

## ARTICLE OPEN



# Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise

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Globally, rising seas threaten massive numbers of people and significant infrastructure. Adaptation strategies increasingly incorporate nature-based solutions. New science can illuminate where these solutions are appropriate in urban environments and what benefits they provide to people. Together with stakeholders in San Mateo County, California, USA, we co-developed nature-based solutions to support adaptation planning. We created six guiding principles to shape planning, summarized vulnerability to sea-level rise and opportunities for nature-based solutions, created three adaptation scenarios, and compared multiple benefits provided by each scenario. Adaptation scenarios that included investments in nature-based solutions deliver up to eight times the benefits of a traditionally engineered baseline as well as additional habitat for key species. The magnitude and distribution of benefits varied at subregional scales along the coastline. Our results demonstrate practical tools and engagement approaches to assessing the multiple benefits of nature-based solutions in an urban estuary that can be replicated in other regions.

*npj Urban Sustainability* (2022)2:13; <https://doi.org/10.1038/s42949-022-00056-y>

## INTRODUCTION

As the climate warms, cities will continue to experience increases in stressors from sea-level rise<sup>1,2</sup>. Sixty-five percent of the world's megacities are within 100 km and 50 m elevation of the coast<sup>3</sup> and one billion people live less than 10 m above current high tide lines<sup>3</sup>. Despite global forcing, the impacts of sea-level rise are experienced locally, putting local governments on the frontlines of planning and implementing adaptation<sup>4</sup>. Sea-level rise offers local and municipal governments opportunities for proactive planning, though it brings challenges related to prioritizing amongst myriad, immediate concerns<sup>5,6</sup>.

One solution is to draw on approaches that both address sea-level rise and deliver diverse benefits to people, improving the livability of urban regions. Nature-based solutions are 'actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits'<sup>7</sup>. Ecosystem-based adaptation is a form of nature-based solution that specifically refers to the 'use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change'<sup>8,9</sup>. Such nature-based solutions include the use of existing natural systems (e.g., protecting a marsh), managing or restoring those systems (e.g., restoring a marsh), or creating new systems (e.g., combining mud flats, marshes, and concrete levees to create a horizontal levee)<sup>7</sup>. All of these types of nature-based solutions can support coastal resilience and risk reduction by using natural processes and landforms to provide protection for both ecosystems and the built environment<sup>10,11</sup>. They can provide not only protection from sea-level rise and storms<sup>12–14</sup>, but also climate change mitigation through carbon sequestration, opportunities for recreation, habitat for key species, and other

benefits<sup>15–20</sup>. These benefits—ecosystem services or nature's contributions to people—help connect healthy, functioning ecosystems to human wellbeing<sup>21,22</sup>.

Implementing nature-based solutions in urban environments can bring unique challenges. Some stem from biophysical constraints and their interaction with the built environment. For example, in urban environments, space is often at a premium, and coastal habitats are at risk of coastal squeeze, in which there isn't space for them to migrate upslope as sea-level rises<sup>23–25</sup>. Also, sediment supply in urban environments is often dramatically reduced from more natural conditions, starving marshes of sediment, preventing accretion, and thus making it difficult, if not impossible, for them to keep up with sea-level rise<sup>26–28</sup>. Other challenges relate to ownership, governance, regulations, and funding. In urban areas, patchy ownership of real estate along the shoreline complicates coordinated action. Similarly, governmental jurisdictions are often complex and overlapping. Meeting joint objectives requires integration among various levels of government, extensive stakeholder engagement, agreement about the risks faced and feasibility of solutions, and policies that enable desired actions<sup>29</sup>. Regulatory challenges exist too—for example, regulations designed to prevent the filling of wetlands can prevent the 'beneficial use' of sediments for such purposes<sup>30,31</sup>. Finally, coastal adaptation strategies can be expensive; finding the revenue to devote to future challenges can be difficult for already stressed communities<sup>32</sup>.

There are also significant concerns related to environmental justice. The growing interest in nature-based solutions, especially in urban contexts, has sparked critiques calling attention to the unintended consequences associated with green infrastructure projects. These effects are primarily displacement associated with increased property values and other forms of 'eco-

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gentrification<sup>33–39</sup>. Much of this work has focused on the environmental justice implications associated with urban parks and greenspaces<sup>33,34</sup>, tree planting<sup>36</sup>, and stormwater infrastructure<sup>38,40</sup>. Less work has been focused on the social concerns associated with coastal natural infrastructure, but early examples of ‘climate gentrification’ or ‘resilience gentrification’ highlight the potential to disproportionately impact vulnerable communities in climate resilience and adaptation planning<sup>37,38,41</sup>.

All of these challenges are especially pronounced in California’s San Francisco Bay Area. California is amongst the US states most exposed to sea-level rise and the San Francisco Bay Area is particularly at-risk<sup>42</sup>. The Bay Area is also one of the most ethnically and racially diverse regions in the country<sup>43</sup>. Within the Bay Area, San Mateo County (one of nine counties) stands out with over \$39 billion in assets, more than 30,000 residential parcels, and 3000 commercial parcels at risk of exposure to flooding and erosion over the next 50–100 years<sup>44</sup>. Many populations throughout San Mateo are more vulnerable to the effects of sea-level rise because of factors such as age, race, income, housing vulnerability, and pre-existing health conditions<sup>45</sup>. Rising seas and land subsidence have already increased flooding in the Bay Area<sup>44</sup>, making this threat difficult to ignore, especially for socially vulnerable communities.

There is a longstanding history of traditional shoreline engineering in the bay; 6% of the shoreline is behind levees and 75% of the shoreline consists of berms, embankments, transportation infrastructure, or other engineering<sup>46</sup>. More of these projects are planned and some existing hardened shorelines are being raised or rebuilt to address the growing threat of sea-level rise.

Green and hybrid adaptation strategies are also under consideration as design, evaluation of costs and benefits, and community acceptance and awareness of these approaches grows. There is an opportunity now to connect habitat protection and restoration to sea-level rise adaptation planning. At the regional scale, the Bay Area Conservation and Development Commission (BCDC) has recently completed an assessment of the vulnerability of critical assets to sea-level rise<sup>47</sup>. Within San Mateo County, planners are extending their local vulnerability assessment<sup>45</sup> to inform adaptation planning. The County recently created One Shoreline, an agency dedicated to increasing collaboration amongst the county and 20 cities to address inland flooding, sea-level rise, and stormwater<sup>48</sup>.

To accompany political and governance opportunities, new science is necessary to understand where and when nature-based solutions are appropriate and what benefits they can provide. In the Bay Area, as in other regions, targets for the restoration of natural habitats exist<sup>49</sup>, but little guidance is available about where restoration might be suitable from a biophysical perspective and where it might provide the most benefits to people. Also missing are studies that assess the multiple benefits of nature-based solutions in urban environments. The median cost of restoring a hectare of salt marsh is over \$170,000 (2020 US dollars)<sup>50</sup>. Over 300,000 acres have been restored in the US between 2006 and 2015<sup>51</sup>, implying over 50 billion in restoration expenditures in the US alone. Understanding and quantifying the diverse benefits of nature-based solutions remains a critical need for rationalizing these expenditures and sustaining support for such efforts.

Here, we report on the results of a partnership designed to co-develop nature-based solutions for climate adaptation planning in San Mateo County. The partnership included County staff, a regional science institute (San Francisco Estuary Institute, SFEI), and researchers from Stanford University’s Natural Capital Project, as well as numerous government and NGO stakeholders engaged by the County. We started by working with stakeholders to create a set of guiding principles for adaptation efforts and then asked three key questions: (1) how does exposure to sea-level rise vary

along the County’s Bay shore? (2) where are nature-based solutions feasible in this highly urban environment? and (3) what additional benefits (ecosystem services) might be provided through the use of nature-based solutions as compared to more traditional, engineered solutions?

## RESULTS

### Guiding principles, exposure, and suitability

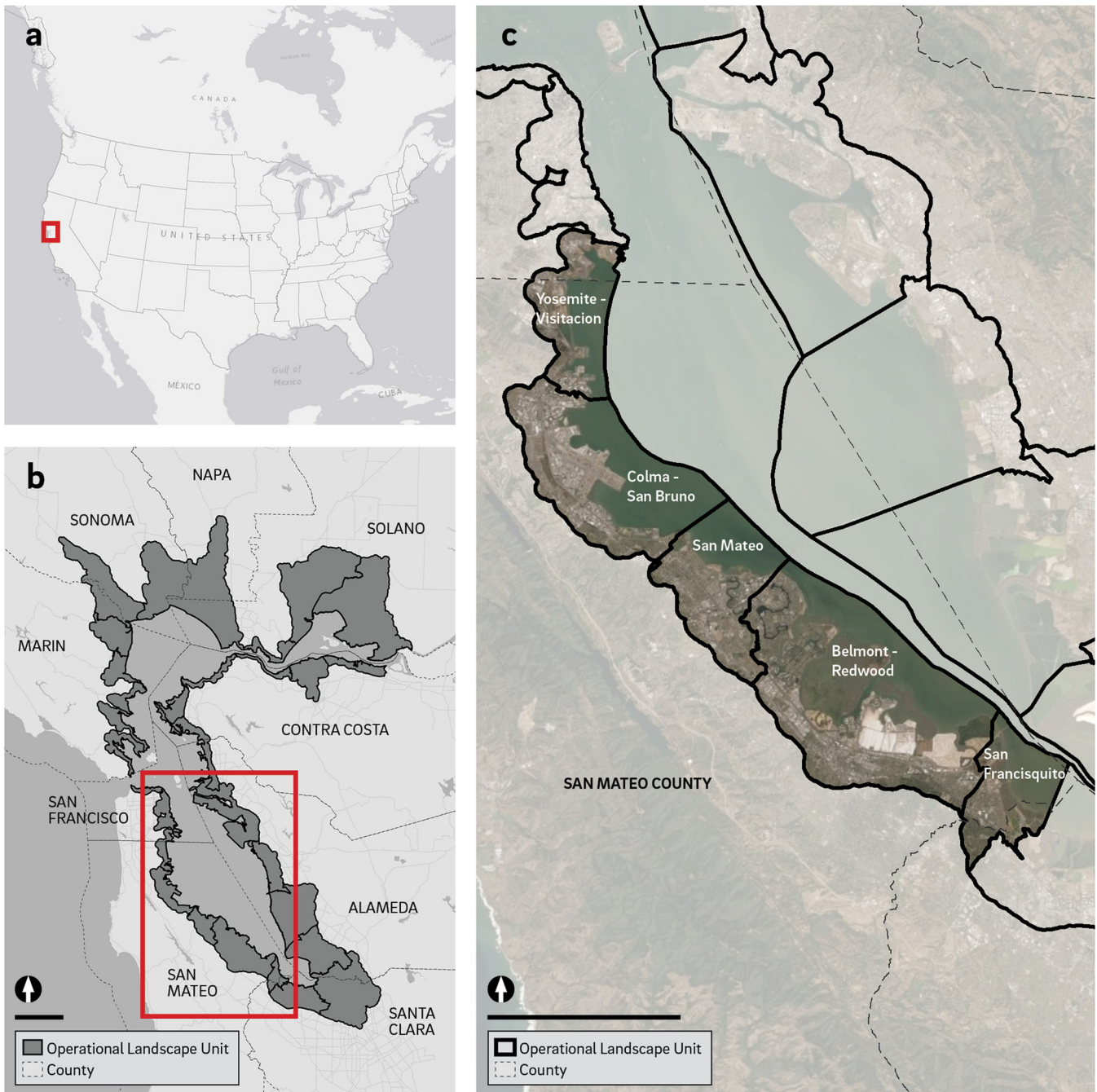
In partnership with stakeholders, we first created six guiding principles to shape the County’s adaptation work (Supplementary Note 1). Here, we focus most on the fifth principle: ‘Prioritize nature-based actions—work to withstand flooding and erosion while retaining the structure, function, and support of natural processes and ecosystem services,’ though all other principles underpin this work.

To help prioritize nature-based solutions, we first summarized exposure to sea-level rise and the biophysical suitability of nature-based solutions throughout the County’s five Operational Landscape Units (OLUs) (Fig. 1). OLU are geographic areas that share certain physical characteristics that influence the production and flow of coastal ecosystem functions, services, and vulnerabilities<sup>24,52</sup>. For exposure, we considered three sea-level rise scenarios: the current sea-level baseline; the baseline plus 1 m sea-level rise; and the baseline plus 2 m sea-level rise, (all plus a 1% annual chance storm) (Fig. 2). Approximately 50% of the area of four OLU will be inundated even under the mid-level scenario; only one OLU is expected to experience <15% inundation under all sea-level rise scenarios (Fig. 2b). Our exposure maps (adapted from the County-scale vulnerability assessment<sup>45</sup> to include OLU) show where communities and infrastructure are vulnerable under different projections of sea-level rise (Fig. 2a, Supplementary Fig. 1).

Next, we used the San Francisco Bay Shoreline Adaptation Atlas<sup>24</sup> to summarize the suitability of the County’s OLU for five types of nature-based adaptation solutions that could help reduce flood exposure (Fig. 3, Supplementary Table 1, Supplementary Table 2). In the Atlas, suitability is determined using biophysical characteristics (e.g., water depth, substrate type, wave climate), historical habitats (e.g., maps from ca 1800), and current shoreline development (e.g., marinas, ports, urban development). Beach restoration, ecotone levees (combinations of marshes and traditional levees<sup>53</sup>), and tidal marsh restoration are suitable in 4/5 OLU; there are opportunities for submerged aquatic vegetation restoration in 3/5 OLU; and nearshore reefs can be incorporated in 2/5 OLU (Fig. 3b). See ‘Methods’ for further narrowing of this biophysical suitability to include more social dimensions as we created scenarios.

### Adaptation scenario creation and assessment

Through engagement with stakeholders brought together by the County (Fig. 4), we co-developed three spatially explicit adaptation scenarios to inform adaptation decisions (Fig. 5). The scenarios incorporate the biophysical context of each reach of shoreline as well as adaptation options suitable for each OLU (Fig. 5). To allow for a comparison of the benefits of different adaptation solutions, we designed each of the three scenarios to deliver equivalent flood protection. Specifically, the levee crest elevations, marsh restoration widths, and other specifications of each adaptation scenario avoids overtopping from a 1% chance of flood and 1 m of sea-level rise. The first scenario (‘What we might have done’) represents what the shoreline could have looked like if decision-makers had armored the entire shoreline over the last several decades. This scenario serves as a reference point. The second scenario (‘What we are doing’) characterizes a future based on existing and planned conservation and restoration activities. In this scenario, we protect existing marshes and restore marshes in

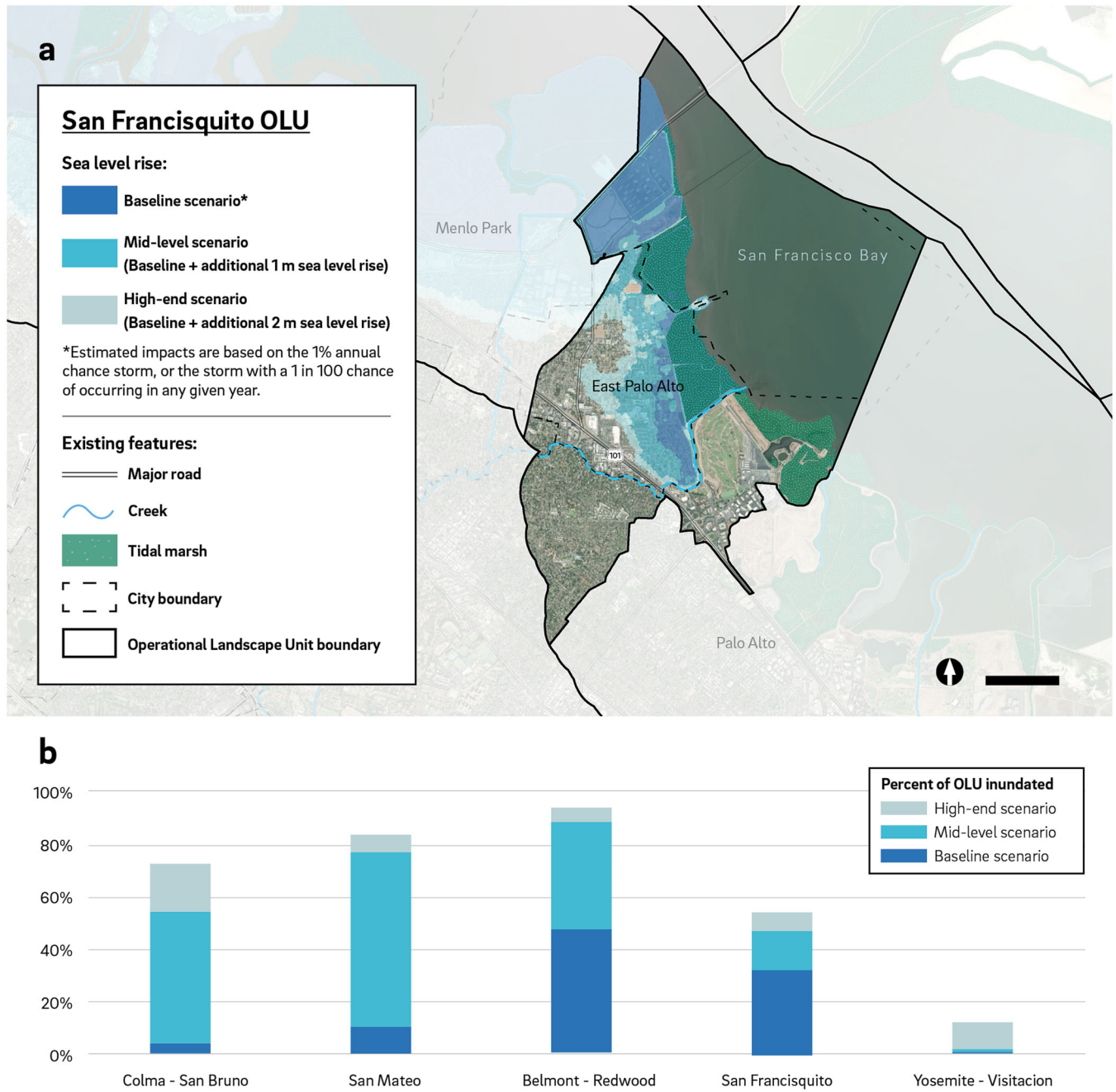


**Fig. 1** Maps of the study area. **a** The San Francisco Bay Area, California, USA, **b** San Mateo County, and **c** the 5 Operational Landscape Units (OLUs) within the County. OLU are connected geographic areas sharing physical characteristics that influence their shared vulnerability and adaptability to sea-level rise. Black scale bars in panels (b) and (c) represent 10 km.

locations where projects are underway or undergoing approval. The final scenario ('What we could do next') builds upon the second, adding additional nature-based features that protect marshes and communities where feasible, according to our suitability maps (Figs. 3, S2). To explore differences in the expected benefits provided to people by the year 2050 for each scenario, we quantified three ecosystem services—stormwater nutrient pollution reduction, recreation, and carbon sequestration—as well as the provision of habitat for a species of special concern.

Adaptation options that include investment in nature-based solutions deliver up to eight times the benefits of an engineered

baseline (Table 1). Our models suggest that a future shoreline with existing and planned restoration projects will feature five times more marsh (which is habitat for, among other things, the endangered Ridgway's Rail (*Rallus obsoletus*)), and deliver five times the carbon sequestration and six times the stormwater pollution reduction of an engineered shoreline. Such a future will also provide an additional 50 ha of beach. A future shoreline that incorporates additional feasible nature-based solutions could provide up to six times the marsh area, eight times the stormwater pollution reduction, and six times the carbon sequestration of an engineered baseline. Furthermore, this scenario provides an additional 170 ha of beach.

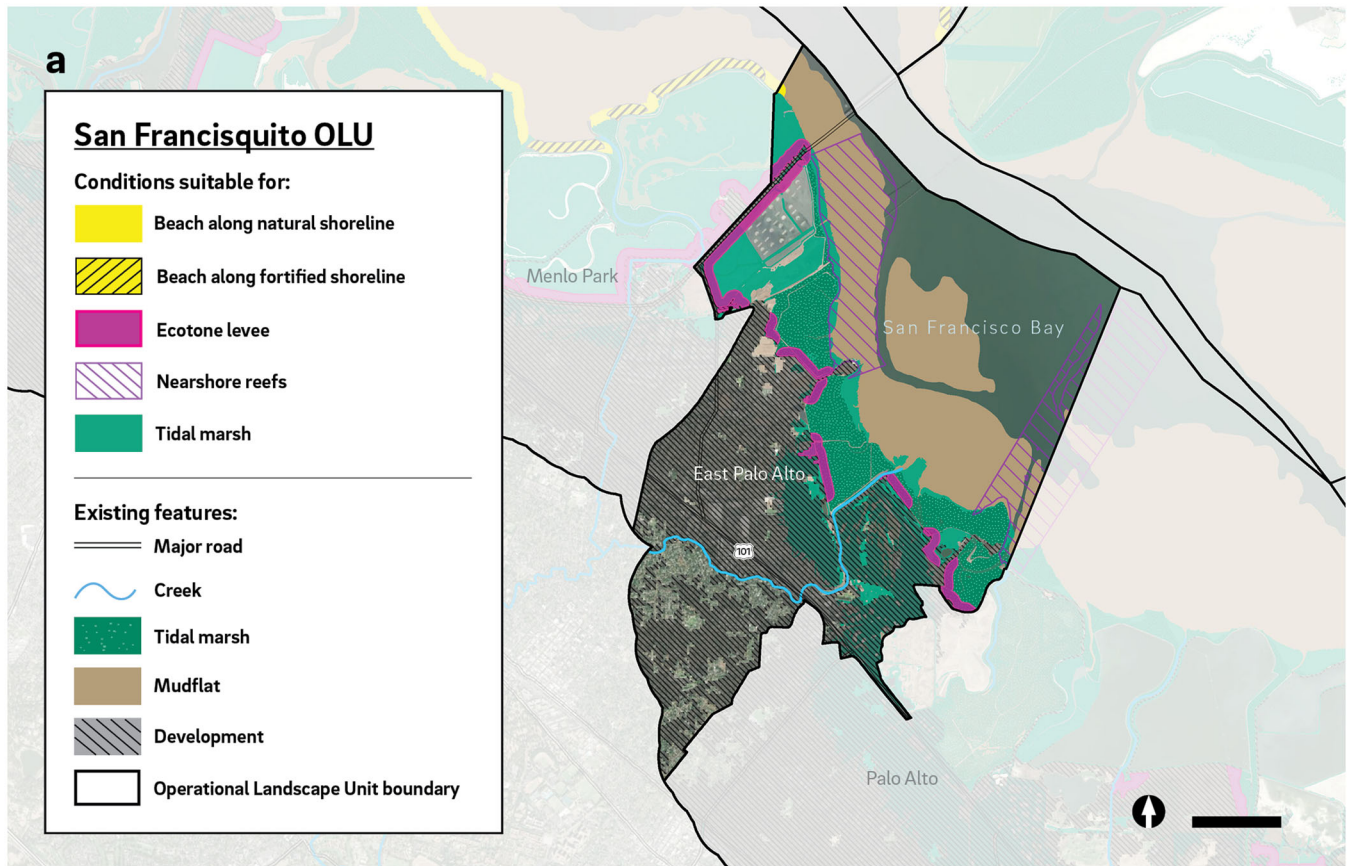


**Fig. 2** **Sea-level rise exposure.** **a** Exposure in the San Francisquito Operational Landscape Unit (OLU) and **b** exposure throughout the County's 5 OLU. San Francisquito is the southernmost OLU in San Mateo County. Darker blues represent expected flooding in the baseline scenario and lighter blues represent flooding in the mid-level and high-end scenarios. Black scale bar in panel (a) represents 1 km.

Summarized across the County, recreation does not differ across the three scenarios (Table 1). However, this result masks differential effects by OLU; the northern OLUs tend to gain or maintain visitors with beach restoration activities in scenarios 2 and 3, and southern OLUs tend to lose visitors with marsh restoration activities (Fig. 6). All else being equal, marshes are associated with lower recreation and beaches are associated with higher recreation. We also find that recreational use of engineered structures depends on their design. For example, engineered structures with trails are associated with more visitors than engineered structures without such infrastructure (Supplementary Table 10).

The distribution of existing and future coastal habitats and the range of services they provide to people varies significantly throughout the County (Fig. 6), driven by the geomorphic and ecological nature of the OLU. For example, the Belmont-Redwood OLU is home to much of the County's existing and potential marshes. Thus, we see significant carbon sequestration, storm-water pollution reduction, and habitat provision provided by the marshes in this OLU. On the other hand, it receives relatively little coastal recreation in any scenario and sees reductions in recreation as the marsh area increases through restoration (Fig. 6).

To the north, the Yosemite-Visitation OLU has no marsh area because of the shoreline's proximity to deep water and high wave



**b**

	Beaches	Ecotone levees	Nearshore reefs	Submerged aquatic vegetation (eelgrass)	Tidal marshes
San Francisquito	○	●	●	○	●
Belmont - Redwood	●	●	○	○	●
San Mateo	●	◐	○	●	◐
Colma - San Bruno	●	◐	○	●	◐
Yosemite - Visitacion	●	○	●	●	○

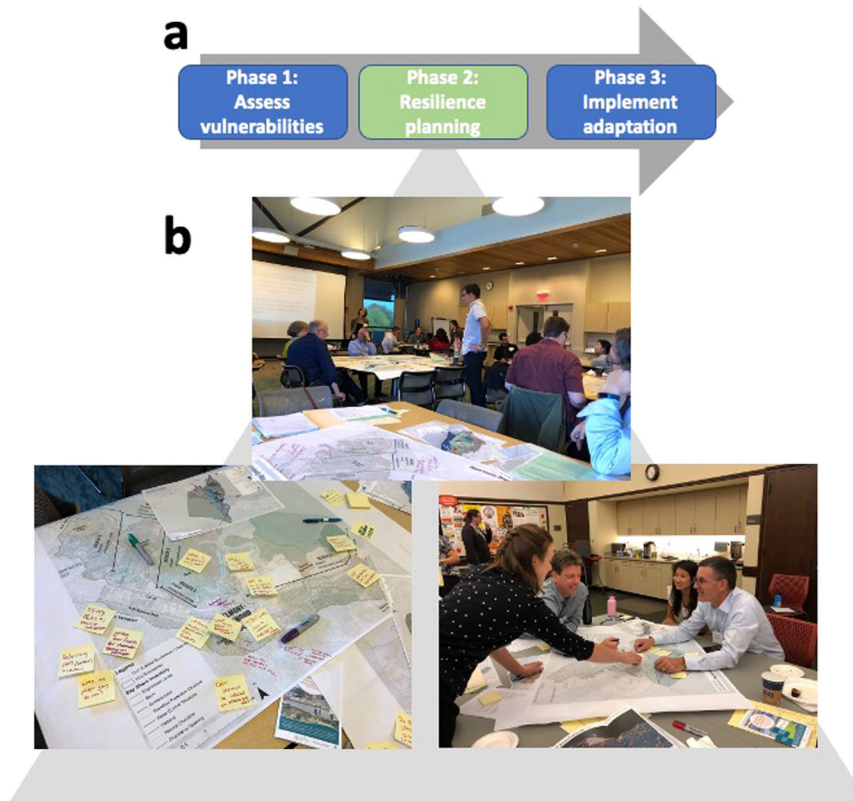
Legend: ○ Limited suitability ◐ Some suitability ● High suitability

**Fig. 3 Biophysical suitability of nature-based adaptation opportunities—particularly ecotone levees, nearshore reefs, and tidal marshes.** **a** Suitability in San Francisquito and **b** throughout the County’s 5 OLU’s (also including beaches and submerged aquatic vegetation). Neighboring regions are masked, but show differences: for example, the suitability of long stretches of the Belmont-Redwood OLU shoreline to the northwest for beaches along both natural and fortified shorelines. We summarized biophysical suitabilities by OLU from the regional suitability assessment in the San Francisco Bay Shoreline Adaptation Atlas<sup>24</sup>. Black scale bar in panel (a) represents 1 km.

energy and thus offers none of the services provided by marshes. However, this region offers significant beach access and experiences the most recreation in the county (~50% of the County’s total modeled recreation). Our suitability analysis indicates restoration of an additional 43 ha of the beach is possible in this OLU. New beaches soften the shoreline, respond to high wave energy, and recreate the pocket beaches historically present in the area. Results from Scenario 3 (‘What we could do next’) suggest that further beach restoration—not currently underway or planned—would increase recreation in the Yosemite-Visitacion OLU (Fig. 6).

**DISCUSSION**

Throughout this work, we saw that science—delivered through discussions and as maps, tables, and figures—helped provide useful boundary objects for fostering conversations with leaders and stakeholders. Iterative, co-creation of guiding principles for sea-level rise adaptation planning enabled the identification of shared goals and outcomes as well as barriers to implementation. Co-development of shared goals, future scenarios, and knowledge exchange between stakeholders is an important part of adaptation as it enhances sustainable solutions for urban



**Fig. 4 The engagement process.** We conducted this work in conjunction with the County of San Mateo's Office of Sustainability and their broader sea-level rise planning efforts, which includes three phases (a). This work was part of the second phase of that effort, going from information about vulnerabilities to the exploration of adaptation options. In partnership with the County, we participated in several stakeholder meetings (b) to help create the guiding principles to shape adaptation options and scenarios, to get feedback on the suitability of nature-based solutions, and to share results comparing ecosystem services delivered by different adaptation scenarios.

transformation<sup>54,55</sup>. Maps of exposure and of opportunities for adaptation sparked important conversations that informed our creation of the three adaptation scenarios. We found that co-creation of scenarios that connected different pathways of adaptation with impacts on nature and on nature's contributions to people allowed us to generate more salient results<sup>56</sup>. The work benefitted from candid discussions with public works directors and land managers about their own experiences with flooding and the feasibility of adaptation options. We ultimately produced fact sheets (Supplementary Note 2) that the County distributed amongst leaders to help communicate results and inform adaptation decisions.

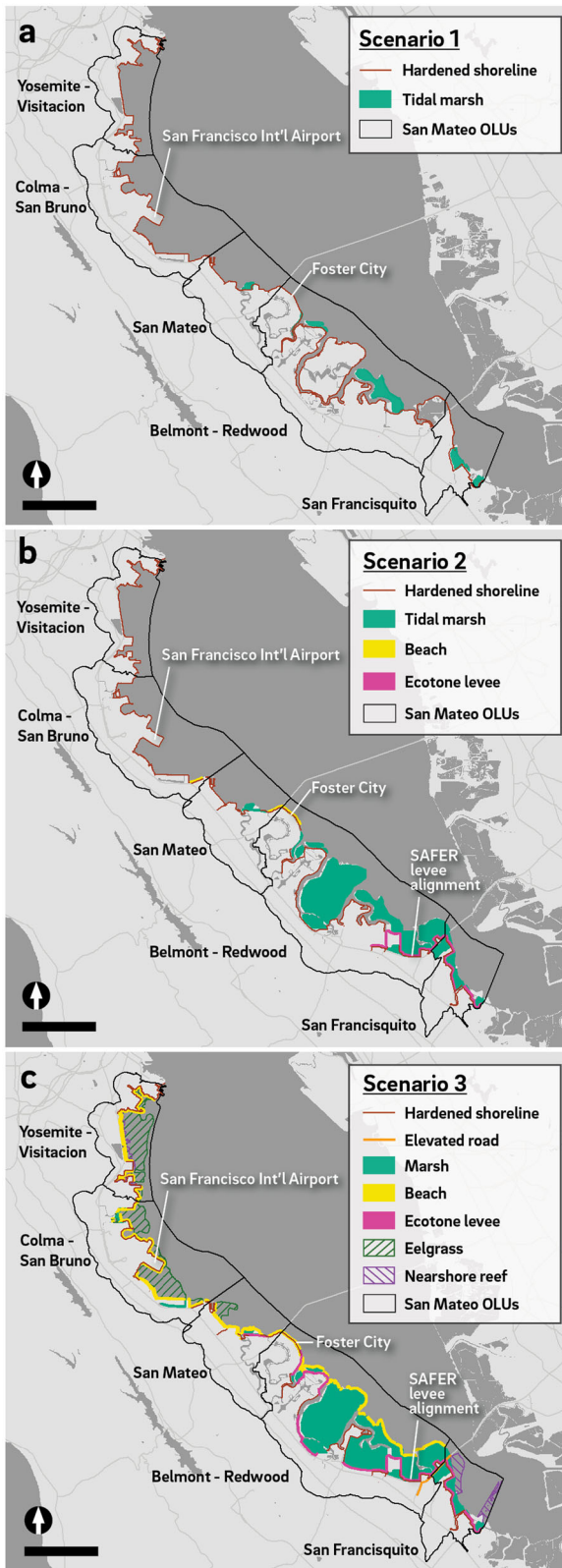
However, throughout the engagement, we faced significant challenges. We saw how hard it is for leaders and communities to have conversations about changing or moving land uses. We saw the challenges of flood managers working to plan for the future while managing for flood protection today. And we saw how few options there are for nature-based solutions in cases of coastal squeeze<sup>57,58</sup> such as in San Mateo County, where rising sea levels, shoreline armoring, urban development, and other factors lead to limited space for coastal habitats. We had hoped to explore more dramatic and creative adaptation scenarios (e.g., those that can be generated from imaginative, arts-based processes<sup>59</sup>), but in consultation with partners and stakeholders, found that the exploration of the incremental changes included in our scenarios was a more practical, helpful approach (i.e., focusing on adaptive and strategic scenarios, rather than transformative ones<sup>60</sup>).

The Nature Futures Framework lays out three value perspectives on how people relate to nature: 'Nature for Nature' (intrinsic

value), 'Nature for Society' (instrumental value) and 'Nature as Culture' (relational value)<sup>61</sup>. While we focus on 'Nature for Society' by exploring how alternative adaptation solutions are likely to impact the flows of benefits to people, such values are intimately connected to 'Nature for Nature' (e.g., exploring changes in habitat for the endangered Ridgway's Rail) and 'Nature as Culture' (e.g., modeling changes in recreation, one embodiment of the reciprocal people-nature relationship that brings diverse health benefits to people and can encourage stewardship of natural spaces<sup>62,63</sup>).

Planning for sea-level rise often follows ownership or jurisdictional divides. However, changes to the shoreline in one location may have unintended consequences in other locations, for example as seawalls push water to other shorelines<sup>64</sup>. Thus, the scale of sea-level rise planning should reflect the scale at which natural processes—such as tides, waves, and sediment movement—affect shorelines<sup>24</sup>. Using shoreline planning areas such as OLU provides communities with a way to develop coherent, geographically appropriate adaptation strategies<sup>24</sup>.

Often the discourse about adaptation to sea-level rise includes false dichotomies between 'gray' and 'green' solutions. However, implemented solutions will often be hybrids, mixing gray and green infrastructure as feasible and desired. Creative combinations of hybrid measures have been shown to increase coastal protection benefits<sup>65–67</sup>. The goal of these combined approaches is that each line of defense will play a complementary role in reducing vulnerability to flooding and stabilizing the shoreline<sup>65</sup>. One example in our analysis is the possible addition of a beach



**Fig. 5** Three scenarios of adaptation across the five OLU of San Mateo County. Scenario 1 represents an engineered shoreline, or ‘What we might have done.’ This scenario serves as a baseline or comparison for the other two. Scenario 2 represents currently planned or permitted conservation and restoration projects, or ‘What we are doing.’ Scenario 3 uses information from our suitability assessment to include additional nature-based features, or ‘What we could do next.’ Black scale bars represent 5 km.

bayward of a vertical levee and flood wall along the northern reach of Foster City in Scenario 3 (Fig. 5).

A surprising finding from the analysis of ecosystem services was that restoring and protecting marsh reduces visitation. This result may be partly explained by policies that deliberately limit accessibility to protect the marshes and associated wildlife. Access to marshes in the region is limited during the nesting season for the endangered Ridgway’s Rails (ca. 6 months per year) and thus this relationship only holds for our case study. Developing a better understanding of the drivers of this result is essential given the importance of salt marsh restoration elsewhere as part of the portfolio of adaptation strategies to sea-level rise.

An avenue for advancing this research is to explicitly map the beneficiaries of each scenario to better understand who benefits from nature-based solutions and resulting equity concerns. However, with the exception of recreation, the benefits we modeled are provided on a largely global (carbon) or regional (nutrient retention, habitat for Rails) basis. Given that increases in marsh areas are associated with decreases in visitation, further work is required to understand how and if the addition of these nature-based solutions may contribute to gentrification and other distributional issues.

Our approach has four important limitations. First, we considered upland land use as unchangeable. In the future, as sea level continues to rise, there will be difficult decisions about changing land use and the need to adapt, realign, or retreat<sup>68–70</sup>. The exposure and suitability maps do not reflect these changes because they are difficult to forecast; our scenarios do not include them because they were unacceptable to the stakeholders we engaged. Second, the co-benefits we explored here are only a subset of the multiple benefits that can be provided by urban nature. Third, we use relatively simple modeling approaches to estimate the benefits that will flow to people from the different adaptation options. Each model relies on simplifying assumptions and therefore yields first approximations that are best compared across scenarios. These assumptions are detailed in the Methods and Supplementary Methods. Finally, we did not include costs of different adaptation options (Scenarios 1–3), nor did we measure benefits in common units. Thus, this analysis cannot provide information about the net benefits of alternative scenarios in a cost-benefit analysis framework<sup>32</sup>. Methods for measuring adaptation costs in the study area were investigated in a 2017 study; it used an estimate of over \$5,000 USD/m for simple levees<sup>71</sup>, which is surely an underestimate given the current costs of materials. We seek to complement cost analyses by exploring the value of key ecosystem service benefits associated with a variety of adaptation approaches.

Additional work that explores a more complete assessment of both costs and benefits of adaptation options—in addition to the costs of doing nothing—will be an important next step for this field. Existing work has laid critical groundwork for such analyses<sup>72–75</sup>. An adaptation approach that meanders along the shoreline to maintain salt marsh frontage for seawalls could end up being more than double the overall length and cost than an approach that employs straighter lines further into the bay<sup>32</sup>, suggesting a potential tradeoff with ecosystem benefits of salt marsh.

One important goal of this work was to bring siloed local government staff together to consider adaptation planning at a county-wide scale. A key next step will be to engage community members and other types of stakeholders to further discuss the social acceptability of different adaptation strategies and the lack thereof.

Some nature-based opportunities, as incorporated into Scenario 2, are already being implemented; others have funding and permitting in place and will be implemented soon. For example, in the San Francisquito Creek OLU, key projects aimed at reconnecting San Francisquito Creek to its marshes are complete. Also,

green stormwater infrastructure in several locations within the watershed aims to reduce fluvial flooding in the lower-lying developed areas. In the Colma-San Bruno OLU, floodplain and marsh restoration as well as beach planning are underway to enhance the resilience of Colma Creek to sea-level rise<sup>76</sup>. Monitoring the impacts of these projects will be key. On the current trajectory, Scenario 2 could be fully implemented by 2030.

Scenario 3 ('What we could do next') shows where further natural and nature-based solutions are possible but does not explore pathways to achieving them. However, further nature-based opportunities (i.e., from Scenario 3) are under consideration. For example, decision-makers in Burlingame used our analyses to inform the creation of a shoreline adaptation plan for their hotel district<sup>77</sup>. Ultimately, implementation of Scenario 3 depends on funding (local, state, and federal), political will, and regulatory agreements. Also, it depends on planning and environmental compliance—which can together take upwards of 10–15 years from start to finish. Fortunately, the Bay Area Conservation and Development Commission (BCDC) recently removed a key barrier to allow bay filling for projects aimed at restoring and enhancing natural habitat to adapt to sea-level rise<sup>31</sup>. A central motivator of this work was to explore and quantify the multiple benefits of nature-based solutions as an input to planning discussions to, if warranted, help make the case for additional nature-based solutions.

Sea-level rise adaptation strategies in one part of the Bay can have implications for distant stretches of shoreline<sup>64,78,79</sup>. Working across jurisdictions to plan adaptation strategies is critical to

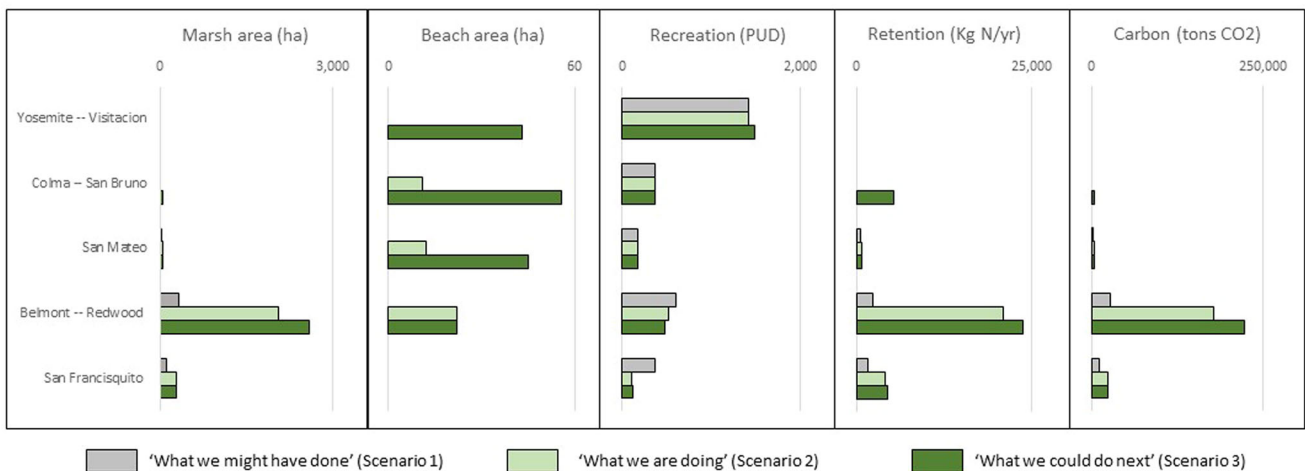
addressing the problem of sea-level rise. Even at the scale of San Mateo County, the footprint of adaptation projects can span multiple cities and require the approval of several state and federal agencies with different priorities, compounding governance challenges. To address this, San Mateo County has set up a new flood- and sea-level rise district designed to work across the County<sup>48</sup>. This is a rare example of multiple cities working together to address more holistically the regional risk of flooding.

The risk from sea-level rise results not only from biophysical factors but also from socio-economic and historic ones. Before the establishment of BCDC, the development of marshes along the edges of the Bay was commonplace. Municipalities, such as Foster City, built upon artificial fill where coastal habitats once were, are more at risk as seas rise. Perhaps most importantly, communities with similar biophysical risks do not necessarily have similar vulnerabilities—some communities have more resources than others. For example, due to higher property values in some areas, some cities have access to funding through tax increases or assessment districts (e.g., City of Foster City or City of San Mateo), whereas cities with a lower tax base and lower property values have fewer options to generate the funding needed for adaptation through this strategy (e.g., East Palo Alto). Moreover, while jobs associated with adaptation actions are considered costs when making decisions using cost-benefit analysis<sup>80</sup>, communities may actually assign a positive value to job creation if there is significant unemployment or a desire for higher skilled jobs. Careful thought about the variety of social objectives, resource gaps, and potential equity pitfalls are necessary as leaders at all levels consider risk, exposure, vulnerability, and adaptation.

This work adds to the growing body of research from around the world demonstrating that nature-based solutions help protect coastlines and yield diverse ecosystem services<sup>14,15,72,81–83</sup>. Nature-based solutions are often 'no- or low-regret' options because they serve multiple functions, reduce vulnerability, and help build resilience<sup>84</sup>. However, significant challenges still hamper their broader uptake. Nature-based solutions are not feasible in all locations (e.g., because of a lack of space in urban environments), the protective benefits (and co-benefits) they provide can depend on various ecological and storm-specific factors, they can take more time to be established than traditional engineered structures, the planning community lacks expertise in designing and executing them, and there are often regulatory or cultural barriers to their inclusion in adaptation portfolios<sup>83</sup>. The recent publication of the International Guidelines on Natural and

**Table 1.** Changes in habitat and ecosystem services provided by Scenario 2 ('What we are doing') and Scenario 3 ('What we could do next') relative to the engineered baseline ('What we might have done') without investing in nature-based solutions.

Co-benefits	Scenario 2	Scenario 3
Marsh area/Ridgeway Rail habitat	5x	6x
Beach area	+50 ha	+200 ha
Recreation	1x	1x
Runoff retention	6x	8x
Carbon sequestration	5x	6x



**Fig. 6** Habitat and ecosystem services across San Mateo County's five Operational Landscape Units (OLUs) compared across the three adaptation scenarios. The scenarios compare: (1) 'What we might have done,' (2) 'What we are doing,' and (3) 'What we could do next.' Recreation is measured in 'PUD' or photo-user days, a proxy for the number of visitors. Carbon sequestration is measured from 2018–2050 for existing marsh and from 2030–2050 for new marsh.

Nature-Based Features for Flood Risk Management and accompanying Engineering With Nature Atlas that describes over 100 nature-based adaptation projects around the world is a key step in reducing some of these challenges.<sup>85–87</sup>

Our approach included: co-developing guiding principles for adaptation; identifying exposure to sea-level rise and the suitability of nature-based solutions within functional landscape scale units; mapping and measuring the co-benefits of the nature-based solutions; and engaging with stakeholders throughout the process to ensure the relevance and utility of our results. By demonstrating the multiple benefits provided by nature-based approaches, this work can serve as an example for jurisdictions throughout the Bay and beyond seeking to leverage ecosystems in their efforts to adapt to climate change.

## METHODS

### Guiding principles

To generate the guiding principles at the foundation of this work, leaders at the County of San Mateo Office of Sustainability conducted numerous working sessions with stakeholders throughout the County. The team held meetings in libraries and other public spaces and often had 60–70 participants that included County and City planners, public works officials, staffers from offices of elected officials, NGO personnel, and land-managers. After listening sessions, the team crafted draft principles followed by additional meetings to revise and finalize the principles. We also held meetings throughout this work to gather feedback on maps, to inform the creation of scenarios, and to share ecosystem service modeling results.

### Summarizing exposure to sea-level rise

We used the San Mateo County Sea Change Sea Level Rise Vulnerability Assessment<sup>45</sup> to summarize the extent of sea-level rise across the five OLU in the County. The County's assessment summarized risk by city and by asset class (roads, hospitals, schools). We recast these analyses to visualize the exposure of multiple assets at the cross-jurisdictional and geophysically-connected OLU scale. Following the County lead, we examined three sea-level rise scenarios: a baseline scenario (a 1% annual chance flood event), a mid-level scenario (1% flood event plus 1 m sea-level rise), and a high-end scenario (1% flood event plus 2 m sea-level rise)<sup>45</sup>.

### Identifying suitability of nature-based opportunities for adaptation

We identified where a range of nature-based adaptation measures could be implemented in San Mateo County OLU to mitigate the effects of sea-level rise. We define adaptation measures as specific interventions to manage the shoreline in response to or in anticipation of climate change vulnerabilities. We did not consider fluvial flooding and groundwater emergence. We drew on work completed previously as part of the San Francisco Bay Shoreline Adaptation Atlas<sup>24</sup>, which defines, describes, and maps the biophysical suitability of more than two dozen sea-level rise adaptation measures across the 30 OLU in the Bay. The five OLU in San Mateo County are highly developed and lack open space on the Bay shore, limiting the suite of nature-based adaptation strategies suitable for this county to: restoration and creation of submerged aquatic vegetation, coarse beaches, tidal marsh, and nearshore oyster reef; as well as the establishment of ecotone levees.

Next, we identified locations along the shoreline which had the enabling conditions required for a given strategy. For example, for marsh restoration, we identified areas where ground elevations were suitable to allow for new marsh wide enough to attenuate local waves and reduce levee erosion. Where marshes already existed that were wide enough, we looked for opportunities to reduce marsh edge erosion by the creation of oyster reefs or eel grass beds to attenuate waves. In places where the land elevation was too low for marshes but there was a low-tide terrace, we looked for opportunities to create coarse beaches to provide the same wave attenuation function as marshes and reduce overtopping and erosion of levees and sea walls.<sup>24,88</sup> We considered coarse beaches (sand, gravel, and shell) in locations with wide enough shallows for sediment resuspension and onshore transport of materials for their potential to slow

wave driven erosion of marshes and other shoreline types<sup>24,88</sup>. Constructed nearshore reefs and enhanced submerged aquatic vegetation have the ability to reduce waves reaching the marsh edge and could trap sediment and reduce marsh erosion, and require subtidal conditions suitable for their survival, which include turbidity and light thresholds<sup>24</sup>. Finally, we identified locations where marshes or diked baylands are adjacent to development or critical infrastructure and thus where ecotone levees<sup>24,53</sup> can provide flood protection to low-lying communities. For further details, see the San Francisco Bay Shoreline Atlas<sup>24</sup>.

### Creation of adaptation scenarios

To compare benefits across scenarios, we held flood protection equal. We designed the flood risk elements (levee crest elevation, width, and elevation of restored beach and marsh) of the three adaptation scenarios such that overtopping does not occur under the conditions of a 100-yr FEMA storm with 1 m of sea-level rise. For each scenario we calculated the minimum width of marsh needed to attenuate 100-year incident waves down to 1 ft in height before reaching the back edge of the marsh and the levee behind it following the method laid out by Bouma et al.<sup>89</sup>. For beaches, we calculated the crest elevation and beach volume for the incident wave conditions. We calculated crest elevations based on the runup of the 100-year significant wave height<sup>90,91</sup>. See the Adaptation Atlas<sup>24</sup> for more details. In all three scenarios we assume that marshes will accrete sediment and keep up with sea-level rise until 2050<sup>51</sup> and that maintenance and management of marshes will be needed beyond 2050. This assumption is reasonable (given high sediment concentrations) until our endpoint of 2050<sup>92</sup>, but after that sediment augmentation for marshes will likely be necessary<sup>93</sup>. Furthermore, we assume no major land-use changes.

Scenario 1 ('What we might have done') describes a shoreline in 2050 that is hardened completely using levees and seawalls (a length of 130 km of hardened shoreline). This scenario envisions a world in which no large tidal marsh restoration had been done in the Bay and ignores existing or planned marsh restoration activities. We created this scenario to help stakeholders understand the value of restoration investments the region has made over the last 40 years. Using Scenario 1 as a basis, Scenario 2 ('What we are doing') incorporates existing and planned restoration projects and their nature-based features as well as existing and planned hardened shoreline (for a total length of 106 km of hardened shoreline). This scenario serves to quantify the benefits the County and region are already receiving from nature-based solutions that are in place or are currently planned.

Building on Scenario 2, Scenario 3 ('What we could do next') adds additional nature-based adaptation features where feasible from both a biophysical perspective (from the suitability analysis) and based on feedback from participants in listening sessions. Feedback from participants in workshops helped to narrow the suite of 'suitable' nature-based solutions from a biophysical perspective to those also 'suitable' in a more social dimension. For example, in our original suitability analysis we considered changes to current land uses (e.g., managed retreat to allow for marsh migration space), but stakeholders were reluctant to include such changes. Similarly, listening sessions helped us update maps based on local knowledge of existing flood protection structures, urban drainage systems, etc. This feedback allowed us to adjust our suitability maps to better match local knowledge and information. Scenario 3 has a total of 79 km of hardened shoreline, 60% of the hardened shoreline of Scenario 1. Restoration of tidal marshes in Scenarios 2 and 3 allow realignment of hardened infrastructure to protect shorter segments of shoreline. In both Scenario 2 and Scenario 3, multiple types of adaptation solutions are needed to achieve the desired level of flood protection. Thus, in many stretches of shoreline, nature-based solutions such as marshes and beaches are accompanied by levees and other hard infrastructure (Fig. 5). Both scenarios with nature-based solutions also involve increasing the length of hardened infrastructure over the current length (54 km)—52 additional km for Scenario 2 and 25 km for Scenario 3—but have their bayward edges softened by nature-based solutions.

### Ecosystem service modeling

We estimated the spatial production of three ecosystem services associated with changes in the extent of tidal marsh and beach habitat—stormwater nutrient pollution reduction, recreation, carbon sequestration—as well as the provision of habitat for a key endangered species. We quantified and compared ecosystem services delivered by

each of the three adaptation scenarios. We summarized services across the whole County for each adaptation scenario and explored spatial variation among OLU's in the production of services. As with all modeling, we had to make particular simplifying assumptions; these introduce potential sources of error and should be considered when interpreting results. Below, we provide basic information about each model, with additional details on each model and its underlying assumptions in the Supplementary Methods.

To estimate stormwater nutrient pollution reduction from marshes for each of the three scenarios we used the InVEST Urban Stormwater Retention model<sup>94</sup> (Supplementary Methods, Supplementary Tables 3–8). We modeled the spatial distribution of pollutant loads in stormwater runoff draining to the Bay (kg N per year) at a 30 m resolution based on precipitation, land cover, and soil data. We estimated stormwater pollution reduction by marshes based on empirical data on nutrient removal rates by marshes for the Bay (Supplementary Methods). We applied removal rates to nutrient loads discharged near (<100 m) marsh areas and estimated the total amount of pollution reduction as the sum of pollutant removal from each marsh section in the area of interest.

To estimate recreation along the Bay's shoreline, we used the InVEST Recreation model to summarize standardized, unique geotagged Flickr "photo user days" by 500 m hexagonal grid cells along the shoreline of the Bay over the period 2005–2017, as a relative proxy for recreation<sup>94–96</sup> (Supplementary Methods, Supplementary Fig. 2). Drawing only from the narrow 500 m buffer centered directly on the shoreline, we assumed that all observed photo user days are representative of recreational visits. We used a count multiple regression model to estimate the relationship between visitation and shoreline type along the entire Bay shoreline (e.g., seawall, tidal marsh, horizontal levee, beach, etc.) (Supplementary Methods, Supplementary Tables 10 and 11), controlling for other factors associated with visitation such as adjacent populations and access (Supplementary Tables 9 and 10). We used the correlational relationship between shoreline type and visitation to predict potential changes in recreation under our three scenarios (Supplementary Fig. 3).

We estimated the carbon sequestered and stored by tidal marshes under each scenario using the InVEST Coastal Blue Carbon model<sup>94,97</sup>. The model estimates carbon stored and sequestered by coastal ecosystems over time in three pools: aboveground biomass, litter, and soil (Supplementary Methods). We gathered key model parameters including carbon stock, accumulation rates, and half-life from studies in the Bay when available, using values from elsewhere in California, or global averages when local data was not available (Supplementary Table 12). For this analysis we assumed that new marsh reflected in adaptation Scenarios 2 and 3 was fully established by 2030 and was not providing any carbon sequestration service from 2018–2030 during a phase of restoration and marsh establishment. In addition, we assumed that all marsh in the County began with the same carbon pool values, accumulated soil carbon at the same (linear) rate, and that none accumulated biomass or litter over time.

Finally, we summarized the habitat availability for Ridgway's Rail (*Rallus obsoletus*), a species listed as 'endangered' according to the US Endangered Species Act, and thus a species of special concern. Ridgway's Rail habitat is restricted almost entirely to the marshes of the San Francisco Bay, making it a good "umbrella" species for the conservation community—protection and restoration of Ridgway's Rail is tightly connected to protection and restoration of marshes, and thus to the support of other elements of marsh-dependent biodiversity. We used a simple linear regression to define the relationship between tidal marsh habitat and rail distribution and found that marsh explained 80% of rail occurrence ( $p < 0.01$ ). Using the relationship determined under current conditions (Ridgway's Rail area =  $-0.0745 + 0.80805 \cdot \text{marsh area}$ ), we estimated Ridgway's Rail habitat area for each future scenario. This model is a first approximation of how marsh area might translate to habitat for this important species; more complex modeling would be necessary to understand the quality of habitat, dispersal across patches, and the persistence of populations. This simple model of Ridgway's Rail habitat helps provide an additional metric—beyond marsh area—that resonated with local stakeholders.

## DATA AVAILABILITY

Data are available at The Center for Open Science's OSF: <https://osf.io/jsx9m/>.

## CODE AVAILABILITY

Source code for the InVEST software is available at: <https://github.com/natcap/invest>.

Received: 4 November 2021; Accepted: 25 April 2022;

Published online: 09 June 2022

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## ACKNOWLEDGEMENTS

This work was supported by the Gordon and Betty Moore Foundation and the Marianne and Marcus Wallenberg Foundation.

## AUTHOR CONTRIBUTIONS

All authors contributed to the design and execution of this project and reviewed and edited the manuscript. A.D.G., J. Silver, J.B., P.H., and R.G. wrote the original draft. J.B. and J.L. conducted the exposure and suitability analyses. J. Silver, P.H., R.G., S.W., K.W., K.A., and A.D.G. conducted the ecosystem service modeling. E.P. made the maps. H.P., M.G., and J. Sharma led the engagement with County stakeholders.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s42949-022-00056-y>.

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