Integrating the value of coastal ecosystem services into climate change adaptation planning (#40100)

First revision

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Integrating the value of coastal ecosystem services into climate change adaptation planning

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Coastal habitats can protect communities from coastal hazards, yet these critical habitats, and the diverse ecosystem services they provide, are threatened by coastal development and impacts from a changing climate. Ever increasing pressure on coastal habitats calls for coastal climate adaptation efforts that mitigate or adapt to these pressures in ways that maintain integrity of coastal landscapes. An important challenge for decision makers is determining the best mitigation and adaptation strategies that not only protect human lives and property, but also protect the ability of coastal habitats to provide a broad suite of benefits. Here, we present a potential pathway for local-scale climate change adaptation planning and implementation through the identification and mapping of natural habitats that provide the greatest benefits to coastal communities. The methodology coupled a coastal vulnerability model with a climate adaptation policy assessment in an effort to identify priority locations for nature-based solutions that reduce vulnerability of critical assets using feasible land use policy methods. Our results demonstrate the critical role of natural habitats in providing the ecosystem service of coastal protection in California. We found that specific dune habitats play a role in reducing erosion and inundation of the coastline and that key wetland areas help coastal areas to absorb energy from storms and provide a protective service for the coast. Climate change and adaptation planning are globally relevant issues in which the scalability and transferability of solutions must be considered. This work outlines a framework for adaptation planning at a local-scale, and the next steps of this work can address the scalability to regional, national, and international scales.

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Abstract

Coastal habitats can protect communities from coastal hazards, yet these critical habitats, and the diverse ecosystem services they provide, are threatened by coastal development and impacts from a changing climate. Ever increasing pressure on coastal habitats calls for coastal climate adaptation efforts that mitigate or adapt to these pressures in ways that maintain integrity of coastal landscapes. A key challenge for coastal planners is determining the best climate mitigation and adaptation strategies that not only protect human lives and property, but also protect the ability of coastal habitats to provide a broad suite of benefits. Here, we present a potential pathway for local-scale climate change adaptation planning and implementation through the identification and mapping of natural habitats that provide the greatest benefits to coastal communities. The methodology coupled a coastal vulnerability model with a climate adaptation policy assessment in an effort to identify priority locations for nature-based solutions that reduce vulnerability of critical assets using feasible land use policy methods. Our results demonstrate the critical role of natural habitats in providing the ecosystem service of coastal protection in California. We found that specific dune habitats play a role in reducing erosion and inundation of the coastline and that key wetland areas help coastal areas to absorb energy from storms and provide a protective service for the coast. Climate change and adaptation planning are globally relevant issues in which the scalability and transferability of solutions must be considered. This work outlines a framework for adaptation planning at a local-scale, and the next steps of this work can address the scalability to regional, national, and international scales.

Introduction

Ecosystem services are the stream of vital benefits flowing from natural capital to people (Barbier et al., 2011; Costanza et al., 1997). Coastal habitats—such as seagrass, kelp forests, salt marshes, and dunes—provide benefits that are extremely valuable to society, such as carbon sequestration, nutrient cycling, sustaining biodiversity, as well as tourism and recreation (Agardy, 1993; Barbier et al., 2011; Beck et al., 2018, 2001; Duarte, 2017; Guerry et al. 2012; Pendleton et al., 2011). In addition, coastal ecosystems provide a plethora of sociocultural ecosystem services, described as non-material spiritual, bequest value, emotional, aesthetic, and health benefits (Duraiappah et al., 2005a; Ghermandi et al., 2009; Sandifer and Sutton-Grier, 2014).

Coastal habitats also provide the ~~specific~~ ecosystem service of coastal protection, which directly benefits coastal communities by reducing the effects of coastal flooding and erosion caused by storms and rising seas (Arkema et al. 2015; Barbier et al., 2011; Möller et al., 2014; Narayan et al., 2017; Spalding et al., 2014). Coastal habitats buffer the coastline from waves and storm surges, and reduce coastal erosion (Arkema et al., 2013; Barbier et al., 2011). Yet, these critical coastal habitats are threatened by existing coastal infrastructure and impacts from a changing climate (Defeo et al., 2009; Dugan et al., 2011; Guannel et al., 2015; Heady et al., 2018). As coastal development and rising sea levels damage or destroy natural habitats, communities and infrastructure become increasingly vulnerable to storms and erosion (Guannel et al., 2015; Neumann et al., 2015; Nicholls et al., 1999).

In coastal California, ever increasing pressure on coastal habitats call for land management and adaptation efforts that mitigate or adapt to these pressures in ways that maintain the integrity of coastal landscapes (California Coastal Commission, 2015). Without coastal adaptation efforts that incorporate conservation or restoration of coastal habitats, these ecosystems will continue to be lost, and their protective benefits (together with diverse co-benefits such as carbon storage and sequestration, recreational opportunities, and wildlife habitat) will disappear with them (Neumann et al., 2015). Maintaining natural capital to protect and support vibrant coastal communities is especially critical in the face of intensifying climate change effects. This effort is no small task, and it presents coastal communities with a significant challenge—and opportunity—to proactively manage land use via protection and restoration of coastal habitats (Caldwell and Segal, 2007; Sutton-Grier et al., 2018).

To foster coastal adaptation, some planners and decision makers are considering incorporating a suite of natural or nature-based infrastructure strategies. Nature based solutions (NbS) work with nature to address an environmental or societal challenge, benefiting humans and biodiversity (Seddon et al., 2021) and will be crucial in addressing the challenges related to climate change adaptation and mitigation, biodiversity loss, and human wellbeing (Seddon et al., 2020). Nature-based infrastructure strategies are key components of overall NbS efforts, which are built systems that combine natural ecosystems with engineered structures to provide added protection as well as multiple other services to communities (Sutton-Grier et al., 2018). For example, stream-design culverts can help to reduce damage to property and roads from coastal flooding whilst restoring natural tidal flow (Gillespie et al., 2014). As nature-based infrastructure strategies gain traction, there is a need to accurately identify suitable locations and appropriate settings for these strategies to ensure long-term delivery of the protective service and additional beneficial ecosystem services (Temmerman et al., 2013; Arkema and Ruckelshaus, 2017; Ruckelshaus et al., 2016). While hardened shoreline structures can protect infrastructure immediately behind them, the structures can also alter sediment transport regimes, eventually leading to beach erosion in front of and adjacent to armoring (Griggs, 2005; Kraus, 1988).

An important challenge for decisionmakers is determining the best mitigation and adaptation strategies that not only protect human lives and property, but also protect the ability of coastal habitats to provide the broad suite of benefits we rely on (Aerts et al., 2014; Heady et al., 2018). Modeling and mapping of ecosystem services can support the assessment of place-based coastal protection services provided by coastal habitats and support science-based climate adaptation strategies (Arkema et al., 2017, 2013). We used the Coastal Vulnerability model to evaluate the role that coastal habitats play in reducing exposure to erosion and flooding by comparing the exposure index value of a given coastal segment with habitats present and with habitats absent. These comparisons are informative when evaluating the coastal protection benefits and tradeoffs among adaptation strategies. In particular, this model can illustrate relative differences in protection conferred by hardened shoreline structures versus natural and nature-based alternatives. The model can examine the relative impact of conserving, restoring, or destroying different habitat types at any given location.

Here, we utilized an ecosystem-service modeling approach to ask the following: 1) What is the role of natural habitat in providing the ecosystem service of coastal protection? and 2) Where are coastal habitat locations that might be prioritized for restoration and management in order to reduce risk to coastal ecosystems, people and property? We determined the role of natural habitat in reducing exposure to erosion and inundation throughout the Pacific coast of Marin County, California, USA using the Coastal Vulnerability Model. We also evaluated the extent of these coastal protection benefits by mapping where the resulting estimates of high hazard exposure aligned with various land use zoning designations and identified areas where large numbers of people and property were exposed to coastal hazards. In collaboration with local decision makers, we linked our ecosystem service mapping and assessment to coastal adaptation decision making, and synthesized potential nature-based strategies relevant to these local coastal communities. By tailoring our mapping to the local area, we can suggest management interventions which will have the highest likelihood of success in protecting people and the environment in this locality.

Materials & Methods

Study area

The Pacific coast of Marin county, California includes extensive natural habitats that provide a suite of ecosystem services (Figure 1). We examined two case study areas of particular economic and ecological significance for the county's coastline: Dillon Beach and the Stinson Beach-Bolinas Lagoon area. Dillon Beach is in Marin's northernmost coastal community with a suite of habitats including predominantly dune systems and surf grass (Figure 2A). These natural habitats influence the cultural attachment to the coast for Dillon Beach residents and visitors alike (Tierney, 2017). For example, recreation is an important ecosystem service in coastal areas and supports beach use, camping, bird watching, fishing, boating, and surfing (Barbier et al., 2011; Tierney, 2017). Further, the coastal ecosystems in this area provide critical habitat for a seabird colony and support two marine mammals haul out locations (Hayden et al., 2017). Natural habitats of Stinson Beach and Bolinas Lagoon include primarily coastal surf grass and kelp habitat (Figure 3), with wetland habitat in the tidal embayment of Bolinas Lagoon, and a low dune system along Stinson Beach sandspit. Bolinas Lagoon shelters a predominantly saline, shallow water mosaic of mudflats, riparian areas, and tidal salt marsh that covers approximately 4.5 km^2. Wetlands in Bolinas Lagoon help coastal areas absorb energy from storms and provide a protective service for the adjacent lagoon shoreline. Bolinas Lagoon is a "Wetland of International Importance" (Ramsar Convention, 2018) and provides critical habitat for wintering shorebirds along the Pacific Flyway.

Policy context and analysis

Adaptation to climate change impacts has gained prominence in scientific and policy agendas within the last decade (Moser and Ekstrom, 2010) and many governmental and non-governmental actors at the national, regional, and local levels are developing adaptation plans. Overcoming adaptation barriers involves incremental policy, planning, and management choices (Ekstrom and Moser, 2014; Melius and Caldwell, 2015). California features a relatively prominent policy framework for protecting the state's shoreline and coastal managers have recently bolstered this foundation with additional guidance and funding (California Coastal Commission, 2018, 2015).

Adapting to the threats that climate change poses to California's coastal communities can be addressed through the state's land use policies. The California Coastal Act (California Public Resources Code, 1976) serves as the state's coastal management program and legal framework. It was enacted in 1976 to regulate land use and development in the coastal zone—i.e. an area extending seaward three miles and landward according to legally defined boundaries (California Public Resources Code, 1976). The Coastal Act requires local governments in the coastal zone to prepare Local Coastal Programs (LCPs), including land use plans and implementing measures, such as zoning ordinances (California Public Resources Code §§ 30500-30526).The California Coastal Commission reviews and approves LCPs as consistent with—and adequate to carry out—Coastal Act policies, after which that local government becomes the lead agency for permitting most coastal development above the mean high tide line, subject to limited California Coastal Commission appeal authority (California Public Resources Code §§ 30514a-30514b). Thus, LCPs are a critical decision and entry point for local-level coastal adaptation actions (Caldwell and Segal, 2007).

Specifically, LCP updates are one substantial policy mechanism for local governments to address coastal climate adaptation in California (Berke and Lyles, 2013). Here, we set out to advance the understanding of how natural habitats reduce vulnerability of coastal assets (e.g., infrastructure, parks, habitats) and analyze the legal and policy considerations relevant to the LCP update process. Further, we sought to incorporate the California Coastal Commission's sea-level rise policy recommendations in our coastal vulnerability modeling efforts to assist the county in developing approaches that integrate current ecosystem service science where suitable.

We began our policy research by evaluating academic and practitioner guidance on potentially appropriate coastal adaptation strategies for sea-level rise. We reviewed guidance documents and reports that outline land use planning and regulatory options that could be considered in coastal areas (Grannis, 2011; Siders, 2013). We also researched relevant state- and county-level laws and policies on acceptable strategies for near- and long-term adaptation to coastal hazards. We identified the legal and practical limitations these policies place on adaptation options in Marin and explored potential changes to the existing policies that may increase adaptive capacity. In each of the case study locations, we identified near-term natural or nature-based coastal adaptation strategies that could maintain or enhance existing coastal protection services. Specifically, we assessed exposure to coastal hazards and adaptation options of case study locations in the county to better understand the different dimensions of these vulnerabilities.

Ecosystem service mapping and assessment

We conducted a coastal vulnerability analysis using a spatial approach with the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) Coastal Vulnerability model (Sharp et al., 2018). InVEST is a free and open-source suite of software models created by the Natural Capital Project at Stanford University (https://naturalcapitalproject.stanford.edu/) used to map and place value on the goods and services supplied by natural capital. The models account for both service supply (e.g., natural habitats as buffers for storm waves) and the location and activities of people who benefit from services (e.g., the location of people and infrastructure potentially affected by coastal storms). The InVEST Coastal Vulnerability model produces a numeric Exposure Index (EI), which ranges from 1 to 5 (5 = highest risk; 1 = lowest risk). This index provides a ranked estimate of which coastline segments have relatively high or low exposure to coastal erosion and inundation due to sea-level rise and storms. While this index is relative and does not calculate absolute probabilities of erosion and inundation, it provides a heuristic way of comparing coastal segments and highlights areas where multiple conditions creating high exposure to hazards coincide.

The Coastal Vulnerability model data inputs serve as proxies for various complex shoreline processes that influence exposure to erosion and inundation. The data inputs include: a polyline with attributes about local coastal geomorphology along the shoreline, polygons representing the location of natural habitats (e.g., seagrass, kelp, wetlands, etc.), rates of projected net sea-level change, a depth contour that can be used as an indicator for surge level (edge of the continental shelf), a digital elevation model representing the topography and bathymetry of the coastal area, and a point shapefile containing values of observed storm wind speed and wave power (Table 1). Natural habitats within a specified distance of the coastline (Table S2) confer protection from waves to the nearby coastal segment. When multiple habitats are present, this protection increases nonlinearly and causes input risk ranking to decrease (Supplemental Material). While the model does not account for possible changes in the coastline shape over time, the EI incorporates which habitats are most likely to experience coastal erosion and flooding. The model provides a relative estimate of exposure under different land use scenarios (Supplemental Material).

We used data specific to California for geomorphology, coastal habitat area, rate of sea-level rise through 2030 (Table 1). We coupled these data with global models of wind and wave power (Wave Watch III) , and the edge of the continental shelf (surge potential). The geomorphology data input was represented by a polyline with attributes about local coastal geomorphology along the shoreline based on the NOAA Environmental Sensitivity Index (Peterson, 2002). In order to account for locations of armoring from man-made structures, we used an inventory of barriers that have potential to retain sandy beach area from the California Coastal Commission (2014). Due to changes in hydrodynamics, soft sediment areas adjacent to hardened barrier structures are highly likely to erode (Kraus, 1988). We altered the geomorphology rank of coastal segments that were within 75m of (but not directly behind) armoring structures to reflect this increased risk (Table S1). Polygons representing the location of natural habitats (e.g., seagrass, kelp, wetlands, etc.) from the California Department of Fish and Wildlife website created for Marine Life Protection Act process (California Department of Fish and Wildlife, 2015). A point shapefile containing values of observed storm wind speed and wave power across an area of interest using Wave Watch III data provided by NOAA. A polyline of the edge of the continental shelf serves as a proxy for oceanic surge potential. In general, a longer distance between the coastline and the edge of the continental shelf will result in a higher storm surge. The model does not account for land barriers in front of coastal segments that would alter storm surge. A 5-meter resolution bathymetry/topography digital elevation model of California's coastal land and waters from the United States Geological Service (Foxgrover and Barnard, 2012) was used with mean sea-level datum at 0-m. Rates of projected net sea-level change through 2030 were derived from local variation in global sea-level rise and coastal land subsidence/uplift rates (National Research Council, 2012).

We mapped the benefits of natural habitats in reducing exposure to coastal impacts throughout the Pacific coast of Marin county. We also evaluated these benefits in key areas of local importance, including Dillon Beach and the Stinson Beach-Bolinas Lagoon area. The model produces a qualitative estimate of risk in terms of an EI for every 250m segment of coastline. The EI differentiates areas with relatively high or low exposure to coastal erosion and inundation during storms. By coupling these results with coastal features of interest (e.g. infrastructure, land use zoning, or population), the model can show areas along a given coastline where people or property are most vulnerable to storm waves and surge. EI values were assigned classifications of "High" exposure, "Medium" exposure, and "Low" exposure based on percentile ranks in the overall EI distribution (Table S1). We classified the role of habitats in reducing EI values using the same percentile ranks (Supplemental Material). We mapped where the resulting estimates of high hazard exposure aligned with various land use zoning designations in Marin county (Marin County Community Development Agency, 2015) and identified areas where large numbers of people and property were exposed to coastal hazards. All modeling was performed with InVEST version 3.3 (Sharp et al., 2018), and all other geospatial operations were performed with ArcMap 10.1 (ESRI).

Results

Coastal exposure and the role of natural habitat

Across the Marin coastline areas of wetlands and dune habitat provided varying degrees of coastal protection from storms and sea-level rise. Overall, these natural habitats provided the highest degrees of protection from coastal hazards along the northern shore of Point Reyes and around Dillon Beach (Figure 2b). Specifically, the high dune habitat at Dillon Beach aids in protecting important roads and the small community at Lawson's Landing, while also providing key recreational beach going and camping opportunities. The surf grass along the agricultural areas bordering Estero de San Antonio play a lower relative role in reducing exposure to coastal impacts. In addition, the low dune system along Stinson Beach and near the mouth of Bolinas Lagoon plays a medium role in reducing exposure to erosion and inundation from storms compared to the rest of the Marin coastline (Figure 3b).

The low and high dune systems in the northern portion of Marin county played the highest relative role in reducing exposure to erosion and inundation from storms. Coastal habitats in the southern portion of Marin county played the lowest protective role (Figure 4). We used Marin county's zoning layers (Marin County Community Development Agency, 2015) coupled with the outputs of the InVEST Coastal Vulnerability model to identify how priority or high-exposure locations align with the county's various land-use or zoning designations. These overlay results informed the type of coastal adaptation strategies most feasible in each location. For example, when high-exposure areas correspond with residential zoning designations with existing structures they can reduce the feasibility of habitat restoration or retreat options that might conflict with private property rights or result in politically challenging debates (Melius and Caldwell, 2015).

The high dune habitat at Dillon Beach (Figure 2a) plays a relatively high role countywide in reducing erosion and inundation of the coastline (Figure 2b). This area of the county has less than 100-m of hardened structures along the coastline, increasing reliance on natural habitats for protective services. Dune habitats directly in front of the main residential commercial center near Lawson's Landing reduced the coastal exposure for this area. As the dunes transition to surf grass, we found that the relative coastal protection reduces to intermediate levels. On the opposite side of Tomales Bay, the shoreline benefits from an EI reduction, the largest reduction in the Dillon Beach area (Figure 3b). Though multiple different habitat types are located in Tomales Bay, only eelgrass is within appropriate proximity of these segments of coastline to confer protection. At Dillon Beach, in the short to medium term, a large-scale dune restoration project is possible on the south end of the beach—near the mouth of Tomales Bay. Here, experimental design areas and monitoring could aid in testing the protective services dunes provide. Dune restoration may help to protect exposed "Residential" parcels (including residential structures) as well as the "Resort and Commercial Recreation" areas and important inland wetland habitat. Marin would be at the forefront of helping to develop data to determine dune restoration design metrics and elements of success as well as how hydrological and geomorphological conditions in different areas contribute to the success or failure of restored dunes as a natural infrastructure alternative to armoring. This project could add to the body of evidence from similar demonstration sites previously approved by the Coastal Conservancy in Humboldt and Monterey Counties. Coastal dune restoration on the west coast of North America was pioneered in the Lanphere Dunes in Humboldt county in the 1980s and many case studies published from the dune restoration projects can provide valuable support (Pickart, 2013).

In Stinson Beach, a primary short-term option is to "hold the line" or protect existing natural and built infrastructure in place by using physical barriers to the sea and applying a hybrid concept in this area. This could include a horizontal levee along Bolinas Lagoon and beach nourishment and/or dune restoration along the Stinson Beach coastline. The horizontal levee could provide significant protection to the western section of Bolinas Lagoon zoned as "Agriculture Residential Planned." A longer-term option in Stinson Beach is to "adjust to the line" or accommodate the infrastructure by using development conditions and/or restrictions that provide incentives to reduce the exposure of existing or rebuilt infrastructure to increased inundation from storm events. To the extent that other natural habitats in the lagoon can be protected, restored, or enhanced, there will be benefits provided by a horizontal levee project. Zoning designations in the Stinson Beach and Bolinas Lagoon areas limit the availability of policy options. This is because "at risk" areas correspond with a patchwork of high- and low-density housing designations in the Stinson Beach area, generally. However, the western side of Bolinas Lagoon is zoned as open space and residential agriculture planned, thus, the most feasible locations for wetland restoration occur along the western side of Bolinas Lagoon.

Discussion

We determined the role of natural habitat in reducing exposure to erosion and inundation throughout the Pacific coast of Marin county, California, USA using a coastal vulnerability model. The InVEST Coastal Vulnerability model allowed us to identify relative exposure to inundation and erosion for coastal settings and identify locations where coastal habitats play a significant role in reducing that exposure (Arkema et al., 2013; Ruckelshaus et al., 2016). Previous studies have reported that coastal habitats (seagrass, mangrove and coral reefs) may have a greater collective effect in reducing coastal vulnerability when they exist near each other, than individual habitats do (Guannel et al., 2016). Nonetheless, individual habitat types are still an effective barrier to storm conditions, but the level of protection depends on geomorphic, hydrodynamic and ecological context of the location (Pinsky et al., 2013). While this tool is not a replacement for site-level hydrological analyses of inundation extent (e.g., Coastal Storm Modeling System) or habitat shifts (e.g., Sea Level Rise Affecting Marshes Model), it provides a means for quickly comparing relative risk across a coastline and prioritizing areas for more detailed (and often more time-intensive) flood analysis. The map products created from the InVEST tool support the spatial evaluation of climate adaptation planning alternatives under different sea-level rise scenarios and consideration of how ecosystem services provided by coastal protection are likely to change in the future. Outputs can be used to better understand the relative contributions of these different model variables to coastal exposure and highlight the protective services offered by natural habitats to coastal populations. In particular, the model highlights change in exposure with loss or restoration of habitat area. By coupling the exposure assessment mapping with land use planning spatial layers and framing the terminology to reference terms of art relevant to community planning, this information can help coastal managers, planners, landowners and other stakeholders identify regions of greater risk to coastal hazards. This information can, in turn, better inform coastal resource use like development strategies and permitting.

We also evaluated the extent of these coastal protection benefits by mapping where the resulting estimates of high hazard exposure aligned with various land use zoning designations in and identified areas where large numbers of people and property were exposed to coastal hazards. This modeling and mapping approach allowed visual representation of the role that natural habitats play in reducing coastal exposure in Marin county and helped to inform priority locations for nature-based adaptation strategies during collaborative work with local planning agencies. InVEST is most effectively used within a decision-making process that starts with stakeholder consultations (Arkema et al., 2017; Arkema and Ruckelshaus, 2017). While nature-based strategies have gained in popularity, questions remain about how to best implement them as a component of coastal adaptation decision-making (Arkema and Ruckelshaus, 2017). Uncertainty persists regarding the effectiveness of the protective service of certain nature-based approaches when compared directly to an armored coastline, particularly when considering the spatial heterogeneity in the magnitude of protection provided (Koch et al., 2009). Though California understands the harm that hard armoring can inflict on adjacent ecosystems and public access points, and has even cautioned against using hard armoring altogether, the rate of armoring continues to increase along the coast due to the inequitable distribution of wealth, desire to delay inevitable retreat, and significant judicially imposed limits on the state's ability to prevent coastal residents from armoring their property. The collaborative applied research approach adopted in Marin county showcases how to integrate nature-based solutions in the face of community conditions otherwise prone to hard armoring because of the nuanced, tailored research and associated results.

Through the use of the InVEST Coastal Vulnerability tool, we provided scientific information in a format relevant for planning discussions and decisions to meet the requirements of the California Coastal Act. This information can serve as a basis to determine where natural protections can be prioritized with inclusion of additional, localized considerations. Marin county is setting a precedent in updating their planning documents for climate adaptation in a way that takes ecosystem services analysis into account. The vulnerabilities identified in this process informed incorporation of appropriate coastal adaptation strategies and resilience measures into Marin county's LCP amendments and update process as well as the county's overall adaptation planning process —as specifically referenced in the "Adaptation Framework" section of the Marin Ocean Coast Sea Level Rise Adaptation Report (Marin County Community Development Agency, 2018).

Engagement between the planning community and members of the public is a pillar of the Local Coastal Program planning process. Members from Marin county's planning offices spearheaded a significant public engagement effort on a range of topics, including the benefits of natural adaptation options. The figures and analysis from InVEST modeling informed the production of materials and messaging points for public meetings and key stakeholder discussions. In addition, members of the planning community developed an engagement tool named “Game of Floods” to further educate audiences about the tradeoffs from pursuing specific adaptation activities—including those based on services from natural systems. These engagement tools helped facilitate dialogue between researchers, planners, and members of the local communities, ultimately leading to a more salient analysis and planning process.

California has been engaged in adaptation planning for over fifty years (California Coastal Commission, 2018). California’s Constitution and strong Public Trust Doctrine immortalize Californians’ right to public coastal access (Herzog, supra note 8), and the California Coastal Act of 1976 creates a framework by which coastal municipalities must plan to adapt to climate change and manage coastal development. (California Public Resources Code, 1976). While there are policies in place at the state level to encourage prospective planning, a “one-size fits all model” of coastal adaptation is insufficient along the California coastline (Reiblich, et al. 2017) because coastal jurisdictions vary in geomorphic characteristics (e.g., beaches, bluffs, estuaries), coastal and nearshore processes (e.g., waves, currents, sediment budgets), rates of sea-level rise (Griggs et. al., 2017), as well as other factors, including unique cultures and political views. By co-developing our methodology with local planners in Marin county, against the backdrop of state-level guidance, we tailored information and refined our analysis according to Marin county’s jurisdictional context and specific requirements — encompassing both rural and urban coastal communities with varied coastal landforms and ecosystems. The vulnerability modeling and policy analysis conducted in Marin county established methods and transferable tools for incorporating coastal climate information into coastal adaptation planning processes. By strategically considering multiple services provided by habitats when determining adaptation strategies, jurisdictions can work to protect people and property while also protecting or restoring dwindling critical habitat and the full suite of benefits those habitats provide to people (Heady et al., 2018; Sutton-Grier et al., 2018). Climate adaptation planning in an era of rising sea levels requires a comprehensive understanding of the dynamic interplay between the ecological, legal, social, economic, and political systems in these particular jurisdictions.

Conclusions

In this study, we linked our quantification of coastal ecosystem services directly to climate adaptation decision making, and highlighted the opportunity for nature-based strategies in two case study locations in California, USA. As a result of this information, policy recommendations included beach nourishment and dune restoration projects for the locations with dune habitats, and a horizontal levee for the wetlands. We anticipate that this approach will serve as a starting point and framework for further interdisciplinary work focused on bridging the gap between the best available science, law and policy in an iterative climate adaptation planning process at local scales. The adaptive capacity and sensitivity of coastal ecosystems vary greatly, and are also affected by management interventions (Morris et al., 2018) and climate change in combination with other anthropogenic stressors (Seddon et al., 2020).

Beyond California, climate change and adaptation planning are globally relevant issues in which the scalability and transferability of solutions should be considered. In the U.S., low-income and ethnic minority groups are disproportionately vulnerable to the effects of climate-induced coastal flooding, and this trend extends globally, where marginalized communities are often the most predisposed to climatic hazards (Reid et al., 2009). Future work could be expanded to recognize the importance and pervasive nature of environmental injustice in terms of coastal flooding. For instance, by coupling these results with global population information, the model can show areas along a given coastline where humans are most vulnerable to storm waves and surge under different scenarios. This index has been used to evaluate the relative risk these hazards pose to different social groups as well as property (Arkema et al., 2013; Langridge et al. 2014; Ruckelshaus et al., 2016). Through this environmental justice lens, it is important to recognize that lower-income and ethnic minority coastal communities are disproportionately threatened by sea-level rise and coastal storms (Felsenstein and Lichter, 2013; Stallworthy, 2006). For instance, >99% of socially vulnerable people in Gulf regions of the U.S. live in areas which will likely not receive protection from coastal flooding (Martinich et al., 2013), and have already experienced the impact of Hurricane Katrina in 2005 and Hurricane Sandy in 2012.

Without climate adaptation efforts that incorporate conservation or restoration of coastal habitats, these ecosystems will continue to be lost, and their protective benefits will disappear with them. This work has outlined a framework for adaptation planning at a local-scale, and the next steps of this work can address the scalability to the regional, national, and international scale. Over time, coastal communities like Marin will have "lessons learned" from the implementation of their nature-based adaptation planning. These lessons learned will then inform the next iteration of sea-level rise adaptation planning. Moving beyond the suitability and feasibility analysis of nature-based strategies (Reiblich et al., 2019), communities like Marin will soon be able to determine whether these strategies actually produced the intended results. On the leading edge of adaptation planning, many California coastal communities like Marin—rural and urban—find themselves pioneers in implementing sea-level rise adaptation strategies that incorporate nature-based strategies. Nature-based solutions such as these align with both national and sub-national long-term climate and biodiversity targets such as the USA's Paris Agreement commitments, the 30x30 initiative, and the California Air Resources Board's AB32 Climate Scoping Plan (Rous, 2014). Researchers and policymakers are urged to consider adaptation and mitigation strategies through nature-based infrastructure, which will be crucial in managing the impacts of climate change now and in the coming years as we tackle the climate and biodiversity crises (Seddon et al., 2020).

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Data Accessibility

Outputs from the Coastal Vulnerability Model can be accessed here:

https://figshare.com/articles/dataset/Marin_coastal_exposure_zip/7817981

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Table 1(on next page)

The Coastal Vulnerability model data inputs serve as proxies for various complex shoreline processes that influence exposure to erosion and inundation.

Table 1. The Coastal Vulnerability model data inputs serve as proxies for various complex shoreline processes that influence exposure to erosion and inundation.

	Data input	Data description	Data source
Geomorphology	A line shapefile input was used to calculate the Geomorphology ranking of each section of shoreline	A polyline with attributes about local coastal geomorphology along the shoreline	NOAA Environmental Sensitivity Index
Coastal habitat	The model used the input layers to calculate a Natural Habitat ranking for each shoreline segment	Polygons representing the location of coastal habitats	California Department of Fish and Wildlife website created for Marine Life Protection Act
Wind and wave exposure	Wind and wave data were given in a grid of points spaced approximately 50km apart off the coast of Marin County	A point shapefile containing values of observed storm wind speed and wave power across areas of interest. For each point, the risk ranking was based on the top 10% of values for wind speed and wave height	WaveWatch III data, provided by NOAA
Surge potential	Distance from shore to the edge of the continental shelf was used as a proxy for oceanic surge distance; longer distances between the coastline and edge of shelf results in higher storm surges	A polyline of the edge of the continental shelf around the North American west coast	InVEST Coastal Vulnerability Model data download materials (Sharp et al. 2018)
Relief	An elevation raster was used to determine low-lying coastal areas	5m resolution bathymetry/topography digital elevation model of California's coastal land and waters	United States Geological Service (Foxgrover and Barnard, 2012)
Sea level rise	The upper range of SLR projections were used as a precautionary approach	Rates of projected net sea level change up to 2030 were informed from local variation in global SLR and coastal land subsidence/uplift rates	National Research Council, 2012

Figure 1

Figure 1.

Coastal habitats of Marin County that can confer protection from coastal hazards such as inundation and erosion. Habitats include kelp, wetlands, eelgrass, surfgrass, and sand dunes. Grey lines denote county boundaries.


California
Marin County
Dillon Beach
Tomales Bay
San Pablo Bay
Marin County
San Francisco Bay
Bolinas
Stinson Beach
San Francisco
Habitat
Kelp
Wetlands
Eelgrass
Surfgrass
High Dunes
Low Dunes
Seawalls and Revetments
N
0
10
20
Km

Figure 2

Figure 2.

(A) Coastal habitats around Dillon Beach that confer protection from coastal hazards such as inundation and erosion. **(B)** The relative role of coastal habitats around Dillon Beach in reducing exposure to erosion and inundation from storms (darker colors denote a greater role). Relevant land use zoning information is included. Specifically, dunes aid in protecting important roads and the small community at Lawson's Landing while also providing key recreational beach going and camping opportunities. The surfgrass along the agricultural areas bordering Estero de San Antonio play a lower relative role in reducing exposure to coastal impacts. Role of habitats is relative to the entire coast of Marin County.

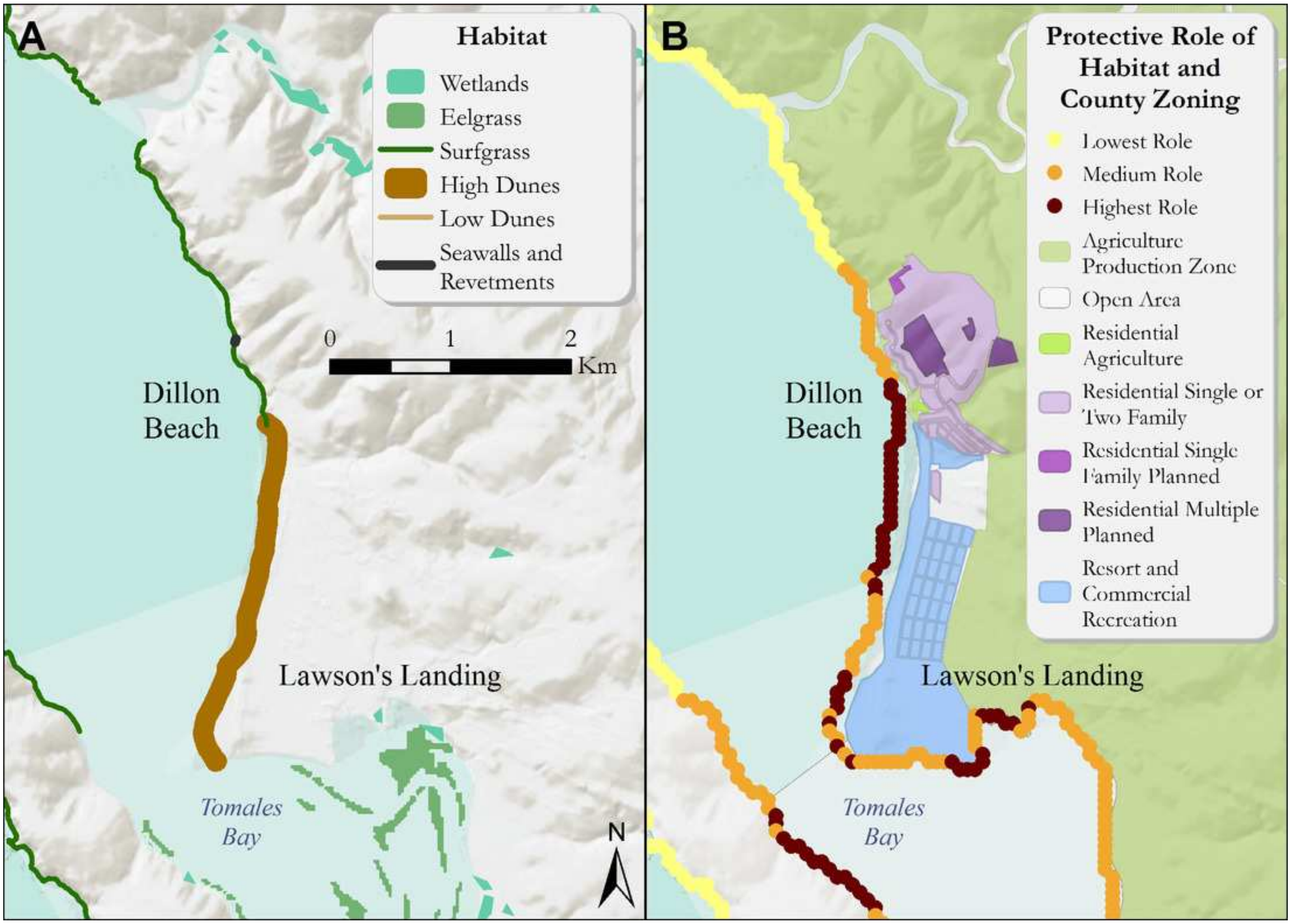

A
Habitat
Wetlands
Eelgrass
Surfgrass
High Dunes
Low Dunes
Seawalls and Revetments
0 1 2 Km
Dillon Beach
Lawson's Landing
Tomales Bay
N
B
Protective Role of Habitat and County Zoning
Lowest Role
Medium Role
Highest Role
Agriculture Production Zone
Open Area
Residential Agriculture
Residential Single or Two Family
Residential Single Family Planned
Residential Multiple Planned
Resort and Commercial Recreation
Dillon Beach
Lawson's Landing
Tomales Bay

Figure 3

Figure 3.

Figure 3. (A) Coastal habitats around Bolinas, Bolinas Lagoon, and Stinson Beach that confer protection from coastal hazards. **(B)** The relative role of coastal habitats around Bolinas and Stinson Beach in reducing exposure to erosion and inundation from storms (darker colors denote a greater role). Relevant land use zoning information is included. Specifically, the mouth of Bolinas Lagoon and the neighborhood behind Stinson Beach receive the greatest relative protection from coastal beach and dune systems. Role of habitats is relative to the entire coast of Marin County.

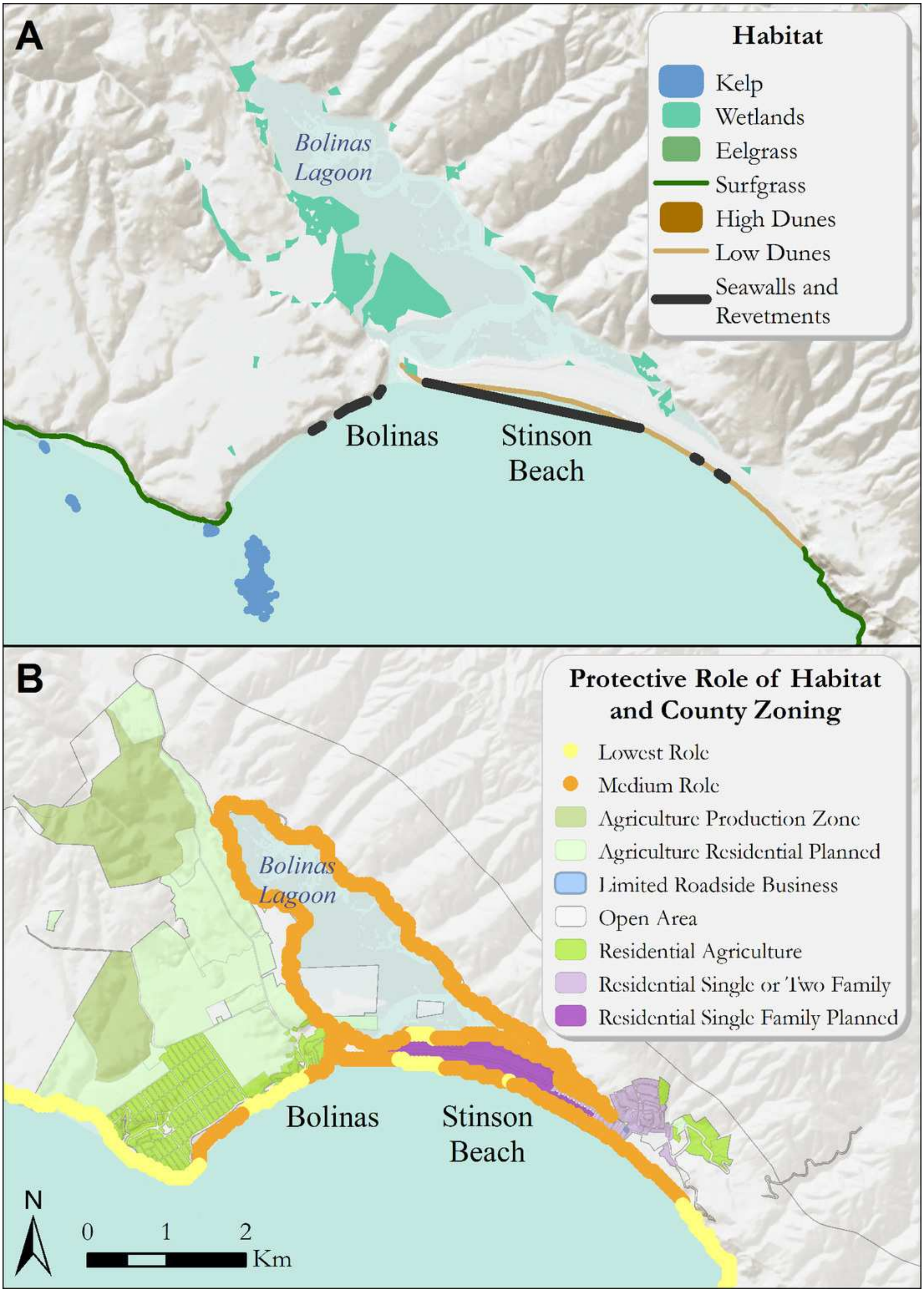
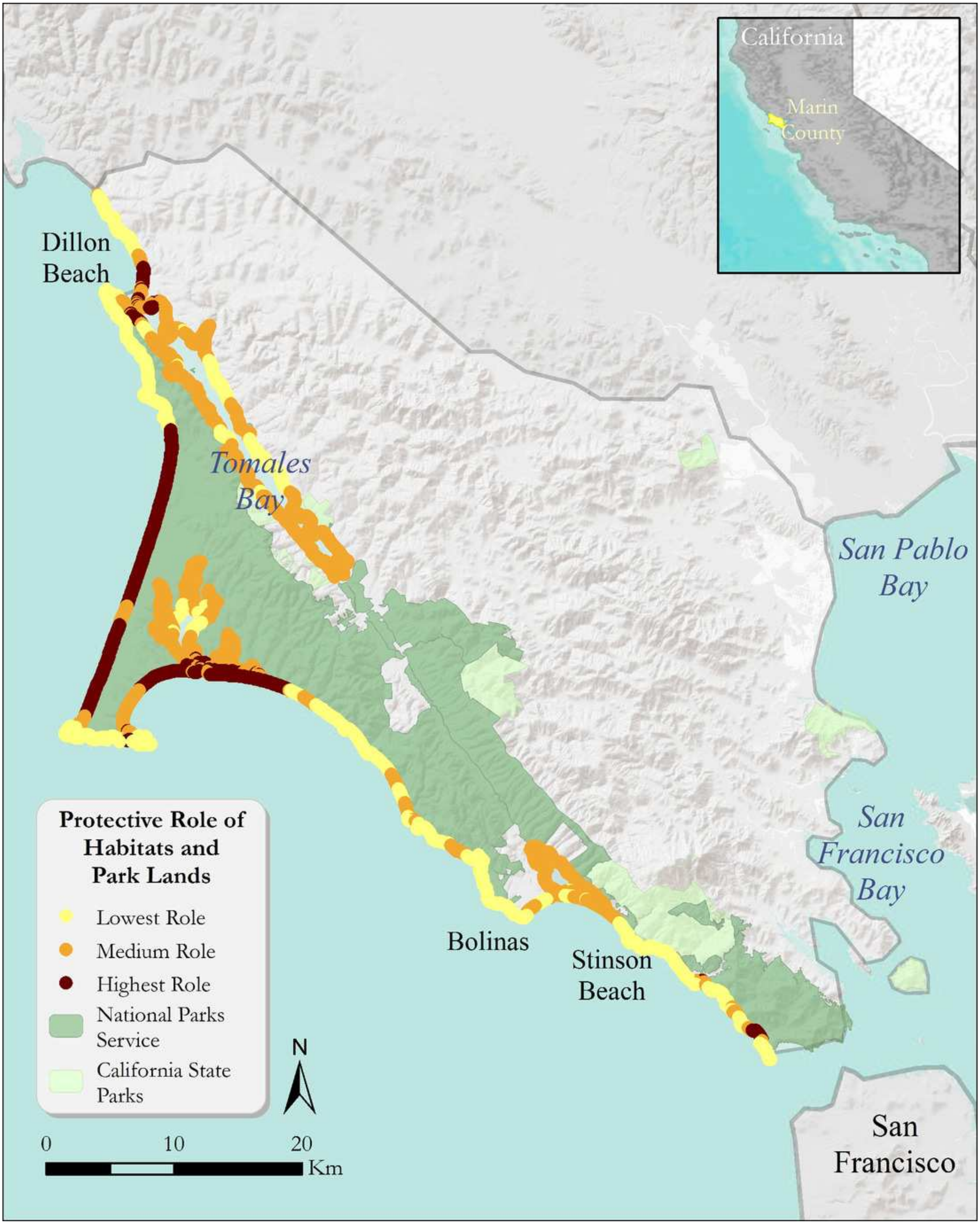

A
Habitat
Kelp
Wetlands
Eelgrass
Surfgrass
High Dunes
Low Dunes
Seawalls and Revetments
Bolinas Lagoon
Bolinas
Stinson Beach
B
Protective Role of Habitat and County Zoning
Lowest Role
Medium Role
Agriculture Production Zone
Agriculture Residential Planned
Limited Roadside Business
Open Area
Residential Agriculture
Residential Single or Two Family
Residential Single Family Planned
Bolinas Lagoon
Bolinas
Stinson Beach
N
0 1 2
Km

Figure 4

Figure 4.

The relative role of coastal habitats in Marin County in reducing exposure to erosion and inundation from storms (darker colors denote a greater role). Relevant State and National Park Lands are included.


California
Marin
County
Dillon
Beach
Tomales
Bay
San Pablo
Bay
San
Francisco
Bay
Bolinas
Stinson
Beach
San
Francisco
Protective Role of
Habitats and
Park Lands
Lowest Role
Medium Role
Highest Role
National Parks
Service
California State
Parks
N
0
10
20
Km