one possible way in which markets for ecosystem services in coastal areas could evolve.

Another potential application of market principles in coastal management is suggested by the experience transforming command and control regulatory approaches to tradable permits. This is an area with a long history and substantial experience in a variety of different applications, particularly related to air and water quality. A coastal management application of this principle could be developed for the allocation of shoreline protection. A tradable permit system where the incentives favor the use of less environmentally damaging natural infrastructure that maintains or expands ecosystem services such as habitat and biodiversity for an equivalent level of regulating services could be shown to be superior to regulatory systems that encourage hard armored sea walls where there is a net loss of ecosystem services. The structure of the incentives would be established, as in a cap and trade system, to reflect the environmental sensitivity within a given stretch of coastline (Colgan and Newkirk 2016).

9. SUMMARY

There is a growing awareness that the effects of climate change can no longer be avoided. Damages to resources, ecosystems, and economies are already occurring, but at levels that are likely to be small fractions of what lies ahead, particularly if effective reductions of greenhouse gases and mitigation of climate change does not occur. Put simply, adaptation to climate change is inevitable. The only question whether it is done well or badly, whether adaptation wastes scarce resources or makes the best use of what can be done.

In this paper, I explore some of the ways in which economic theory and analysis can shape our adaptive responses related to effects on coasts and oceans focusing on four questions:

- How can economics help confront the profound uncertainty that shapes all decisions regarding climate change?
- How should adaptation be paid for?
- What are the socioeconomic values at risk from climate change?
- Can market mechanisms be used to make adaptation more efficient?

9.1 Dealing with Uncertainty

Climate change's magnitude and its effects are of such profound scope and such unknown dimensions that economists have raised questions about the ability of economics to say much that is practical. The debate arose over the issue about how much of society's resources should be diverted into arrangements to significantly reduce the amount of greenhouse gases emitted into the atmosphere but the same problem carries over into the extent of sea level rise for which planning will be undertaken. There are a number of integrated climate-economic models that present plausible futures, and there are various efforts to convert uncertainty (unknown probabilities) into risked (known probabilities) from which standard economic models can be constructed. These efforts are helpful to raise awareness and to motivate actions, but at the end of the day no one knows how much climate will change or sea levels will rise and thus precisely how much money to spend to deal with it. The systems are too complex, the time horizons too long and the extent to which fundamentally unpredictable human choices will shape the future all combine to make economic models that seek to define some optimal level of adaptation efforts of little actual use to those who must make decisions now about what to do to affect a future thirty or more years into the future.

The evidence from the literature reviewed suggests, however, that there are important insights from economics and other fields that can and should be brought to bear on adaptation decisions but that these insights must be part of a more broadly conceived decision making process. A sequential, iterative adaptation

planning process that utilizes continually updated adaptation plans based on new information about options, risks, benefits and costs, allows decisions to be made about steps to be addressed at present (such as how new development or major rebuilds of existing infrastructure) but leaves until later decisions for which there is insufficient information. The key to making this iterative process work is that at each decision-making stage, the information needed to shift strategies to more (or less) investment in adaptation is always identified and a plan for acquiring that information put in place.

Such an approach is also appropriate to the way in which most adaptation decisions will be made, which is at the local or regional level where the effects of climate change and sea level rise will be most clearly observed. Most of the effects on oceans and coasts from climate change will be highly localized, and it is at these local levels that decisions will be needed. Flexible, iterative adaptation planning will combine the best economic information, risk assessment processes such as Bayesian analysis that are suitable for addressing unprecedented climate change issues, and stakeholder processes that build on peoples' known approaches to risk management. They will acknowledge risk aversion, but focus on what can be done now, while making clear what information will be needed to act in the future. The economic information available, including a sense of where the funding will come from, will be focused on providing a sense there is a measure of control over the effects of sea level rise.

When decision making about adaptation can be built around these principles, the chances of cost-effective adaptation are increased, but never guaranteed. It is not pleasant for economists to contemplate a world devoid of any economic model that provides an optimal answer and instead one where messy and complicated processes must be continually undertaken.

9.2 Funding

The need to think about adaptation to sea level rise is becoming more widely acknowledged, but the first question for many local officials is not “what should we do”; it is “where will we find the money?” The total amount of resources to be devoted to adaptation will be determined in both the public and private sectors. But where those resources will come from and how they will be distributed are issues about which economics can provide critical insights.

The distinction between public goods and private goods helps identify multiple ways for accumulating the needed resources to at least begin the adaptation process. Traditional public expenditures can be combined with incentivized private expenditures, financing innovations such as green bonds, purpose-built revenue districts, and new approaches to insurance to create a pool of financial resources from which funding packages can be custom built for the many different circumstances where adaptation is necessary.

Two innovations in finance are likely to play important roles in adaptation funding pool: green bonds and the restructuring of insurance. Green bonds combine economic returns to the investors with impacts on social goods. The vast majority of this type of financing is currently devoted to climate change mitigation (renewable energy, etc.) rather than adaptation, but adaptation's share is likely to grow if measurable performance standards for adaptation project become available.

Catastrophe bonds are drawing new capital into reinsurance, the backup to property insurers, which will have the effect of keeping private insurance available in the face of the large increases in exposure. That increasing exposure also increases the incentives for insurers and reinsurers to invest in adaptation, particularly to participate in the financing of projects that reduce flooding and inundation risks from sea level rise. But the ability of catastrophe bond issuers to participate in funding of adaptation (to translate catastrophe bonds into resilience bonds) is uncertain because of the short maturity periods of catastrophe bonds and the conflict between minimizing risk through diversification of exposure and minimizing risk through structural measures.

The evolving pool of potential resources suggests a four-part strategy:

- Use general tax revenues to fund the largest projects with the greatest benefits or where no other options are available.
- Encourage the formation of local financing districts using fees, taxes and tax increments, insurance savings, and other funding streams flowing from the benefits of reduced flood risks and use the revenues to fund versions of green bonds.
- Funds for disaster responses should always pay for both recovery and reduced risks. Every disaster is an opportunity to reduce risks and no opportunity should be missed to do so.

- Flood insurance, public or private, should be managed and priced to encourage risk reducing adaptation actions whenever possible. Revised building codes that mandate risk reducing adaptation should be funded through reduced insurance cost.

This list of options is primarily directed at adaptation strategies that involve rearranging and reorganizing the built and natural environments so as to minimize the effects of flooding and inundation at least for some period. The ultimate adaptation strategy of retreat from the shoreline calls for an entirely different set of considerations into play. Retreat eliminates the kind of community level financing options what may play a major role in protection/rebuilding strategies. Insurance proceeds and disaster recovery funds may provide resources for retreat, but retreat will rarely be the first or even second preference. There are also many locations, such as those in Alaska and Louisiana, where storms and flooding are not the threat but a combination of eroding and lands and rising sea levels. For these locations, no financing strategy outside of Quadrant I is likely feasible. Support for significant retreat will put additional pressure to find ways to use the other funding sources so that only unique challenges need draw on general funding.

9.3 Assessing Vulnerability

A key part of the discussions about climate change, particularly sea level rise, has been a proliferation of studies measuring the potential damages to property, both private and public. Such studies are now undertaken regularly at different geographic scales and they have been extremely useful in raising awareness of the dangers of sea level rise. But the pictures that have been painted are incomplete and may underestimate the seriousness of the problem.

Most property damage studies combine estimates of sea level rise and resultant flooding with location specific property value data, usually from property tax or real estate databases. The result is often estimates of flooding that will occur 50 to 100 years hence linked to today's buildings and property values. A similar problem exists when the dependent socioeconomic variables include employment, output, vulnerable populations, or other measures: current conditions matched against future threats. Seasonal changes in the population and

A timing problem also exists with respect to flooding. Floods are temporary; water recedes, and recovery begins. The actual future that will unfold will, in most cases be cycles of increasing frequency of damages, recovery, and rebuilding. These cycles will reshape regional economies in ways not entirely predictable but also largely ignored in current studies.

Economic vulnerability studies need to evolve to incorporate a greater measure of dynamics both in terms of the changes possible that will shape vulnerability and will reshape it over time through hazard cycles. This is not merely a question of estimating vulnerability levels. The economic consequences of sea level rise could include a large scale geographic restructuring of local, regional, and perhaps national economies. Examining how locational rigidities, such as clusters or labor force constraints might accelerate or retard regional changes as flooding becomes more frequent needs to be become part of vulnerability. Improving estimates of vulnerability is critical not only to improve awareness of the risks but also to estimating the benefits from avoided damages that are critical to the assessment of adaptation options.

A similar set of questions about the industrial and geographic nature of adaptation in fisheries, where changes in ocean temperatures and chemistry (ocean acidification) will significantly alter the distribution and abundance of commercially important species. In some places, the fishing industry will adapt by shifting between species, as has been the case in response to management restrictions. But in other places, particularly those dependent on fish harvesting income for a significant portion of their regional income or dependent on single species will face more profound economic adaptation challenges. These consequences are yet to be examined.

9.4 Allocating the Coast Using Market Mechanisms

The final section of the paper considers the use of market mechanisms to help adaptation decisions. Market mechanisms are the predominant form of policy recommended for reducing greenhouse gas emissions because of their flexibility and adaptability to many different situations. This attention on market systems is concurrent with the significantly increased attention by economists on the concept of ecosystem services, which provides a way to better understand the economic values of natural resources and a potential means for markets to function to allocate resources.

Two market-based approaches are discussed. Markets for ecosystems services are being established in places such as Australia. Such markets are likely to help preserve critical ecosystems, particularly if their economic value for flood protection can be recognized and incorporated into adaptation strategies. Tradable permit approaches may also provide needed improvements to the command and control regulatory approach to managing the external effects of shoreline armoring by better pricing the regulating services of natural infrastructure.

10. SUGGESTIONS FOR FURTHER RESEARCH

This overview indicates that economics has a vital role in helping shaping the responses of coastal areas to climate change, particularly sea level rise. The broad outlines of the theoretical and empirical tasks that must be undertaken by economists has been suggested, but the real work lies ahead in translating these outlines into specific research. The agenda of that research is far larger than can be enumerated here, but there are some cross-cutting themes across the four questions that have been explored that may be of some use in guiding future efforts. These are:

1. Developing the data to undertake the benefit cost analyses of options for adaptation.
2. Learning how economic information is best used by decision makers and stakeholder processes undertaking adaptation planning.
3. Examining in detail the options for financing mechanisms that permit the beneficiaries of adaptation measures to pay for those measures in the most efficient manner.
4. Exploring options to improve the use of insurance to more effectively cover losses and to pay for risk-minimizing actions during disaster recovery.

These can be considered cross cutting areas in several ways. The concept of ecosystem services will become more and more important in estimating the benefits and costs of adaptation options, and methods to value such services will become more important. The “regulating values” of ecosystems as flood mitigating natural capital may also become the basis for market based approaches. At the same time, most of the benefits to be realized from flood control adaptation are the avoided costs of damages. Current studies estimate such benefits from

current coastal uses. But such uses may change significantly over the next 50-70 years. At a minimum, understanding the regional economic dynamics discussed in the section on vulnerability assessment will greatly improve the estimates of benefits and costs.

The work by Susskind et al. (2015) demonstrates that stakeholder based decision processes can address the complex issues involved in coastal adaptation. But this research should be considered in the category of “proof of concept”. Much more research needs to be done to help communities learn to assess risks with methods such as Bayesian analysis, to conceive of adaptation as a multi-decadal process, and to accompany decisions to postpone action (which are easy) with information maps to guide future decision makers (which will be hard).

Equally important, the same stakeholder processes, or closely related ones, will also be needed to design and implement financing mechanisms based on using the benefits of adaptation to fund the actions. Economists need to help sort out who pays and who benefits to design such mechanisms, as well as speak to the efficiency and equity effects of different approaches such as fees, taxes, tax increments, and insurance premium savings. These issues will lie at the heart of the difficult choices about community-based funding strategies.

Finally, there are many issues involved in improving flood insurance, but none more important than sorting out the appropriate roles of public and private insurance/reinsurance, addressing the stresses of self-insurance for public facilities, and finding ways to combine recovery and risk reduction to avoid self-perpetuating (and self-defeating) cycles of disaster recovery that only returns to the status quo.

11. CONCLUSIONS

Adapting shorelines and coasts, with their enormous economic values, to the coming age of sea level rise presents unprecedented challenges to those who must manage the built and natural environments. That a threat exists is well known but neither the size nor the timing of that threat is known. The costs are currently beyond calculation, but despite all this, actions must be taken if for no other reason than commitments are being made today to development and conservation of coasts that may be short lived if done in ignorance of sea level rise and other

climate change threats. Finding the best solutions in a world of limited resources will require the tools of economics, but the tools must be embedded in new processes for decisions about the built and natural environments that reflect the long term and iterative nature of both threats and response.

The endpoint of this process is not an optimal adaptation strategy but a series of choices based on continually updated and revised information about options, risks, costs, and benefits. As such it is more akin to Charles Lindblom's definition of incremental as opposed to rational comprehensive decision making, which he called "muddling through". (Lindblom 1959) This may not appear to be very hopeful result to those who seek an optimum adaptation strategy or who seek a level of certainty prior to action that will never be available. But muddling through is surely a better choice than the dismal theorem.

REFERENCES

- Alvarez, Adam. 2015. *Investing in Hurricanes*. Hamilton, Bermuda: Alvarez & Associates Ltd.
- Amer, Muhammad, Tugrul U. Daim, and Antonie Jetter. 2013. "A Review of Scenario Planning." *Futures* 46. Elsevier Ltd: 23–40.
doi:10.1016/j.futures.2012.10.003.
- Atlantic States Marine Fisheries Commission. 2015. "ASMFC Stock Assessment Overview: American Lobster." Arlington, VA.
- Beck, Michael W., and Glenn-Marie Lange, eds. 2016. *Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs*. Washington DC: The World Bank.
- Beller, By Thomas, and Isle De Jean Charles. 2016. "The Residents of This Louisiana Island Are America ' S First ' Climate Refugees .'" *Smithsonian*, June.
- Bonn, Aletta, Mark S. Reed, Chris D. Evans, Hans Joosten, Clifton Bain, Jenny Farmer, Igino Emmer, et al. 2014. "Investing in Nature: Developing Ecosystem Service Markets for Peatland Restoration." *Ecosystem Services* 9: 54–65. doi:10.1016/j.ecoser.2014.06.011.
- Brady, Dennis. 2016. "As Sea Levels Rise , Nearly 1.9 Million U . S . Homes Could Be Underwater by 2100." *The Washington Post*, August 24.
- California Coastal Commission. 2015. "Sea Level Rise Policy Guidance." Sacramento CA.
- Cicin-Sain, Biliiana, and Robert W Knecht. 1998. *Integrated Coastal and Ocean Management: Concepts and Practices*. Book. Washington DC: Island Press.
- Colgan, C.S., J. Kartez, and M. Sheils. 2016. "Climate Adaptation and Resiliency Planning for New England Communities : First Steps and Next Steps." Portland, ME.
- Colgan, C.S., and Sarah Newkirk. 2016. "A Prototype Market-Based Approach to Regulating Shoreline Protection in California." 2016–03. Monterey, CA.
- Colgan, C S, and J Adkins. 2006. "Hurricane Damage to the U.S. Ocean Economy in 2005." Article. *Monthly Labor Review*, no. November.
- Colgan, C S, and S Merrill. 2008. "The Effects of Climate Change on Economic Activity in Maine: Coastal York County Case Study." Article. *Maine Policy Review* 17 (January): 66–79.

- Committee on Risk-Based Methods for Insurance Premiums. 2015. *Tying Flood Insurance to Flood Risk for Low-Lying Structures in the Floodplain*. Washington DC: National Academies Press.
- Cooley, Sarah R, and Scott C Doney. 2009. "Anticipating Ocean Acidification's Economic Consequences for Commercial Fisheries." *Environmental Research Letters* 4 (2): 24007. doi:10.1088/1748-9326/4/2/024007.
- Cutter, Susan L, Bryan J Boruff, and W Shirley. 2003. "Social Vulnerability to Environmental Hazards*." *Social Science Quarterly* 84 (2): 242–61. doi:10.1111/1540-6237.8402002.
- Cyert, Richard, and Morris DeGroot. 1997. *Bayesian Analysis and Uncertainty Theory*. Chapman an. London.
- Doyle, Martin W., and Todd K. BenDor. 2009. "Planning for Ecosystem Service Markets." *Journal of the American Planning Association* 76 (1): 59–72. doi:10.1080/01944360903360100.
- Dye, R., and D. Merriman. 2006. "Tax Increment Financing." *Land Lines* 18 (1).
- Economics of Climate Adaptation Working Group. 2009. "SHAPING CLIMATE-RESILIENT DEVELOPMENT: A Framework for Decusion Making."
- Eggleston, J., and J. Pope. 2013. "Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region." *USGS Circular 1392*. Reston, VA.
- ENVIRON International Corporation. 2015. "Economic Analysis of Nature-Based Adaptation to Climate Change-Ventura County California."
- European Commission, Organization for Economic Cooperation & Development, United Nations, and The World Bank. 2013. *System of Environmental-Economic Accounting 2012 Experimental Ecosystem Accounting*.
- FEMA. 2009. "BCA Reference Guide." Washington DC.
- Global Change and Vulnerability Unit. 2012. "Distributed Global GDP Data Set." <http://preview.grid.unep.ch/index.php?preview=data&events=socec&evcat=1>.
- Gordon, Kate. 2014. "A CLIMATE RISK ASSESSMENT FOR THE UNITED STATES RISKY BUSINESS : The Economic Risks of Climate Change in the United States."
- Gutierrez, Benjamin T., Nathaniel G. Plant, and E. Robert Thieler. 2011. "A Bayesian Network to Predict Coastal Vulnerability to Sea Level Rise." *Journal of Geophysical Research: Earth Surface* 116 (2): 1–15. doi:10.1029/2010JF001891.

- Hallegatte, Stéphane, Nicola Ranger, Olivier Mestre, Patrice Dumas, Jan Corfee-Morlot, Celine Herweijer, and Robert Muir Wood. 2011. "Assessing Climate Change Impacts, Sea Level Rise and Storm Surge Risk in Port Cities: A Case Study on Copenhagen." *Climatic Change* 104 (1): 113–37. doi:10.1007/s10584-010-9978-3.
- Heal, Geoffrey, and Antony Millner. 2014. "Uncertainty and Decision Making in Climate Change Economics." *Review of Environmental Economics and Policy* 8 (1): 120–37. doi:10.1093/reep/ret023.
- Himes-Cornell, Amber, and Stephen Kasperski. 2015. "Assessing Climate Change Vulnerability in Alaska's Fishing Communities." *Fisheries Research* 162: 1–11. doi:10.1016/j.fishres.2014.09.010.
- Hinkel, Jochen, Robert J. Nicholls, Athanasios T. Vafeidis, Richard S J Tol, and Thaleia Avagianou. 2010. "Assessing Risk of and Adaptation to Sea-Level Rise in the European Union: An Application of DIVA." *Mitigation and Adaptation Strategies for Global Change* 15 (7): 703–19. doi:10.1007/s11027-010-9237-y.
- ICLEI. 2013. "San Diego Regional Research Agenda for Sea Level Rise Project Partners ICLEI-Local Governments for."
- Intergovernmental Panel on Climate Change. 2008. "Glossary of Terms for Working Group II." New York.
- . 2014. "Climate Change 2014 Synthesis Report Summary Chapter for Policymakers." doi:10.1017/CBO9781107415324.
- Ives, Mike. 2016. "A Remote Pacific Island Nation Threatened by Rising Seas." *The New York Times*, July 2.
- J.P. Morgan Global Research, and The Rockefeller Foundation. 2010. "Impact Investments: An Emerging Asset Class." New York.
- Jackson, Antoinette. 2013. "Federal Funding and Financing Programs Post Disaster." In *Building Community Resilience Post Disaster*, edited by Dorcas R. Gilmore and Diane Standaert. Chicago: American Bar Association.
- Jarzabkowski, Paula, Rebecca Bednarek, and Paul Spee. 2015. *Making a Market for Acts of God: The Practice of Risk Trading in the Global Reinsurance Industry*. New York: Oxford University Press.
- Jepson, Michael, and Lisa L Colburn. 2013. "Development of Social Indicators of Fishing Community Vulnerability and Resilience in the U.S. Southeast and Northeast Regions." NOAA Tech. Memo. NMFS-F/SPO-129.
- Jorgenson, Dale W, Richard J Goettle, Brian H Hurd, and Joel B Smith. 2004.

- “Market Consequences of Global Climate Change.” *Pew Center on Global Climate Change*.
- Kahn, Matthew E. 2016. “The Climate Change Adaptation Literature.” *Review of Environmental Economics and Policy* 10 (1): 166–78.
doi:10.1093/reep/rev023.
- Kahneman, Daniel, and Amos Tversky. 1979. “Prospect Theory: An Analysis of Decision Making Under Risk.” *Econometrica* 47 (2).
- . 2000. *Choices, Values and Frames*. New York: Cambridge University Press.
- Khazai, Bijan, Mirjam Merz, Carola Schulz, and Dietmar Borst. 2013. “An Integrated Indicator Framework for Spatial Assessment of Industrial and Social Vulnerability to Indirect Disaster Losses.” *Natural Hazards* 67 (2): 145–67. doi:10.1007/s11069-013-0551-z.
- King, R O. 2005. “Federal Flood Insurance: The Repetitive Loss Problem.” RL32972. *CRS Report for Congress*. Washington DC.
- Kleypas, Joan A., and Kimberly K. Yates. 2009. “Coral Reefs and Ocean Acidification.” *Oceanography*. doi:10.5670/oceanog.2009.101.
- Kneese, Allen, and Charles Schulze. 1975. *Pollution, Prices, and Public Policy*. Washington, D.C.: Resources for the Future.
- Knight, Frank. 1921. *Risk, Uncertainty, and Profit*. New York: Augustus M. Kelly.
- Kroeker, Kristy J., Fiorenza Micheli, and Maria Cristina Gambi. 2013. “Ocean Acidification Causes Ecosystem Shifts via Altered Competitive Interactions.” *Nature Climate Change* 3 (2): 156–59.
doi:10.1038/nclimate1680.
- Kunreuther, Howard, G Heal, M Allen, O Edenhofer, CB Field, and G Yohe. 2013. “Risk Management and Climate Change.” *Nature Climate Change* 3 (March): 447–50. doi:10.1038/NCLIMATE1740.
- Lempert, Robert. 2014. “Embedding (Some) Benefit-Cost Concepts into Decision Support Processes with Deep Uncertainty .” *Journal of Benefit Cost Analysis* 5 (3): 487–514.
- Lempert, Robert, Ryan Sriver, and Klaus Keller. 2012. “Characterizing Uncertain Sea Level Rise Projections To Support Investment Decisions.” *California Climate Change Center*. Sacramento CA.
- Li, Jia, Michael Mullan, and Jennifer Helgeson. 2014. “Improving the Practice of Economic Analysis of Climate Change Adaptation.” *Journal of Benefit-Cost*

- Analysis* 5 (3): 445–67. doi:10.1515/jbca-2014-9004.
- Lindblom, Charles E. 1959. “The Science of Muddling Through.” *Public Administration Review* 19: 79–88.
- McGuire, Chad, Michael Goodman, and Jason Wright. 2015. “Subsidizing Risk : The Regressive and Counterproductive Nature of National Flood Insurance.” ENV-2015-01. Dartmouth, Massachusetts.
- McKibben, Bill. 2016. “We Need to Literally Declare War on Climate Change.” *The New Republic*.
- Melillo, J.M., T.C. Richmond, and Gary Yohe. 2014. “Highlights of Climate Change Impacts in the United States: The Third National Climate Assessment.” Washington DC: U.S. Global Change Research Program. doi:10.7930/J01Z429C.On.
- Mendelsohn, Robert. 2008. “Is the Stern Review an Economic Analysis.” *Review of Environmental Economics and Policy* 2 (1): 45–60. doi:10.1093/reep/rem023.
- Michel-Kerjan, Erwann O. 2010. “Catastrophe Economics: The National Flood Insurance Program.” *Journal of Economic Perspectives* 24 (4): 165–86. doi:10.1257/jep.24.4.165.
- Miller, Trey. 2012. “Financing the Operation and Maintenance Costs of Hurricane Protection Infrastructure.” *Environment, Energy, and Economic Development Program*. Santa Monica, CA.
- Mooney, Chris. 2015. “The Remote Alaskan Village That Needs to Be Relocated due to Climate Change.” *The Washington Post*, February 24.
- Mu, Jianhong E., and Yong Chen. 2016. “Impacts of Large Natural Disasters on Regional Income.” *Natural Hazards* 83 (3). Springer Netherlands: 1485–1503. doi:10.1007/s11069-016-2372-3.
- Myers, D., and a. Kitsuse. 2000. “Constructing the Future in Planning: A Survey of Theories and Tools.” *Journal of Planning Education and Research* 19: 221–31. doi:10.1177/0739456X0001900301.
- Narayan, Siddharth, Michael W. Beck, Borja G. Reguero, Iñigo J. Losada, Bregje van Wesenbeeck, Nigel Pontee, James N. Sanchirico, Jane Carter Ingram, Glenn-Marie Lange, and Kelly A. Burks-Copes. 2016. “The Effectiveness, Costs and Coastal Protection Benefits of Natural and Nature-Based Defences.” *Plos One* 11 (5): e0154735. doi:10.1371/journal.pone.0154735.
- National Flood Insurance Program. 2006. “Community Rating System.” Washington DC.

- Neumann, James E, Daniel E Hudgens, Jane Leber Herr, and Jennifer Kassakian. 2003. "Appendix XIII Market Impacts of Sea Level Rise on California Coasts." In *Global Climate Change and California*, 23. Sacramento CA: California Energy Commission.
- Newkirk, Sarah, Kelly Leo, Walter Heady, Brian Cohen, Juliano Calli, Philip King, Aaron McGregor, et al. 2016. "Economic Impacts of Climate Adaptation Strategies for Southern Monterey Bay." Oakland, CA.
- Nordhaus, William D. 2011. "The Economics of Tail Events with an Application to Climate Change." *Review of Environmental Economics and Policy* 5 (2): 240–57. doi:10.1093/reep/rer004.
- Pelling, Mark. 2011. *Adaptation to Climate Change: From Resilience to Transformation*. New York: Routledge.
- Pindyck, Robert S. 2011. "Fat Tails, Thin Tails, and Climate Change Policy." *Review of Environmental Economics and Policy* 5 (2): 258–74. doi:10.1093/reep/rer005.
- Porter, Michael. 1998. *The Competitive Advantage of Nations*. New York: The Free Press.
- Ribaudo, Marc, Catherine Greene, LeRoy Hansen, and Daniel Hellerstein. 2010. "Ecosystem Services from Agriculture: Steps for Expanding Markets." *Ecological Economics* 69 (11): 2085–92. doi:10.1016/j.ecolecon.2010.02.004.
- Ropeik, David. 2010. *How Risky Is It Really? Why Our Fears Don't Always Match the Facts*. New York: McGraw Hill.
- Ruckelshaus, M.H., G. Guannel, K. Arkema, G. Verutes, R. Griffin, A. Guerry, J. Silver, J. Faries, J. Brenner, and A. Rosenthal. 2016. "Evaluating the Benefits of Green Infrastructure for Coastal Areas: Location, Location, Location." *Coastal Management* 44. Taylor & Francis: 504–16. doi:10.1080/08920753.2016.1208882.
- Shepard, Christine C., Caitlin M. Crain, and Michael W. Beck. 2011. "The Protective Role of Coastal Marshes: A Systematic Review and Meta-Analysis." *PLoS ONE* 6 (11). doi:10.1371/journal.pone.0027374.
- Song, Jie, Zhong-Ren Peng, Liyuan Zhao, and Chih-Hung Hsu. 2016. "Developing a Theoretical Framework for Integrated Vulnerability of Businesses to Sea Level Rise." *Natural Hazards*. Springer Netherlands. doi:10.1007/s11069-016-2483-x.
- Stern, Nicholas. 2007. *The Economics of Climate Change: The Stern Review*.

- New York: Cambridge University Press.
- Sukhdev, Pavan, Heidi Wittmer, Christoph Schröter-Schlaack, Carsten Nesshöver, Joshua Bishop, Patrick ten Brink, Haripriya Gundimeda, Pushpam Kumar, and Ben Simmons. 2010. *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*. Environment. http://www.iges.or.jp/jp/news/topic/pdf/1103teeb/teeb_synthesis_j.pdf.
- Susskind, Lawrence, David Rumore, Carri Hulet, and Patrick Field. 2015. *Managing Climate Risks in Coastal Communities: Strategies for Engagement, Readiness and Adaptation*. New York: Anthem.
- Swiss Re. 2012. "What Are Insurance Linked Securities," no. September: 1–17.
- The Council of the European Union. 2002. "Council Regulation (EC) No 2012/2002 of 11 November 2002 Establishing the European Union Solidarity Fund." *Official Journal of the European Union* L311: 3–8. [file:///J:/Digital/Library/Articles/Unknown/n-2002/Council/Regulation\(EC\)/No/20122002/nof/n11/November/establishingtheEuropeanUnionSolidarityFund.pdf](file:///J:/Digital/Library/Articles/Unknown/n-2002/Council/Regulation(EC)/No/20122002/nof/n11/November/establishingtheEuropeanUnionSolidarityFund.pdf).
- The Rhodium Group. 2014. "American Climate Prospectus: Economic Risks in the United States." Article. New York.
- The Seychelles National Climate Change Committee. 2009. "Seychelles National Climate Change Strategy."
- The World Bank. n.d. "What Are Green Bonds?" Washington DC.
- Tietenberg, Thomas. 2006. *Emissions Trading Principles and Practice*. 2nd ed. Washington, DC: Resources for the Future.
- Tol, Richard S J, Richard J T Klein, and Robert J Nicholls. 2008. "Towards Successful Adaptation to Sea-Level Rise along Europe's Coasts." *Journal of Coastal Research* 24(2): 432–42. doi:10.2112/07A-0016.1.
- Toman, Michael. 2014. "The Need for Multiple Types of Information to Inform Climate Change Assessment." *Journal of Benefit-Cost Analysis* 5 (3): 469–485. doi:10.1515/jbca-2014-9005.
- Vajhala, Shaking, and James Rhodes. 2015. "ReBound - Catastrophe Bonds for Resilience Report."
- Victorian Government. 2011. *ecoMarkets - Valuing Our Environment*. Melbourne: Department of Sustainability and Environment. <http://www.snh.gov.uk/docs/B304460.pdf>.
- Von Neumann, Jon, and Oskar Morgenstern. 1944. *Theory of Games and*

- Economic Behavior*. Princeton: Princeton University Press.
- WAVES Partnership. 2016. "Wealth Accounting and the Valuation of Ecosystem Services." <https://www.wavespartnership.org/en>.
- Wdowinski, Shimon, Ronald Bray, Ben P. Kirtman, and Zhaohua Wu. 2016. "Increasing Flooding Hazard in Coastal Communities due to Rising Sea Level: Case Study of Miami Beach, Florida." *Journal of Ocean & Coastal Management* 126.
- Weber, Jean-Louis. 2011. *An Experimental Framework for Ecosystem Capital Accounting in Europe*. *Eea*. doi:10.2800/83749.
- Weitzman, Martin. 2007. "A Review of The Stern Review on the Economics of Climate Change." *Journal of Economic Literature* XLV (September): 703–24.
- Weitzman, Martin L. 2011. "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change." *Review of Environmental Economics and Policy* 5 (2): 275–92. doi:10.1093/reep/rer006.
- Weyant, John. 2014. "Integrated Assessment of Climate Change: State of the Literature." *Journal of Benefit-Cost Analysis* 5 (3): 377–409. doi:10.1515/jbca-2014-9002.
- Weyant, John P. 2008. "A Critique of the Stern Review's Mitigation Cost Analyses and Integrated Assessment." *Review of Environmental Economics and Policy* 2 (1): 77–93. doi:10.1093/reep/rem022.
- World Economic Forum. 2013. *The Green Investment Report: The Ways and Means to Unlock Private Finance for Green Growth*. http://www3.weforum.org/docs/WEF_GreenInvestment_Report_2013.pdf.
- Wu, Junjie, Paul W. Barkley, and Bruce Weber, eds. 2008. *Frontiers in Resource and Rural Economics*. Washington DC: Resources for the Future.
- Yoskowitz, David, James Gibeaut, and Ali McKenzie. 2009. "The Socio-Economic Impact of Sea Level Rise in the Galveston Bay Region." Corpus Christi, TX.
- Zorrilla, Pedro, Gema Carmona, Consuelo Varela-ortega, John Bromley, and Hans Jorgen Henriksen. 2010. "Evaluation of Bayesian Networks in Participatory Water Resources Management , Upper Guadiana Basin , Spain" 15 (3): 11–12.