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Key lessons for incorporating natural infrastructure into regional climate adaptation planning

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ABSTRACT

Sea-level rise, potential changes in the intensity and frequency of storms, and consequent shoreline erosion and flooding will have increasing impacts on the economy and culture of coastal regions. A growing body of evidence suggests that coastal ecosystems—natural infrastructure—can play an important role in reducing the vulnerability of people and property to these impacts. To effectively inform climate adaptation planning, experts often struggle to develop relevant local and regional information at a scale that is appropriate for decision-making. In addition, institutional capacity and resource constraints often limit planners' ability to incorporate innovative, scientifically based approaches into planning. In this paper, we detail our collaborative process in two coastal California counties to account for the role of natural infrastructure in climate adaptation planning. We used an interdisciplinary team of scientists, economists, engineers, and law and policy experts and planners, and an iterative engagement process to (1) identify natural infrastructure that is geographically relevant to local jurisdictional planning units, (2) refine data and models to reflect regional processes, and (3) develop metrics likely to resonate within the local decision contexts. Using an open source decision-support tool, we demonstrated that protecting existing natural infrastructure—including coastal dunes and wetlands—could reduce the vulnerability of water resource-related structures, coastal populations, and farmland most exposed to coastal flooding and erosion. This information formed part of the rationale for priority climate adaptation projects the county governments are now pursuing. Our collaborative and iterative approach, as well as replicable use of an open source decision-support tool, facilitated inclusion of relevant natural infrastructure information into regional climate adaptation planning processes and products. This approach can be applied in diverse coastal climate adaptation planning contexts to locate and characterize the degree to which specific natural habitats can reduce vulnerability to sea-level rise and storms.

1. Introduction

Sea-level rise and extreme storm events will have significant consequences for the economy and culture of coastal regions through gradual inundation, and increased frequency of flooding and rates of erosion (Heberger et al., 2009; Griggs and Haddad, 2011; National Research Council, 2012). Sea-level rise also could lead to loss of coastal wetlands, dunes, and beaches, particularly if the shoreward migration of these natural habitats is blocked by development (Griggs, 2005; Kraus and Mcdougal, 2013; Berry et al., 2013). Prevailing responses to the risk of coastal flooding and erosion are engineered approaches (hereafter referred to as 'built'

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infrastructure such as levees and seawalls, in contrast to 'natural' infrastructure such as dunes and coastal wetland). However, seawalls can be costly; in California capital costs for new seawalls average approximately $7 000 per linear foot and yearly maintenance costs average approximately 3% of construction costs (Heberger et al., 2009; King et al., 2010; ESA PWA et al., 2012). Further, built infrastructure may only address one part of a multidimensional problem. For example, built infrastructure designed to prevent future inundation may have indirect effects, such as loss of recreational beaches or fish nursery habitat due to seawall construction, and ultimately fail to address the long-term needs of human communities (Caldwell and Segall, 2007; Turner et al., 2010; Adger et al., 2011).

Natural infrastructure can play an important role in mitigating risks to coastal communities from climate change impacts. These habitats can protect communities from erosion and flooding by dissipating wave energy and stabilizing the shoreline (Millennium Ecosystem Assessment, 2005; Barbier et al., 2008; Everard et al., 2010; Gedan et al., 2010; Shepard et al., 2011; Pinsky et al., 2013) and in some cases can do so cost-effectively in comparison to built infrastructure approaches (ECA, 2009; Jones et al., 2012; Lowe et al., 2013; Lowe et al. (2013) estimated marsh restoration costs in the San Francisco Bay in California at approximately $10 000/acre). Unlike built infrastructure, natural infrastructure has the capacity to migrate upslope as sea level changes and even slow the relative rate of sea-level rise by accumulating sediments that allow the coastline to keep pace with rising waters (Reed, 1995; McKee et al., 2007; Kirwan and Temmerman, 2009; Gedan et al., 2010). In addition to coastal protection, natural infrastructure can provide multiple benefits to many different sectors of the community, including provision of fishery habitat, water quality regulation, and recreation values (Zedler and Kercher, 2005; Barbier et al., 2008; Everard et al., 2010).

A critical challenge lies in introducing feasible natural infrastructure strategies to decision-makers and planners at the regional and local scale. To include natural infrastructure in coastal planning, decision-makers seek to understand where and when habitats (alone, or in combination with built infrastructure) can provide adequate coastal flooding and erosion risk reduction. Scientists and other disciplinary experts can provide practical guidance and evidence to support planners and decision-makers in selecting this relatively under-utilized approach to climate preparedness, particularly where built infrastructure approaches might be more familiar and override other less-familiar options (Hart et al., 2012). Here we report on the engagement process and outcomes from a unique collaboration between an interdisciplinary academic team and county-level planners in California. This collaboration was designed to overcome the challenges associated with co-production of practical and transferable information for integrating natural infrastructure into regional climate adaptation planning in coastal California.

California is an ideal state in which to explore the role of natural infrastructure in climate adaptation planning because a) the effects of climate change, including sea-level rise, are already apparent (Caldwell et al., 2013); b) the existing policy framework—including the California Climate Change Adaptation Planning Guide (CNRA, 2012) and Integrated Regional Water Management plan requirements (CDWR 2011)—encourages adaptation planning; c) intact natural habitats still provide coastal protection from sea-level rise and storms as well as provide co-benefits such as improved fisheries habitat and recreational opportunities; and d) existing laws expressly protect these coastal habitats (California Coastal Act, 1976; California Endangered Species Act, 1984; Caldwell and Segall, 2007; Farber, 2008; Eichenberg et al., 2010; Peloso and Caldwell, 2011). However, it remains difficult to translate scientific information in a way that enables integration of natural infrastructure into climate adaptation plans for several reasons. First, these approaches are new and relatively untested compared to the more established practices that rely solely on built infrastructure (Hart et al., 2012; Rayner, 2005). Second, even with new knowledge and tools that help assess climate risk and potential contribution of natural infrastructure to coastal protection (Everard et al., 2010; Shepard et al., 2011; Pinsky et al., 2013; Jones et al., 2012; Arkema et al., 2013), there is a gap in how to translate and apply this information in practice at the regional and local level to real decision contexts.

Cash et al. (2003) proposed a framework for improving the effectiveness of translating scientific information into action that includes three key attributes that can be applied to the climate adaptation context: saliency, credibility, and legitimacy (Moser and Ekstrom, 2010; Lemos et al., 2012). Saliency refers to the responsiveness of the information to the policy context. Credibility refers to the perceived quality and validity of the information. Legitimacy refers to the perceived fairness of the process of producing the information (Cash et al., 2003). These three attributes are more likely present if there is iterative communication between scientists and planners that facilitates information flow and understanding (Cash et al., 2003). In addition, joint production of information using "boundary objects"— an interface that translates between the scientific and planning languages including decision-support tools or collaborative products such as maps, models or reports (Guston 2001; Clark et al., 2010)—can increase the presence of these three attributes. This interface increases saliency of the scientific information by engaging end-users early in the process, the credibility by incorporating multiple types of expertise in the process, and the legitimacy by providing increased access to the information production process (Cash et al., 2003; White et al., 2010; Guston, 2001).

We developed an interdisciplinary collaboration between planners and academic scientists, economists, engineers, spatial analysts, and law and policy experts focused on producing management-relevant science that can serve as evidence and guidance for translating and applying natural infrastructure approaches in integrated watershed planning conducted in the state of California. Our unique team used an iterative communication approach to facilitate translation of scientific information. We also used an open source decision-support tool as a "boundary object" to facilitate communication across groups, communicate scientific information using management-relevant metrics and scales, visualize analyses and outputs, and clarify goals in a format that is relevant to climate adaptation planning needs (Cash et al., 2003; White et al., 2010; Ekstrom et al., 2011). Utilizing a free, open-source tool also maximizes the replicability and transferability of our approach, allowing others to use the approach and tool tailored to local conditions, using local data, and embedded within local decision-making.

In this paper, we first provide background on the integrated water management planning process in California and regionally specific information on the Monterey Bay area, including habitats that provide coastal protection services and regional and state policy context. We then describe our collaborative approach to co-producing regionally relevant information on where protection of natural infrastructure could reduce vulnerability of people, farmland, and water-resources related structures in the Monterey Bay area and how that information is used in an integrated watershed planning context.

2. Integrated Regional Water Management planning in California

In 2002, the State of California implemented an Integrated Regional Water Management (IRWM) planning process to encourage local, stakeholder-driven collaborative approaches to solving water resources challenges. A key driving force to encourage IRWM planning was the availability of funding for planning and implementation of integrated regional water management (CDWR, 2012). The IRWM planning process encourages fragmented jurisdictions and institutions to work together to reduce conflict and establish more sustainable water management (Lubell and Lippert, 2011), including a focus on a multi-benefit approach. In California, IRWM plans follow specific guidelines (CDWR, 2012) to outline collaborative strategies for water management. IRWM plans are required to include a prioritization scheme for projects submitted to the state for funding (CDWR, 2012).

In response to observed and potential future effects of climate change, the California Department of Water Resources revised IRWM Guidelines in 2010 to require a chapter in water management plans addressing adaptation and mitigation responses to climate change (CDWR, 2011). A guidance handbook developed by the Department of Water Resources outlines four steps for completing a climate change adaptation analysis: 1) assess vulnerability; 2) measure impacts; 3) develop and evaluate strategies; and 4) implement under uncertainty (CDWR, 2011). The state's multi-benefit approach, emphasis on sustainable water management, and requirements for a climate change vulnerability analysis provide opportunities for including natural infrastructure approaches to climate adaptation. Our case study focused on two IRWM planning regions, Greater Monterey County (Monterey) and Santa Cruz, both located in the Monterey Bay area in California (Fig. 1).

3. Introduction to the Monterey Bay Area case study

Coastal natural habitats within the Monterey and Santa Cruz IRWM regions include coastal dunes, kelp forests, and wetlands (Fig. 2). These habitats provide many ecosystem services relevant to regional water management such as water quality improvement, groundwater recharge, fish nursery habitat, and erosion and flood

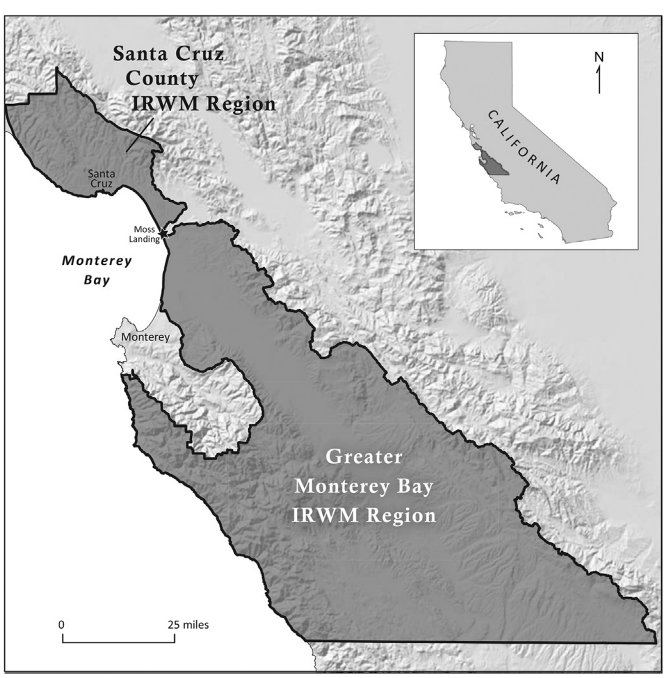

Fig. 1. Santa Cruz and Greater Monterey County Integrated Regional Water Management planning regions. Bold lines outline the two different regions.

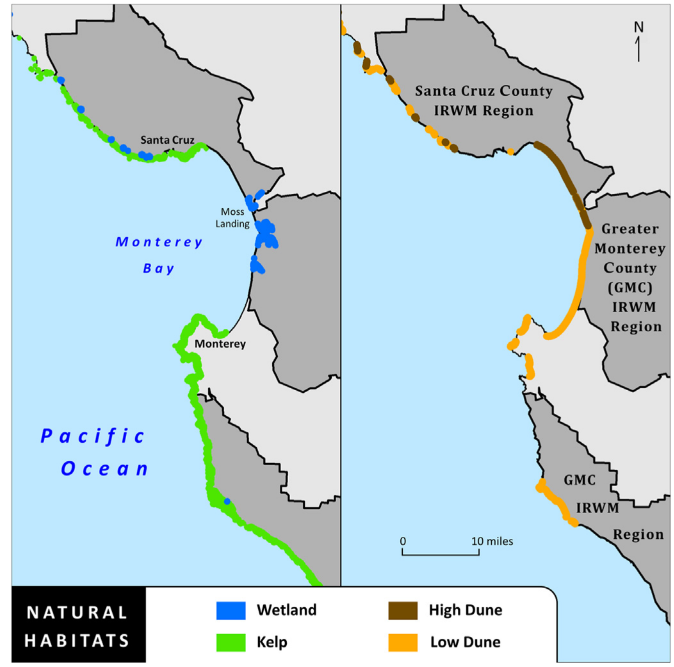

Fig. 2. Distribution of the coastal habitats used in the coastal vulnerability analysis in the Santa Cruz and Greater Monterey County IRWM planning regions. (Kelp was not included in the Santa Cruz vulnerability analysis – see text).

protection (Zedler and Kercher, 2005; Barbier et al., 2008; Defeo et al., 2009; Pinsky et al., 2013). These natural habitats also provide opportunities for recreation and tourism (Zedler and Kercher, 2005; Defeo et al., 2009), both of which are among the top three employment sectors in the Monterey and Santa Cruz IRWM regions (CA EDD, 2010).

Sea-level rise could lead to loss of these habitats and the services they provide (Zedler and Kercher, 2005; King et al., 2010), particularly if development or built infrastructure blocks their migration upslope. Currently approximately 11% of California's coast is blocked from upslope migration by seawalls and revetments (Griggs, 2005). King et al. (2010) found that sea-level rise on California beaches backed by coastal armoring could result in the loss of 90% of existing beach area and $80 million in state and local recreation spending. In Santa Cruz County, Heberger et al. (2009) found that 17% of wetland habitat will be unable to migrate with sea-level rise due to existing development. They also found that while approximately 43% of wetlands not blocked by development may be able to migrate into land currently used as farmland and parks if the land is suitable for wetlands, loss of the farmland and parks would lead to economic losses for the region (Heberger et al., 2009).

The Monterey Bay region is addressing these concerns with several planning and climate initiatives through state and local governments, guided by legislation and policy guidance documents (Executive Order S-13-08, 2008, CDNR, 2009; CO CAT, 2010; Abeles et al., 2011; Atchison, 2011; CDWR, 2011; CNRA, 2012; ESA PWA et al., 2012). Below we outline how our collaborative work supports and furthers these efforts and provide information on where natural infrastructure adaptation strategies are being incorporated into planning in this region.

4. Incorporating natural infrastructure into regional vulnerability analysis

We used an approach similar to the analysis conducted by Arkema et al. (2013) which assessed vulnerability of coastal communities to erosion and flooding at a national scale, and the value of natural habitats in protecting coastal regions from these hazards. Arkema et al. (2013) used the coastal vulnerability model in the InVEST (Integrated Valuation of Environmental Services and Tradeoffs) decision-support tool (Kareiva et al., 2011; Tallis et al., 2013; Arkema et al., 2013) to analyze physical vulnerability of coastal regions of the United States at a 1-km scale and examine how sea-level rise scenarios and removal of coastal protective habitats affected people and property (Arkema et al., 2013). This vulnerability model is similar in concept to the United States Geological Survey's qualitative Coastal Vulnerability Index (Thieler and Hammar-Klose, 2000), but the InVEST model also includes the documented role of natural habitats in reducing exposure of the coast to erosion and flooding and resultant changes in vulnerability of people and development (Arkema et al., 2013; Tallis et al., 2013).

We produced and integrated salient and credible information to estimate coastal vulnerability for the Monterey Bay region following the Arkema et al. (2013) analysis. The county planners helped define the appropriate scale, data, metrics, and visualization most useful for regional planning. Fig. 3 illustrates the components and iterative approach of the regional vulnerability analysis.

4.1. Coastal vulnerability model

The coastal vulnerability model in InVEST (Arkema et al., 2013; Tallis et al., 2013) is based on seven physical and biological characteristics of the region—geomorphology, natural habitats, relief, wave exposure, wind exposure, surge potential, and sea-level change—each ranked for its potential to increase or decrease exposure to erosion and flooding from ocean storms or sea-level rise (Fig. 4). To produce an overall hazard index of exposure to erosion and flooding, the coastline is divided into segments (of user-defined size) and, using input datasets for each of the biological and physical variables (Appendix A), the model generates absolute values for each of the variables (e.g., distance to shelf, average elevation in meters, wave power) for each coastal segment. The model then ranks each segment of coastline for each variable from very low exposure (Rank = 1) to very high exposure (Rank = 5) to erosion and flooding (Fig. 4). Ranks for geomorphology and habitats are absolute and depend on categorical variables. Ranks for the other five variables are relative and depend on the distribution of values for all coastline segments (Fig. 4). The model then estimates exposure to coastal hazards for each shoreline segment using a vulnerability index comprised of rank exposure values for each of the seven variables.[1]

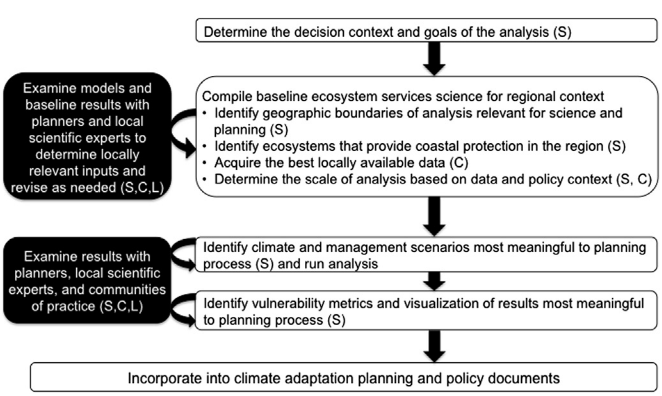

Fig. 3. Conceptual diagram outlining a regional approach for assessing vulnerability to coastal hazards that includes the ability of natural infrastructure to reduce vulnerability of people and development. Letters next to each action symbolize where saliency (S), credibility (C), and legitimacy (L) are enhanced within the process (Cash et al., 2003).

Exposure to Erosion and Flooding

Rank Variable	Very Low 1	Low 2	Moderate 3	High 4	Very High 5
Geomorphology	Rocky high cliff, **Cement armoring**	Medium cliff, Indented coast, **Wood armoring**	Low cliff, Alluvial plain	Cobble beach, Estuary, Lagoon, Bluff	Barrier beach, Sand beach
Natural Habitats		**High dune, Coastal wetland**	**Low dune**	**Kelp**	**No habitat**
Relief	1st Quantile	2nd Quantile	3rd Quantile	4th Quantile	5th Quantile
Wave Exposure	1st Quantile	2nd Quantile	3rd Quantile	4th Quantile	5th Quantile
Wind Exposure	1st Quantile	2nd Quantile	3rd Quantile	4th Quantile	5th Quantile
Surge Potential	1st Quantile	2nd Quantile	3rd Quantile	4th Quantile	5th Quantile
Sea Level Change	**Baseline**		**Moderate**		**Highest**
Long-term Erosion Rate	**Top 50% Accretion**	**Lower 50% Accretion**	**Null**	**Lower 50% Erosion**	**Top 50% Erosion**

Fig. 4. List of biophysical variables and ranking system for exposure to erosion and flooding used in the Santa Cruz and Greater Monterey County IRWM planning regions. Bold variables are those that were revised from the US-wide analysis by Arkema et al. (2013) for our regional analysis.

4.2. Determining baseline exposure to erosion and flooding

As first steps in the regional vulnerability analysis our interdisciplinary team identified the key decisions to be informed, and relevant goals, timelines, and published guidelines (CDWR, 2011; CDWR, 2012). Initial scientific analyses calculated the level of shoreline protection that existing habitats provide based on their current distribution. The interdisciplinary team then used these baseline results to facilitate discussions with planners to refine model inputs for more specific scales, habitats, and data of interest. For example, in one early analysis, we used the entire Monterey Bay region to present the initial results to the planners and used these introductory discussions to ensure the analysis matched the specific boundaries of the Santa Cruz and Monterey IRWM planning regions. This iterative process enabled our interdisciplinary team to shift the focus of our analysis to match the criteria and policy language of the specific decision context and helped identify more refined regional data for our analysis.

We made several key modifications from the national scale analysis in Arkema et al. (2013) to make the analysis regionally relevant for IRWM planning based on iterative engagement between our interdisciplinary team and planners, as well as input from local experts. The coastal vulnerability model and the other models in the InVEST "toolbox" are open source and flexible and therefore can be modified to reflect local processes that may affect exposure to erosion and flooding. For example, the coastal vulnerability model is flexible in which habitats are included as candidates for coastal protection services. The Monterey analysis included kelp beds due to their documented ability to attenuate waves (Arkema et al., 2013; Pinsky et al., 2013). However, we removed giant kelp beds from the Santa Cruz analysis after extensive discussions with local experts because the specific type of kelp and the forcing conditions in this region were determined unlikely to affect long period wave attenuation in comparison to other regions. We also worked with local experts to determine that long-term erosion rates were an important determinant of coastal hazards in the region (Hapke et al., 2006). We therefore included long-term erosion rates provided by local coastal

[1] Vulnerability Index $= \sqrt{\frac{R_{Habitats} R_{Geomorphology} R_{Relif} R_{SLR} R_{wind} R_{Waves} R_{Surge\ Potential}}{7}}$, where R is rank, and subscripts for each rank indicate one of the seven variables. This is a version of the equation used in Arkema et al. (2013) which produces the same results but on a different scale.

engineering experts as another variable in the model by ranking erosion rates relative to the distribution across all segments (ESA PWA, 2014, Fig. 4; Appendix A). In addition, this region has relatively high-quality information on armoring, so we used a two-step process to account for those segments of shoreline where our data included human-made armoring structures (e.g., seawalls, riprap, revetments). First, we categorized structures as either concrete or wood. We then assigned a rank of 1 (lowest risk) to shoreline segments backed by concrete structures and a rank of 2 to those backed by wood structures. A final difference from the Arkema et al. (2013) analysis is that we analyzed the vulnerability of the two counties' coastlines at a finer scale resolution (50-m^2) to better reflect the data available in this region of California and to enhance the utility of the model outputs for local decision-making.

4.3. Identifying scenarios

In order to help characterize the protective role that natural habitats play in reducing exposure to erosion and flooding from sea-level rise and ocean storms, we conducted our analysis with the locally relevant input data described above with the habitats "present" (with their associated ranking) and again with the habitats "removed," setting all habitat segments to the lowest rank (5) (Fig. 4). We assumed that habitats "present" in these scenarios persisted. We compared these two scenarios, with and without habitats, to highlight areas where habitats are providing critical defense against coastal erosion and flooding. We used sea-level rise scenarios in consultation with the planners and in accordance with state climate change guidance (CDWR, 2011; CO-CAT, 2010). We explored the different sea-level rise projections in the Guidance (for example: year 2000 baseline sea levels; 0.4 m sea-level rise by 2050; and 1.4 m sea-level rise by 2100 (CO-CAT, 2010) by reflecting these three projections in the sea-level rise parameter of the vulnerability model as baseline (rank = 1), moderate (rank = 3) and high (rank = 5) respectively. In all, we explored six scenarios: the presence and absence of habitat for each of three sea-level rise projections (baseline, moderate, high).

Although there are several climate variables that may affect the ability of coastal and marine habitats to reduce risks from coastal flooding and erosion in California, our analysis focused on the direct effects of sea-level rise on the risk of coastal communities to erosion and flooding. On the California coast, sea-level rise is the most certain consequence of climate change and thus an important factor to include in our analysis. However, sea-level rise, ocean acidification, and changes to temperature and precipitation also are likely to affect the distribution and abundance of coastal and marine ecosystems (Fabry et al., 2008; National Research Council, 2012; Koch et al., 2013), thus affecting their ability to defend coastlines. The model does not predict migration or loss of habitat under the different sea-level rise scenarios, nor does it predict long- or short-term changes in shoreline position or configuration. Further work is needed to understand which habitats may be able (or unable) to adapt to change associated with several climate variables and how that is likely to affect nature-based climate adaptation planning.

4.4. Identifying and analyzing metrics

We determined the vulnerability metrics to use in our analysis through frequent discussions between the interdisciplinary team and planners and by referencing key guidance documents and previous plans (CDWR, 2011; 2nd Nature, 2013). Metrics included locations of water-resource related structures (e.g., water treatment facilities, sewer lines; data of locations only available for Santa Cruz IRWM region), agricultural land, and disadvantaged families, here defined as people below the poverty line from the 2010 U.S. Census data (Appendix A).

We analyzed the relationship between these metrics and the exposure of the coast to erosion and flooding using an approach similar to the analysis conducted by Arkema et al. (2013). First, we classified the 50-m^2 segments of coastline as highest, medium high, medium low or lowest vulnerability based on quartiles of the full distribution of vulnerability index values (across all coastline segments for all six scenarios). Then, we assessed the number of water-resource related structures (pumps, treatment plants, wells) within 1 km of the 50-m^2 segments of the coast with the highest exposure (top quartile of the vulnerability index values) to erosion and flooding for the Santa Cruz IRWM region. To assess the vulnerability of pipes we selected only the 50-m^2 segments with the highest exposure (top quartile) and determined the number of these segments within 1 km of pipes. To assess the vulnerability of farmland to coastal erosion and flooding, we selected the coastal segments with the highest exposure (top quartile) and determined the number of segments within 1 km distance of farmland. Finally, to assess the vulnerability of people and disadvantaged families to coastal erosion and flooding, we analyzed the average number of people and disadvantaged families associated with each 50-m^2 segment with the highest exposure (top quartile) within a 1 km distance of the coast (Arkema et al., 2013).

5. Vulnerability analysis for the Santa Cruz and Monterey IRWM regions

In this section we report on the results of the vulnerability analyses for the Monterey and Santa Cruz IRWM regions and discuss the challenges and successes of incorporating this information into climate adaptation decisions.

5.1. Coastal vulnerability results for the Greater Monterey County IRWM region

Nearly a tenth of the Monterey coastline is highly exposed (top quartile of the vulnerability index values) to coastal hazards, putting in harms way approximately 15% of the people and 10% of disadvantaged families on the Monterey coastline to flooding and erosion. The area of coastline most exposed to hazards will increase by more than 25% with the highest rise in sea level even with current habitats intact. This rise in sea level will also increase vulnerability of agricultural land, coastal populations, and disadvantaged families (Fig. 5).

Loss of coastal dunes, wetlands, and kelp forests would increase the exposure to erosion and flooding of more than three quarters of the Monterey County coastline (Fig. 2). In particular, without coastal habitats, the area of coastline with the highest exposure to hazards would increase by approximately 10%, putting at high risk an additional 25% of the people and disadvantaged families (Fig. 5). Rising seas exacerbate the problem of habitat loss, such that under the highest sea-level rise scenario with habitat loss over half of the disadvantaged families will be highly vulnerable to coastal hazards and the area of farmland most exposed to erosion and flooding will increase by more than 10% (Fig. 5). Loss of habitat has the biggest impact on vulnerability in the central-southern Monterey Bay coast stretching between the towns of Moss Landing to Monterey, where coastal dunes protect people and farmland from erosion and flooding. In this area, sand mining is accelerating erosion rates and reducing the resiliency of natural dune infrastructure (Thornton, 2006; ESA PWA, 2012).

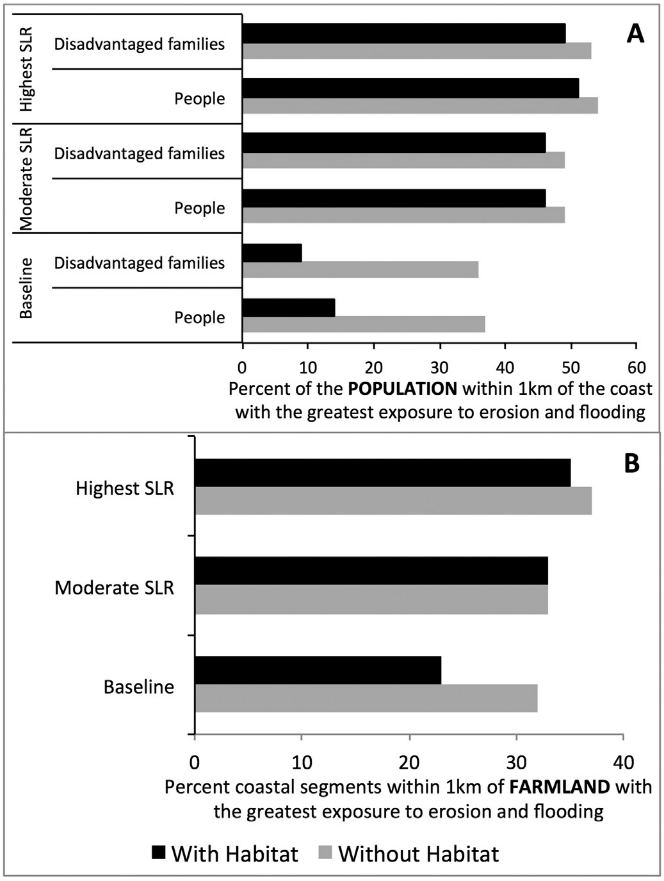

Fig. 5. Greater Monterey County IRWM Region. A) Percent of the population (people) and disadvantaged families (here defined as people below the poverty line from the 2010 U.S. Census data) within 1 km of the highest vulnerability coastal segments; and B) Percent highest vulnerability coastal segments within 1 km of farmland with habitats present (black bars) and habitats removed (gray bars) at baseline, moderate and highest sea-level rise.

5.2. Coastal vulnerability results for the Santa Cruz IRWM region

With the highest rise in sea level almost half of the Santa Cruz coastline is highly exposed (top quartile of the vulnerability index values) to coastal hazards, increasing the vulnerability of people and disadvantaged families most exposed to coastal flooding and erosion by approximately one-third (Fig. 6). This rise in sea level will also increase vulnerability of water-resource related structures and farmland (Fig. 6).

Coastal dunes and wetlands protect over 60% of the Santa Cruz IRWM region coastline (Fig. 2). Loss of these natural habitats increases the water-resource related structures most exposed to erosion and flooding by as much as 10% (Fig. 6). At the highest sea level and with loss of existing habitats there is a 50% increase in farmland most vulnerable to flooding and erosion and an increase in vulnerability of water-resource related structures by approximately 75% (Fig. 6).

6. Using vulnerability analysis results in climate change adaptation planning

Planners used results from our vulnerability analysis to inform the climate adaptation planning process for integrated regional water management in Monterey and Santa Cruz IRWM regions. In Monterey, the vulnerability analysis was included as part of the climate guidance in the final IRWM plan. The information in these

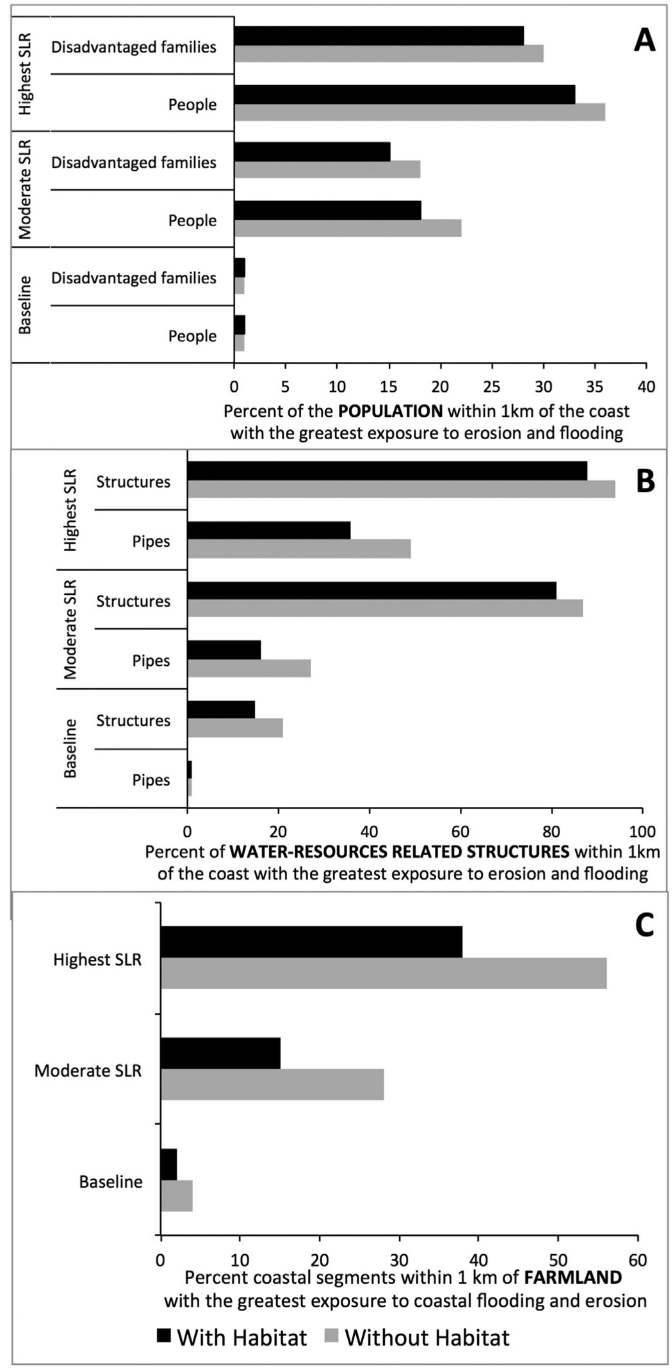

Fig. 6. Santa Cruz County IRWM Region. A) percent of the population (people) and disadvantaged families (here defined as people below the poverty line from the 2010 U.S. Census data) within 1 km of the highest vulnerability coastal segments, B) percent highest vulnerability coastal segments within 1 km of pipe water-resource related infrastructure (pipes) and percent of pump, well, and treatment plant infrastructure (structures) within 1 km of the highest vulnerability coastal segments, and C) percent highest vulnerability coastal segments within 1 km of farmland with habitats present (black bars) and habitats removed (gray bars) at baseline, moderate and highest sea-level rise.

plans helps guide prioritization of water-resources related funding in the regions.

In addition, information about coastal vulnerability and the role of habitats in providing protection to people and infrastructure prompted Monterey planners to submit funding requests to the Regional Water Management Group to: 1) implement coastal dune habitat restoration and protection within the highest vulnerability sections of the coast and 2) conduct a cost-benefit analysis of climate change adaptation strategies, including restoring and protecting natural infrastructure. The climate change adaptation proposal was widely supported by the Monterey County planners (RWMG, 2012) and it has since been funded by the California Coastal Conservancy through a grant program that supports long-term planning for sea-level rise under the Coastal Act.

In Santa Cruz, the IRWM plan is not yet finalized, but information from the analysis is included in the draft plan. In addition, our engagement led to conceptual use of the natural infrastructure information in the planning process (McKenzie et al., in press). Our results highlighted the extent of the Santa Cruz IRWM coastal region that is vulnerable to flooding and erosion under the highest sea-level scenario. Insights from these results informed modifications to the conceptual framework developed by the Santa Cruz IRWM region planners to include strategies that address the multiple benefits associated with natural infrastructure approaches to flood control and sea-level rise (2nd Nature, 2013). The review of these results and maps also led to discussions and preliminary analyses of natural infrastructure restoration and/or enhancement opportunities. We used the maps and outputs from the analysis, historical maps (2nd Nature, 2013) and guidance regarding priorities in the region to identify realistic wetland restoration scenarios that are being considered for inclusion in the Santa Cruz IRWM plan to guide restoration efforts in the region and support multiple benefits.

Our results helped planners prioritize and target the protection or restoration of natural infrastructure to reduce coastal hazards for people, water-related infrastructure, and farmland. However, natural infrastructure may not always be an effective or desirable substitute for built infrastructure or may be most effective in conjunction with built infrastructure (Lowe et al., 2013). More specific quantitative studies that model these shoreline and habitat changes (ESA PWA, 2014), and compare the costs and benefits of specific natural and built infrastructure approaches are necessary to advance from strategic to tactical guidance (McKenzie et al., in press). As mentioned above, we are currently collaborating with local experts using the results from this analysis to guide specific quantitative studies comparing these costs and benefits which would take into account shoreline change and effects of sea-level rise on habitats to provide more tactical guidance.

There are inherent uncertainties in any planning process—and climate adaptation planning is no exception. We addressed some uncertainty in the biophysical realm (driven, in part by uncertainties in social and economic realms) by exploring six sea-level rise and habitat scenarios as explicit recognition of uncertain futures. Although beyond the scope of this study, a more thorough examination of the uncertainty of linked social, economic, and natural systems within a planning process would benefit regional adaptation planning.

7. Producing salient information for regional planning

The iterative process of co-producing regional model results with IRWM planners helped the interdisciplinary team provide analysis, information, and guidance that better matched the IRWM planners' information needs. For example, we discussed possible management and sea-level rise futures with the planners and examined guidance documents to build relevant scenarios. Careful review of guidance documents (CDWR, 2012; CDWR, 2011), consultants' reports (ESA PWA, 2012, 2nd Nature, 2013), and early presentations of model results to the planners and local technical advisory committees (to set expectations and introduce the modeling methodology) led to the collaborative selection of spatial scales and metrics meaningful to the regional and state goals of the plan.

Planners and stakeholders responded to the iterative presentation of interim visual results by volunteering additional local knowledge (including better local data). Interdisciplinary experts and planners also used the interim presentations of results and related discussions with planners and local technical advisory committees to find common language for the scientific outputs, determine the best terminology to present to stakeholders, and increase the usability of the information for practical planning purposes. This process ultimately increased the technical and knowledge capacity of planners while increasing the saliency of the information provided by scientists.

8. Conclusions

Vulnerability assessments that take into account the ways in which natural infrastructure protects communities from sea-level rise and storms are an important step to help communities determine resilient, multi-benefit climate adaptation strategies. However, to produce useful science on where and when natural habitats provide protection and to guide active planning decisions, interdisciplinary experts and planners must co-produce information that is relevant at the regional scale, credible to decision-makers, and sufficiently salient (Cash et al., 2003; Moser and Ekstrom, 2010; Moss and Scarlett, submitted for publication). Our iterative approach to communication using an interdisciplinary team and "boundary object" to facilitate translation of scientific information to the specific decision context led to our work generating products that helped shape the decision space.

Our collaborative work is one of the first regional vulnerability assessments to analyze where natural habitats reduce the vulnerability of water infrastructure and coastal populations to erosion and flooding in coastal California and to use that information to inform public decision-making on climate change adaptation in coastal communities. We find that vulnerability of water-resource related structures and coastal populations increases with sea-level rise, and that the presence of natural habitats reduces vulnerability. However, the protective value of natural habitats is variable along the coast, depending on forcing conditions, habitat type, and distribution of the communities, farmland, and water resources-related infrastructure. Providing maps and data of where natural infrastructure is protecting people and property is an important step in informing the smart use of natural habitats for climate adaptation planning.

California has over 3 400 miles of tidal shoreline that will be impacted by sea-level rise and storms in the future. Protection, restoration, and enhancement of natural habitat to protect coastal regions from these impacts are practical and cost-effective approaches in many regions of California. However, decision-makers and planners need transparent and collaborative tools and approaches at the regional level to support these efforts, particularly in areas of the coast where political limitations or familiarity with built infrastructure approaches may lead to skepticism about the role of natural infrastructure. Our regional approach could be transferred to other coastal decision contexts in California and beyond as these regions decide how to adapt their communities and infrastructure to future sea-level rise.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ocecoaman.2014.03.019.

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