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State and local governments plan for development of most land vulnerable to rising sea level along the US Atlantic coast*

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Abstract
Rising sea level threatens existing coastal wetlands. Overall ecosystems could often survive by migrating inland, if adjacent lands remained vacant. On the basis of 131 state and local land use plans, we estimate that almost 60% of the land below 1 m along the US Atlantic coast is expected to be developed and thus unavailable for the inland migration of wetlands. Less than 10% of the land below 1 m has been set aside for conservation. Environmental regulators routinely grant permits for shore protection structures (which block wetland migration) on the basis of a federal finding that these structures have no cumulative environmental impact. Our results suggest that shore protection does have a cumulative impact. If sea level rise is taken into account, wetland policies that previously seemed to comply with federal law probably violate the Clean Water Act.

Keywords: climate change, adaptation, land use planning, sea level rise, wetland migration, shore protection

S Supplementary data are available from stacks.iop.org/ERL/4/044008/mmedia

* The opinions expressed in this letter do not necessarily reflect the official positions of either the US Environmental Protection Agency, the National Oceanic and Atmospheric Administration, any state or national Sea Grant Program, or the US Government.

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1. Introduction

Changing climate is expected to cause global sea level to rise approximately 20–60 cm during the 21st century if polar ice sheets remain stable [1] but possibly more than 1 m if ice sheets become unstable [2]. Rising sea level inundates low-lying lands, erodes shorelines [3, 4] exacerbates coastal flooding [4, 5] and increases salinity in estuaries [4, 6, 7] and aquifers [6, 8, 9].

Site-specific responses to sea level rise are broadly classified into two pathways: shore protection and retreat [10]. Shore protection (e.g. bulkheads, dikes, beachfill) can minimize disruptions to coastal communities from floods and shore erosion, but it prevents the inland migration of coastal ecosystems, which are instead squeezed between the rising sea and bulkheads built to protect the communities [4, 11–13]. Retreat (e.g. prohibiting or removing hazardous construction) can allow ecosystems to migrate inland [10, 14], but land and structures can be lost [12]. The resulting disruption can be minimal in undeveloped areas [10, 12] but potentially severe in populated areas, especially if retreat occurs after shore protection fails during a storm [15].

Property owners and land use agencies have generally not decided how they will respond to sea level rise, nor have they prepared maps delineating where shore protection and retreat are likely [10]. The absence of such maps prevents a realistic assessment of the consequences of rising sea level, and can impair efforts to prepare for those consequences [10]. For example, the Clean Water Act allows the US Army Corps of Engineers to routinely issue permits for a class of activities, provided that the activities do not have a cumulative environmental impact [16]. The Corps has issued a regulatory finding that shore protection will not have a cumulative impact [17] and used it to justify a policy under which property owners are routinely granted permits to build bulkheads [18]. Yet no one has estimated (and the regulatory finding did not consider) the portion of coast likely to be bulkheaded as sea level rises [10, 19].

This letter maps and quantifies a baseline, business-as-usual scenario of coastal development and shore protection for the Atlantic coast of the United States from Massachusetts to Florida. Taken together, land use plans, existing land use, regulations, and shore protection policies can provide a baseline expectation regarding the composition of future shore protection and retreat. With this analysis, planners from the local to national level can assess the extent to which coastal wetlands might migrate inland or be lost (and identify infrastructure that would eventually require remedial attention) and then evaluate other options. The following sections describe methods, results, and some implications for policies to protect coastal wetlands; additional methods, tables, and maps are in the supplementary material. Although this letter provides summary maps and tables, we are also making our results available as shapefiles and raster data sets with a 30 m grid suitable for ArcGIS and other geographical information systems software [20].

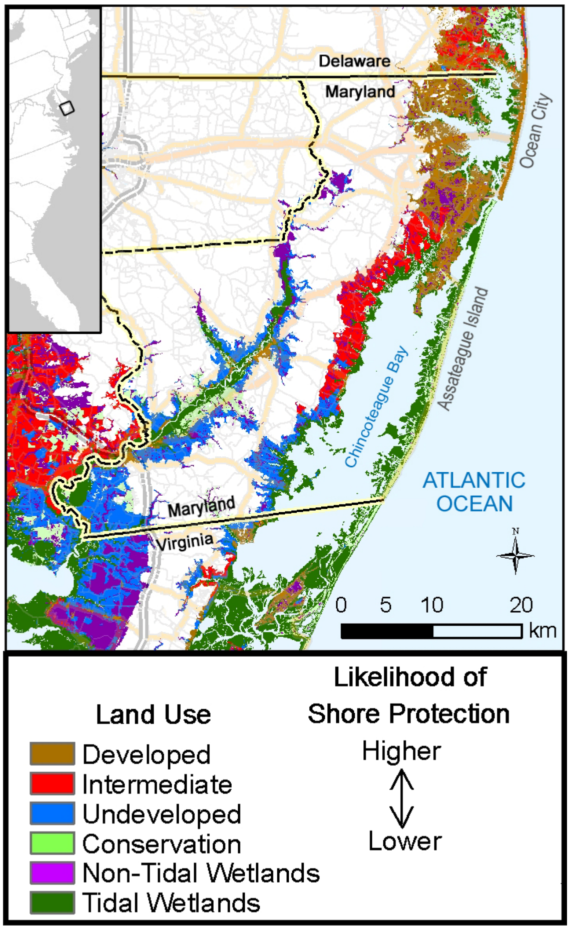

Figure 1. Land use and likelihood of shore protection along the Maryland coast. This map shows lands within 5 m above spring high water. Along the Atlantic Ocean, Ocean City is densely developed and the state government is committed to shore protection, while Assateague Island is owned by the National Park Service, which is committed to allowing natural shoreline processes to operate in conservation lands. Along the coastal bays, the northern areas opposite Ocean City are developed with many shores already bulkheaded. The southern areas along Chincoteague Bay shown in blue are generally farms with agricultural-preservation easements that prevent residential development; although the easements allow shore protection, farmers in this area have rarely erected bulkheads in the past. The land use plan shows future development for most of the area shown in red.

2. Methods

With the assistance of local planners responsible for land use in 131 jurisdictions from Massachusetts to Florida (table S1 available at stacks.iop.org/ERL/4/044008/mmedia), we used available planning data (tables S2 and S3 available at stacks.iop.org/ERL/4/044008/mmedia) and identified relevant government policies (tables S4 and S5 available at stacks.iop.org/ERL/4/044008/mmedia) to divide coastal dry lands into four categories representing different likelihoods of shore protection. We used wetlands data (table S6 available at stacks.iop.org/ERL/4/044008/mmedia) to distinguish dry lands from wetlands, and made no attempt to account for future development in wetlands. Our initial classification focused on land use. *Developed* lands have generally been protected in the past when threatened by erosion or flooding [12, 13]; hence they are most likely to be protected in the future [10, 21]. At the other extreme, *conservation* lands are generally allowed to respond naturally to shore processes [22] and hence are least likely to be protected [10]. We used available land use/land cover data for moderate and high-density development to define *developed*, and conservation lands data sets to define *conservation* (table S2 available at stacks.iop.org/ERL/4/044008/mmedia).

We divided the remaining dry lands into two categories: areas expected to remain *undeveloped* and an *intermediate* category consisting of existing low-density development, places where land use plans anticipate future development, and military bases in rural areas. Undeveloped lands are rarely protected [10]; but even lightly developed lands are generally protected along estuaries [13], which account for most of the shoreline along the US Atlantic coast. Hence, under current policies, shore protection is more likely in *intermediate* lands but less likely in *undeveloped* lands [10]. In urban counties and other places where near-total development is expected, we used parks and agricultural-preservation data to identify the relatively few lands unlikely to be developed (table S2 available at stacks.iop.org/ERL/4/044008/mmedia). In rural areas, state or local planning documents identify lands where development *is* expected.

With our classification of coastal land use as a starting point, we then visited the local planners to further refine the maps. The planners indicated that our four land use categories generally correspond to the land that is most likely, likely, unlikely, or least likely to be protected as sea level rises (assuming a continuation of current policies and practices). Given that correspondence, our tables and figures 1 and 2 have land use labels instead of likelihood labels so that our primary source of information is more transparent. (The supplementary information (available at stacks.iop.org/ERL/4/044008/mmedia) provides additional detail and caveats on this issue, as well as descriptions of the data, study area boundaries, and GIS processing methods.) We created county-specific maps for the land within approximately 5 m above spring high water, which we sent to the planners for additional refinements (except for Florida, whose local governments only provided land use data below the USGS 3 m contour). We also calculated the area of each land category at various elevations between 0 and 5 m above spring high water.

The planners provided us with four types of refinements.

- Specific parcels of land that had been developed since the published data was created.
- Specific data sets (table S3 available at stacks.iop.org/ERL/4/044008/mmedia) that more accurately defined the land use within their jurisdictions than the general data sets in table S2 (available at stacks.iop.org/ERL/4/044008/mmedia).
- Land use policies expected to alter development trends (table S4 available at stacks.iop.org/ERL/4/044008/mmedia) in specific areas, such as prohibitions on development within a 100-year floodplain.
- Shoreline policies that cause the likelihood of shore protection in some areas to diverge from what would be expected considering land use alone (table S5 available at stacks.iop.org/ERL/4/044008/mmedia). For example, dikes are being constructed to protect (*undeveloped*) farmland in North Carolina, and cliff regulations in Calvert County (Maryland) prohibit shore protection along *developed* cliffs (table S5 available at stacks.iop.org/ERL/4/044008/mmedia).

Figure 1 maps the four land classifications (as well as wetlands) for an example county in Maryland.

Limitations in available data almost certainly cause our results to understate the level of existing and future development. Most land use data are 5–10 years old and thus omit recent development. More importantly, rural land use plans identify priority growth areas where local governments are encouraging development to concentrate, but not all areas where development will eventually occur. Development often takes place in other areas, especially once the priority areas have been developed.

3. Results and implications

Most of the ocean coast is *developed* or *intermediate*, but *conservation* lands account for most of the Virginia ocean coast, and large parts in Massachusetts, North Carolina, and Georgia. Figure 2 shows the entire study area; figures S2–S23 show specific counties and/or states. Measured by area, more than 80% of the land below 1 m in Florida or north of Delaware is *developed* or *intermediate* (tables 1 and S8 available at stacks.iop.org/ERL/4/044008/mmedia). Only 45% of the land from Georgia to Delaware is *developed* or *intermediate*, by contrast, because Maryland and Delaware restrict coastal development (table S4 available at stacks.iop.org/ERL/4/044008/mmedia) and most coastal lands from Virginia to Georgia are farther from major population centers.

The composition of the four land categories shifts modestly as a function of elevation (figure 3). The percentage of *conservation* lands declines with increasing elevation in 10 states and is relatively constant in the other 4 states (figure S2 available at stacks.iop.org/ERL/4/044008/mmedia). The concentration of conservation lands at the lowest elevations is consistent with the acquisition priorities of the national refuge system and other conservation organizations. Many refuges include habitat immediately along estuaries, but do not extend far inland [23]. The proportion of *undeveloped* land is also greater at the lowest elevations, especially in Delaware (where two counties prohibit development in floodplains) and Maryland (where state law prevents development within 300 m of the shore in rural areas). New Jersey is an exception to the general pattern, possibly because all but one of its barrier islands are developed, and the past practice of filling marshes for development [24] has created a legacy of very low-lying development.

Considering our entire study area, 42% of the dry land within 1 m above the tidal wetlands is developed and most likely to be protected given business-as-usual (table 1). Some development either exists or is expected in the land use plans for another 15% of the area. Thus, almost 60% of the lowest dry land is likely to be developed and eventually protected as

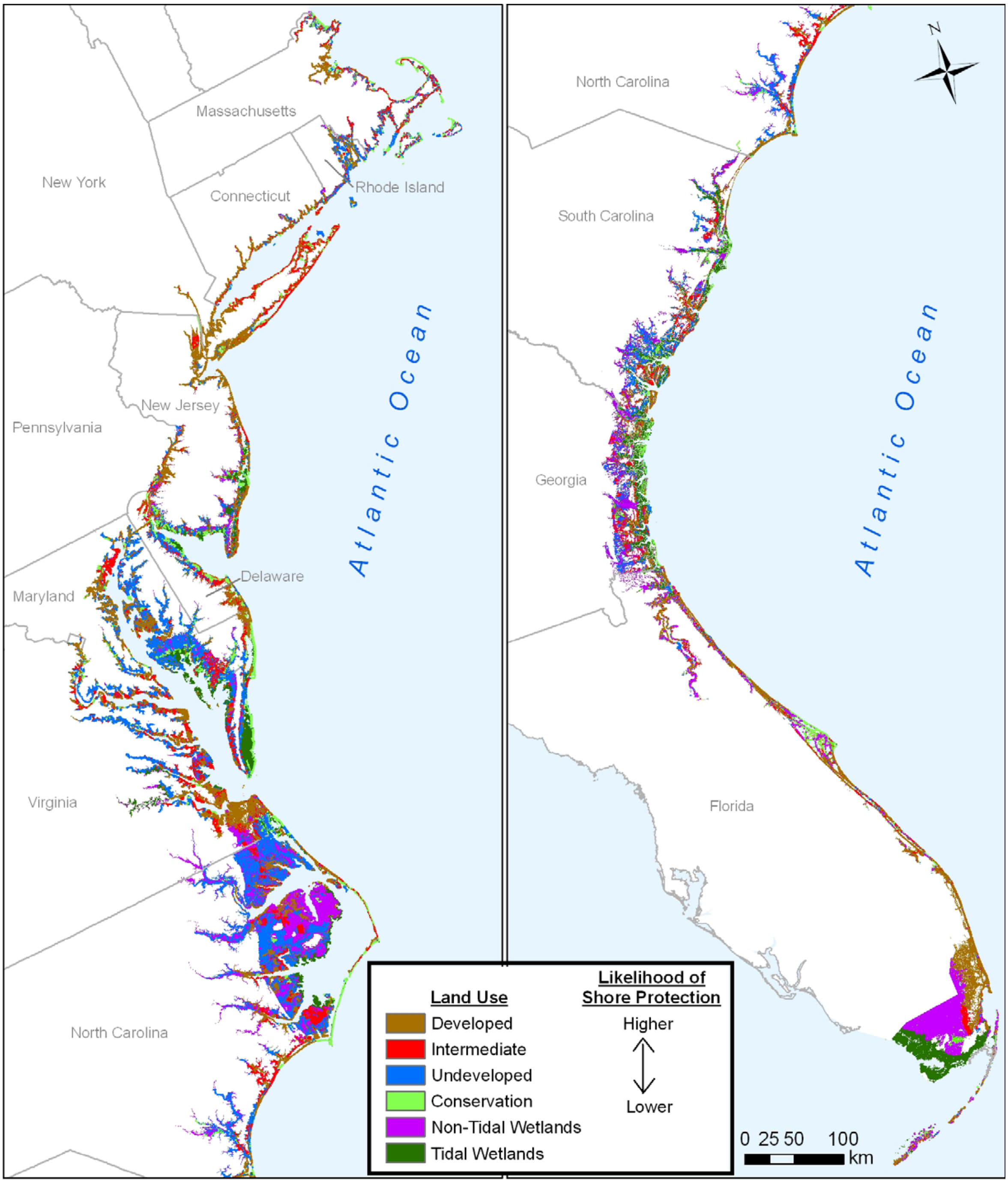

Figure 2. Categories of land use and likelihood of shore protection along the Atlantic coast of the United States. Coastal development is most intense north of Delaware Bay, in Florida, and elsewhere close to metropolitan areas such as Washington, Norfolk, and Charleston. The study area is generally the land within 5 m above spring high water, except for Florida where planning departments provided data for lands below the USGS 3 m contour.

sea level rises. By contrast, only 9% of this land has been set aside for conservation purposes that would allow coastal ecosystems to migrate inland. Land use plans do not anticipate development of the remaining 33%, which is mostly rural today. Eventually, some of those areas may be developed as well, especially from Virginia to Georgia, where there are few institutional limitations on coastal development.

Our results suggest that the majority of low-lying lands along the US Atlantic coast will become populated if business-as-usual development continues. Maintaining this development as sea level rises would require increasingly ambitious shore protection [10]. The US experience protecting populated areas below sea level from flooding is mostly limited to metropolitan New Orleans [15]. Sea level rise could leave communities similarly vulnerable throughout the US Atlantic coast.

The resulting shore protection could imperil a key environmental objective in the United States: the preservation of tidal wetlands. In the 1970s, the United States

Table 1. Land within 1 m above high water by intensity of development along US Atlantic coast.

	Likelihood of shore protection High ⟷ low						
	Per cent of dry land, by land use type[a]				Area		
State	Developed (%)	Intermediate (%)	Undeveloped (%)	Conservation (%)	Dry land (km^2)	Nontidal wetlands (km^2)	Tidal wetland (km^2)
MA	26	29	22	23	110	24	325
RI	36	11	48	5	8	1	29
CT	80	8	7	5	30	2	74
NY	73	18	4	6	165	10	149
NJ	66	15	12	7	275	172	980
PA	49	21	26	4	24	3	6
DE	27	26	23	24	126	32	357
MD	19	16	56	9	449	122	1116
DC	82	5	14	0	4	0	1
VA	39	22	32	7	365	148	1619
NC	28	14	55	3	1362	3050	1272
SC	28	21	41	10	341	272	2229
GA	27	16	23	34	133	349	1511
FL	65	10	12	13	1286	2125	3213
Total	42	15	33	9	4665	6314	12 882

[a] Calculated as the statewide area of a given land use category divided by the area of dry land in the study area. Percentages may not add up to 100% due to rounding.

collectively decided to stop creating new coastal communities by filling marshes and swamps [25, 26], and enacted other policies [13, 19, 26–28] to preserve tidal wetlands along the Atlantic coast. But these ecosystems may not be sustained if sea level accelerates. At the current rate of sea level rise, most tidal wetlands are able to keep pace through sedimentation and peat formation; but their ability to keep pace with a rate greater than 5–10 mm yr^{-1} is doubtful [10]. To survive, these ecosystems would have to migrate inland [4, 10, 11]. With only 9% of the lowest land set aside for conservation, a large-scale migration would require either a halt to construction in most coastal floodplains or an eventual abandonment of many developed areas [10, 19]. But current policies promote the opposite [10].

The existing nationwide permit for shore protection [18] authorizes almost any owner of a small- or medium-sized lot to erect a shore protection structure that prevents ecosystems from migrating inland. The Clean Water Act allows this type of general permit only if it has a minimal cumulative environmental impact [16]. The Corps of Engineers found that the impact is minimal, based on the assumption that building a shore protection structure threatens an area of habitat equal to the footprint of the construction, but that no additional habitat is lost over time [17, 29]. Ignoring the habitat eventually lost by blocking wetland migration is unreasonable, in our view, because preventing the landward migration of aquatic habitat (wetlands, beaches, floodplains, and shallow waters) onto the land being protected is the main reason for shore protection [13, 29]. The Corps should re-evaluate its finding to incorporate the impact on wetland migration.

We think that such a re-evaluation should find that shore protection has a cumulative environmental impact. The Clean Water Act does not explicitly define the term, but the context implies that an impact need not be large to be considered a 'cumulative environmental impact':

- The Corps of Engineers has also declined to define the term or even the magnitude of wetland loss necessary to constitute a cumulative impact under the Clean Water Act [30]. However, its finding of minimal cumulative impact was based on its estimate that the nationwide permit affects about 1 km^2 of wetlands per year (the area of the footprint of the shore protection structures) [17, 28], which is less than 0.01% of the current area of coastal wetlands. When public comments suggested that the loss from all the nationwide permits was ten times what the Corps' estimated, the Corps did not dispute the assertion that such a large impact would be a cumulative impact, but instead asserted that its lower estimate is more accurate [30].
- Under the Clean Water Act, the existence of a cumulative impact does not cause a permit to be denied; it merely requires that the impact of each permit be considered through the issuance of an individual permit, instead of being ignored under a nationwide permit [16].
- Under the National Environmental Policy Act, cumulative impact has been defined as the impact of an activity 'added to other past, present, and reasonably foreseeable future actions' regardless of who takes the other actions [31]. An impact need not be large to satisfy that definition.

The immediate result of recognizing the cumulative impact would be to require property owners to apply for individual permits [16, 18], which could substantially delay permit approval and disrupt the Corps' ability to review other permit applications [17]. To avoid overwhelming the regulatory process, an alternative framework is needed. It might be possible to issue a revised nationwide permit that truly has a minimal cumulative impact, through a combination of shore protection techniques that preserve wetlands [13] and/or requirements to mitigate lost opportunities for wetland

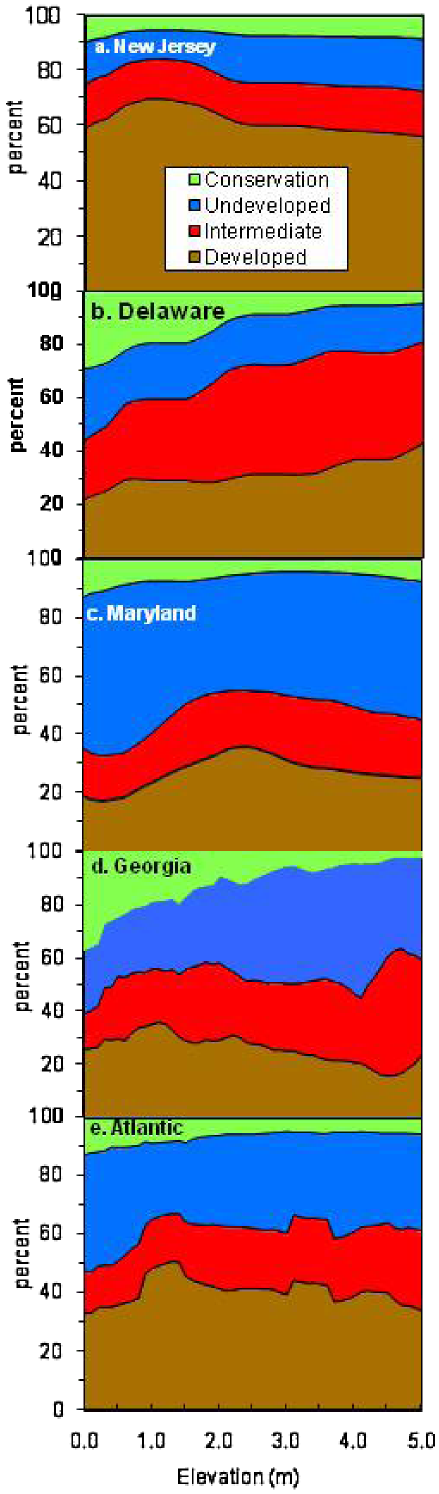

Figure 3. Percentage of dry land within four land use classifications, by elevation. In most states the portion of conservation and undeveloped lands is greatest below 1 m and gradually tapers off at higher elevations, because nature reserves include low land adjacent to wetlands and development is discouraged in floodplains. (a) New Jersey is an exception, primarily because the densely developed coastal communities tend to be in areas with the greatest amount of very low land, such as barrier islands and filled wetlands. (b) Delaware, (c) Maryland and (d) Georgia all follow the typical pattern. (e) Atlanticwide, the portion of developed land decreases above 1.5 m largely because Florida (which is highly developed) accounts for about 35% of the dry land below 1.5 m but only 15% of the dry land above 1.5 m.

migration by facilitating such opportunities elsewhere [19]. A more comprehensive approach would be to consciously manage the impacts of shore protection as sea level rises with estuary-wide plans that define the fates of shorelines as sea level rises [29]. A wide variety of planning and legal mechanisms are available for implementing a planned retreat without hurting property owners [10, 19].

The maps provided by this study can serve as an initial benchmark for evaluating the environmental consequences of the business-as-usual response to sea level rise and possible alternatives that would better preserve the environment and comply with the law. They can also be used to focus efforts on the 30% of low-lying land that is neither developed nor conservation land. Ensuring that some of these lands are abandoned to a rising sea so that ecosystems can adjust would face economic, political, and legal challenges; but defending the entire coast seems even more difficult in the long run [10, 12, 19, 21]. If environmental policies must eventually be revised to ensure that wetlands migrate inland, now is the best time for wetland regulators to update policies to recognize that sea level is rising. It is also a good time for all of us to ask whether this generation should continue to build new communities in vacant land vulnerable to a rising sea.

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