Focus Article

The economics of adaptation along developed coastlines

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Sea-level rise (SLR) increases the risk of permanent inundation of coastal lands and structures, while also increasing the risk of periodic damage from storms and risks to ecological resources. Prior studies have illustrated the importance of considering adaptation measures, such as armoring and beach nourishment, when estimating the economic cost of SLR, but these studies have taken the form either of careful, geographically limited case studies or national estimates based on limited samples. We present a framework for evaluating the economics of adaptation to permanent inundation from SLR that employs detailed local scale data and is spatially comprehensive, and apply the framework to estimate costs of adaptation for the full coastline of the continental US. Our results show that the economic cost of SLR is much larger than prior estimates suggest—more than \$63 billion cumulative discounted cost (at 3%) for a 68 cm SLR by 2100, and \$230 billion undiscounted—yet is only one-fourth the total value of low-lying property vulnerable to SLR, illustrating the importance of careful site-specific consideration of adaptation. Further, the granularity of the framework provides spatial, temporal, and response mode details useful to both national policy-makers and local adaptation planners, and can readily incorporate estimates of ecological and storm surge damages as they become available.

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INTRODUCTION

An increase in sea level has long been understood to be a significant risk to ecologically and economically important coastal systems.[1–3] Climate change is likely to accelerate the historical rate of sea-level rise (SLR), because as temperatures increase, oceans will warm and expand, and land-based ice will melt more rapidly than it is regenerated. The magnitude of these changes remains uncertain; in particular, forecasting the rate of ice sheet melting is so complex that the Intergovernmental Panel on Climate Change (IPCC's) most recent assessment of future SLR excludes consideration of dynamic ice sheet melting.[4] Recognition of the continuing uncertainty in forecasting SLR, however, has expanded the need for a comprehensive framework to assess the costs and benefits of robust adaptation strategies suitable for a wide range of future SLR outcomes. In order to plan adaptation appropriately, the methodology we envision should have four key attributes: (1) the framework should be amenable to consideration of risks to a broad range of coastal resources affected by SLR, including property threatened by inundation and storms, vulnerable ecological resources such as tidal wetlands threatened by rising seas and human response to that risk, and the potential for climate change to alter hurricane frequency and intensity, (2) the framework should be flexible, able to accommodate new science on the rate of SLR and storm risks, as well as new and better data on resources at risk, as it becomes available, (3) the framework should be dynamic, recognizing the irreversible nature of inundation risks, and (4) the framework should be scalable, for potential application to national policy making and local land-use and adaptation planning.

Our work represents an important milestone in developing the desired comprehensive framework, including an application that assesses risks and adaptation costs in response to the threat of

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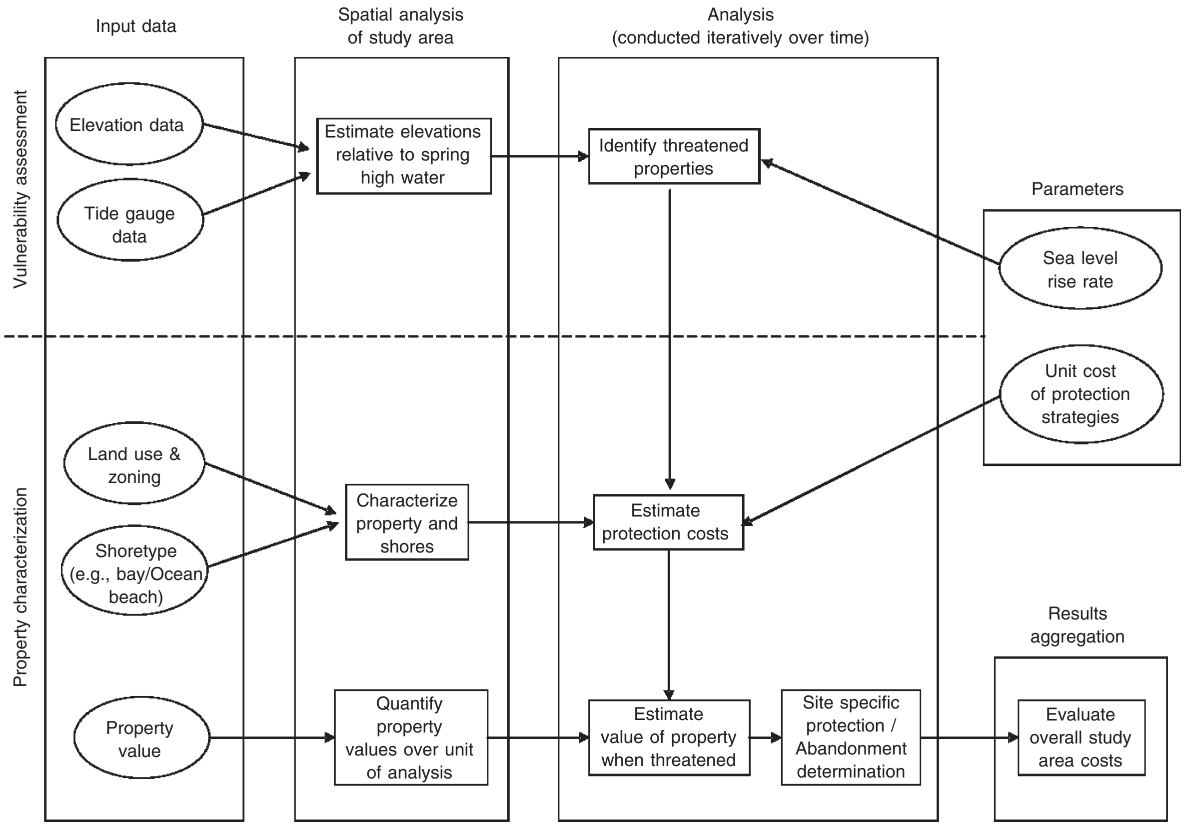

FIGURE 1 | Overall model framework. (Reprinted with permission from Ref 11. Copyright 2010 Taylor & Francis.)

coastal property inundation throughout the US coast. Although several estimates of the impact of SLR on US coasts have been developed before,[5–10] our work updates those estimates with a spatially comprehensive analysis that also reflects new and better elevation and property value data. In this paper, we describe the overall framework and the data sources, methods, and results of our application of the framework to estimate the costs of adapting to SLR.

A FRAMEWORK FOR ASSESSING ADAPTATION

The overall framework of the model is presented in Figure 1. The basic structure involves arraying relevant input data, listed on the left side of Figure 1, and constructing a spatial geodatabase on a 150-m grid cell frame, which can then be analyzed to estimate response to SLR, the cost of the adaptive response, and the 'residual damages' that result in areas where adaptive measures are not cost effective. The grid frame encompasses virtually all areas potentially vulnerable to the effects of SLR, including approximately 300 coastal counties in the continental US. Most of these counties have direct coastal or bay frontage, but some are affected only through proximity to tidally influenced rivers and tributaries, a common geographic feature in the Southern Atlantic and Gulf regions.

Analysis and aggregation modules of the model, depicted in the center right and bottom right corner of Figure 1, access the site-specific data within the geodatabase (e.g., elevation) along with a series of user-defined input parameters (e.g., SLR scenario and the cost of armoring or beach nourishment), and estimate the timing and costs of adapting to SLR over time. Armoring involves a hard structure of some sort—prior work and review suggests concrete structures on ocean-fronting areas, and less expensive bulkheads on bay-fronting areas—and beach nourishment involves placing sand on beach areas. In all cases, long-term maintenance of structures or period re-nourishment is also required, with differential costs for each.

Evaluation of the protection versus retreat decision, with hard structures and beach nourishment characterizing protection, has dominated most of the impact assessment literature. For more detailed analysis designed to support development of adaptation plans at the county or local scales, this set of adaptive actions may be too limited. In our framework, therefore, other response options can be programmed as well—for example, in a smaller scale application to four coastal counties in New Jersey, a version of the framework incorporated an 'elevation' option involving raising of both structures and some surrounding land, was also incorporated—for this first national application we have omitted that option to keep model processing time within reasonable limits.[11] As noted below, we also plan to expand the list of adaptive options as we move to apply the approach to local scale adaptation decision making. The analysis nonetheless is conducted with a great deal of spatial and temporal richness—for each 150-m grid cell in each year of the simulation, through 2100 if desired.

Some elements of the framework, particularly the optimal response model, rely extensively on earlier research by Yohe et al. assessing economic impacts for 30 coastal US sites.[9,12] The optimal response approach is based on a simplified benefit–cost analysis of protective structures and beach nourishment relative to a retreat response—see Refs 11 and 12 for details. To summarize from Ref 12, the planning problem expressed as a optimization problem involves choosing a time between today and 2100 to initiate a protection plan as adaptation to SLR which maximizes the following expression:

$$PV\{B[t_0, T]\} - PV\{C[t_0, T]\} \qquad (1)$$

where t_0 is the time when protection as adaptation is initiated, T is the time when protection that had been initiated subsequently might be abandoned, and the present value of B and C are expressions of the benefits and costs, respectively, of protection over time as a function of the choice of t_0.

Prior theoretical work[12] established that if hard structure protection prior to 2100 is optimal, then it remains optimal to continue to maintain that hard structure in perpetuity, making the otherwise difficult estimation of T irrelevant. As a result, this generic model simplifies to the following decision rules. First, where the cost of measures designed to protect properties from SLR is less than the benefit of avoided property value loss, the time to begin protection that maximizes Eq. (1) is earlier than 2100, and the adaptation cost incurred in response to SLR is estimated as the capital cost of construction plus ongoing maintenance costs. Second, where the estimated protection cost exceeds the benefit of adaptation, the expression is maximized when t_0 is equal to the time horizon of the simulation, in this case 2100. Then retreat (i.e., abandonment) is the estimated response to the threat, and the impact of SLR is lost structure and land value. However, the response analysis itself is also flexible—for example, adaptation decisions can be based either on the optimal response algorithm or a user-defined mapping of planning, zoning, and/or land-use categories to a specific response category (protect or no protect), subject to data availability. A detailed description of the model structure and most input data sources, along with an early application of the approach to four counties which includes a comparison of results using the optimal and user-defined decision rules, can be found in Refs 11 and 12.

A common mistake in climate impact and adaptation analyses is estimating the effects of future climate on current resources. A better approach, where possible, is to project both the level of threat and the resources at risk. Both can be challenging tasks, but at least with SLR the uncertainty in the threat is mainly over magnitude and timing, rather than direction of effect. Projecting resources at risk involves, at minimum, estimating how real property values could appreciate—our approach links future property value to a projection of US Gross Domestic Product (GDP), and is also a flexible input. Ideally, we might also consider less smooth changes in resources at risk, such as locations of newly developed areas, but models of future development potential are particularly uncertain. In addition, it seems clear that new development is very likely to follow construction of coastal protection; since residual damages are minimized in areas that warrant protection, the estimation error that results from our failure to forecast newly developed areas may also be minimized.

Implicit in our response analysis are two key features of the approach: (1) we estimate the optimal timing of a response, largely based on the timing of inundation and (2) abandonment decisions are irreversible, and protection and beach nourishment decisions, while theoretically reversible, are also effectively permanent. Estimating optimal timing demands that we rely on an SLR trajectory, rather than simply an endpoint, and also critically affects the economic cost calculations through application of a positive discount rate. Irreversible decisions are not a requirement of the approach, but prior work suggests that, at least within the optimal response paradigm, these decisions are made once and remain robust over time.[9]

The discussion so far has focused on adaptation from a purely private perspective; in this context, values for nonmarket resources, for example ecologically important wetlands, are not considered in the response. A case can be made that exclusion of ecological values most accurately represents most current adaptation decision-making in the coastal zone, because there are few regulatory mechanisms in place to incorporate a social welfare perspective, outside of Army Corps of Engineers mandates to consider ecological effects. Regardless of how we might choose to characterize current decision-making, it is also clear that from a social perspective it can be desirable to reflect nonmarket values in adaptation planning. It is nonetheless exceedingly difficult to quantify these effects with current data. In separate work, the authors are exploring 'proof of concept' methods to estimate economic values for coastal wetlands threatened by SLR. The important point is that our framework can be readily modified to accommodate nonmarket value, to the extent these can be quantified. For example, in the application we present here, the only 'costs' of armoring property from coastal risks are the capital cost of construction and the ongoing maintenance of the protective structure. External costs of these protective structures, which are often characterized as presenting new threats to coastal wetlands, could be included in the cost–benefit calculation and, in addition, in the estimate of residual costs if the optimal response is to protect. A key advantage of our approach is the high spatial resolution of our data, which allows us to consider the highly site-specific variability of ecological values as data become available.

Finally, the framework can be adapted to reflect risks from storm surge as well as from permanent inundation. At equilibrium, with a similar pattern of storm risks now and in the future, we could argue that shoreline change and therefore coastal damages will be based on property elevation relative to sea level, and the value of property, which are the two critical variables in our approach. If storm risk remains similar with climate change, in any given location we would see shoreline retreat and a movement inland of the storm risk profile for properties not threatened by inundation, but within reach of coastal flooding risks. For regional and national-scale analyses, therefore, a good first approximation of the marginal damage of SLR is the property lost to the sea, or the cost of measures taken to avoid permanent property loss.

At a local scale, however, it could be important to consider incremental storm surge risks more explicitly, for two reasons. First, SLR provides a higher base from which to launch a storm surge, and local topography could channel that surge, and therefore the risk of damage, in ways that a simplified approach might overestimate or underestimate,[13] and that a new class of adaptation options might cost effectively be deployed in response.[14] Second, climate change raises the possibility of changes in storm frequency, intensity, and track, with changes in risk in any specific location likely to be highly site-specific in both direction and magnitude of effect.[15,16] Both factors are likely to be critically important in the economics of local scale adaptation, but for regional and national-scale applications, the first factor at least is less important. Extensions of the framework to consider these risks are already contemplated, and discussed further below; the fact that the current model explicitly incorporates modeling of water flow, in that cells are only subject to inundation if both elevation and connection to tidal water is present, makes the framework well-suited to these extensions.

APPLICATION OF THE FRAMEWORK: COSTS OF ADAPTATION FOR US COASTS

As described above, the adaptation framework we have developed can be applied to a wide range of scales and scopes. An important near-term need of policy makers, however, is to understand the benefits of national efforts to mitigate SLR through greenhouse gas control programs. We apply our modeling framework to estimate adaptation costs for most areas in the US affected by Atlantic, Gulf, and Pacific coastal risks (but excluding Alaska, Hawaii, and island territories). In this section, we describe key data elements used in the framework, the 21st century climate and economic scenario projections, and our results.

Data Sources

Application of the framework requires site-specific data on land elevation, land and structure (property) value, the location and nature of the existing shoreline, including beach and open ocean site identification, and costs of adapting through armoring or beach nourishment. Application of the approach to the full US coast presents challenges related to scale and consistency across a vast coverage area—the total dryland area of all counties included in the model is more than 480,000 square kms, although only a small fraction of that area is vulnerable to inundation even under our highest SLR scenario.

- *Land elevation*. We rely on 30 m digital elevation modeling, available from United States Geological Survey (USGS), and calibrated to a zero elevation in the year 2000 as represented by the mean spring high water mark. Estimated tide ranges and sea-level trends by the National Ocean Service (NOS) helped determine the height of spring high water. For local applications, the framework can also accommodate more detailed Light Detection and Ranging (LiDAR) data.

- *Land and structure value*. The only freely available comprehensive national property value dataset is available from the US Census Bureau, but those data suffer from two problems: (1) they only address owner-occupied structures and (2) they represent self-reported valuations. We therefore obtained the broadest possible coverage of individual parcel assessed values, including all residential, commercial, industrial, institutional, and government properties with an assigned property value, by contracting with a commercial service, with data resolved to the Census Block Group level. In the less than 5% of coastal block groups where assessed values were not available, we relied on census property value data as a default; those areas are almost exclusively in remote parts of the country, where even residual damages from inundation are likely to be small. Property values reflect mostly 2009 property assessments, but also some 2008 and 2007 assessments. We convert all property values to 2006 dollars. Note that, except to the extent they are incorporated or capitalized in property values, public infrastructure is excluded from property values.
- *Shoreline delineation and characteristics*. Identifying the location of the shoreline at mean high water in the year 2000 is an important spatial modeling element. To identify ocean-facing shores, which experience higher maintenance costs for armoring, we manually classified all cells that face the open ocean. To identify beach areas amenable to nourishment, we used National Land Use/Land Cover GIRAS spatial data.
- *Costs of adapting*. For armoring, we relied on analysis of roughly 50 years of data on Army Corps of Engineers coastal protection projects. The data revealed a range of costs from about $1500-$5000 per linear meter of shore. We therefore use a $3250 per meter estimate. Maintenance cost estimates—4% annually for back bay sites and 10% annually for open ocean sites—are consistent with those used in Ref 12. For beach nourishment, we used a generalized relationship that reflects estimated nourishment requirements over five Atlantic Coast sites that result in incremental sand requirements of just over 7.5 cubic meters/meter shoreline/cm SLR, and a default sand cost estimate of just less than $12 per cubic meter. Costs for sand likely vary substantially over space; while our framework can accommodate such variability, for this application we used a single estimate of sand costs. The re-nourishment cycle is 10 years. Bases for all these assumptions are described in detail in Ref 11.

Scenario Specifications

The model is capable of simulating a wide range of SLR trajectories through 2100. For this application, we applied four scenarios, with rates derived from MAGICC modeling,[17,18] as follows and illustrated in Figure 2:

1. Baseline scenario, which simulates a continuation of 20th century SLR rates, based on the IPCC estimate of 1.7 mm/year SLR, and implying 18.7 cm SLR by 2100 compared to 1990 levels.[4]
2. Low scenario, which is based on MAGICC processing[17] of an IPCC B1 scenario, with mid-range ice melting and 2°C sensitivity, and implying 28.5 cm SLR by 2100 compared to 1990 levels.
3. Mid scenario, also based on MAGICC processing[17] but of the IPCC A1b scenario, with high ice melting and 4.5°C sensitivity, and implying 66.9 cm SLR by 2100 compared to 1990 levels.
4. High scenario, based on[18] maximum, and implying 126.3 cm SLR by 2100 compared to 1990 levels.

For each scenario, we also estimate a site-specific, fixed annual rate of land subsidence or uplift, which combines with the SLR scenario to yield site-specific relative SLR. Subsidence is based on annual average measurements from National Oceanic and Atmospheric Administration (NOAA) tide gauge data from 68 sites with at least 25 years of continuous measurements and linear interpolation of subsidence rates for all cells that lie between the selected sites. An estimated 1.7 mm/year is subtracted from the tide gauge annual average to account for the component of relative SLR that is accounted for by 20th century sea-level change,[4] yielding the site-specific subsidence/uplift rate.

For this application, we also assumed 2% annual GDP growth, and an elasticity of real property value with respect to GDP of 0.45, consistent with Ref 11.

RESULTS

Application of our approach generates two types of results—an estimate of the optimal adaptive response

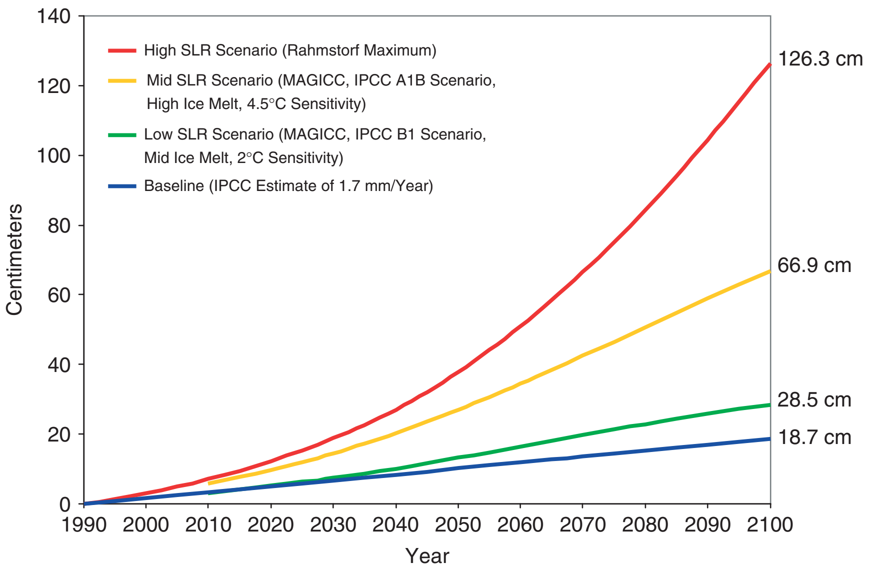

FIGURE 2 | Comparison of SLR trajectories.

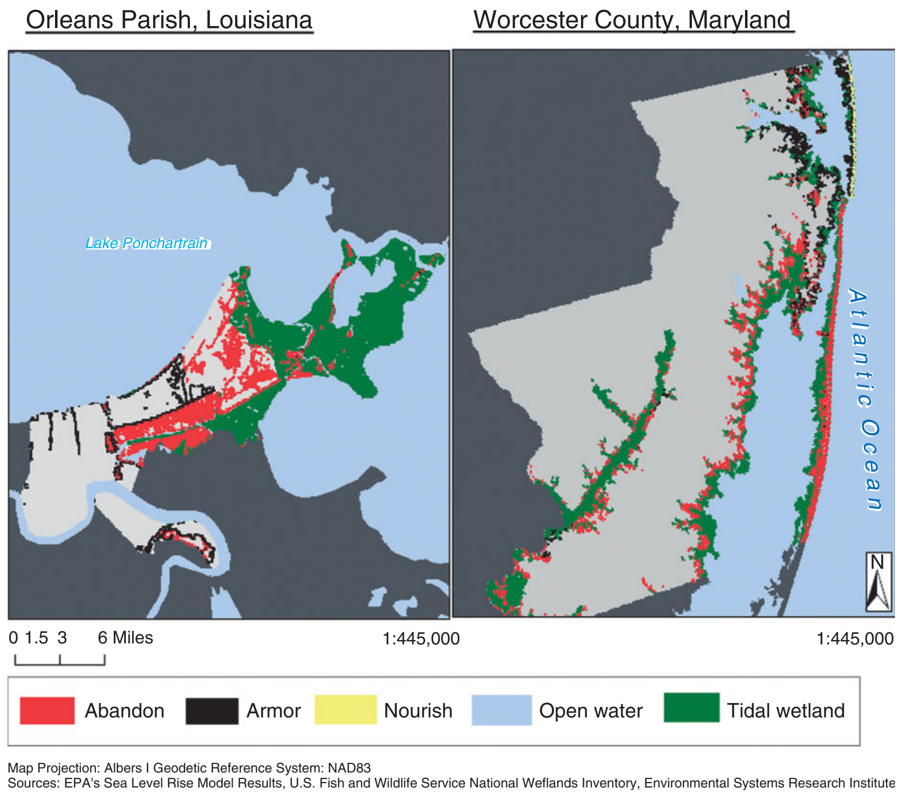

FIGURE 3 | Adaptive response in two counties.

over space and estimates of the cost of this response. Results for the adaptive response are best viewed in map form, generated by linking the model to Geographic Information System (GIS) software and illustrated for two vulnerable US counties in Figure 3. Cells that we project would be nourished are depicted in tan, armored cells in black, and abandoned cells in red. In Orleans Parish (New Orleans), many of the vulnerable areas (including many that currently lie below sea level) warrant protection, including most areas along Lake Pontchartrain, areas bordering the city's canals, and areas along the Mississippi

TABLE 1 | Model Results by Region

	North Atlantic	South Atlantic	Florida	Gulf	Pacific	Total
Baseline SLR Scenario						
Area abandoned (square kms)	387	924	592	4046	222	6171
Length of armoring (kms)	2604	899	4224	716	417	8861
Undiscounted costs (millions $)						
Total costs	$35,850	$15,270	$64,780	$18,200	$7570	$141,670
Discounted costs at 3% (millions $)						
Total costs	$11,850	$5480	$23,960	$5570	$2890	$49,740
Low SLR Scenario						
Area abandoned (square kms)	448	1075	647	4273	232	6675
Length of armoring (kms)	3105	1132	4987	827	508	10559
Undiscounted costs (millions $)						
Total costs	$42,630	$18,070	$74,300	$20,110	$9290	$164,390
Discounted costs at 3% (millions $)						
Total costs	$12,650	$5790	$25,120	$5770	$3110	$52,450
Mid SLR Scenario						
Area abandoned (square kms)	747	1583	815	5423	310	8878
Length of armoring (kms)	4211	1541	5973	1125	982	13831
Undiscounted costs (millions $)						
Total costs	$63,380	$27,430	$100,310	$27,110	$18,120	$236,360
Discounted costs at 3% (millions $)						
Total costs	$15,840	$7190	$29,510	$6620	$4340	$63,500
High SLR Scenario						
Area abandoned (square kms)	1255	2320	1242	7288	444	12550
Length of armoring (kms)	5978	2242	9174	2156	1312	20862
Undiscounted costs (millions $)						
Total costs	$87,940	$38,910	$130,860	$40,140	$26,630	$324,480
Discounted costs at 3% (millions $)						
Total costs	$18,980	$8590	$33,680	$7760	$5510	$74,520

River, in the southern portion of the city. Most of the protected areas that might be vulnerable are landward of the line of armoring along these water bodies, which prevents water flow from inundated large areas of the city. Other, sparsely developed areas of the city to the east show up in red, suggesting that the optimal adaptive response is abandonment. Nourishment is not employed, because there are no beaches in this part of Louisiana. Worcester County, Maryland, by contrast, has many cells in the northeast, along the Atlantic Ocean, that warrant nourishment, some cells where armoring is the projected response, and many low-lying but sparsely populated areas lining the bay shores where abandonment is the projected response, even with a lower capital and maintenance cost for armoring along bays, which are less expensive to protect because of the lower wave energy.

National and regional results for each of the four scenarios are presented in Tables 1 and 2. Total costs represent the sum of residual damage plus adaptation expense that could be attributed to SLR over this century along the four scenarios—Table 1 shows only the sum of these components, but Table 2 provides more detailed breakouts for the mid SLR scenario, with the value of abandoned property being the residual damage and the cost of armoring and nourishment providing the adaptation cost. Substantial costs of adaptation are incurred even in the baseline scenario—more than $140 billion, nationally, with almost half of the total cost in Florida. Costs of adaptation are greater in the low scenario, but

TABLE 2 | Detailed Results for the Mid SLR Scenario

	North Atlantic	South Atlantic	Florida	Gulf	Pacific	Total
At Risk Based on Mid SLR Scenario						
Area at risk (square kms)	1747	2990	2990	6076	1113	14916
Value of land at risk						
Undiscounted value (millions $)	$273,530	$41,030	$553,920	$49,650	$136,950	$1,055,080
Discounted value at 3% (millions $)	$176,500	$26,950	$286,670	$25,710	$83,840	$599,670
Mid SLR Scenario						
Area abandoned (square kms)	747	1583	815	5423	310	8878
Length of armoring (kms)	4211	1541	5973	1125	982	13831
Undiscounted costs (millions $)						
Value of abandoned property	$7570	$6240	$7880	$15,940	$2680	$40,320
Cost of armoring	$35,130	$13,940	$71,000	$7410	$8290	$135,770
Cost of nourishment	$20,680	$7250	$21,430	$3760	$7150	$60,260
Total costs	$63,380	$27,430	$100,310	$27,110	$18,120	$236,360
Discounted costs at 3% (millions $)						
Value of abandoned property	$1820	$2020	$2960	$3970	$1010	$11,790
Cost of armoring	$10,390	$3920	$22,870	$1970	$2130	$41,270
Cost of nourishment	$3630	$1250	$3680	$670	$1210	$10,440
Total costs	$15,840	$7190	$29,510	$6620	$4340	$63,500

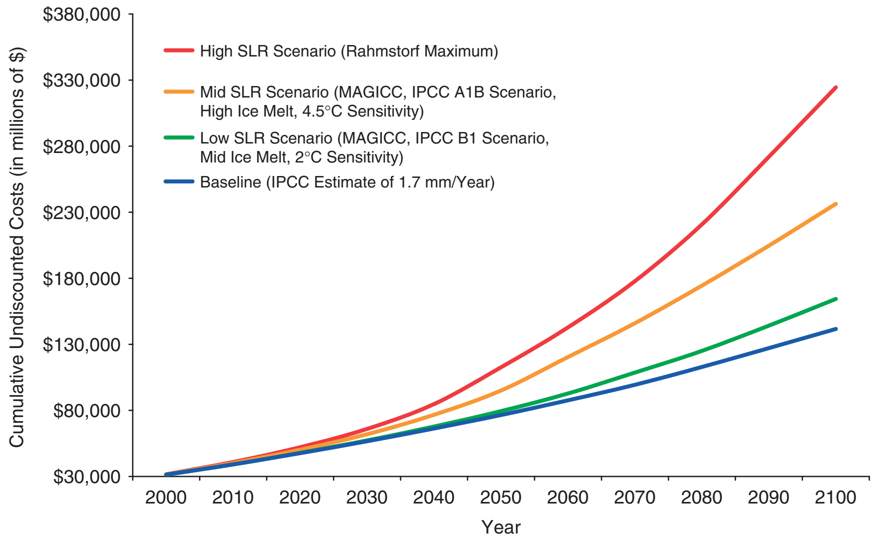

FIGURE 4 | Timing of adaptation costs.

only by about 10% compared to the baseline. Timing of the incremental costs for the low versus baseline scenario are later, which with the effect of discounting yields an adaptation cost estimate only about 5% higher than baseline. Total undiscounted adaptation costs increase substantially in mid and high scenarios, but again, the timing of these costs matters when considering the discounted costs, which are greater for higher SLR scenarios, but by a far smaller margin than the undiscounted costs. This issue of timing is critical for both planning purposes and for comparing benefits of greenhouse gas control policies to costs, which will be realized over widely varying timeframes, with costs incurred early and benefits realized late in the century. The timing of undiscounted costs is illustrated in Figure 4, for all four scenarios.

In Table 2, we present more detailed results for the mid-scenario. The data presented illustrate the importance of careful modeling of adaptation; while over $1 billion of property nationwide is vulnerable to being lost to SLR simply because of its elevation, adaptation reduces the undiscounted damage of SLR by more than a factor of four. In addition, the regional results show the importance of property value in estimating costs of adaptation. The Gulf Coast has roughly twice as much land area vulnerable to SLR in this scenario than Florida, but the land is worth far less, and includes much less beachfront. As a result, almost 90% of the vulnerable land in the Gulf Coast is projected to be abandoned, while for Florida the comparable figure is 25%.

CONCLUSION

The costs of protection, elevation, and abandonment presented in Table 1 are high compared to prior estimates. Cumulative estimates of the undiscounted costs of SLR in the US developed in the late 1980s were as high as $300 billion for a 1 m scenario through 2100,[19], but those estimates reflected only the value of property at risk and did not consider the effect of efficient adaptation. Yohe et al.[9] used a site sampling technique with adaptation, but they reported net costs through 2100 of $35 billion for 1 m of SLR. Our estimates are much higher—for only 68 cm of SLR by 2100 (our mid-scenario), total undiscounted costs of SLR are more than $230 billion; discounting at 3% yields estimates of more than $63 billion. There are three reasons for the increase: (1) rapid increases in the value of coastal property at risk increase both the degree to which protection is optimal and the value of lands projected to be abandoned, (2) our estimates are spatially comprehensive, and avoid errors that might be associated with sampling (although, admittedly, the effect of sampling could lead to over- or under-estimates), and (3) our estimates are derived from more recent elevation data, suggesting more land area is vulnerable to SLR than previously thought.

Our spatially comprehensive framework, which also combines detailed site-specific data, lends itself to a wide range of applications. At the local level, the next step is to explicitly consider the effects of storm surge, as well as adaptive measures specific to that coastal risk (e.g., structure elevation and floodproofing), as the risk of storm surge is altered by SLR.[13,14] We are also actively researching incorporation of nonmarket values reflected both in the cost of armoring, which can cause wetlands to be flooded rather than migrating inland as seas rise, and in abandonment, which can cause the nature of ecological values to change. Once demonstrated at the local level, these impacts of SLR can also be incorporated at the national level, providing further information on the benefits of mitigating climate change. The application presented here, while incomplete, provides important evidence that the costs of SLR in the US, even considering an efficient adaptation response, could be very large.

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