Global Environmental Change xxx (xxxx) xxx-xxx

ELSEVIER

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: http://ees.elsevier.com

Incorporating blue carbon sequestration benefits into sub-national climate policies

L.M. Wedding [a,b,1,*], M. Moritsch [b,1], G. Verutes [c], K. Arkema [d], E. Hartge [b], J. Reiblich [b], J. Douglass [b], S. Taylor [a], A. Strong [e]

[a] School of Geography and the Environment, University of Oxford, Oxford, United Kingdom
[b] Stanford Center for Ocean Solutions, Stanford University, Stanford, United States
[c] Campus Do Mar, Universidade de Santiago de Compostela, Santiago de Compostela, Spain
[d] Natural Capital Project, Stanford University, Stanford, United States
[e] Hamilton College, Clinton, NY, United States

ARTICLE INFO

Keywords
Ecosystem services
Climate mitigation
Blue carbon
Carbon sequestration
Carbon budget
Climate policy
Nature-based solutions

ABSTRACT

The emissions reduction pledges made by individual countries through the 2015 Paris Agreement represent the current global commitment to mitigate greenhouse gas emissions in the face of the enduring climate crisis. Natural lands carbon sequestration and storage are critical for successful pathways to global decarbonization (i.e., as a negative emissions technology). Coastal vegetated habitats maintain carbon sequestration rates exceeding forest sequestration rates on a per unit area basis by nearly two orders of magnitude. These blue carbon habitats and their associated carbon sequestration benefits are vulnerable to losses from land-use change and sea-level rise. Incorporation of blue carbon habitats in climate change policy is one strategy for both maintaining these habitats and conserving significant carbon sequestration capabilities. Previous policy assessments have found the potential for incorporation of coastal carbon sequestration in national-level policies, yet there has – to date – been little inclusion of blue carbon in the national-scale implementation of Paris commitments. Recently, sub-national jurisdictions have gained attention as models for pathways to decarbonization. However, few previous studies have examined sub-national level policy opportunities for operationalizing blue carbon into climate decision-making. California is uniquely poised to integrate benefits from blue carbon into its coastal planning and management and its suite of climate mitigation policies. Here, we evaluated legal authorities and policy contexts addressing sequestration specifically from blue carbon habitats. We synthesized the progressive action in California's approaches to mitigate carbon emissions including statutory, regulatory, and non-regulatory opportunities to incorporate blue carbon ecosystem service information into state- and local-level management decisions. To illustrate how actionable blue carbon information can be produced for use in decision-making, we conducted a spatial analysis of blue carbon sequestration in several locations in California across multiple agencies and management contexts. We found that the average market values of carbon sequestration services in 2100 ranged from $7,730 to $44,000 ha-1 per hectare and that the social cost of carbon sequestration value was 1.3 to 2.7 times the market value. We also demonstrated that restoration of small areas with high sequestration rates can be comparable to the sequestration of existing marshes. Our results illustrate how accessible information about carbon sequestration in coastal habitats can directly be incorporated into existing policy frameworks at the sub-national scale. Incorporating blue carbon sequestration benefits into sub-national climate policies can serve as a model for the development of future policy approaches for negative emissions technologies, with consequences for the success of the Paris Agreement and science-based decarbonization by mid-century.

1. Introduction

The 2015 Paris Agreement represents a global commitment to mitigate anthropogenic greenhouse gas emissions through the implementation of emission reduction pledges made by individual country Parties (United Nations, 2015). However, the success of national-scale climate policies faces numerous structural and political obstacles (Zhang et al., 2017; Zhang et al., 2017). In particular, the institutional frameworks for incorporating carbon sequestration services into national-scale implementation of the Paris Agreement are under-developed (Levin et al., 2018). Free of some of these obstacles, sub-national actors are at the forefront of efforts to reduce carbon emissions globally (Somanathan et al., 2014; Zhang et al., 2017). This is particularly true in the United States, which has initiated a withdrawal from the Paris Agreement in 2019, but in which several large sub-national actors continue to pursue comprehensive climate mitigation policies. The approach utilized by sub-national entities to incorporate carbon sequestration services into their climate policies can ultimately serve as a model for the development of future policies at sub-national and national levels, with real consequences for the success of global decarbonization efforts.

* Corresponding author.
E-mail address: lisa.wedding@ouce.ox.ac.uk (L.M. Wedding)
[1] Authors contributed equally to this work.

Here, we assess the potential of sub-national policies to incorporate blue carbon sequestration services by examining the current treatment and future opportunities for incorporating carbon services into practical policymaking in California, a U.S. state with progressive climate policies. In particular, we focus on "blue carbon", or the carbon sequestered in coastal vegetated habitats because of its potential influence on the total climate budget (Mcleod et al., 2011). This will serve as a case study for blue carbon policy development at the sub-national scale, as this area is underdeveloped and has significant potential for co-benefits and coastal restoration.

Blue carbon generally refers to the carbon sequestered and stored in coastal vegetated habitats, including mangrove forests, seagrass meadows, and tidal marshes. Once removed from the atmosphere through photosynthesis, organic carbon can remain in biomass in these ecosystems for decades and in sediment for thousands of years, helping mitigate damages of anthropogenic climate change (Barbier et al., 2011; Duarte et al., 2005; Mcleod et al., 2011). Terrestrial forests have long been at the center of natural land carbon sequestration solutions, with numerous efforts to advance climate change mitigation through reforestation, afforestation, and reductions in deforestation (Binkley et al., 1997; Olander et al., 2015; Paul et al., 2002; van Kooten et al., 2009). Yet, coastal vegetated habitats maintain carbon capture rates exceeding forest sequestration rates by nearly two orders of magnitude on a per unit area basis. Tidal marshes sequester an average of over 200 ($\pm$24) g C m^{-2} yr^{-1}, while in comparison, tropical forests sequester an average of 4.0 ($\pm$0.5) g C m^{-2} yr^{-1} (Mcleod et al., 2011). Such carbon sequestration potential is especially significant in coastal regions such as the state of California, which encompasses some of the largest areas of remaining blue carbon ecosystems along the west coast of the United States.

Analogous to deforestation, the loss of coastal habitats due to human activity has resulted in significant losses to the potential for global carbon sequestration potential. An estimated one-third of all coastal vegetated habitats that sequester carbon (e.g., mangrove forests, seagrass beds, and tidal marshes) have been lost over the past several decades (Mcleod et al., 2011). With the significant degradation and loss of these blue carbon habitats (e.g., by coastal development, aquaculture), the disturbed soils release CO_2 back into the atmosphere, increasing greenhouse gas concentrations. Due to their high carbon sequestration potential, the role of blue carbon habitats in mitigating climate change has been recognized as critical (Pendleton et al., 2013; Sutton-Grier et al., 2014). However, to date, there has been little formal consideration of blue carbon in policy, especially at sub-national levels.

Ultimately, coastal and marine ecosystems can deliver a wide range of ecosystem services (defined as natural processes attributes which directly or indirectly benefit humans) beyond just carbon sequestration, (de Groot et al., 2002). The conservation and restoration of these ecosystems thus provide a salient avenue for pursuing nature-based solutions (NBS). The use of NBS may be effective not only for tackling the climate crisis but also synergistically improving biodiversity and contributing to sustainable development, aligning with the ethos of the U.N. Sustainable Development Goals (Seddon et al., 2020). Nevertheless, blue carbon ecosystems are increasingly threatened by a dangerous synergy between both direct and indirect anthropogenic stressors, ranging from deforestation to climate change (Halpern et al., 2007). Moreover, concerns over cost-effectiveness and long-term reliability compared with hard engineering alternatives have hindered recognition of NBS provided by coastal ecosystems (Seddon et al., 2020). However, with climate policy increasingly focusing on greenhouse gas removal methods, there is a need to map and quantify the value of ecosystems to understand the consequences of continued loss of and damage to marine and oceanic environments (United Nations Economic and Social Council, 2020). These blue carbon ecosystems present multiple mitigation and adaptation solutions to climate change. Below, we highlight the status quo and opportunities for blue carbon incorporation into climate policies across global, U.S. national and California jurisdictional levels.

2. Blue carbon in global climate policy

It is clear that protecting coastal ecosystems, such as mangroves and seagrass meadows, corresponds with Sustainable Development Goal

vides a strategy to sequester carbon, aligning with SDG 13.2. Furthermore, goal 13.2 aims to 'include climate change measures into national policies'. Under the 2015 Paris Agreement, which included the first reference to the word 'ocean' in a formal decision under the UN Framework Convention on Climate Change treaty system since the early 1990s, individual countries submitted country-specific emissions reduction plans and commitments in the form of Nationally Determined Contributions (NDCs). Every five years, countries will update these commitments and, on a separate five-year cycle, take stock of how the implementation is going. Though very few of the 2015 NDCs mentioned the term 'blue carbon', some 55 country pledges do highlight opportunities for using coastal carbon sequestration to meet greenhouse gas mitigation targets (Dixon and Krankina, 1995; Herr and Landis, 2016). The use of a country's natural assets, such as coastal ecosystems which sequester large amounts of carbon, could be included in the quantification of their greenhouse gas emissions or allow for more ambitious NDCs (Nationally Determined Contributions). Further, the development of modalities and case examples of idealized blue carbon policies could help advance future country pledges that increase the ambition of climate action. While the Paris Agreement rules concerning inter-Party carbon trading and accounting have not been fully finalized, greater incorporation of blue carbon into Paris implementation is possible.

3. Blue carbon in federal Decision-making

In the United States – currently the world's second-largest emitter of greenhouse gases and the world's largest historical emitter– there is no comprehensive legal framework that mandates protection of coastal blue carbon or that requires that estimates of sequestration services be considered in decision-making (Pendleton et al., 2013). While blue carbon is not explicitly included in any federal statute, existing federal laws do provide statutory authorities under which agencies *could* incorporate sequestration services (Olander et al., 2015; Sutton-Grier et al., 2014). Sutton-Grier et al. (2014) reviewed opportunities for the consideration of blue carbon in existing federal statutes, including the Clean Water compensatory wetland mitigation requirements, research and grant-making provisions under the Coastal Zone Management Act, environmental impact statement requirements under the National Environmental Policy Act, and the economic valuation provisions of the Natural Resources Damage Assessment process. Each of these regulatory processes opens an opportunity for the valuation of carbon sequestration, though executive agency discretion to do so is strongly influenced by the politics of the administration in control of the executive branch.

Furthermore, a deeper recognition of the value that carbon sequestration co-benefits (habitat, biodiversity, flood control) could bring federal regulatory practice an increased uptake in decision-making contexts from climate adaptation planning grant-making, environmental impact assessment to natural disaster responses. Such incorporation would likely to lead to decisions that increase CO_2 mitigation. The only formalized approach for valuing coastal sequestration in the United States is currently through the voluntary carbon market. In 2013, the Verified Carbon Standard (VCS) – a non-governmental entity that develops protocols and a registry for carbon offsets – approved the first-ever blue carbon sequestration protocol (Verra, 2018). This protocol enables carbon polluters or emitters to fund activities that preserve, restore, or expand blue carbon ecosystems and generate carbon credits that can be used to offset emissions. Thus far, use of the VCS Coastal Wetland Protocol on the voluntary market has been relatively limited. Blue carbon is one of many available carbon offset protocols on the voluntary market, and, unlike the capture of methane from anaerobic biodigesters, has greater inherent ecological uncertainty and risks of permanence (American Carbon Registry, 2017).

4. California as a golden opportunity for blue carbon

California's legal, statutory, and regulatory frameworks present clear opportunities for incorporation of carbon sequestration services in management practices across multiple agencies and management contexts. For example, the state has a commitment to 100% zero-carbon electric-

Most saliently, California has a greenhouse gas emissions reduction target of net zero emissions by 2045, established by executive order and SB 100 in 2018. The 2006 AB32 Global Warming Solutions Act had previously established a goal of 80% emissions reductions by 2050 relative to 1990 levels for the state. It is clear that to achieve the net zero goal in 2045, California must take advantage of negative emissions technologies in its natural lands. Yet, despite the comparatively large area of coastal blue carbon ecosystems (over 1,200 km^2 of tidal marshes; over 60 km^2 of seagrass; California Department of Fish and Wildlife, 2015), California has not yet taken specific actions to incorporate coastal carbon sequestration into its aggressive climate policies. California is uniquely poised to integrate benefits from blue carbon into its coastal planning and management and into its suite of climate mitigation policies. With progressive action in approaches to mitigate carbon emissions, statutory, regulatory, and non-regulatory opportunities exist to incorporate blue carbon ecosystem service information into state- and local-level management decisions (Table 1). The potential importance of blue carbon in California stems

Table 1
An overview of policy- and habitat-based strategies to include blue carbon ecosystems in climate targets, as demonstrated in California.

	Desired outcomes	Aim of strategy	Scientific information needed	Policy opportunities at sub-national scale (California)
	Environmental impact assessments			
Policy-based measures Policy-based Measures Policy-based measures	Create incentive to protect marine areas with carbon sequestering environments to remove carbon from the water and air	To investigate ways in which CO_2 can be removed from the atmosphere and marine environment on a sub-national scale. Identify areas with carbon sequestering capabilities on land and in coastal environments.	Monitoring programs at a range of spatial scales for: Ocean acidification Ocean oxygen concentration Ocean and atmospheric carbon dioxide concentration Financial and societal benefits of blue carbon sequestration	California Ocean Protection Council's task force addressing chemical changes manifested through ocean acidification and hypoxia. The task force recommended that CO_2 be removed from air and water (California Ocean Protection Council, 2018; California Assembly Bill No. 2139, 2016; Chan et al., 2016)
	Climate policies with a focus on carbon sequestration			
	A more holistic approach to carbon management for climate policy which recognisesrecognizes the links between atmospheric and oceanic/coastal carbon sequestration.	Identify the relationship between oceanic and atmospheric carbon cycling so government agencies can cooperate in quantifying and managing carbon storage methods.	Data and frameworks which quantify the relationships between atmospheric carbon and marine carbon storage on a range of spatiotemporal scales. Quantification of the social and financial benefits of carbon sequestration in marine habitats. Risks to these habitats - human and natural (California Department of Fish and Wildlife, 2015)	Several government agencies are involved in policy frameworks concerning carbon sequestration (air and ocean pollution), due to California's large stock of marine blue carbon ecosystems (California Ocean Protection Council, 2018; California Air Resources Board, 2017; Nunez, 2006).
	Ecosystem service assessments			

	Desired outcomes	Aim of strategy	Scientific information needed	Policy opportunities at sub-national scale (California)
Habitat-based Measures Habitat-based Measures Habitat-based measures	Subnational policymakers could consider their natural resources, such as marine carbon sequestering habitats, in making their climate goals when carbon storage is concerned.	Net zero carbon goals can be made easier to achieve if carbon sequestering ecosystems are considered in these types of policies, both land and marine.	Quantification of an area's natural carbon storage ecosystems on land and sea and the social and financial implications of this. Modelled scenarios of how this may change over time: human and natural risks.	California is committed to achieving 100% carbon-free electricity generation by 2045, considers land carbon in policy implementation (de León, 2018)
	Growing appreciation of blue carbon ecosystems may lead to the establishment of new MPAs, protected by sub-national law.	Development plans which may degrade blue carbon habitats and associated ecosystems may be discouraged or forbidden under sub-national law (California Coastal Commission, 2015).	Quantification of carbon sequestration for a range of coastal habitats, and modelled scenario outcomes if these habitats were removed or damaged.	The California Coastal Act (1976) can approve or deny coastal development requests in account of coastal blue carbon habitats (California Public Resources Code, 1976)
		New protection measures can be imposed on important blue carbon habitats at any time, even if these areas were not previously protected or under no imminent threat.	Locations of important carbon sequestering habitats within an authority's jurisdiction and quantification of environmental importance of these ecosystems.	The California Coastal Commission can establish Environmentally Sensitive Habitat Areas (ESHAs) to protect blue carbon ecosystems (California Public Resources Code, 1976)
	Marine Protected Areas (MPAs)			
	Ecosystems will remain prosperous if managed correctly, maintaining the crucial ecosystem service of carbon sequestration, alongside many others. Climate Action Plans associated with Marine Sanctuaries can improve levels of protection for blue carbon habitats.	To protect species, habitats, and a range of ecosystems services provided by marine, coastal, and estuarine ecosystems within these areas through reducing human-induced damage to ecosystems, such as pollution.	Continued monitoring of the success of an MPA network in terms of biodiversity, overall ecosystem health etc.	A series of Marine Protected Areas as part of the Marine Life Protect Act in 1999 (California Department of Fish and Wildlife, 1999)

Desired outcomes	Aim of strategy	Scientific information needed	Policy opportunities at sub-national scale (California)
Potential to expand existing MPAs and Marine Sanctuaries.	Although MPAs were not initially designed to protect blue carbon habitats, identifying the importance of carbon sequestration can increase a sense of urgency to protect these ecosystems.	Modelled scenarios quantifying the impact of expanding marine sanctuaries in terms of biodiversity, ecosystem health, amount of carbon sequestered, etc.	Four federally protected National Marine Sanctuaries and associated Climate Action Plans (Greater Farallones National Marine Sanctuary, 2016) (e.g. The Greater Farallones National Marine Sanctuary Climate Action Plan) Federally protected National Estuarine Research Reserves, State partnership with NOAA (San Francisco, Elkhorn Slough)

from the large standing stock of coastal blue carbon ecosystems (California Department of Fish and Wildlife, 2015), as well as from the legal and policy frameworks that foster the incorporation of carbon sequestration services in management practices across multiple agencies and management contexts (California Air Resources Board, 2017; California Ocean Protection Council, 2018; Nunez, 2006).

Salient, credible data about blue carbon potential can inform local and state managers about available options for including carbon sequestration services in coastal resource management. California needs to develop robust negative emissions technologies through natural and working lands carbon sequestration to achieve its climate policy objectives. One barrier to advancing blue carbon sequestration into policy-frameworks is the availability of easily accessible data on rates of carbon sequestration from actual coastal habitats. Such information is salient to sub-national decisionmakers as it moves the treatment of blue carbon from the theoretical to the practical. Here, we estimated blue carbon services in California and explored legal authorities and policy contexts addressing sequestration specifically from blue carbon habitats. Specifically, we examined three case studies in California coastal landscapes, in which we estimated carbon removed from the atmosphere by tidal marsh using a model of carbon storage and sequestration (Fig. 1).

5. Blue carbon ecosystem service modeling approach

Existing frameworks for terrestrial carbon sequestration from forest systems note the importance of spatial modeling that analyzes the sequestration services provided by natural habitats, and they can thus inform the development of similar approaches for coastal ecosystems. To illustrate how actionable blue carbon information can be produced for use in decision-making, we conducted a model-based spatial analysis of blue carbon sequestration. We used the InVEST Coastal Blue Carbon Model (BCM) developed by the Natural Capital Project (Sharp et al., 2018) to measure sequestration over time and estimate the discounted value of carbon sequestration in terms of a carbon market. The model calculates carbon sequestration by multiplying the number of years elapsed by the locally specific annual sequestration rate for that habitat (Supplemental Material). The monetary value on a carbon market is found by multiplying the price per metric tonne of carbon dioxide equivalent (TCO_2) by the total mass of carbon sequestered in that time frame using the Net Present Value method, which applies a discount rate to future monetary gains (Fig. S1). The model also calculates the Social Cost of Carbon, which estimates the global average monetary value of climate-related damages induced from each additional metric tonne of CO_2 in the atmosphere (Interagency Working Group on Social Cost of Carbon, United States Government, 2010) (e.g., intensified fires, storms, and droughts), also using the Net Present Value method. Three study locations on the California coast were selected to illustrate the role of blue carbon habitats in meeting policy objectives: tidal marshes of Humboldt Bay (6,839.0 ha), Elkhorn Slough (950.9 ha) and Tijuana River Estuary (322.5 ha).

Carbon sequestration over time, defined as the amount of additional carbon in storage between time points, was calculated based on tidal marsh extent and annual carbon accumulation rates (Table 2) across commonly applied time horizons for land use planning and management: 2030, 2060, and 2100. We used the best available data representing a range of possible carbon sequestration values based on data from peer-reviewed literature and ongoing research. The BCM calculates carbon sequestered or lost from each square pixel of the landscape during transitions between blue carbon habitats and other land cover types. Carbon gains are based on a linear carbon accumulation rates for each habitat type for each location. For each pixel of tidal marsh (Table S1, Fig. S1), we used an average carbon sequestration rate, based on literature values (or unpublished data) from each location. For each source, we used the average, minimum, and maximum rate of carbon sequestration provided. Because only three values were provided in each source, the mean +/- 1 standard deviation sometimes fell outside the range of the data. We chose to use minimum and maximum to more accurately represent the range of possible carbon sequestration rates. The BCM does not account for net carbon sequestration in freshwater (non-tidal) marsh due to the difficulty of accounting for methane emissions from

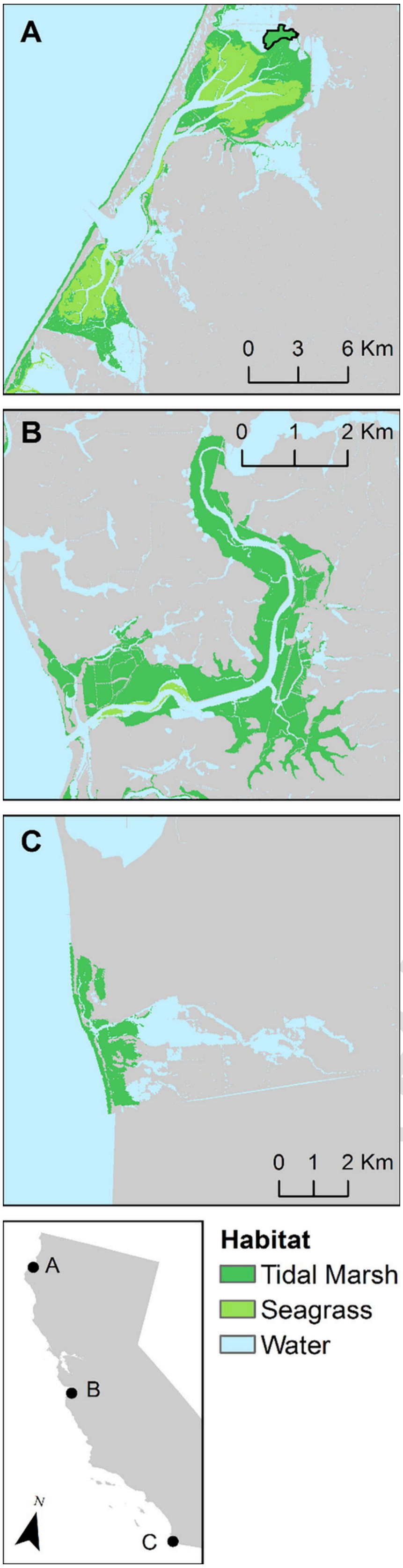

Fig. 1. Map of blue carbon habitat in case study locations in California: (A) Humboldt Bay, (B) Elkhorn Slough, (C) Tijuana River Estuary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Parameters used in Coastal Blue Carbon Model for the three case study locations. Soil carbon accumulation rates for each location were identified from literature values. The mean (minimum–maximum) accumulation rate is listed for each site.

Tidal marsh carbon accumulation parameters	Humboldt Bay	Elkhorn Slough	Tijuana River Estuary
	Soil carbon accumulation rate (T CO_2 ha $^{-1}$ yr $^{-1}$)	40.33 (18.33–77.00) [1]	47.37 (4.62–9.35) [2] 7.08 (1.58–12.58) [3]
Soil half-life (yr)	0.5 [4]	0.5 [4]	0.5 [4]
Economic parameters for all locations			
The market price of one metric ton of carbon (USD)	$13 [5]		
Interest rate for market value	3.0% [6]		
Discount rate for carbon value	3.0% [7]		

methane can reduce overall greenhouse gas sequestration totals, as its radiative forcing potential is higher than that of CO_2 (Etminan et al., 2016). Site-specific methane flux data were absent at our study sites and estimates of methane flux continue to be a source of high uncertainty in wetlands (Holmquist et al., 2018). The BCM does not model methane, though estimates of methane emissions from tidal marshes would provide a more complete greenhouse gas assessment.

We estimated the economic value of total sequestered carbon at each site using: (1) the market value of sequestered carbon in California's existing compliance Cap and Trade Program, and (2) the Social Cost of Carbon (Interagency Working Group on Social Cost of Carbon, United States Government, 2010). The value of carbon in California's carbon market was $13 per ton CO_2– equivalent in 2016 (Climate Policy Initiative, 2018), the start year of our model. The economic valuation was estimated based on the Net Present Value of the amount of carbon sequestered, the monetary value of each ton of sequestered carbon, a discount rate of 3%, and the change in the value of carbon sequestration over time. The market value metric captures the price of offsetting emissions under California policies, while the social cost of carbon captures the actual damages of CO_2 emissions, independent of policy initiatives or market idiosyncrasies. We included both a market and non-market valuation method because market prices do not necessarily reflect the social damages from carbon. The social cost of carbon increases over time, mirroring the magnitude of future consequences of climate change, while it is more difficult to predict long-term variability in market prices.

For each of our case study locations, we assumed a stable marsh extent. While sea-level rise presents a high level of uncertainty for future marsh extent and potential disturbance of soils, it was not within the scope of this study to model marsh migration. In Humboldt Bay, we had the additional opportunity to model carbon sequestration gained by the 2013 restoration tidal flows to McDaniel Slough (Fig. 1), in which 136 ha of former tidal marsh was restored where levees had previously impacted. We compared the three case studies overall and the application of the blue carbon model across three study sites. We then focused on the utility of the BCM to evaluate the potential to sequester carbon in tidal marsh restoration, as this data was available for more detailed analysis in Humboldt Bay.

6. Blue carbon sequestration and economic valuation results

The total marsh extent (area in hectares) was the most significant driver of carbon sequestration across the three case study locations. Elkhorn Slough and Tijuana River Estuary were projected to sequester similar amounts of carbon by 2030, but began to diverge by 2060 (Fig. 2A). Market and social cost of carbon value diverged according to the same timeline (Fig. 3A and C). Humboldt Bay, the largest site, also had the highest average carbon sequestration rate, re-

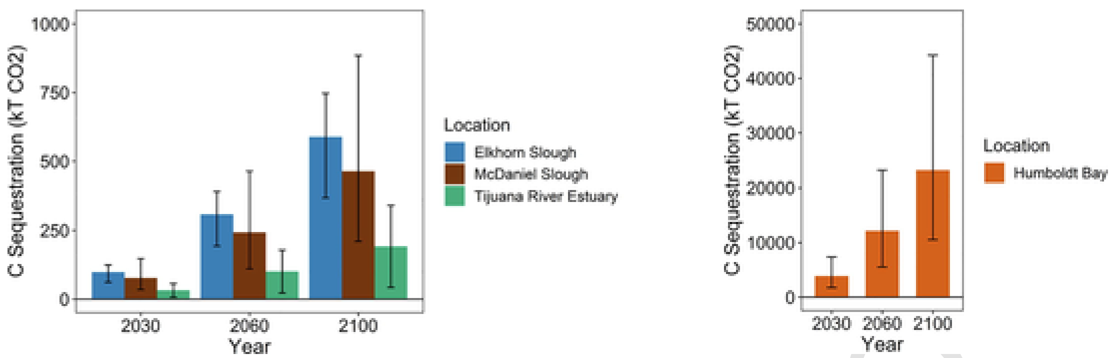

Fig. 2. (A) Carbon sequestration per hectare of tidal marsh, where marsh extent remains the same until 2100, in Elkhorn Slough, McDaniel Slough, and Tijuana River Estuary; (B) in Humboldt Bay. Error bars represent minimum and maximum estimates.

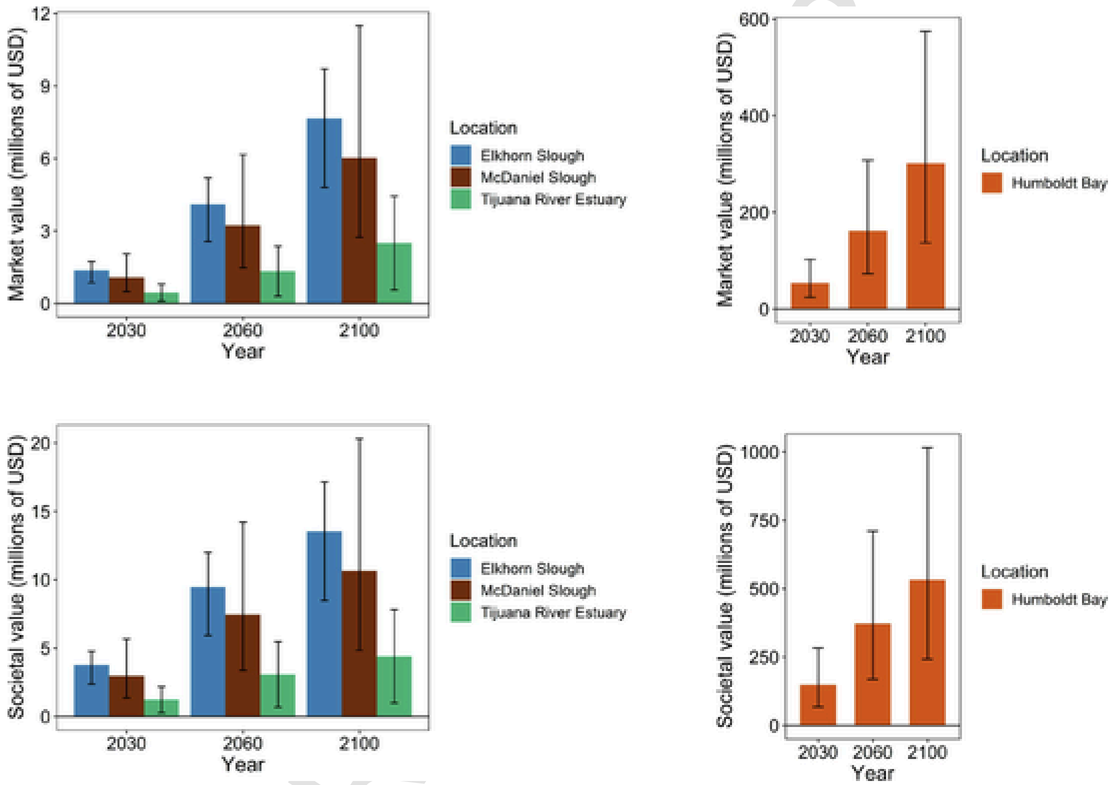

Fig. 3. (A) Total market value of carbon sequestered if the market price and marsh extent remain the same until 2100 for Elkhorn Slough, McDaniel Slough, and Tijuana River Estuary; (B) for Humboldt Bay. (C) Total societal value (Social Cost of Carbon) of carbon sequestration for Elkhorn Slough, McDaniel Slough, and Tijuana River Estuary; (D) for Humboldt Bay. Error bars represent minimum and maximum estimates.

sulting in projected average sequestration 39 times higher than Elkhorn Slough and 120 times higher than Tijuana River Estuary. Total carbon sequestration projected to the year 2100 (Fig. 2A) ranged from an average of 10.5 million (min.) to 44 million (max.) T CO_2. Average market values of carbon sequestration services in 2100 ranged from \$7,730 to \$44,000 ha^{-1} per hectare. The carbon sequestration SCC value was 1.3 to 2.7 times the market value. This pattern is also applied to the restoration area of Humboldt Bay (Fig. 2B).

Between 2016 and 2100, across the entire Elkhorn Slough site, the tidal marsh habitats were projected to sequester between 369,000 and 747,000 T CO_2 (Fig. 2A). By 2100, blue carbon sequestration services in this area could be worth \$4.80 million to \$9.7 million in market value, and \$8.48 million to \$17.2 million using the social cost of carbon (Fig. 3C). Finally, by 2100, Tijuana River Estuary was projected to sequester a total of 42,800 to 341,000 T $CO_{2,}$ (Fig. 2A) with a projected value market value of \$556,000 to \$4.43 million and a social cost of carbon value of \$983,000 to \$7.83 million (Fig. 3A). The restored tidal marsh in McDaniel Slough was projected to sequester 2.4 times more carbon than Tijuana River Estuary, despite having less than half as much marsh area. It was also projected to sequester comparable amounts as Elkhorn Slough (Fig. 3C). This was driven by the high average sequestration rates for Humboldt Bay. The restored tidal marsh in McDaniel Slough is projected to sequester approximately 211,000 to 885,000 T CO_2 from 2016 to 2100, worth \$2.7 to \$12 million in market value and \$4.84 to \$20.3 million using the social cost of carbon.

7. Carbon sequestration data limitations

We estimated carbon removed from the atmosphere by tidal marsh using a model of carbon sequestration. Across the three locations, we identified widely varying market and societal value of that sequestration over time. We also demonstrated that restoration of small areas with high sequestration rates can be comparable to the sequestration of existing marshes. Identifying carbon stock and "hotspots" of carbon sequestration can assist managers in prioritizing locations for conservation, restoration, and climate adaptation actions to manage overall carbon budgeting while also mitigating climate threats. Salient, credible data about blue carbon potential can inform local and state managers about available options for including carbon sequestration services in coastal resource management. Blue carbon ecosystem services science is relatively nascent. Consequently, data and model limitations must be carefully considered when contemplating county- or state-level decision-making in California. There is an opportunity to improve upon the availability of ground-truth information (site-specific or within-site assessment of carbon accumulation rates) in the appropriate spatial resolution for many locations across coastal California. The sensitivity of our blue carbon modeling and mapping results was limited by a lack of site-specific information on local carbon sequestration. As a result, our assessment uses the best available data and there are a number of assumptions and limitations related to such preliminary blue carbon sequestration estimates when relying on scarce data. This underscores the need for additional research to build more robust estimates of carbon sequestration and improve future modeling efforts. There is a clear opportunity to use this initial screening approach to identify areas where further monitoring and sampling will improve data in coastal areas that are most important in terms of carbon sequestration and value. In the policy realm, more attention is likely to be paid to blue carbon as certainty increases regarding contributions to the state's carbon budget. These opportunities are not fully utilized due to a lack of (or lack of access to) detailed, actionable scientific information.

When assessing the production of spatially explicit, actionable information, it is essential to discuss the limitations of the information-development process. For instance, the vast majority of carbon is stored in the marsh soil, so model results are highly sensitive to sediment carbon storage values. The carbon sequestration rates we applied from the literature and ongoing field research varied by an order of magnitude across our study locations, producing a wide range in estimated storage and emissions over time. Additional in-situ carbon data and future monitoring (i.e., ground-truthing, earth observation, etc.) can help address the wide-ranging estimations and increase confidence in model projections, increasing their feasibility for use in policies (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration et al., 2018). Without local carbon sequestration data, the blue carbon model inputs are often based on global averages of carbon-related processes (e.g., storage, disturbance, emissions) for a given habitat type, but these processes vary spatially across and within sites (Brevik and Homburg, 2004; Chumra et al., 2003; Hinson et al., 2017). Average tidal marsh carbon sequestration also varies widely across regions (Chumra et al., 2003). Comparisons of sequestration potential among different regions of California and within the U.S. are still in development (Myer, 2018; Ward et al., 2018).

Without including future development or sea-level rise, our blue carbon model outputs are an optimistic estimate of future carbon sequestration (Caldwell and Segall, 2007; Guannel et al., 2015; Heady et al., 2017). The discrepancy between the market value of carbon sequestered and the social cost of carbon suggests that the market price does not fully reflect the cost of damages incurred if that carbon entered the atmosphere. However, the social cost of carbon is a global metric, while market values are specific to California, so differences in spatial scales of these costs may also contribute to these differences in value.

8. Linking Blue Carbon Science to Policy

Identifying areas of carbon sequestration can assist managers in prioritizing locations for conservation, restoration, and climate adaptation actions to manage overall carbon budgeting while also mitigating climate threats. Our estimates of carbon sequestration of tidal marsh and potential monetary values can help inform what types of policy pathways can be used to integrate blue carbon habitats into broader planning by the state of California. Ranges of tons of CO_2 sequestered in different policy-scenarios can be directly incorporated into numerous decision contexts. Straightforward model-based estimates can provide an initial appraisal for coastal management priority-setting or evaluation of alternatives. Additionally, our results also provide context for how the value of carbon sequestration fits in with other ecosystem services of tidal marsh habitats.

Assessments of the 2060 Social Cost of Carbon value of total se-

1–2 orders of magnitude lower than our estimates (Luisetti et al., 2013). While the Coastal Blue Carbon Model does not specifically quantify co-benefits, such as reducing effects of ocean acidification and coastal hypoxia, it has the potential to make progress towards several policy recommendations of the West Coast Ocean Acidification and Hypoxia Science Panel, including to "advance approaches that remove CO_2 from seawater," as well as recently-passed California Assembly Bill 2139 and Senate Bill 1363, by generating an inventory of locations where conservation and restoration efforts can be applied to mitigate ocean acidification across the state and along the entire West Coast (Califonia Senate Bill No. 1363, 2016; California Assembly Bill No. 2139, 2016). Mapping, measuring, and valuing blue carbon habitats, can make more explicit the role of blue carbon in climate mitigation policy at both the sub-national and national scales, ultimately helping governments achieve their contributions to the 2015 Paris Agreement, and is an essential first step in galvanizing support for more holistic economic valuations (Barbier et al., 2008; Reddy et al., 2016).

9. The Pathway to Decarbonization

As the rules for accounting and accountability under the Paris Agreement continue to be negotiated, clear examples of pathways for how blue carbon habitats can be incorporated into existing policies will serve as key demonstrations for future national government climate mitigation and adaptation commitments made under the Paris Agreement framework. Data availability and certainty represent clear, but surmountable obstacles to sub-national advancement of blue carbon mitigation strategies. With the greater inclusion of blue carbon in decision-making, California has the potential to be a global leader by creating new pathways for sub-national governments to lead climate mitigation efforts while protecting critical services from natural systems. These pathways could serve as guides for the implementation of the Paris Agreement, as countries update their NDCs to increase ambition on the pathway to decarbonization.

10. Data availability

The datasets supporting this article, specifically tabular numerical outputs for the Coastal Blue Carbon Model case studies, have been uploaded as a Supplementary File. The Coastal Blue Carbon model and supporting software documentation (Sharp et al., 2018) are available for download at www.naturalcapitalproject.org.www.naturalcapitalproject.org. This software is open source and offered free of charge.

Uncited references

Burke (2011), Wasson, Dashboard (2018), Ballard et al. (2017).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Elkhorn Slough National Estuarine Research Reserve (NERR), Charlie Endris, and Kerstin Wasson for carbon sequestration data from Elkhorn Slough. We thank the Tijuana River NERR for sharing current and historical data from Tijuana River Estuary. We thank the City of Arcata for supplying spatial inputs for the McDaniel Slough restoration area.

Funding

This work was funded by the Packard Foundation.

Appendix A. Supplementary data

References

Ballard, J., J. Pezda, and D. Spencer. (2017). An Economic Valuation of Southern California Coastal Wetlands. Masters Thesis. University of California Santa Barbara, Bren School of Environmental Science and Management. 1–115.

M.C. Burke An assessment of carbon, nitrogen, and phosphorus storage and the carbon sequestration potential in Arcata's constructed wetlands for wastewater treatment Masters thesis 2011 California State University Humboldt Arcata, CA 1 74.

California Air Resources Board. 2017 The 2017 Climate Change Scoping Plan Update: The Proposed Strategy for Achieving California's 2030 Greenhouse Gas Emissions Target., 156.

California Assembly Bill No. 2139. 2016 Ocean Protection Council: ocean acidification and hypoxia. California Public Resources Code. Section 35631.

California Coastal Commission, 2015. Sea Level Rise Policy Guidance. Sacramento, California, pp. 1–293.

California Department of Fish and Wildlife. 1999 California Marine Life Protection Act. Fish and Game Code. Section 2850-2863.

California Department of Fish and Wildlife. 2015 Marine Region GIS Downloads. Marine Regions GIS Downloads.

California Ocean Protection Council. 2018 California Ocean Acidification Plan (Draft for Public Comment). Sacramento, California, 1–50

Chan, F., et al., 2016. The West Coast Ocean Acidification and Hypoxia Science Panel: Major findings, Recommendations, and Actions. Ocean Science Trust, Oakland, California, pp. 1–37.

Chumra, et al., 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochem. Cycles 17 (4), 1111.

California Public Resources Code. 1976 California Coastal Act. Public Resources Code Division 20. 30000–30900, 137.

California Carbon Dashboard (2018). Market price of one metric ton carbon in California as of 20 Dec. 2016. Climate Policy Initiative Report. URL: http://www.calcarbondash.org. Accessed 17 October 2018.

De León K. 2018 California Senate Bill 100: California Renewables Portfolio Standard Program: emissions of greenhouse gases. California Public Utilities Code Section 399.11.

Greater Farallones National Marine Sanctuary, 2016. Greater Farallones National Marine Sanctuary Climate Action Plan. NOAA National Marine Sanctuaries, San Francisco, California, pp. 1–19.

Guannel et al. (2015). Changes in the Delivery of Ecosystem Services in Galveston Bay, TX, under a Sea-Level Rise Scenario. The Natural Capital Project. Technical report. 1 – 121.

Nunez, 2006 California Assembly Bill No. 32: California Global Warming Solutions Act of 2006. California Public Health and Safety Code. Division 25.5, Chapter 488.

Sharp, R., et al., 2018. InVEST User's Guide. The Natural Capital Project, Stanford, California, pp. 1–374.

Wasson, K. and Elkhorn Slough National Estuarine Research Reserve, unpublished data.