Land Acquisition and Ecosystem Carbon in Coastal California

Produced for the California State Coastal Conservancy
A Project of the Climate Readiness Institute, UC Berkeley

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Table of Contents

Executive Summary

Terrestrial ecosystems play a critical role in the global carbon cycle, and will have an important influence on the trajectory of atmospheric CO_2 and the rate of global climate change in the coming century. Ecosystems sequester carbon from the atmosphere, via photosynthetic fixation of CO_2 by plants, and release carbon to the atmosphere, primarily by decomposition and wildfire. Some of the carbon captured in photosynthesis can be stored in ecosystems, for short or long periods of time, in the form of accumulating woody biomass aboveground, and belowground biomass in roots. Some belowground carbon enters soil carbon stocks where it may be stored for very long periods (decades to centuries).

In this context, conservation and management of terrestrial ecosystems have the potential to play a critical role in climate change mitigation at a global and regional scale. The California Global Warming Solutions Act of 2006 set a goal of reducing state emissions to 1990 levels by 2020. The state set a target for ecosystems (primarily forest ecosystems) of no net loss of carbon by 2020. More recently, ecosystem carbon sequestration was identified by Governor Brown as one of six 'pillars' to achieve the State's new 2030 greenhouse gas reduction goals.

This report for the State Coastal Conservancy focuses on two important components of California's ecosystem carbon sequestration: aboveground carbon sequestration in forests and belowground sequestration in grasslands and rangelands. The Coastal Conservancy has facilitated the permanent protection of more than 400 acquisitions in coastal California, encompassing more than 375,000 acres (>151,750 ha). These properties span California's 22 coastal counties, and a wide range of ecosystems from grasslands to redwood forests.

In the first of three parts of this project, aboveground C values, and net change from 2001 to 2010, were estimated by extracting relevant values for the SCC acquisitions from a statewide analysis based on LandFire vegetation mapping (note that some acquisitions included in this analysis occurred after 2001). We found that SCC acquisitions store more than 7 Mg (=million metric tons) of aboveground carbon, with an average density of more than 50 MgC/ha. This is more than 2.5 x higher than the average for California statewide, and reflects the importance of redwood forests in the SCC portfolio, which hold more than 50% of the total carbon stock.

Based on the most recent LandFire methodology, net change in aboveground carbon stocks (2001-2010) for the SCC acquisitions is estimated as a net gain (ecosystem sequestration) of $2.6 * 10^5$ Mg (+3.4%). This net change reflects significant losses from properties that experienced wildfire, balanced by post-fire recovery and plant growth in unburned areas, especially old-growth forest. The key role of fire in net aboveground C sequestration points to the importance of proactive forest management to maximize the value of forest ecosystems in meeting state CO_2 emissions objectives.

The second component of this project evaluated the potential role of avoided development, and avoided CO_2 emissions, that could be attributed to conservation and protection of SCC acquisitions. Based on appraisals listing the alternative 'highest and best use' that the property could have been converted to, we developed counterfactual scenarios for the loss of C that would have resulted from conversion, and by extension the value that can be attributed to land conservation. For a selected set of 75 of the largest acquisitions, we found that about 5% of the land would have been subject to conversion, either to residential development or agriculture (primarily vineyards). Potential C losses from this conversion would have been approximately 1.35% of standing C; this value is lower than the amount of land converted because development preferentially occurs on lower C vegetation types, especially grasslands and shrublands. In addition, some of the C that would be lost during development would be recovered by tree planting in residential areas and crop growth on agricultural lands. Higher values of avoided C loss occur in limited cases where conversion of high C forest ecosystems may have been prevented by conservation. Overall, we conclude that the benefits of avoided development in terms of ecosystem C sequestration are a limited component of the overall value of SCC acquisitions.

The third component of the project used a biogeochemical simulation model (DayCent) to examine soil C sequestration resulting from one-time compost addition to California grasslands, comparing ecosystem responses at four coastal sites in San Diego, Santa Barbara, Marin, and Mendocino counties. Experimental tests of the models are underway at all four sites as part of a larger statewide project. Model simulations show sustained enhancement of soil C throughout the 21st century following one-time compost addition, with a maximum enhancement of >1.5 Mg C/ha about 15 years following compost addition. C sequestration exceeded long-term increases in methane and other greenhouse gas emissions, and climate mitigation benefits were greater under a lower emissions scenario (RCP4.5) compared to high emissions (RCP8.5), creating a virtuous cycle in which emissions reductions at a global scale increase the value of land-based mitigation strategies, such as compost addition.

Results of the project were presented in a public webinar, available at: https://figshare.com/articles/_/5594437 (doi: 10.6084/m9.figshare.5594437)

Background

Terrestrial ecosystems play a critical role in the global carbon (C) cycle, and will have an important influence on the trajectory of atmospheric CO_2, and hence the rate of global climate change in the coming century. Ecosystems sequester C from the atmosphere, via photosynthetic fixation of CO_2 by plants, and release C to the atmosphere by decomposition and other plant, microbial and animal respiration, and wildfire. Some of the carbon captured in photosynthesis can be stored in ecosystems, for short or long periods of time, in the form of accumulating woody biomass aboveground, and belowground biomass in roots. Some belowground carbon enters soil carbon stocks where it may be stored for very long periods (decades to centuries).

Each year at a global scale, approximately 120 x 10^9 Mg C is fixed in photosynthesis and a similar amount is released by respiration and fire, compared to only 7 x 10^9 Mg C emitted via fossil fuels. Thus, even small imbalances between uptake and loss of C by ecosystems have the potential to offset or exacerbate the emissions of C to the atmosphere by burning of fossil fuels. Human activities play a central role in this balance, through activities such as deforestation and land use change which can release C stores by burning and decomposition of woody biomass and release of soil C to the atmosphere; alternatively, management strategies such as reforestation, ecosystem restoration and improved agricultural practices have the potential enhance long-lived plant biomass and soil C stocks, leading to net ecosystems C sequestration.

In this context, conservation and management of terrestrial ecosystems has the potential to play a critical role in climate change mitigation at a national and regional scale. Forests were estimated to be a net C sink[1] in the United States from 1990 to 2012 (US_EPA, 2014), but there are still gaps in ecosystem C accounting, especially concerning the impacts of wildfires. The California Global Warming Solutions Act of 2006 set a goal of reducing state emissions to 1990 levels by 2020. The state set a target for ecosystems (primarily forest ecosystems) of no net loss of C by 2020 (California_Air_Resources_Board, 2008).

More recently, ecosystem C sequestration was identified by Governor Brown as one of six ‘pillars’ to achieve 2030 greenhouse gas reduction goals[2]. Two components of ecosystem C sequestration that are of most relevance to this report are aboveground C sequestration in forests and belowground sequestration in grasslands and rangelands[3]. (Another component that could be important for the State Coastal Conservancy is the role of wetlands, salt marshes, and Delta islands; this topic was beyond the scope of this report).

Forest management to enhance C sequestration is the focus of the California Forest Carbon Plan, currently in public review (State_of_California, 2017). As discussed further below, management of fuel loads and fire regimes is central to forest C dynamics, as well as implementation of sustainable forest management systems. Enhanced soil C sequestration, as well as soil moisture retention and grassland productivity, is a focus of the Healthy Soils Initiative[4], also under development during 2017. Forest and soil C protocols, developed under the aegis of the American Carbon Registry and overseen by the CA Air Resources Board, create a mechanism to certify forest and soil management plans so they can be incorporated into the

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[1] Conventionally, the land-surface is referred to as a ‘sink’ when there is a net flow of C from the atmosphere into ecosystems, and a ‘source’ when ecosystems are net emitters of C to the atmosphere

[2] https://www.arb.ca.gov/cc/pillars/pillars.htm

[3] https://www.arb.ca.gov/cc/natandworkinglands/natandworkinglands.htm

[4] https://www.cdfa.ca.gov/oefi/healthysoils/

state's cap-and-trade program, providing a revenue source for continued management.

Considerable research is now focused on improving estimates and accounting of terrestrial ecosystem C in California in an effort to determine the source/sink balance of the land surface, and its contribution to California's greenhouse gas emissions. Gonzalez et al. (2015), using remote sensing products combined with forest plot analysis of C stocks, estimated that California's natural lands had 850 ± 230 Tg aboveground C (95% CI) in 2010, and had undergone a net loss of -69 ± 15 Tg from 2001 to 2010. The majority of aboveground C is found in forest ecosystems, which can store up to 600 Mg ha^{-1}, while grasslands typically contain only about 1 Mg ha^{-1} and shrublands are intermediate. Two-thirds of the losses were recorded on lands that experienced wildfires during the decade of analysis, including large fires in the Klamath, Big Sur, Transverse and Peninsular Ranges. Saah et al. (2015) updated the methods and analysis of Gonzalez et al., accounting for urban and agricultural lands as well as estimated growth increments in old-growth forest. The methods and results of these studies are discussed in more detail below, as both data sets were incorporated into the analyses for this project.

Estimates of belowground C are more difficult due to high spatial heterogeneity, and limited ability to calibrate and scale estimates using remote sensing. At a global scale, it is estimated that soils contain over 2000 Pg C (1 Pg = 10^{15} g), several times more than total aboveground biomass (Batjes, 2016); belowground C is especially important in grasslands and rangelands where plants tend to allocate a high proportion of their photosynthate to roots in search for water and nutrients. California is estimated to have approximately 25 million ha of rangelands (DeLonge *et al.*, 2014). Silver et al. (2010) reviewed the literature for soil C stocks in California, and found values as high as 250 Mg ha^{-1} in the top meter of soil in grasslands, with higher values in systems with woody plants and roots extending deeper in the soil profile. Biogeochemical models provide a powerful method to estimate ecosystem C dynamics over long periods of time, and their potential response to changing climate and land management practices (Ryals et al. 2015); this approach was utilized here to evaluate potential strategies to enhance belowground soil C in California grasslands across a gradient of coastal climate conditions.

Given the importance of terrestrial ecosystems for climate change and climate change mitigation, it is important to consider the role of open space conservation in ecosystem C sequestration. At a global scale, land use change and deforestation are the major source of C emissions from ecosystems, contributing more than 10% of total greenhouse gas emissions worldwide (IPCC, 2014). In California, 49.2 million acres (19.9 million ha)[5] are protected, managed by over 1000 different agencies and organizations[6], representing almost 50% of the state. The majority of these lands (>85%) are federally owned, primarily distributed across the Sierra Nevada, Klamath, Transverse and Peninsular Ranges, and the desert. State, NGO and private ownership is more important in the Coast Ranges and along the coast itself. Land protection ensures that the ecosystems will not be converted in development, and can be managed for biodiversity conservation, wildlife habitat, watershed protection, public enjoyment, and to enhance their potential for C sequestration.

In the coming century, the impact of climate change on ecosystem C stocks and sequestration is also a growing concern. The area burned in wildfire has risen over the last several decades at

[5] In this report, we use acres when describing the size of properties due to conventions, but switch to metric units for describing the density and amounts of C. 1 acre = 0.4047 ha

[6] http://www.calands.org/

least in part due to warming temperatures and an extended fire season (Dennison *et al.*, 2014). The incidence and size of high severity fire, such as the 2012 Rim Fire, also raise the possibility of increased C losses due to wildfire in the coming century, and long-term declines in the ecosystem C storage (Liang *et al.*, 2017). Management practices that may reduce the potential for catastrophic fire are a major focus of research and policy consideration.

Climate change may also alter ecosystem function, even without wildfire, and impact C sequestration. The 2012-2016 California drought has led to tree mortality across more than 20% of California's forest lands[7], and the majority of the C stored in the dead trees will be emitted to the atmosphere as the trees either decompose or burn (a fraction will also be transferred to the soils from decomposing litter and wood). Increasing heat stress and drought may reduce photosynthetic productivity of surviving trees, further reducing C sequestration (Schlesinger *et al.*, 2016). Rapid regrowth of forests following fire and drought has the potential to partially offset these losses over time, though rates and trajectories of recovery are uncertain.

In rangelands, increased drought can lower plant production, decreasing forage for the state's livestock industry (Chou *et al.*, 2008). Management approaches such as compost amendments have been proposed to enhance resilience to drought and increase soil C sequestration while maintaining or increasing plant growth and forage production for livestock (Ryals & Silver, 2012; Ryals *et al.*, 2014). The sensitivity of grassland C cycling to predicted changes in climate is poorly understood, as is the ability of compost to potentially help mediate some of these impacts.

The factors outlined above set the context for the present study evaluating the role of land conservation in the maintenance of ecosystem C stocks and net sequestration from the atmosphere. The State Coastal Conservancy (SCC) was created by the California State Legislature to promote open space conservation across a broad swatch of coastal California (Fig. 0.1). From 1980 to 2013 the SCC has facilitated protection of more than 400 properties covering approximately 375,000 acres. Acquisitions range in size from less than 1/10 of an acre to the 80,733 acre Hearst Ranch, and span 22 of California's counties, across the SCC's jurisdiction from San Diego to Humboldt.

This project included three tasks related to SCC acquisitions and ecosystem C:

- Task 1. Spatial analysis of land cover, vegetation types, climate zones, and aboveground C stocks and net C sequestration (2001-2010) across the SCC jurisdiction.
- Task 2. Analysis of avoided development and potential for avoided C emissions based on counterfactual scenarios of the alternative 'highest and best use' for the acquired parcels.
- Task 3. Biogeochemical modeling of grassland C dynamics and belowground C storage in response to alternative management scenarios and future climate scenarios.

[7] https://www.fs.fed.us/news/releases/new-aerial-survey-identifies-more-100-million-dead-trees-california

Task 1: Land Cover, Vegetation, Climate, Fire History, & Aboveground Carbon Storage and Sequestration (2001-2010)

Authors: David Ackerly, Patrick Gonzalez, Isabel Schroeter, Stefania di Tomasso, Maggi Kelly, John Battles

The objective of Task 1 was to conduct a series of spatial analyses overlaying the SCC parcel maps on GIS data for vegetation, climate, fire history and aboveground C stock datasets, providing a synthetic overview and spatial context for the SCC portfolio.

SCC Acquisitions – Geography, Climate, Vegetation, and Fire History

In collaboration with SCC, we constructed a well-curated GIS project including shapefiles for 408 parcels protected by the SCC from 1980 to 2013[8]. Acquisitions range in size from less than 1/10 of an acre to the 80,733 acre Hearst Ranch, for a total of just over 375,000 acres. Acquisitions span 22 of California's counties, across the SCC's jurisdiction from San Diego to Humboldt (Table 1.1, Fig. 1.1); county maps showing outlines of the acquisitions are shown in Appendix 1 (Fig. A1a-v). More than half of all SCC acreage was acquired during the decade from 2001-2010, including the Hearst Ranch. As a result, the analysis of changes in C stocks from 2001-2010 starts before many acquisitions were added to the portfolio. This analysis is not intended to credit changes in C stocks to SCC acquisition or management, but rather to highlight the key factors influencing aboveground C stocks and changes in these coastal California ecosystems.

Climate

Coastal California spans 9.5 degrees of latitude and a corresponding range of climate conditions. Temperature is strongly influenced by latitude as well as proximity to the ocean, with cool summers and mild winters close to the coast; precipitation increases in the north, exceeding 4 m per year in the far NW of the state (Fig. A1.2). The Basin Characterization Model (Flint *et al.*, 2013) integrates precipitation and temperature, as well as solar radiation, topography and soil mapping, to estimate actual evapotranspiration (AET, a measure of plant productivity) and climatic water deficit (CWD, a measure of excess energy load in summer that is not met by available water). CWD provides an important measure of summer drought stress. Both AET and CWD can contribute to wildfire intensity, as higher AET can increase plant growth and fuel production during the growing season, while high CWD contributes to fuel moisture drying out in summer, setting the stage for wildfires.

By extracting climate data and plotting variables against each other, the climate space of the SCC jurisdiction can be visualized, and the distribution of acquisitions viewed in context (Fig. 1.2). Though the SCC jurisdiction extends inland encompassing coastal counties, and much of the Klamath Basin, most acquisitions have been focused along the coast. This is reflected in climate space, with the protected lands falling in mild to warm winter temperatures (Fig. 1.2a). Due to the extensive geographic coverage from south to north, SCC parcels span a broad range of precipitation, AET and CWD (Fig 1.2b-d). Acquisitions do not cover the cooler winter temperatures and the lower AET-CWD combinations that would represent Klamath highlands and some other interior regions.

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[8] 65 of the acquisitions were missing acquisition dates, so earliest date may have been before 1980.

Vegetation

Vegetation types captured in SCC acquisitions were analyzed based on the LandFire vegetation mapping (Ryan & Opperman, 2013), which provides the basis for mapping C stocks in California (Gonzalez *et al.*, 2015; Saah *et al.*, 2015). SCC lands cover a wide range of vegetation, from coastal redwood forests to Southern California coastal sage (Table 1.2). Redwood forests covered the largest area (23%), followed by grassland (16%), mixed woodlands (12 and 8% in two different classes), and a range of shrublands and mixed shrubland/oak woodlands.

Vegetation types can be grouped into three broad classes–grassland, shrublands, and woodlands/forests–to capture patterns in geographic and climatic space. Following broad patterns in vegetation distributions across the state, acquisitions primarily covered in woodlands and forest are mostly distributed in the northern and central regions, while grassland and shrub-dominated acquisitions prevail in the central and southern regions (Fig. 1.3).

Wildfire

From 1980-2015, wildfires impacted 49 of the 408 SCC acquisitions (Fig. 1.5). Net and cumulative area burned were calculated for each decade (1980-1989, 1990-1999, 2000-2009), the 2010-2015 half-decade, and 1980-2015 overall. Net area is the area burned in each time period, counting multiple burns on the same pixels once, and cumulative area is the total area burned, counting repeat burns separately (cumulative area burned can exceed the total size of a parcel due to multiple fires). Over the 1980-2015 time period, net area burned across the 49 acquisitions was 26,531 acres (7.1% of total SCC acquisition area), and cumulative area burned was 38,798 acres (10.3% of total area) (Table 1.3).

Though there is some uncertainty in the assignment of vegetation types to individual pixels, discrimination of grassland, shrubland and woodland/forest is fairly reliable. Changes recorded from 2001 to 2010 in the acquisitions that experienced at least one fire demonstrate a significant reduction in shrub-dominated ecosystems and corresponding increase in grasslands, with little change in area of woodlands and forests (Fig. 1.6). These changes likely represent two distinct phenomena: one would be actual type conversion from shrubland to grassland, as has been observed in Southern California, especially in response to multiple fires that occur at short intervals of < 5 years. Alternatively, the early successional shrubland environments may be classified as grassland in the first several years after fire, until the shrubs resprout and recover. Either way, these represent significant short-term changes in aboveground C storage, as discussed below.

Two properties contributed a large portion of the total area burned, and the vegetation change shown in Fig. 1.6 (see Table A1.1). Lauff's Ranch, a 12,000 acre parcel in northeastern Napa Co. on the border with Yolo Co., was impacted by two large fires. The Sixteen Fire, in 1999 (~40,000 acres), burned the northern portion of the property and the Rumsey Fire, in 2004 (>40,000 acres) burned the entire acquisition. The property was classified primarily as shrubland in 2001, but in 2010 virtually all of that area was classified as grassland.

Malibu Creek Watershed-Ahmanson Ranch, a 2,200 acre acquisition in Los Angeles Co., was almost entirely burned by the Topanga Fire in 2005 (23,000 acres) and also a smaller fire in the 1980s. This property also exhibited a shift from mostly shrubland to mostly grassland (possible early successional shrubland, as noted above), though it is a smaller acquisition so it contributes less to the overall patterns in Fig. 1.6.

Carbon storage and sequestration

Total C stocks and net change from 2001 to 2010, representing either sequestration (if positive) or emissions (if negative), were calculated using the LandFire project methodology (Gonzalez *et al.*, 2015; Saah *et al.*, 2015). Remote sensing classification of vegetation type, height and cover, were combined with calibrated measures of C density in each class, based on forest plot data, to assign pixels in the 2001 and 2010 LandFire maps to individual biomass classes, addressing natural lands only. Uncertainty in both total C storage and net change was estimated in relation to three factors: 1) C density of biomass, 2) biomass density of each biomass class, and 3) uncertainty in the vegetation type mapping (the latter contributed the greatest source of uncertainty overall). Collectively, these uncertainties allow for an assessment of statistical significance of inferred changes, i.e. if the 95% confidence intervals do not include 0, then the change is inferred to represent significant net sequestration or emissions. Gonzalez et al. also noted that this methodology would underestimate C accumulation in old-growth forests, as these sites would not be considered to change biomass class. Saah et al. (2015) addressed the C accumulation in old-growth forest, imputing an average 6% growth adjustment in mature forest pixels (based on estimates from UF Forest Service inventory data). This update reflects the current methodology for evaluation of C stock and change adopted by the CA Air Resources Board, However, the updated data set does not allow for direct calculation of uncertainties or confidence intervals in the inferred changes. P. Gonzalez and D. Saah both extracted and analyzed carbon stocks and change from their data sets for each parcel in the SCC portfolio, as well as totals across acquisitions summed by dominant vegetation class and in burned vs. unburned parcels.

Following methodology in Gonzalez et al. (2015), the 408 SCC acquisitions contained a total of 7.3 (±3.3 95% CI) million metric tons (7.3 x 10^6 Mg) of aboveground C (AGC) in vegetation in 2010. The 20 properties with the highest AGC contributed over 85% of the total across the SCC portfolio (Table A1.2); the top three are the Garcia River and Mill Creek acquisitions, both of which are large tracts of redwood forest, and the Hearst Ranch which has a wide mix of vegetation and is by far the largest acquisition in the portfolio. Across the entire SCC portfolio, 5% of AGC was stored in shrub-dominated ecosystems, 36% in broadleaf and mixed forests, and 58% in conifer forests (56% in redwoods, 2% in other conifer forests).

Average AGC density across all acquisition was 52.7 Mg/ha. The highest AGC density in the SCC portfolio is the Big Lagoon Acquisition in Humboldt Co. (370 Mg/ha) and 24 acquisitions had AGC density > 100 Mg/ha (Table A1.3). For reference, AGC of California vegetation varies from less than 1-2 Mg/ha in sparsely vegetated ecosystems and grasslands to almost 600 Mg/ha in tall, closed canopy coastal redwood forests. Across the state, average AGC density in 2010 was 20 Mg/ha (based on Gonzalez et al. 2015). Thus, the ecosystems within the SCC portfolio on average have about 2.5 x higher carbon density compared to statewide averages.

In shrub and tree-dominated vegetation, carbon density increases with rainfall (Fig. 1.7). For tree-dominated systems, these patterns reflect the taller forests, higher canopy cover, and prevalence of redwoods at very high rainfall levels on the North Coast. The trend is weaker in shrublands, and carbon densities are much lower overall (compare y-axis values in Fig. 1.7), but the pattern presumably reflects taller and/or higher density shrub cover detected in the LandFire remote sensing methodology in the wetter regions of the North Coast compared to the hotter, drier South Coast where shrublands are more widespread.

Carbon stocks in 2001 and 2010, and the change over the decade, are shown for the state of California (Fig. 1.8) and for the Preservation Ranch, Sonoma Co., as an illustration of a single SCC acquisition (Fig. 1.9). Based on Gonzalez' methodology, total change in AGC on SCC parcels from 2001 to 2010 was a significant reduction of $-1.5 * 10^5$ Mg (95% confidence interval: -1.02 to -1.98×10^5 Mg), representing a 2% reduction from 2001 levels (Table 1.4, Fig. 1.10a). A 2% reduction is higher than the average of 0.8% recorded statewide for the same time period. The net emissions recorded on SCC lands were almost entirely attributable to net losses from shrublands, with a small but significant loss from tree-dominated systems as well. Note that the modest emissions from forest lands reflect the net effect of losses, primarily on parcels that burned, balanced by net sequestration in other locations.

Saah's updated methodology suggests positive, net sequestration of carbon, with total change in AGC on SCC parcels of $2.6 * 10^5$ Mg, representing a 3.4% increase from 2001 to 2010 (Fig. 1.10a). Net changes were close to 0 for parcels that experienced fire, and the totals gains were contributed on the remaining lands that did not burn. Significance values for change in C stores are not available from Saah's study at this time. The most important difference between the two methods, which likely accounts for most of the difference in results reported here, is the attribution of 6% net growth in old-growth forest pixels that were not recorded to transition to a higher height or canopy cover category. As redwoods contribute most of the carbon in the SCC spatial footprint, imputed growth of 6% across some substantial number of pixels would lead to the assessment of net sequestration.

Occurrence of fires was recorded by two different methods. Gonzalez et al. (2015) overlaid the national Monitoring Trends in Burn Severity (MTBS) dataset for fire occurrence from 2001-2010 on the LandFire vegetation map to determine which pixels had burned. For this report, we also tabulated total losses from acquisitions that had experienced any fire, even if only to a portion of the property, vs. those that had experienced no fire. Based on the MTBS overlay, 63% of the net losses originated from pixels that burned (Table 1.4, Fig. 1.10b). Losses from unburned pixels in this analysis may reflect low-intensity fires that are not recorded by MTBS, harvesting in managed forests, or changes in vegetation classification of individual pixels; we were not able to determine the relative importance of these factors. Based on the acquisitions overall, we found that 98% of net losses occurred on 21 acquisitions that experienced wildfires in the 2001-2010 interval (individual assessments were negative for all 21 of these properties) (Fig. 1.10b, see Table A1.1). The single largest loss was recorded on Lauff's Ranch, in northern Napa County, where extensive areas of shrubland were recorded as converted to herbaceous (i.e. grassland) vegetation (see Discussion). Based on Saah's updated methodology, net losses on burned acquisitions were close to 0 (growth balancing fire losses) while net C accumulation was almost entirely attributed to parcels that did not burn. While estimates vary based on different combinations of methods, the overall conclusion is a clear indication that wildfire is the primary factor leading to loss of aboveground C in California's forests and shrublands, balancing growth and accumulation in unburned vegetation, especially old-growth forest.

Discussion

Two important conclusions emerge from these analyses regarding the role of land acquisition and management in relation to aboveground C storage and sequestration: 1) the importance of forests, particularly redwoods, for aboveground carbon storage in California ecosystems; and 2) the critical role of fire, and fire-management, in maintaining existing aboveground C stocks in shrublands and forests.

Forests are the primary reservoirs of aboveground carbon in terrestrial ecosystems. In particular, California's redwoods represent some of the highest C density forests in the world (Van Pelt *et al.*, 2016). SCC acquisitions, together with investments and holdings of Save the Redwoods, CA State Parks, the National Park Service, local NGOs and private holdings, play a critical role in the conservation and management of these ecosystems. Only about 5% of old-growth redwood survives, as most of the original forest area is now converted following logging to younger, secondary redwood forest, offering potential for continuing management to enhance carbon sequestration[9].

California has played an important role in the development of carbon offset protocols for sustainable forest management, creating an income stream for management actions than enhance carbon sequestration by participation in California's cap-and-trade market. Three SCC acquisitions are currently registered carbon offset projects, all of them dominated by coastal redwood forests and managed by The Conservation Fund[10]: Garcia Forest, Big River & Salmon Creek, and Preservation Ranch. Based on 2016 assessments, the three projects manage stocks of 5.3, 3.6, and 3.9 million metric tons of C, respectively, and have received credits for enhanced annual sequestration of 1.9 to 2.6% of stocks (i.e. sequestration credited to sustainable management practices, over and above the baseline scenario of forest growth in the absence of these practices) (Table 1.5). SCC funding played an important role in initial financing of the acquisition and establishment of these projects, and their long-term success will be an important indicator of the state's ability to incentivize sustainable forest management as a component of achieving overall emissions reductions goals.

The second point emerging from these analyses, and highlighted in Gonzalez et al. (2015), is the critical role of fire as a factor that impacts long-term carbon storage and sequestration. Just as forests represent the most important reservoirs of aboveground carbon, fire management in forests presents the greatest challenges to enhance net AGC sequestration. Many decades of experience demonstrate that fire suppression is not feasible, nor ecologically desirable, in California's Mediterranean-type climate. Additionally, it is now well documented that fire suppression can lead to accumulative of fuels and contribute to catastrophic wildfire, such as the 2012 Rim Fire, that results in high fire severity and carbon emissions. This problem is most apparent in the mid-elevation pine forests of the Sierra Nevada, though recent fires in the North Coast have also exhibited very high severity and tree mortality (e.g., 2015 Valley Fire in Lake Co.). The California Forest Carbon Plan[11] (draft currently released for public comment) focuses on the important role of forests in the state's climate action plan, and the critical challenges posed by forest management in relation to wildfire. Coastal forests, especially redwoods, are less susceptible to C loss from wildfire due to cooler climates and prevalence of lower intensity fires, so these management issues are less critical in SCC acquisitions and other conserved forests along the California coast, compared to challenges in the Sierra Nevada.

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9 https://www.savetheredwoods.org/about-us/faqs/

10 https://www.conservationfund.org/projects/north-coast-forest-conservation-initiative

11 http://fire.ca.gov/fcat/downloads/California%20Forest%20Carbon%20Plan%20Draft%20for%20Public%20Review_Jan17.pdf

Grasslands and shrublands also experience frequent fire, but the impact on aboveground C sequestration is minimal as these systems have little potential for long-term accumulation of C in aboveground stocks (see Task 3 report below for discussion of potential belowground C sequestration in grasslands). California's grasslands are primarily composed of exotic annual species which grow and die within one season. Aboveground C in these systems is essentially in balance, as net primary productivity each growing season will be balanced by decomposition after the grasses die, though some of the organic carbon in the decomposing litter may find its way into the soil and enhance belowground C (see discussion of Project 3 below). Fire will have little influence on this cycle, as it simply represents an alternative to decomposition as a mechanism to release carbon in the biomass back to the atmosphere.

California's shrublands are highly flammable, and also offer little opportunity for long-term accumulation of aboveground C. Chaparral, the dominant shrubland on dry slopes of central and southern California, typically experiences stand-replacing or canopy fires in which all aboveground biomass is incinerated or left as standing or fallen woody material which will eventually decompose. Shrublands may accumulate carbon for many decades in the absence of fire, which could offer short-term climate benefits, but in the long-term California's flammable shrublands should be viewed as essentially carbon neutral with respect to aboveground biomass. Consideration of belowground C in shrublands was beyond the scope of this proposal, and may be an important consideration as root and soil C increase through repeated fire cycles. We are not aware of any research addressing belowground C in California shrublands.

In sum, the SCC acquisitions store a large amount of aboveground C, relative to their land area, primarily due to the large area of redwoods spread across a number of acquisitions. Sustained net carbon sequestration in forestlands will depend critically on the frequency, extent and severity of wildfire, which generates large carbon emissions, as well as the implementation of sustainable forest management practices in properties which are harvested. Climate change poses a challenge, as warmer and potentially drier conditions could lead to enhanced fire probability, as well as the potential for future droughts causing tree mortality, as observe in the 2012-2016 drought. Management strategies to enhance drought resilience, primarily by reducing canopy density, are being discussed (Bradford & Bell, 2017), and could become important in future decades. Belowground storage, and potentials for net sequestration in grasslands based on alternative management strategies, are discussed under Task 3.

Table 1.1 Distribution of parcels and acres across California counties

County	Number of acquisitions	Acreage in county
Alameda	10	3,654
Contra Costa	26	10,562
Del Norte	5	1,038
Humboldt	35	12,728
Lake	1	8
Los Angeles	29	3,512
Marin	25	12,056
Mendocino	36	64,611
Monterey	45	14,616
Napa	16	24,373
Orange	13	1,201
San Diego	17	1,176
San Francisco	1	2
San Luis Obispo	29	90,375
San Mateo	33	12,564
Santa Barbara	15	5,979
Santa Clara	13	7,766
Santa Cruz	20	18,319
Solano	13	13,379
Sonoma	32	45,620
Ventura	10	6,323
Yolo	1	141
Total*	**425**	**350,003**

*Total number of acquisitions is greater than 408 due to parcels that straddle county lines

Table 1.2 Total acreage of vegetation types across all acquisitions. Sorted in decreasing order by 2010 totals

Biomass Order Name	Total 2001	2001 % of total	Total 2010	2010 % of total	Change 2010-2001	percent change
California Coastal Redwood Forest	86,599	23.1%	88,537	23.6%	1,938	2.24
Grassland	45,830	12.2%	59,812	15.9%	13,982	30.51
Central and Southern California Mixed Evergreen Woodland	46,369	12.4%	46,386	12.4%	17	0.04
Water or non-California	26,648	7.1%	32,446	8.6%	5,798	21.76
Mediterranean California Mixed Evergreen Forest	31,091	8.3%	32,344	8.6%	1,253	4.03
California Mesic Chaparral	34,354	9.2%	28,526	7.6%	-5,828	-16.96
Southern California Coastal Scrub	16,804	4.5%	14,221	3.8%	-2,583	-15.37
Southern California Oak Woodland and Savanna	12,767	3.4%	12,885	3.4%	118	0.92
California Montane Woodland and Chaparral	9,696	2.6%	7,781	2.1%	-1,915	-19.75
Southern California Dry-Mesic Chaparral	8,399	2.2%	7,615	2.0%	-784	-9.34
Northern and Central California Dry-Mesic Chaparral	13,893	3.7%	7,090	1.9%	-6,804	-48.97
Herbaceous-shrub-steppe	6,220	1.7%	5,913	1.6%	-307	-4.93
California Montane Riparian Systems	4,548	1.2%	5,505	1.5%	957	21.04
Mediterranean California Dry-Mesic Mixed Conifer Forest and Woodland	5,342	1.4%	5,458	1.5%	116	2.16
Herbaceous Wet	11,212	3.0%	4,042	1.1%	-7,169	-63.94
California Lower Montane Blue Oak-Foothill Pine Woodland and Savanna	3,717	1.0%	3,604	1.0%	-113	-3.04
Other (summed)	11,670	3.1%	12,995	3.5%	1,325	0.11
Total	**375,159**		**375,160**			

Table 1.3 **Summary of area burned by wildfire, by time period and cumulative from 1980-2015. For SCC parcels, net area refers to the acres burned per time period, counting multiple fires in the same pixel once; For parcels, jurisdiction and statewide, cumulative area refers to total area of all fires, counting locations burned twice or more independently each time. Cumulative totals also shown as a percentage of total parcel number and areas (shown on bottom line)**

TimePeriod	SCC Parcels Burned (num)	SCC Net Area Burned (acres)	SCC Cumulative Area Burned (acres)	SCC Jurisdiction Cumulative Area Burned (million acres)	Statewide Cumulative Area Burned (million acres)
1980_1989	20	6,322	6,412	1.83	3.05
1990_1999	28	10,393	10,663	1.37	3.36
2000_2009	20	20,264	21,092	3.67	6.54
2010_2015	4	630	630	0.82	3.07
1980_2015	49	26,531	38,798	7.68	16.02
1980_2015 (% total)	12.0%	7.1%	10.3%	27.1%	15.8%
	SCC Parcels (Num)		SCC Total Area (acres)	SCC Jurisdiction Area (million acres)	Statewide Area (million acres)
Totals for reference	408	375,167	375,167	28.3	101.2

Table 1.7 Aboveground C stocks and change from 2001-2010, in tons of C (values extracted from Gonzalez et al. 2015)

	2001	± 95% CI	2010	± 95% CI	2001-2010	± 95% CI	Significant*
Total coast	7.4×10^6	3.9×10^6	7.3×10^6	3.3×10^6	-1.5×10^5	0.48×10^5	Yes
Trees	6.9×10^6	3.2×10^6	6.9×10^6	3.2×10^6	18×10^3	8.3×10^3	Yes
Shrubs	0.52×10^6	0.36×10^6	0.39×10^6	0.31×10^6	-140×10^3	80×10^3	Yes
Herbaceous	25×10^3	49×10^3	33×10^3	89×10^3	7.9×10^3	19×10^3	No
No dominant	83	480	240	1 200	160	960	No
Non-vegetated	390	3 800	390	4 400	6	83	No
Fires	0.19×10^6	74 000	97 000	58 000	-93 000	35 000	Yes
No fires	7.2×10^6	3.2×10^6	7.2×10^6	3.2×10^6	-55×10^3	23×10^3	Yes

* 95% confidence intervals do not include zero

Table 1.8 Summary of size, carbon stocks and GHG reductions credited to three forest carbon offset projects supported by the Coastal Conservancy

	Garcia Forest Reserve	Big River/Salmon Creek	Preservation Ranch (Buckeye Forest)
Acquisition	2003	2006	2013
Size (acres)	22,455	15,911	19,552
AGC stocks (million MtCO2e)	5.261	3.572	3.901
Net GHG reductions (MtCO2e)	102,161	91,213	98,559
GHG reductions (% AGC stocks)	1.94%	2.55%	2.53%

Figure 1.1

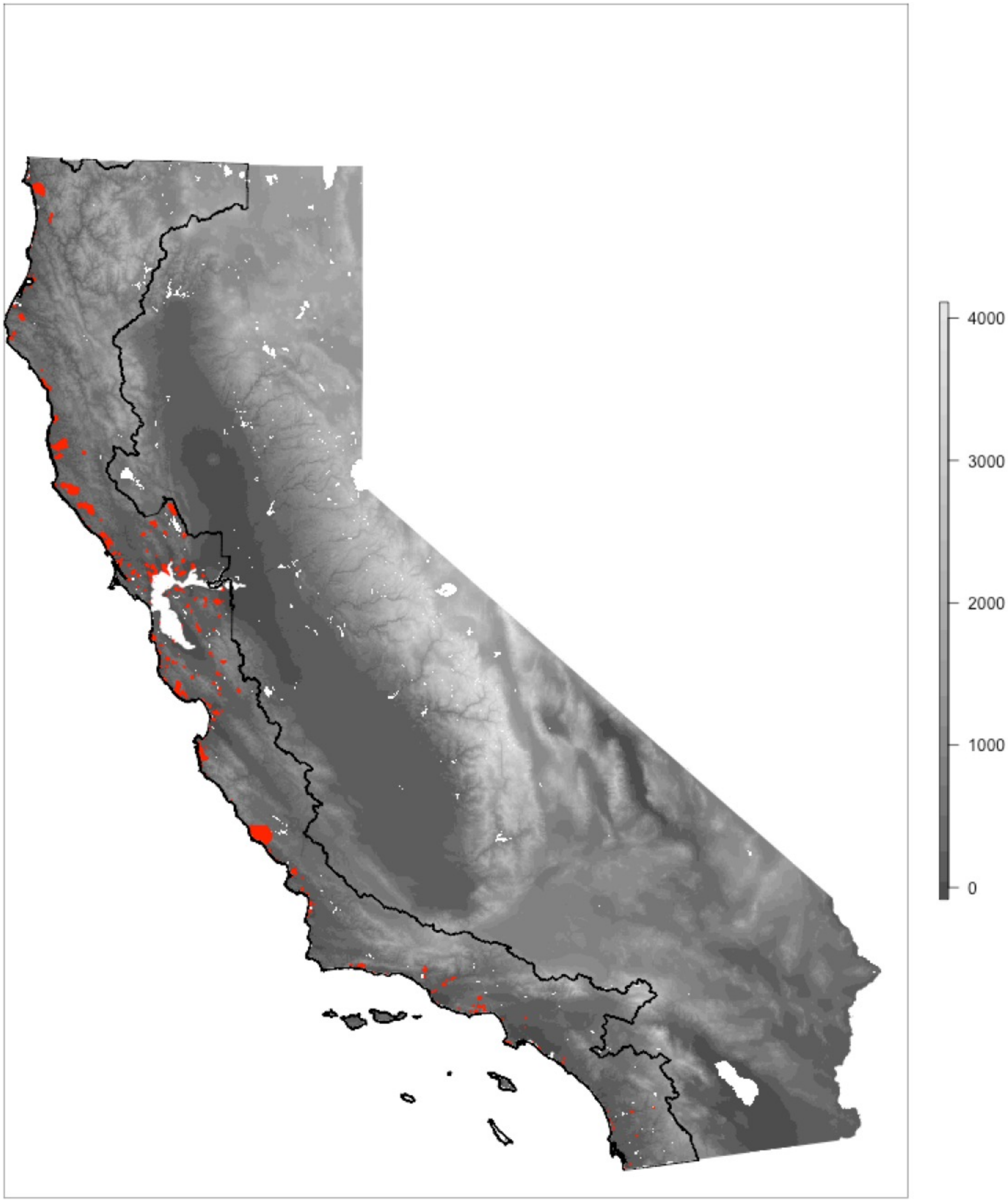

Fig. 1.1. Location of State Coastal Conservancy Properties (red) and legal jurisdiction (black outline). Background shows elevation (m).

Figure 1.2

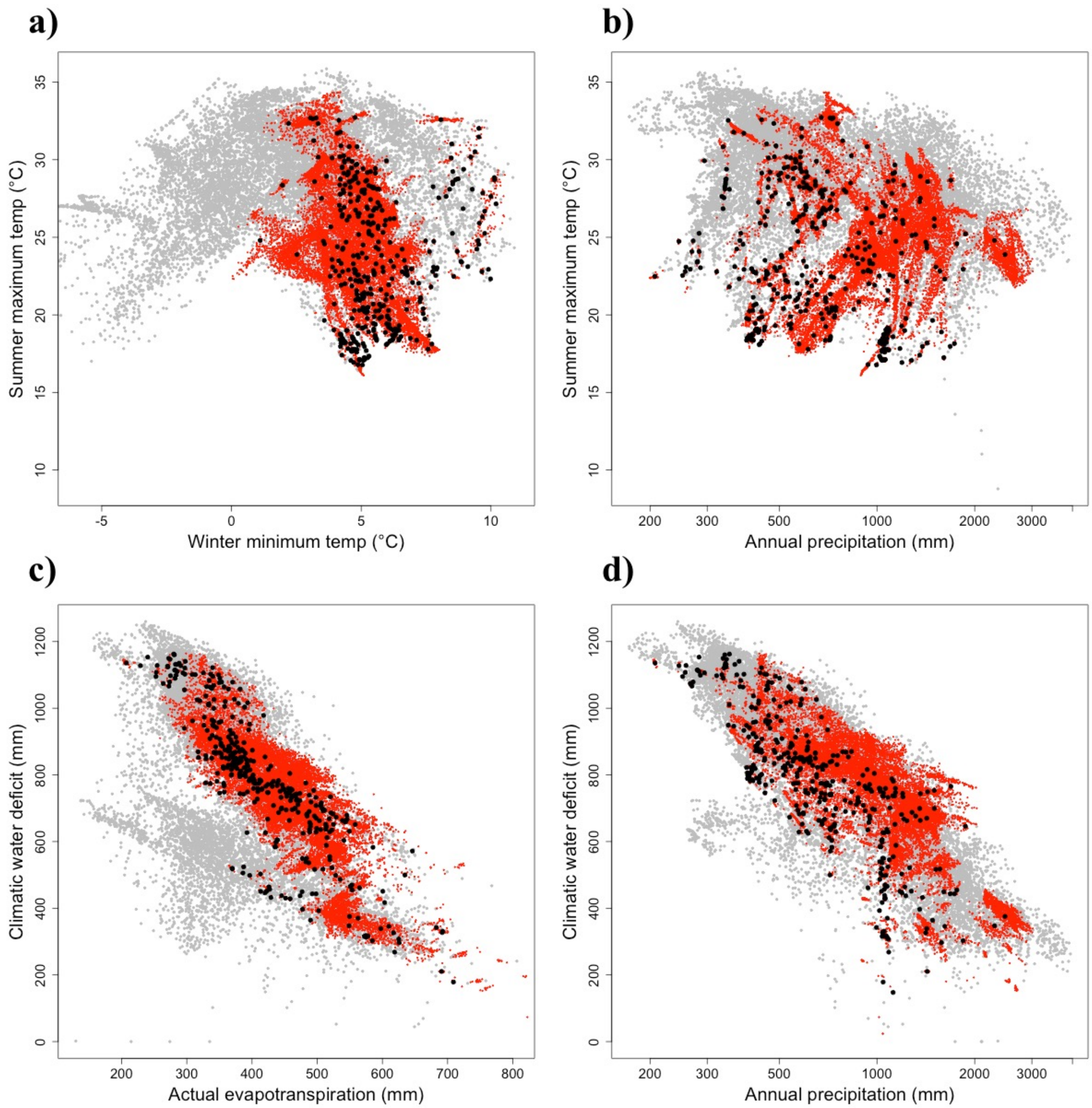

Fig. 1.2. Climate space for coastal California. In each panel, climate values for two different variables are extracted from maps and plotted against each other. Gray points: SCC jurisdictional area; red points: all pixels within SCC acquisitions; black points: averages for 358 acquisitions (50 acquisitions were too small to detect in GIS analysis). a) summer maximum vs. winter minimum temperatures; b) summer maximum temperature vs. precipitation; c) climatic water deficit vs. actual evapotranspiration; d) climatic water deficit vs. precipitation.

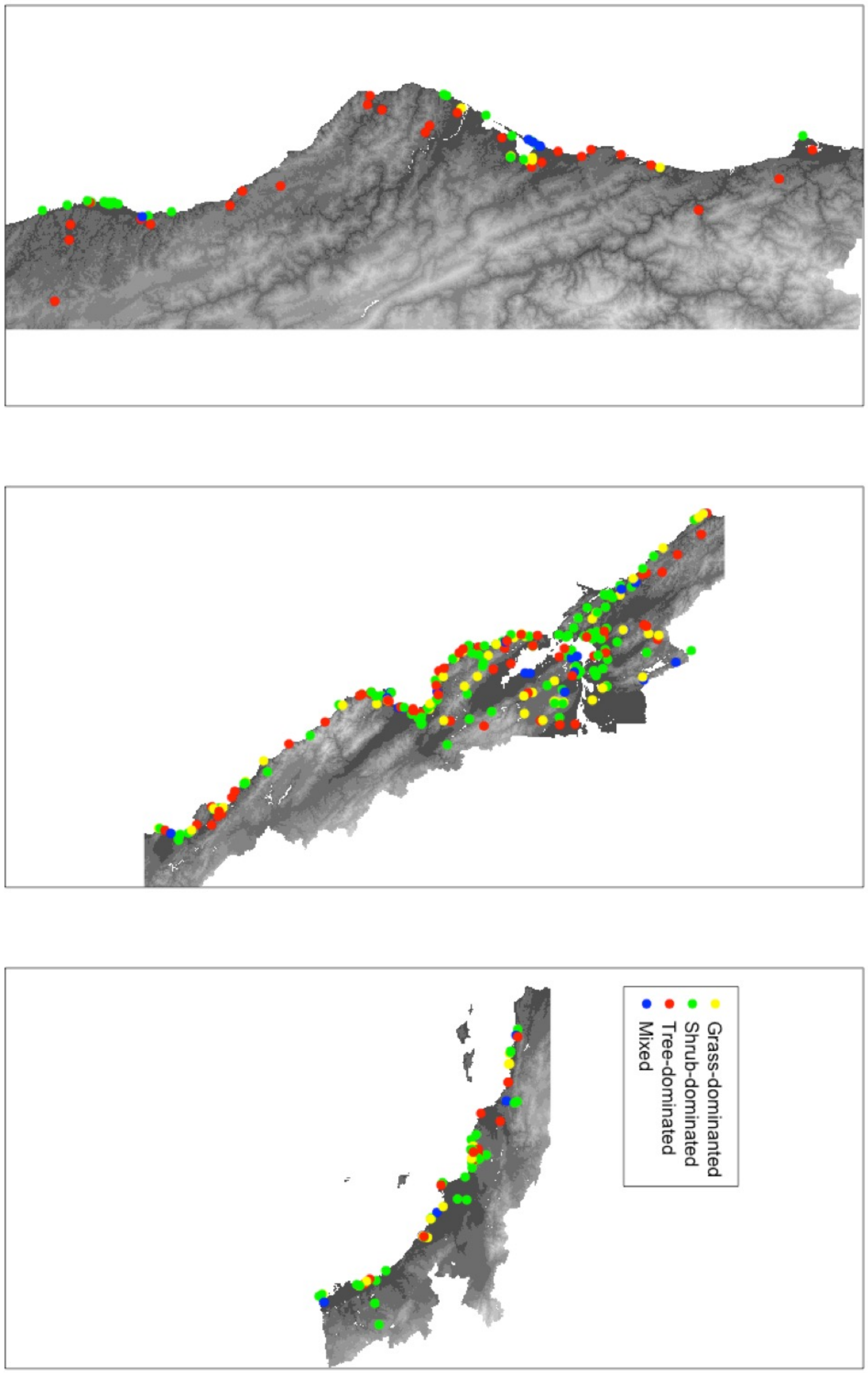

Figure 1.3

Fig. 1.3. Dominant vegetation types in each of the SCC acquisitions, broken up in spatial zones for visualization. Spatial scale is the same in all panels.

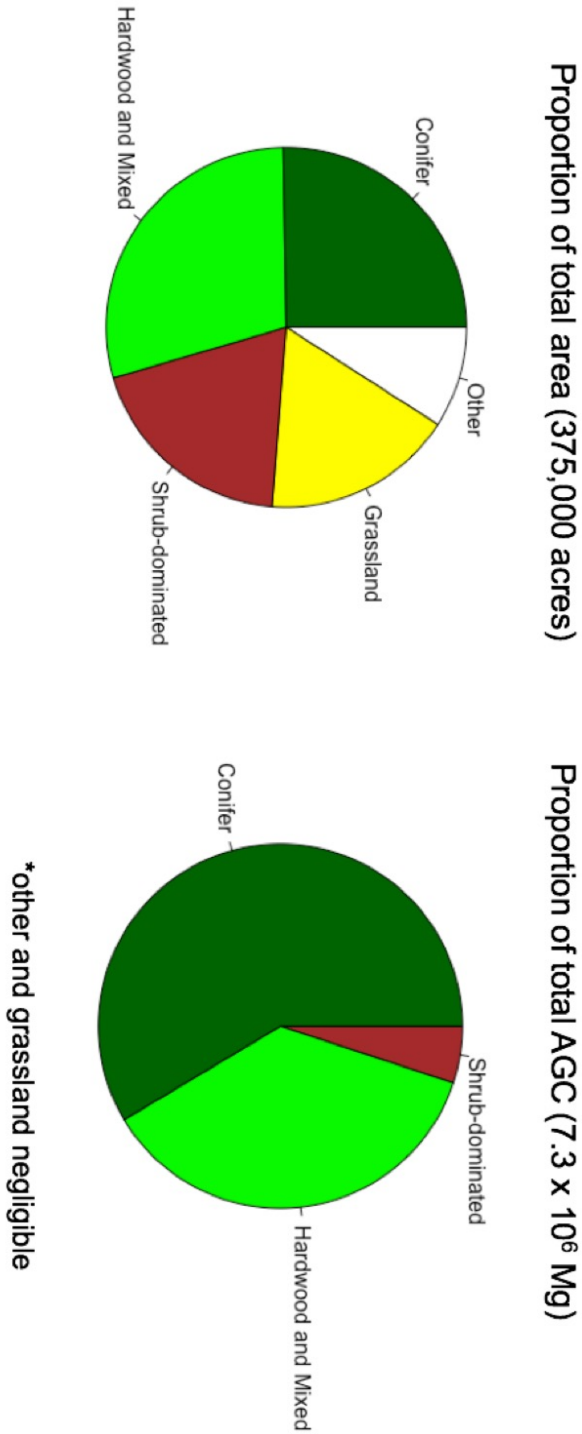

Figure 1.4

Fig. 1.4. Proportion of total area (a) and total aboveground C (b) among four major vegetation groups (‘Other’ refers to water and other non-vegetated areas).

Figure 1.5

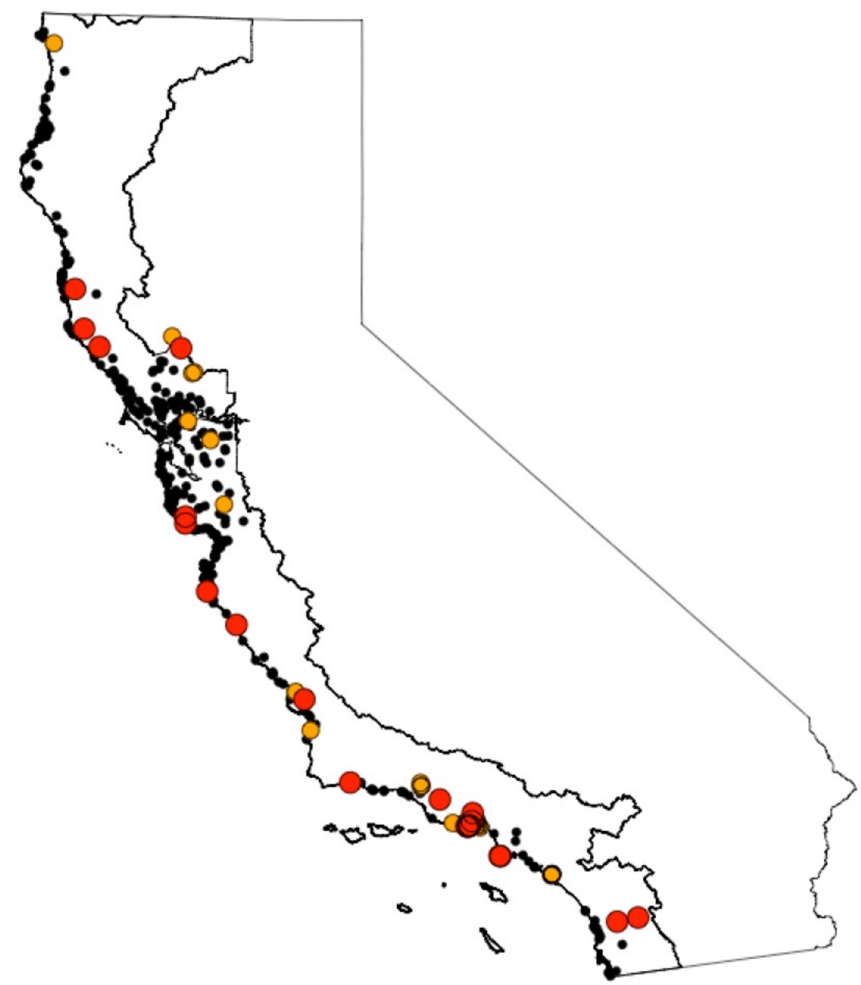

Fig. 1.5. Location of acquisitions that experienced wildfire between 1980-2015 (orange or red) and 2001-2010 (red).

Figure 1.6

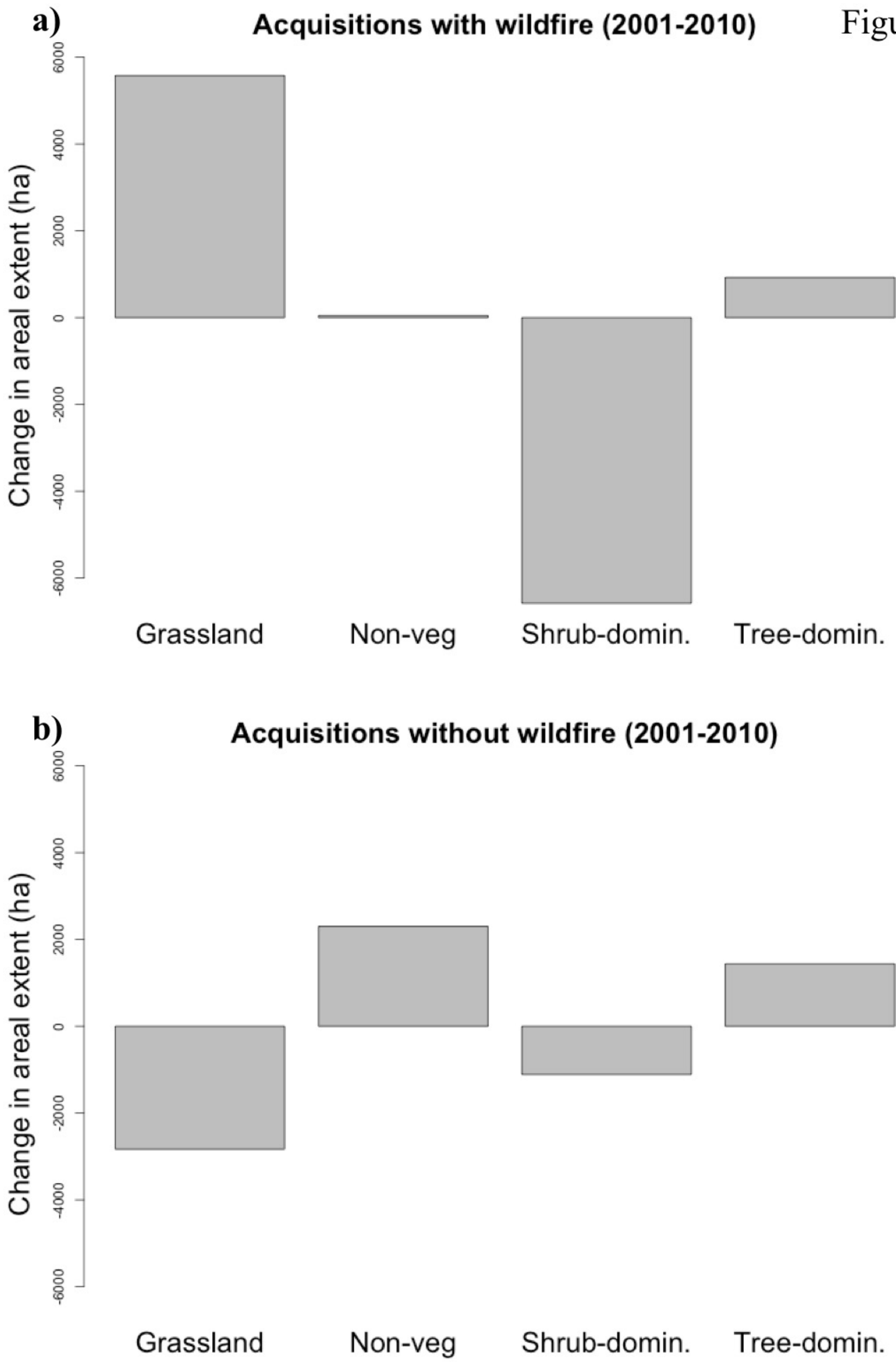

Fig. 1.6. Changes in areal extent of major vegetation classes in a) acquisitions that experienced at least one wildfire (2001-2010), and b) acquisitions that did not experience wildfire (2001-2010).

Figure 1.7

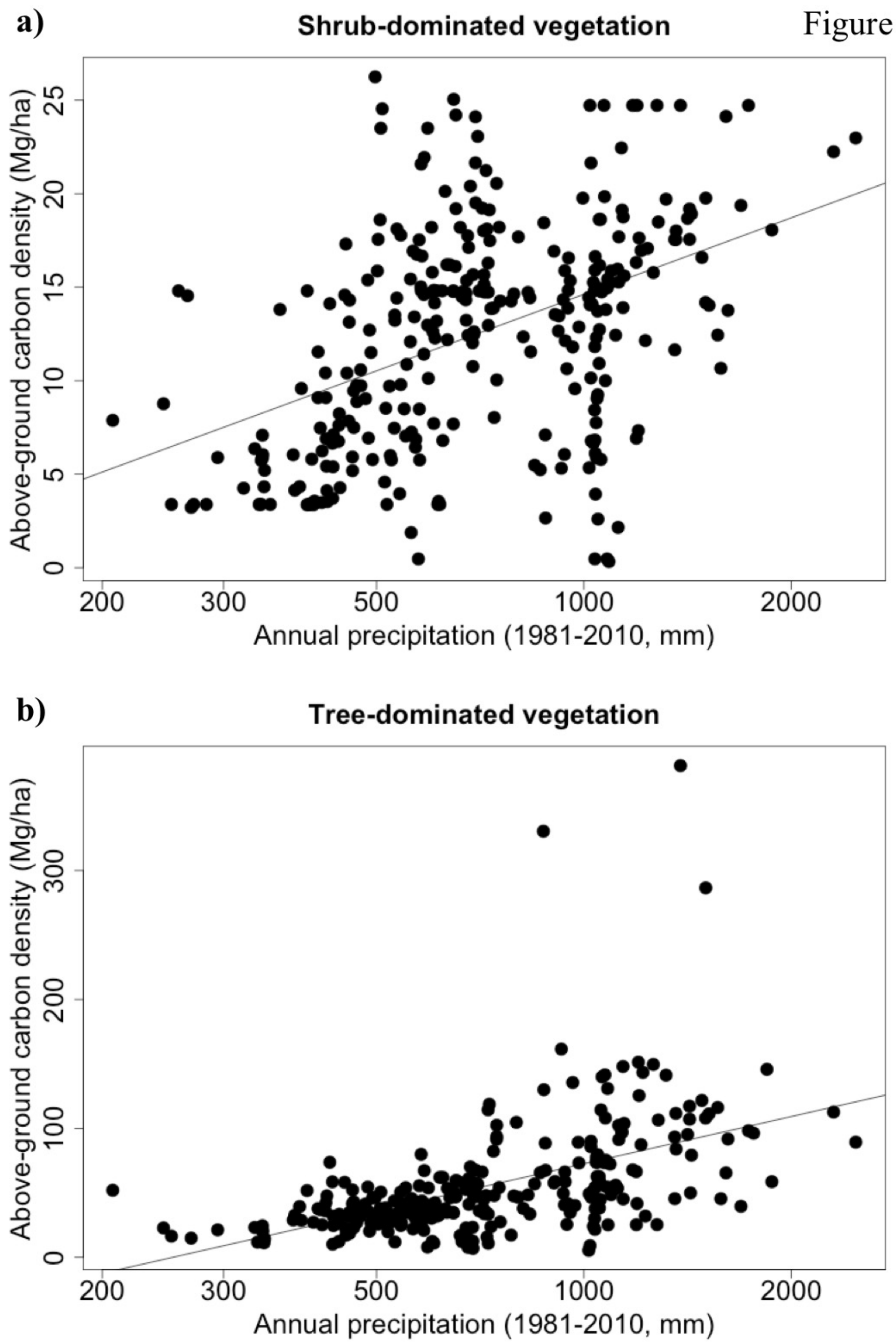

Fig. 1.7. Average carbon density of vegetation versus mean annual precipitation (1981-2010, mm). a) Shrub-dominated ecosystems; b) Tree-dominated ecosystems. Note differences in scale on y-axis.

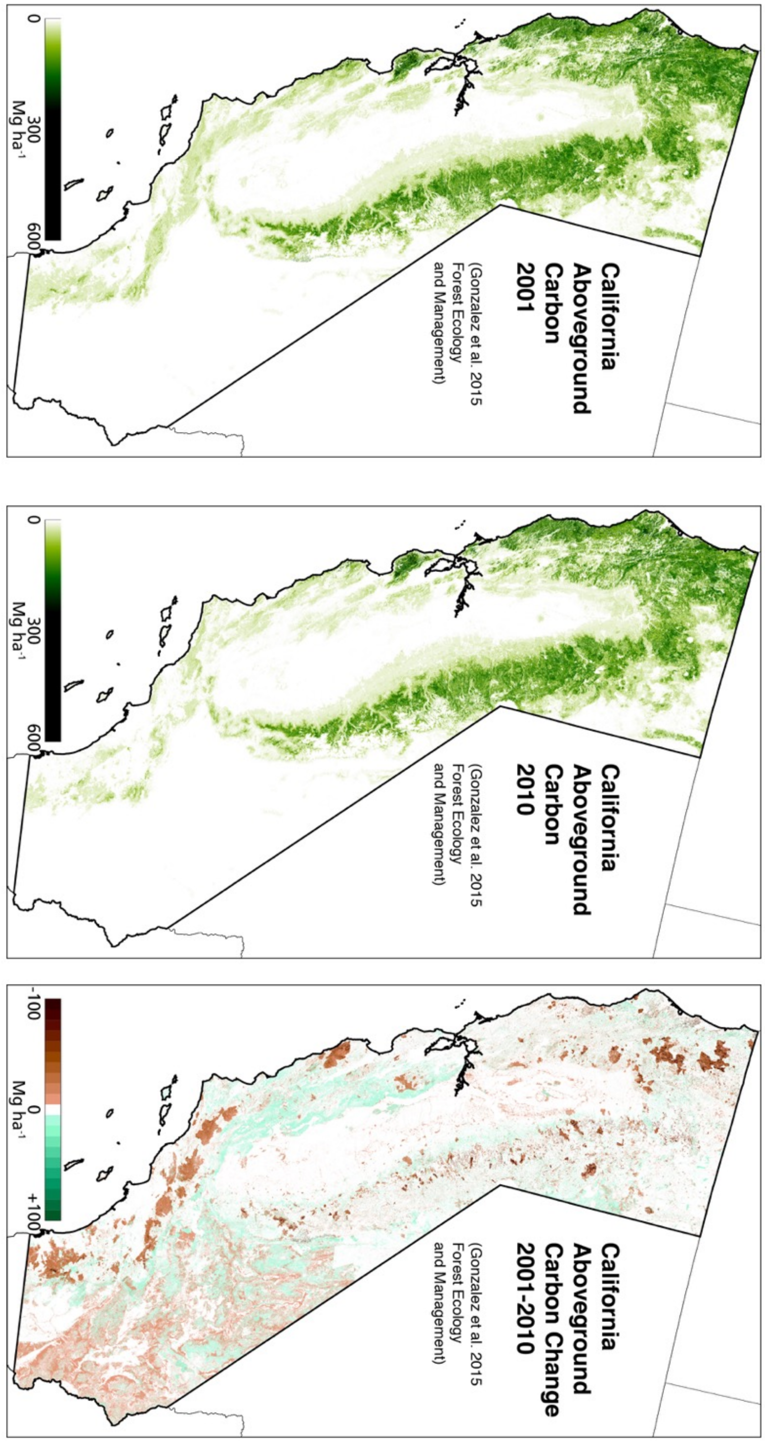

Figure 1.8

Fig. 1.8. Aboveground C stocks in 2001 and 2010, and change over the decade, for state of California. From Gonzalez et al. 2015

Figure 1.9

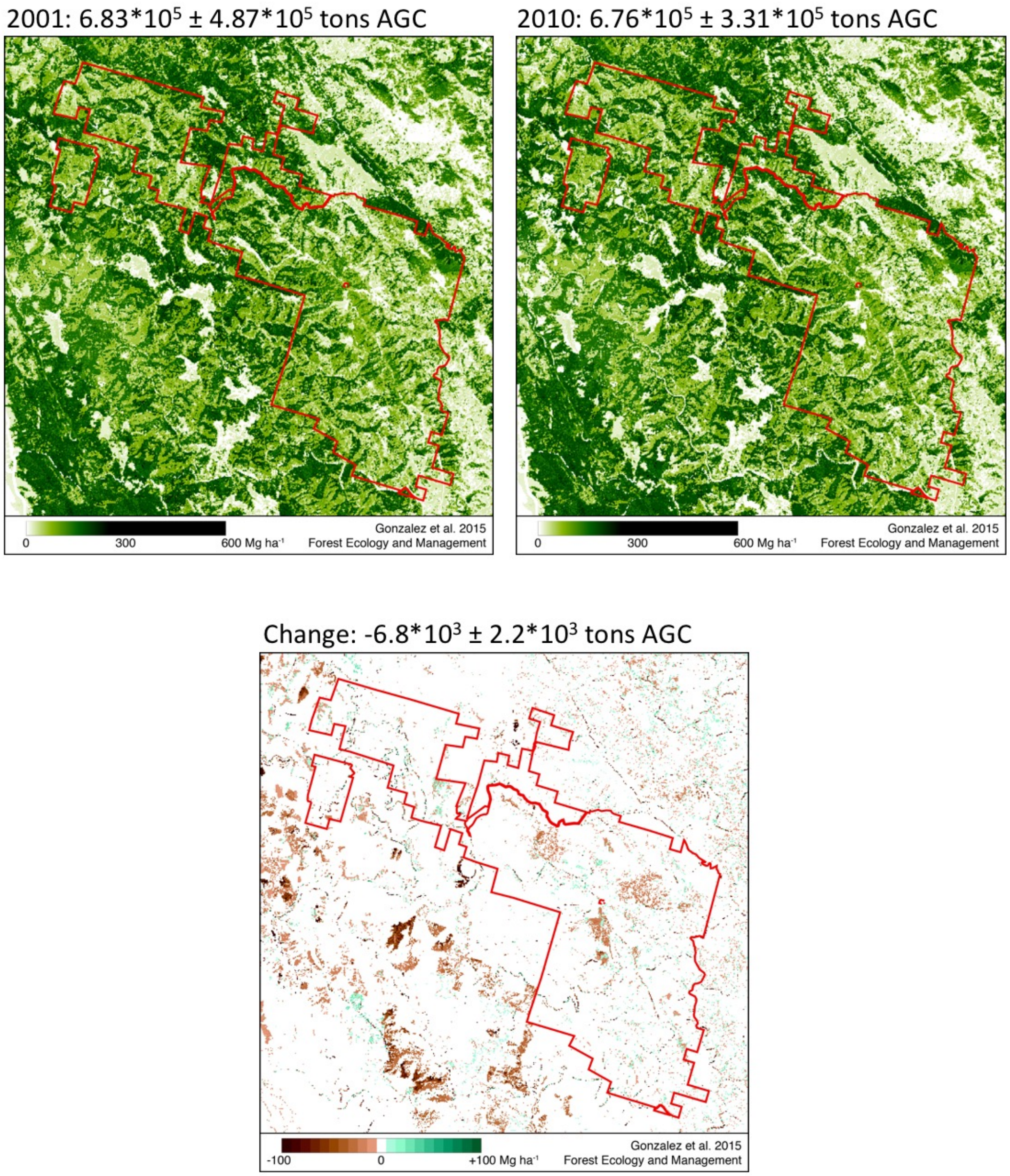

Fig. 1.9. Aboveground C stocks in 2001 and 2010, and change over the decade, for Preservation Ranch, Sonoma Co. illustrating analyses for individual acquisitions. From Gonzalez et al. 2015

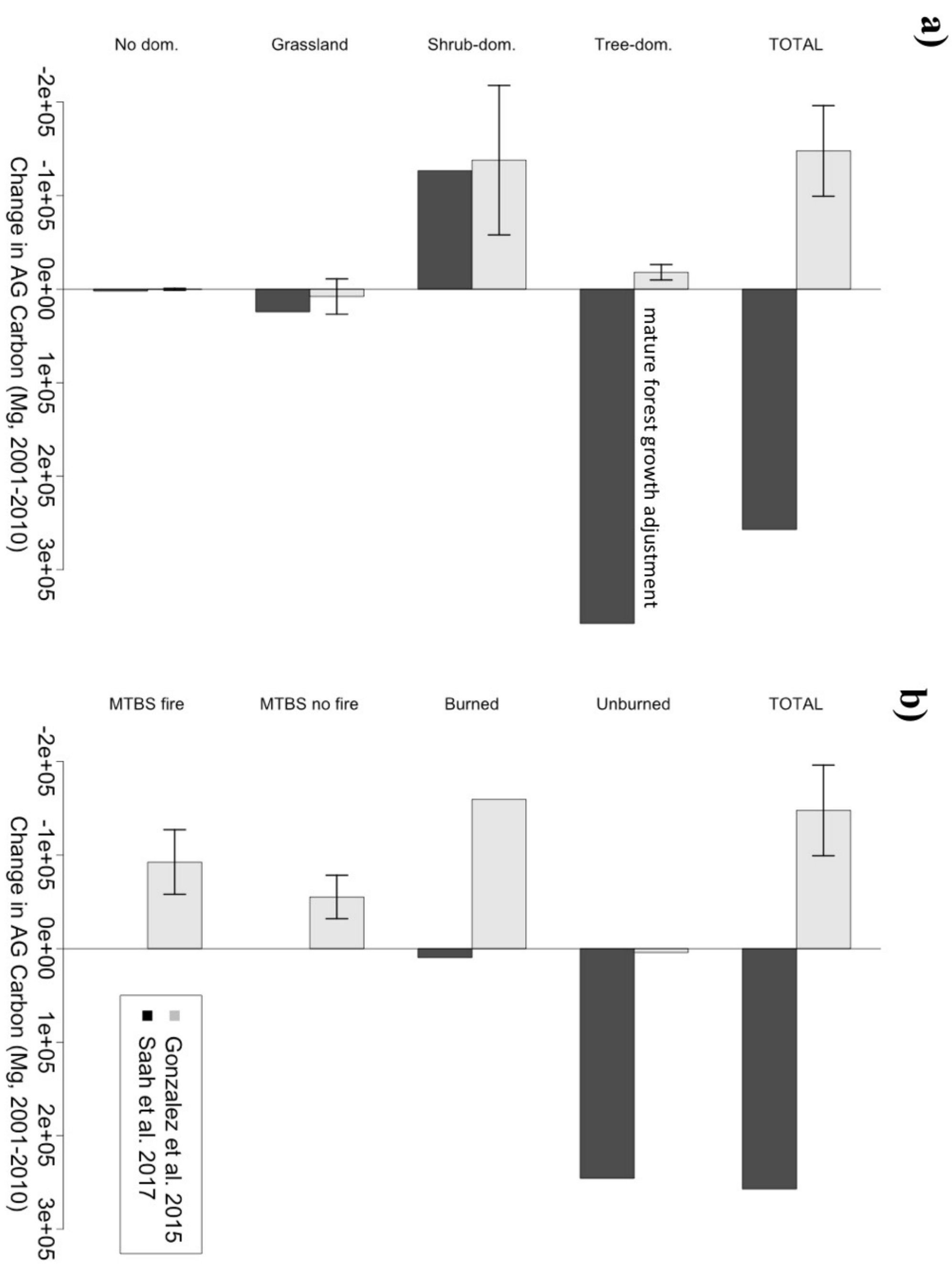
a)
No dom.
Grassland
Shrub-dom.
Tree-dom.
TOTAL
mature forest growth adjustment
-2e+05
-1e+05
0e+00
1e+05
2e+05
3e+05
Change in AG Carbon (Mg, 2001-2010)
b)
MTBS fire
MTBS no fire
Burned
Unburned
TOTAL
-2e+05
-1e+05
0e+00
1e+05
2e+05
3e+05
Change in AG Carbon (Mg, 2001-2010)
Gonzalez et al. 2015
Saah et al. 2017

Figure 1.10

Fig. 1.10. Change in total carbon stocks 2001-2010 for all SCC acquisitions (top row, a and b), for areas occupied by different vegetation types (a) and for burned vs. unburned areas (b). Error bars represent 95% confidence intervals where available for Gonzalez et al. (2015) analyses. a) Breakdown by major vegetation classes. 'No-dom.' = no-dominant vegetation or non-vegetated areas. b) Breakdown by burned vs. unburned areas. Rows 2 and 3 (from top): acquisitions that had one or more fires vs. no fires (2001-2010) with C change summed over the entire acquisition (including areas that may have been outside CalFire FRAP fire perimeters). Rows 4 and 5: pixel-level breakdown for areas burned vs. not burned based on national MTBS data set (not available for Saah analysis).

Task 2: Avoided Land Use Conversions and Above Ground Carbon Loss

Authors: Van Butsic, Diana Moanga, Isabel Schroeter

Development for residential and agricultural uses is a significant driver of land use change in California, and a major goal of Coastal Conservancy land acquisitions is to maintain open space by purchasing land threatened by development. Preventing conversions through land acquisitions may also lead to avoided C emissions if the baseline land cover (e.g., conifer forest) has more above ground C than potential converted land uses (e.g., residential development or vineyards). The goal here was to quantify the avoided land use conversions and the associated avoided emissions from above ground C created by Coastal Conservancy acquisitions.

Developing a counterfactual landscape

The first step in calculating avoided conversions and emissions is to develop a counterfactual scenario for each property. This scenario represents what would have happened if the Coastal Conservancy had not acquired the property. Developing counterfactual scenarios is an uncertain exercise since it is impossible to know exactly what would have happened if the Coastal Conservancy had not acted. Many methods exist for developing such scenarios including statistical modeling and scenario building. Here, to determine the counterfactual land use, we relied on detailed appraisal reports solicited by the Coastal Conservancy which described the "Highest and Best Use" (HBU) of each property. The HBU represents what a professional appraiser familiar with the property and the local land market believes the property would be used for in order to maximize economic rents. HBU's therefore are a good representation of what would have happened if the property had been used to maximize economic gains instead of being purchased by the Coastal Conservancy for the public good.

HBUs broadly describe land use (e.g., 300 acres of residential development and 200 acres of vineyard development would take place on a particular parcel), but typically do not describe precisely where the conversion would occur. Therefore, it is usually impossible to tell from the HBU alone what vegetation cover would be converted in the counterfactual. Since C emissions are dependent not only on the amount of land converted, but also the vegetation type converted, we estimated the vegetation type of the counterfactual conversion by assuming that conversions on each property would follow similar trends to conversions nearby.

For example, if the HBU called for 300 acres of residential development, we looked at all conversions to residential development between 2001-2011 within 50 km of the property and calculated the percent conversion from each vegetation type (i.e., 20% of all residential conversion was from conifer forest, 40% from grasslands, and 40% from deciduous forest). We then applied this to the counterfactual scenario such that 20% of residential development called for by the HBU on the SCC acquisition would come from conifer forest, 40% from grasslands and 40% from deciduous. This process was repeated for each property in our study for both residential development and agricultural lands (See Appendix 2A for more details on building the counterfactual scenarios). For this analysis, when lands converted to either residential development or vineyards, we assumed an above ground C value of 0.0 MG C/ha (i.e. all C is lost during development).

Avoided land use conversions and avoided above ground carbon loss

Overall, we developed counterfactual scenarios for 73 Coastal Conservancy properties which had detailed HBU's. These properties represented 284,133.25 acres (76% of all Coastal Conservancy holdings by area) with the largest parcel in our sample being the 80,733 acre Hearst Ranch and the smallest parcel the 307 acre Rancho Corral Acquisition. The mean property size was 3,894 acres and the median size was 1,293 acres.

Out of the 73 properties, the HBU of 16 of these properties was such that no conversions would have occurred, so none were avoided by acquisition. These properties fell into three main categories. First, there were properties where conversions to residential or agricultural uses were unlikely due the location of the property, steepness of the terrain, or the general unsuitability of a parcel for home development or agriculture. Second, a number of properties were best suited for continued timber operations and had no potential for residential development or agriculture. Third, on a number of parcels, the presence of endangered species coupled with strong local opposition to rural development created barriers to development that appraisers regarded as insurmountable. These properties actually would have been in high demand as rural residential lots, but the barriers to successfully gaining approval for development were so great that appraisers thought investment in the properties for such a purpose would be unlikely. For these 16 properties, we concluded that there were no avoided conversions or avoided emissions due to the Coastal Conservancy purchases.

There were 57 properties, covering a total of 238,002 acres that would have undergone some conversion to either agricultural or developed uses under the counterfactual scenario. Based on the counterfactual scenarios, a total of 13,859 acres (5.82% were prevented from converting to residential development or agricultural uses on these parcels, of which 6,867 acres were predicted to convert to development and 6,992 to agricultural uses.

A closer look at several properties reveals that Lauff's Ranch was the largest single property in terms of avoided conversions, with 3500 acres of conversion prevented (all from vineyard establishment) (Figure 2.1), while Hearst Ranch was the single largest location of avoided conversions to residential use with 1277 acres of residential development avoided (Figure 2.2). Preservation Ranch (Figure 2.3), the second largest property that would have been converted under the counterfactual scenario is one of the five properties (Hearst Ranch, North Point Ranch, Roche Ranch and Wildlake Ranch) that would have been converted to both residential development and vineyard production. As a percent of area, the properties with the largest avoided conversions were: Bahia Ranch (65.5% avoided), Gleason Ranch (41.9% avoided), Cowell Ranch (33.4% avoided) and North Point Joint Venture (32.3% avoided).

The avoided land use conversion for all 57 properties translates into $55 * 10^3$ Mg of avoided above ground C loss (1.35% out of a total of $4 * 10^6$ Mg total above ground C on the 57 properties). Sixty-three percent of all avoided above ground C loss came from two properties – Usal Forest Shady Dell ($25 * 10^3$ Mg) (Figure 2.4) and Montesol ranch ($12 * 10^3$ Mg) (Figure 2.5) – properties with both high development potential and vegetation with extremely high C density. Lauff's Ranch, which had the largest area of avoided conversions had only the fourth most C avoided and had only 7% of the avoided C as Usal Forest Shady Dell, despite contributing 2872 more acres of avoided conversion. The top 8 properties in terms of lost above ground C under the counterfactual scenario are: Usal Ranch, Montesol Ranch, Cemex Redwoods, Lauff's Ranch, Wildlake Ranch, North Point Ranch, Roche Ranch and Bahia Ranch (Figure 2.6). In terms of percent of vegetation cover lost and percent carbon lost we found that the properties that have the highest percent of vegetation cover lost do not necessarily also have the highest percent of carbon lost under the counterfactual scenario (Figure 2.7).

Discussion

Overall, the low avoided C loss (1.35% of all potential C) relative to avoided conversions (5.82% of all potential acres) is likely driven by two factors. First, the highest C ecosystems in the Coastal Conservancy's portfolio are located along the North Coast where there is less demand for residential development, and agricultural production is generally low. Therefore, there are fewer overall avoided conversions in these ecosystems than in areas closer to urban centers, or in areas with potential for high value vineyards. Second, even on properties with high C ecosystems, past conversions show that developers have a preference for converting grasslands rather than higher C ecosystems. In the properties we analyzed, over 60% of all conversions occurred on grasslands while another 17% take place on chaparral. In concert then, both low demand for conversion in high C ecosystems coupled with a preference for converting low C areas in all ecosystems, means that the total effect of Conservancy purchases on avoided C loss is modest.

One area of uncertainty in our analysis is the assumption that above ground C is 0.0 Mg C/ha after conversion to residential development and vineyards. This estimate will be approximately true immediately after conversion, but as yards and vineyards mature, above ground C stocks will increase over time in most situations. While highly variable, above ground C can be substantial on developed lots where trees have been planted. For instance, urban forests in coastal California have C densities averaging > 15 Mg C/ha, with values as high as 35 Mg C/ha in Marin County (Bjorkman *et al.*, 2015). Likewise, mature vineyards can contain over 4 Mg C ha^{-1} (Carlisle *et al.*, 2010). Both of these values are greater than average above ground C values for grasslands and some shrublands. Therefore, avoided conversions from grasslands and shrublands may actually have a negative impact on long term above ground C stocks, since residential development and vineyards can actually have more above ground C than these natural systems.

Another area of uncertainty is that we do not know if the avoided conversions eventually took place somewhere else on the landscape and if so where. When a Coastal Conservancy acquisition prevents conversion in one area, it does not decrease the overall demand for housing or agricultural lands. Therefore, this demand many simply manifest somewhere else on the landscape causing conversions in other places. However, it is also true that by decreasing the supply of land for housing and agriculture, local prices for land may go up, reducing demand and potential conversions. These competing forces make it unclear how much, if any, of the avoided conversions took place in other locations. Likewise, if some conversions did happen, we do not know if these conversions happened in places with higher or lower carbon density. We also do not know if these conversions took place in areas that would lead to greater emissions through vehicle miles traveled. Given these uncertainties, it is important to interpret our results as only the direct impacts of property acquisition. The indirect consequences discussed here are not calculated in this study.

It is important to note that while our study looks only at avoided C loss through avoided land use conversions, but there are other ways in which Coastal Conservancy parcels can impact C storage that were not modeled here. Most significantly, we do not address how changes in forest and range management brought about by Conservancy ownership may increase above ground C stocks. Given the magnitude of changes in C stocks possible via different forest management strategies (project 1, above), as well as the large potential for increased C storage in grasslands (project 3, below), the Coastal Conservancy may make more substantial contributions to increasing C stocks in California via ecosystem management, rather than avoided emissions of above-ground C.

Indeed, a number of the Coastal Conservancies most iconic purchases are of carbon dense redwood forest in the northern part of the state. These forests are some of the most carbon dense in the world, and the additional carbon that can be sequestered under optimal management is substantial. For instance, experiments along the North Coast have shown that redwood stands optimally managed for carbon sequestration can increase sequestration rates by over 40% vs non-optimal management (Jones & O'Hara, 2012). In addition, management to prevent wildfire in these carbon rich areas can substantially limit emissions. Therefore, it may be that the greatest impact the Coastal Conservancy can have on carbon sequestration is through management.

Task 2 - Figures

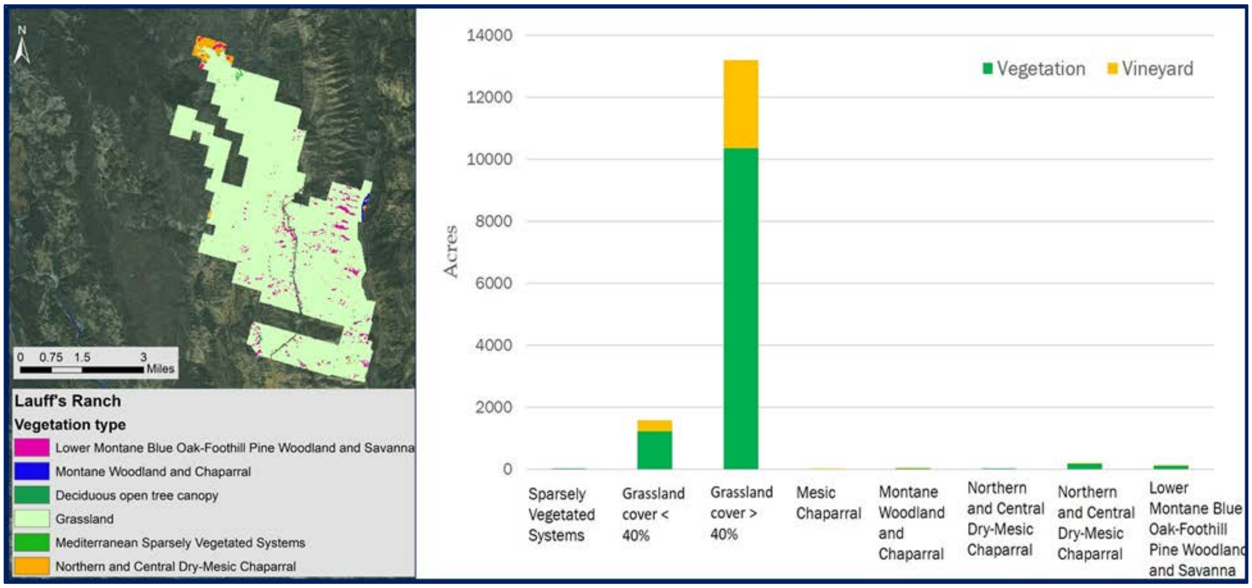

Figure 2.1. Lauff's Ranch vegetation cover (left), and land cover under counterfactual (right).

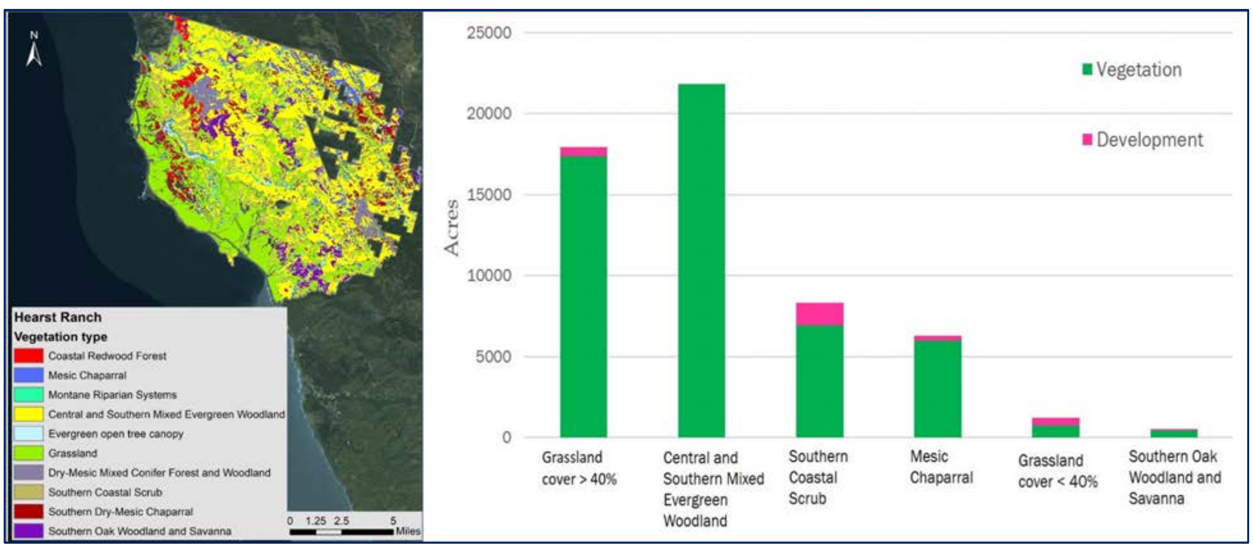

Figure 2.2. Hearst Ranch vegetation cover (left) and land cover under counterfactual (right) (showing only 6 land cover classes).

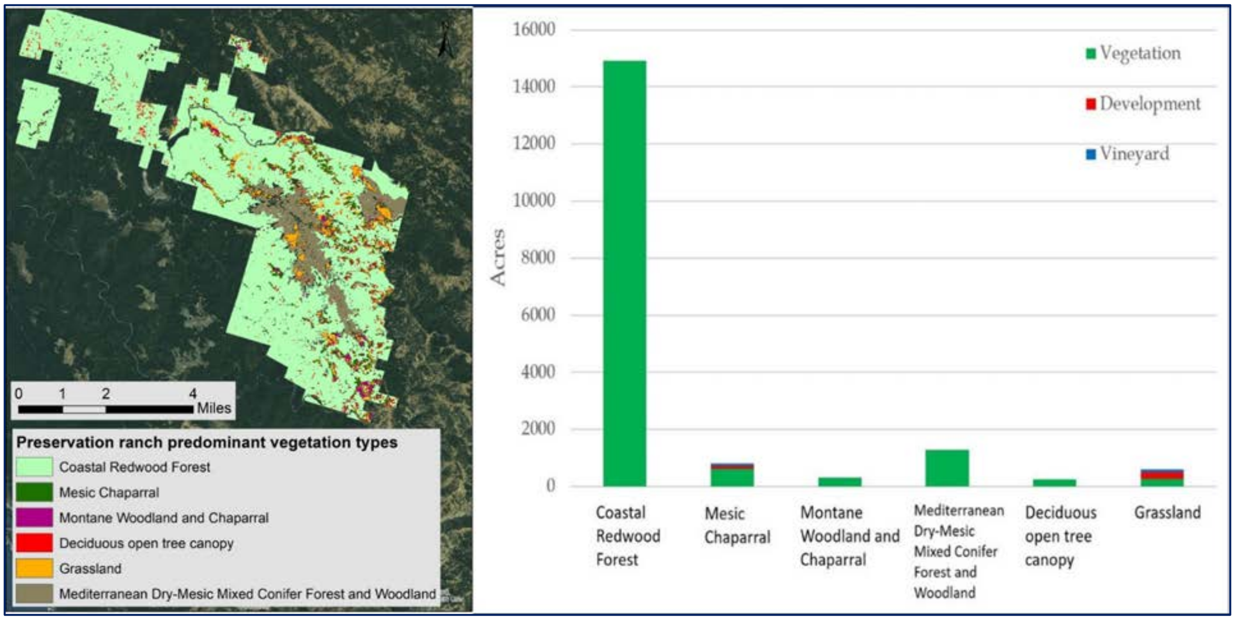

Figure 2.3. Preservation Ranch vegetation cover (left) and land cover under counterfactual (right) (showing only 6 land cover classes).

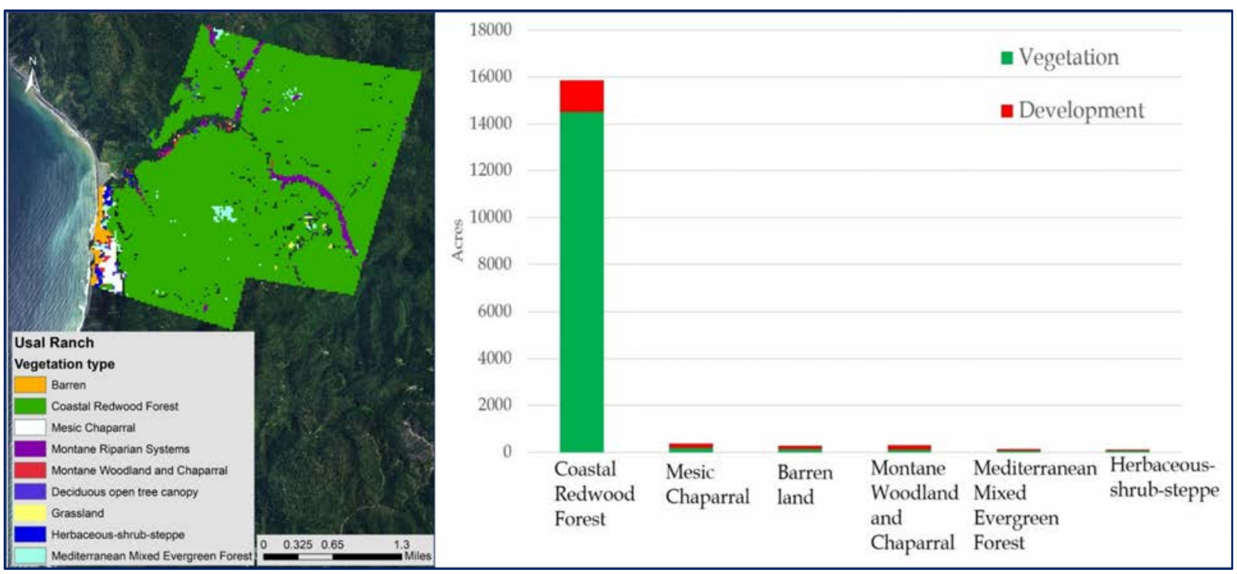

Figure 2.4. Usal Forest Shady Dell Acquisition vegetation cover (left) and land cover under counterfactual (right) (showing only 6 land cover classes).

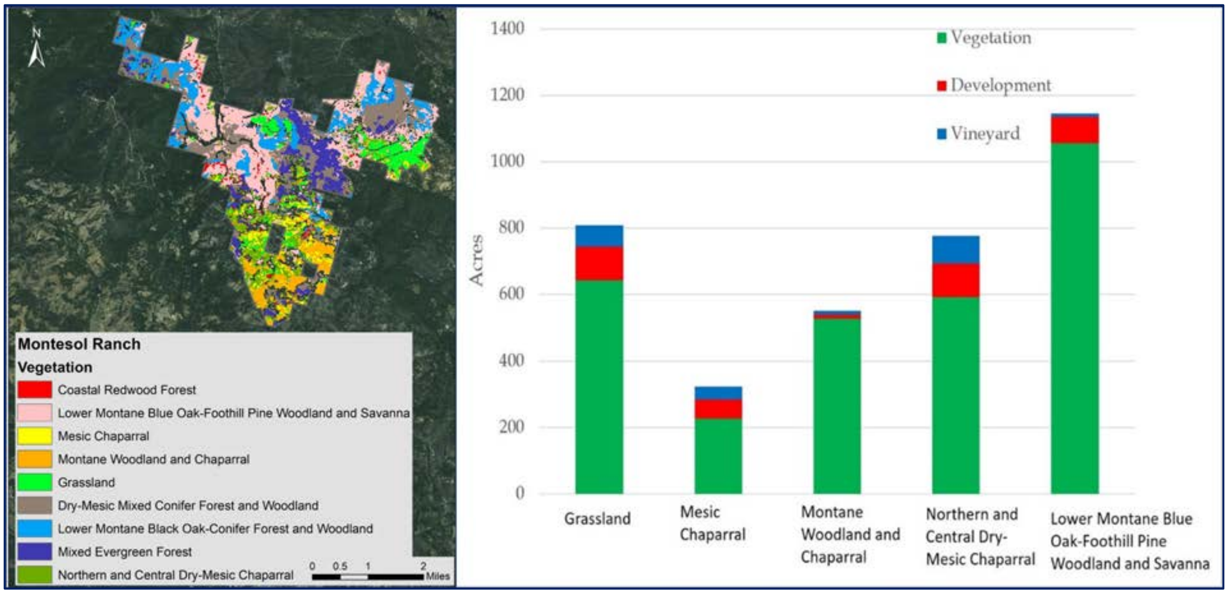

Figure 2.5. Montesol Ranch vegetation cover (left) and land cover under counterfactual (right) (showing only 6 land cover classes).

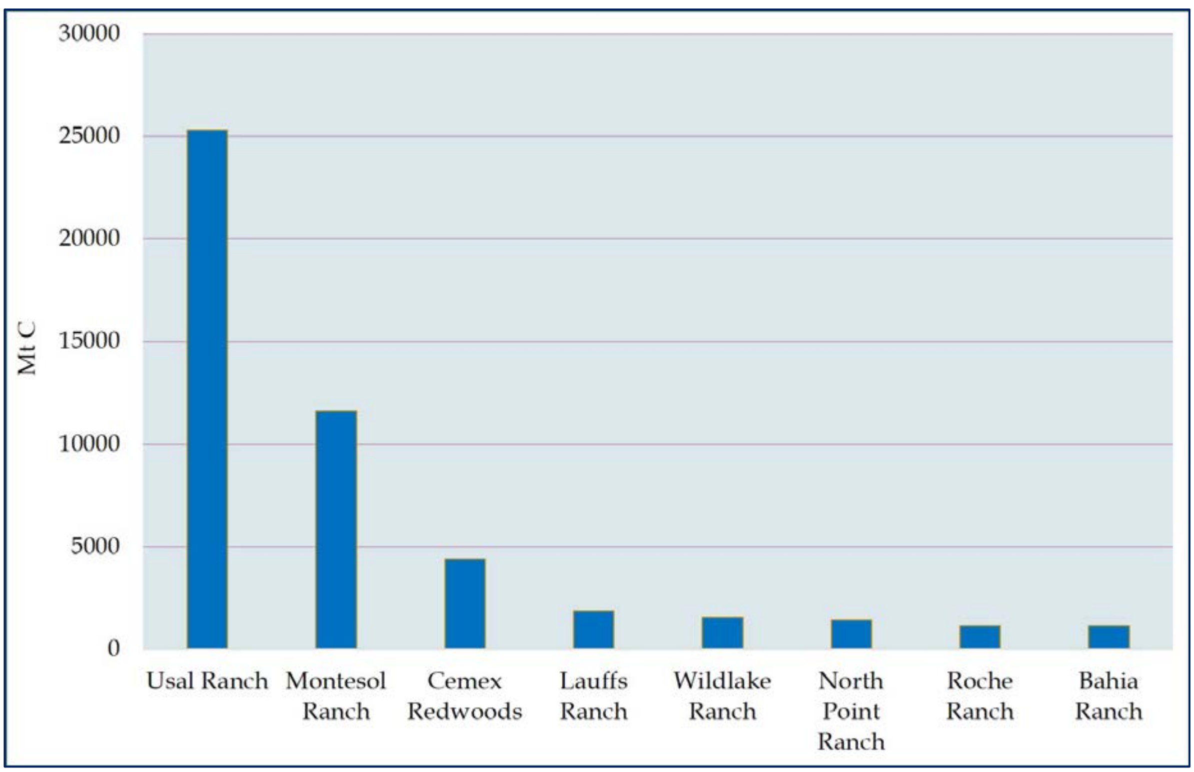

Figure 2.6. Top 8 properties in terms of carbon lost under the counterfactual scenario.

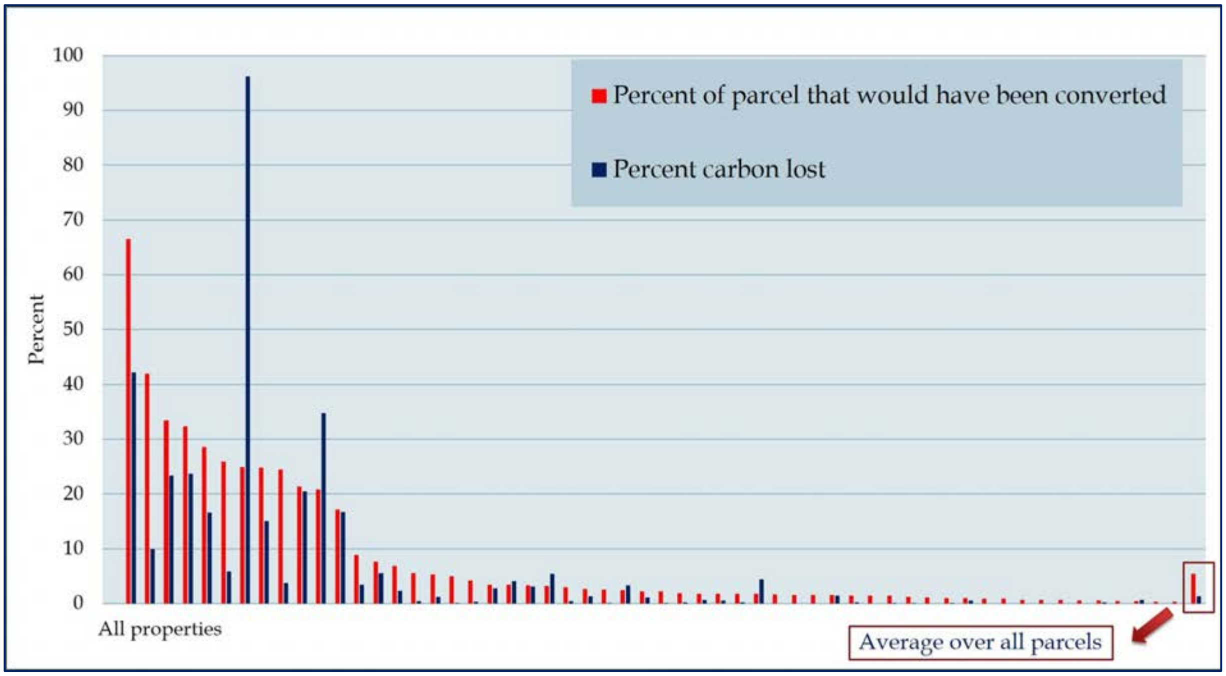

Figure 2.7. Perfect of parcel that would have been converted to agricultural or developed uses (red), and percent carbon loss (blue) for all studied properties.

Task 3: Potential for Soil Carbon Sequestration Through Rangeland Management

Authors: Allegra Mayer, Whendee Silver

Summary

While progress is being made toward emissions reductions, achieving the international warming target of no more than 2 °C by 2100 will require active removal of carbon dioxide from the atmosphere. This research explores the potential for rangeland soils and ecosystems to sequester soil carbon (C) and mitigate climate change over time. We parameterized a site-level biogeochemical model (DayCent) to measure and predict the effect of compost applications on rangeland productivity and soil C. In this report, we compare the results of the DayCent model from four sites within the Coastal Conservancy jurisdiction along a coastal climate gradient from San Diego, CA in the south to Mendocino, CA in the north, and model the impact of climate change under a high emissions scenario and reduced emissions scenario on the C cycle at these sites. Model results show that a single application of compost leads to a net increase in soil C for decades across all four sites.

Maximum soil C sequestration relative to control simulations occurred approximately 15 years after a ¼ inch compost was applied to the land, resulting in a maximum net C drawdown of 6.6 Mg CO2eq/ha (Mendocino) to 5.5 Mg CO2eq/ha (Marin) by 2030 and a continued climate benefit from enhanced C storage through the end of the century. Compost application resulted in enhanced soil C in both climate scenarios, but the reduced emissions climate scenario resulted in greater net C storage than the high emissions scenario by 2100. This points to a virtuous cycle in which emissions reductions at a global scale increase the value of land-based mitigation strategies, such as compost addition.

Introduction

Anthropogenic greenhouse gas emissions have resulted in increased global surface temperatures in the last century (Hartmann *et al.*, 2013). Slowing this warming trend will require both drastic emissions reductions as well as the active drawdown of carbon (C) from the atmosphere (Gasser *et al.*, 2015). Land management approaches that increase plant growth and/or add C directly to soils have the potential to increase soil organic carbon (SOC) storage. Field studies from managed grasslands in Marin and Yuba counties showed that a one-time addition of compost can have a lasting and climate-beneficial impact on plant productivity and soil C storage (Ryals & Silver, 2012; Ryals *et al.*, 2014).

Here, we used the DayCent biogeochemical model to explore the effects of compost application across a latitudinal and climate gradient along the coast of California. The model simulates grassland productivity and the movement of C between soil, vegetation, and the atmosphere over time and under different climate and management conditions.

These simulations explored:

- how management (a one-time compost addition) affects long term production and soil C storage in a range of California coastal rangelands
- how environmental variables (background climate) influence the effect of management changes

- how projected future climate change influences soil C storage, and how compost application impacts C dynamics under potential future climate conditions

Site descriptions

We parameterized the model using four grassland sites within the Coastal Conservancy Jurisdiction that are representative of a range of California's coastal climates. These four sites are part of a larger NRCS and UC Berkeley field experiment where compost was applied in fall of 2016 to plots in these and 12 other sites. Compost application at the Marin site took place in 2008. The field results will eventually be used to validate the model results from this study. All sites were managed rangelands and have been grazed for most of the last century. The four coastal sites have a Mediterranean-type climate (cool, wet winters and warm, dry summers), and are dominated by nonnative annual grass and forb species. The Mendocino site is in Covelo, CA (39.84°N, 123.257°W) with soil classified as Cole loam Argixeroll (Mollisol). The Marin site is in Nicasio, CA (38.06°W, 122.71°N) in the Tocaloma-Saurin-Bonnydoon soil series classified as a Typic Haploxeroll (Mollisol). The Santa Barbara site is in Los Olivos, CA (34.71°N, 120.13°W); soils are a Ballard gravelly fine sandy loam, classified as a Typic Argixeroll (Mollisol). The San Diego Site is in Santa Ysabel, CA (33.15° N, 116.69° W), at higher elevation (1,135 m) compared to the other sites. The soil is Holland fine sandy loam, characterized as an Ultic Haploxeralf (Alfisol). Additional site characteristics are described in Table 3.1.

Table 3.1: Characteristics of modeled sites

Site	Observed ANPP (Mg C/ha)	Observed bulk SOC (Mg C/ ha)	% Clay (0-30cm)	% Sand (0-30 cm)	Historic 30 yr mean annual precip. (cm)	Mean minimum daily temp. (°C)	Mean maximum daily temp. (°C)
Mendocino	0.6 - 0.9	29.55	16	49	108	4.6	22.3
Marin	1.0 - 2.0	40.95	27	44	97	8.3	20.0
Santa Barbara	0.4 - 0.9	21.07	9	67	38	8.0	25.1
San Diego	0.8 - 1.0	15.03	16	66	67	7.2	21.0

Methodology

DayCent (Parton *et al.*, 1998) was used to simulate climate and management driven changes in each rangeland system. The model is driven with site-specific historic climate data, as well as measured soil texture, bulk density, and annual forage production values. The model simulations were run for a 3,000 year period for each site using the measured soil texture values and assuming perennial grassland coverage to achieve steady state values for the C pools, before running perturbation simulations. Simulations of future conditions were driven by daily climate data extracted from the CanESM2-ES Earth System Model, one of the four models recommended by the California 4th Climate Assessment for analyses of climate impacts in

California, and the one that is closest to the average of projected climates across the ensemble of future models. We used the Representative Concentration Pathway (RCP) 4.5 scenario (assuming some emissions reductions) and the RCP 8.5 scenario (assuming minimal emissions reductions) extracted for the site-specific (2.8°x 2.8°) geographical grid of the CanESM2-ES Earth System Model. For each climate scenario, we ran a control run assuming that current management continued throughout the century. We also did a simulation with a compost trial consisting of a one-time ¼ inch addition of compost to the site. The compost addition replicated the actual management of the NRCS/UC Berkeley field experiment, which used a compost composed of a mixture of greenwaste, cow manure, and goat manure. The compost amendment added C at a rate of 640 g C/m^2 (6.40 Mg C/ha) with a C:N ratio of 17.6.

Results

Climate Change

Under the RCP8.5 scenario of the CanESM2-ES climate model, projections for mean annual precipitation exhibit increases across the 21^{st} century (comparing 2000-2010 to 2090-2100), ranging from an additional 150 mm/yr in Mendocino to an additional 250 mm/yr in Marin (Fig. 3.1). Under RCP8.5, three out of four sites also experience a substantial increase in precipitation variability at the end of the century (Figure 3.1**)**. The standard deviation of interannual precipitation increased by 50-85% in Marin, San Diego, and Santa Barbara, while Mendocino experienced only a small change. Standard deviation in daily precipitation did not increase over the century under RCP4.5, except in Marin which is projected to experience a modest increase. Mean minimum temperatures were also affected by climate change, with values increasing by just under 2°C in the RCP4.5 scenario, and up to 5°C in the RCP8.5 scenario. Maximum temperature was largely unaffected by climate change at these sites.

Effect of compost

A one-time application of compost in 2016 (or 2008 for the Marin site) resulted in enhanced soil C in all three of the soil C pools: the active pool (turnover time of days to one year), the slow pool (turnover time from decades to one century), and the passive pool (turnover time from centuries to millennia) (Figure 3.2**)**. The effect on soil C was dominated by an increase in the slow carbon pool. Values exceeded baseline scenarios at all sites and all pools for the entire period of analysis. The increase in the slow C pool was greater in RCP 8.5 than in the RCP 4.5 scenario during the first few decades after compost addition. In 2030, the Mendocino site had 1.63 Mg C/ha and 1.84 Mg C/ha more in the compost treated soils than in the control for the RCP 4.5 and 8.5 scenarios, respectively. The smallest difference was seen in Santa Barbara, which also peaked in 2030 with a maximum increase of +1.54 Mg C/ha in the composted compared to the control simulation.

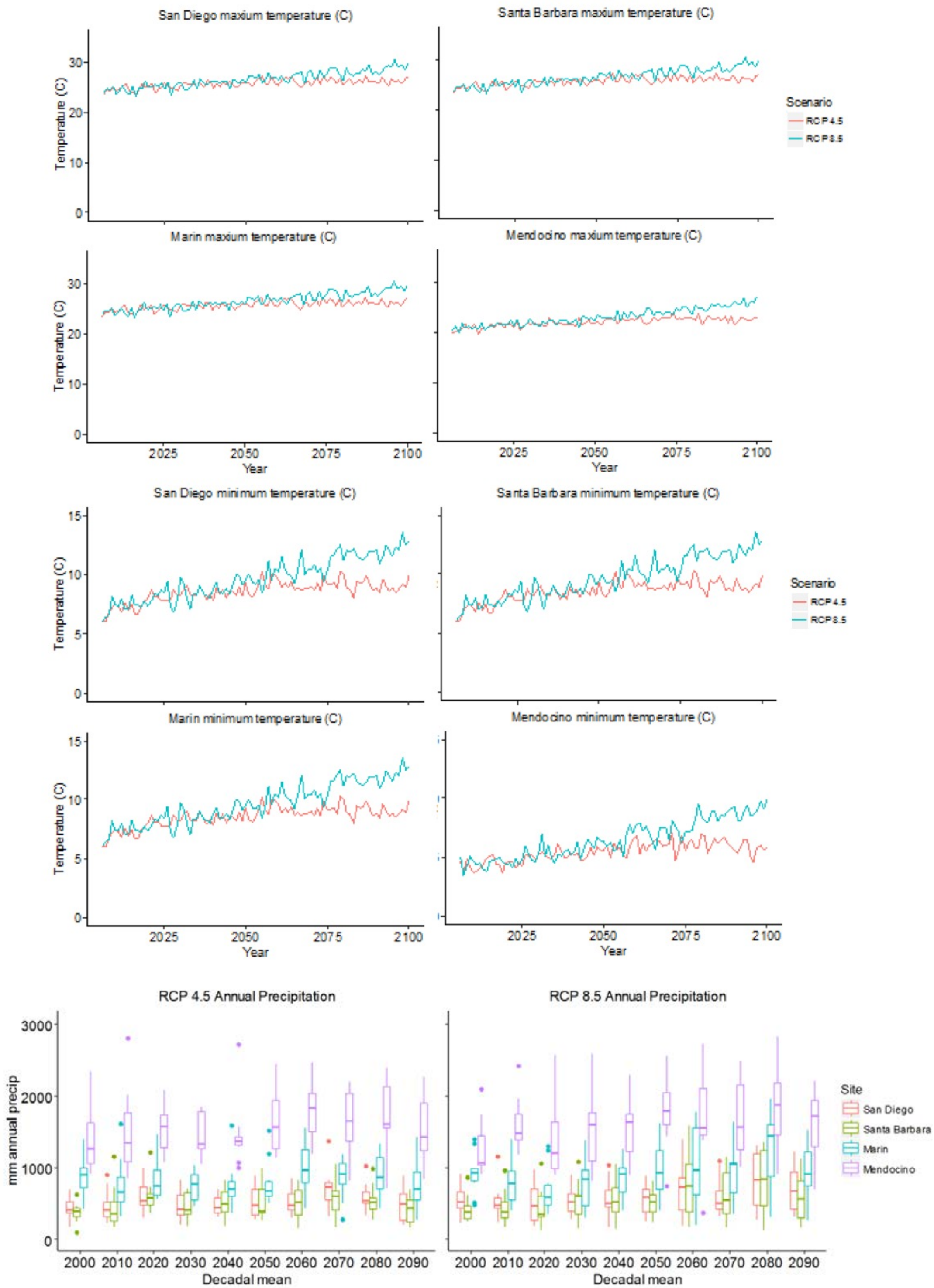

Figure 3.1: Projected climate change in the next century under the CanESM2-ES climate model, resulting in increased annual precipitation at all coastal sites. Precipitation and minimum temperature becomes more variable in the high emissions scenario (RCP 8.5) compared to a reduced emissions scenario (RCP 4.5).

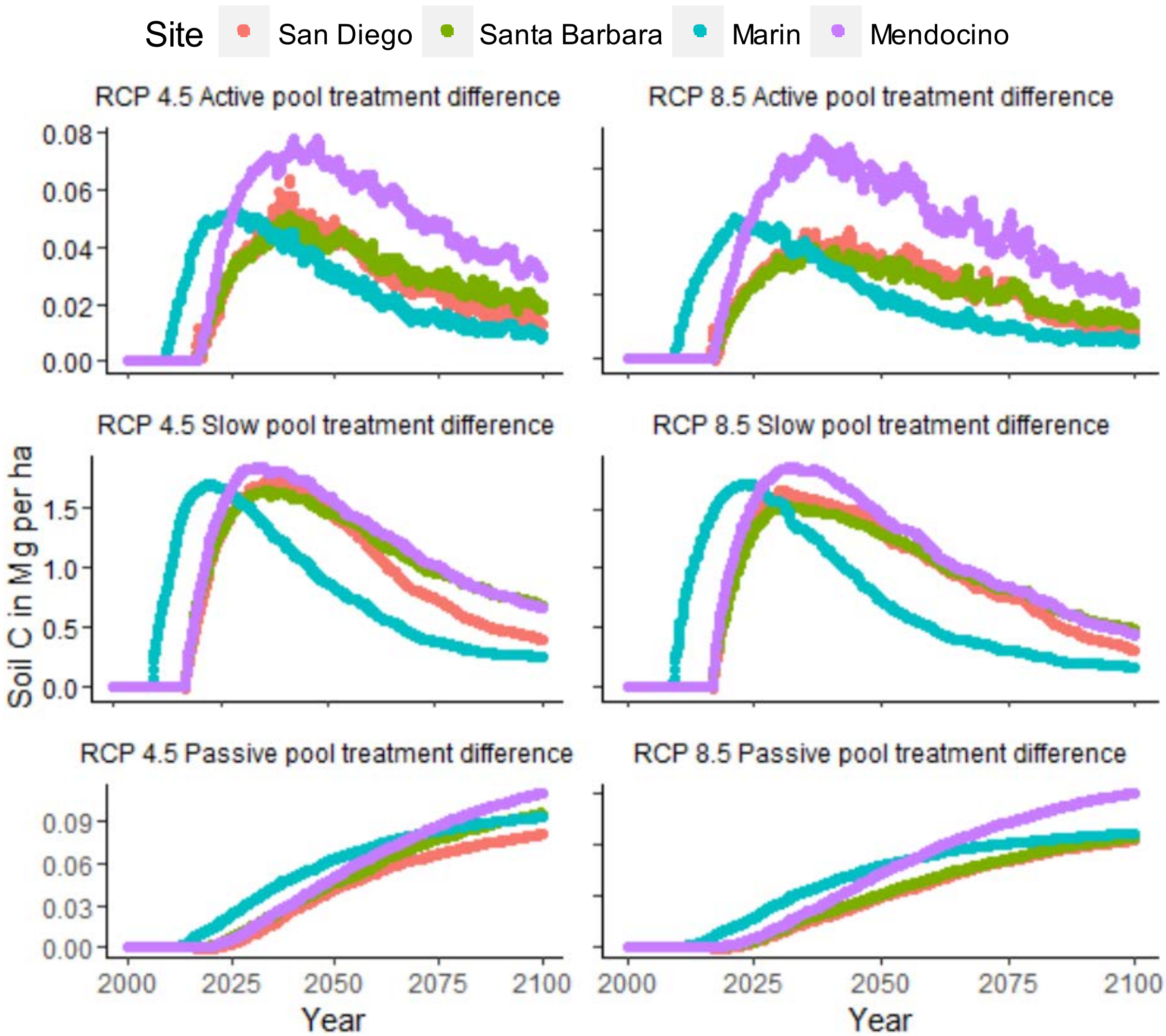

Figure 3.2: Compost amendment to rangelands enhances C sequestration in all C pools and across a range of coastal sites. This figure shows the difference between the simulated soil C for the treatment simulation (amended one-time with compost) and the control simulation (no compost amendment) for the three SOC pools represented in DayCent. The left column shows results due to climate extracted for each site from the reduced emissions (RCP4.5) scenario in CanESM2 and the right column is driven by climate data extracted from the high emissions (RCP8.5) scenario.

Net primary productivity of these annual grasslands was enhanced for the remainder of the century after the compost amendment (Figure 3.3). Despite high interannual variability in NPP, the compost amendment increased NPP in all sites. This increase in above and belowground productivity was largely responsible for the increased movement of C into soil. Because compost increases water holding capacity of soil and acts a slow-release fertilizer (Diacono & Montemurro, 2010), vegetation growth receives an initial boost. This boost of productivity increases photosynthetic drawdown of atmospheric C into vegetation, both above- and belowground, continuing a cycle of increased productivity and soil C storage more than a decade past the initial compost application. While productivity stops actively increasing after 2030, productivity in the compost amended simulations remained higher than the productivity in the control simulations until the end of the century.

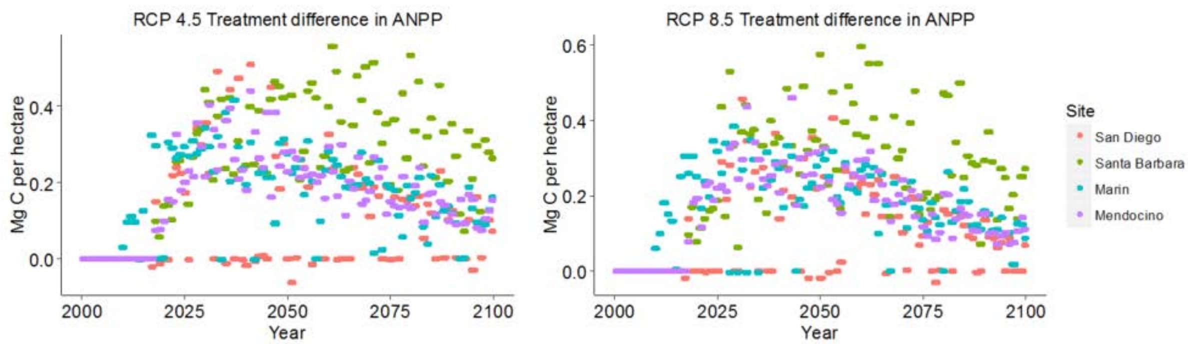

Figure 3.3: A single compost addition increased NPP compared to the control for the remainder of the century at all four sites. Compost had the greatest maximum effect (+0.61 Mg C/ha in 2045) at the site with the lowest historical level of NPP (Santa Barbara), and the smallest maximum effect (+0.35 Mg C/ha in 2033) at the site with the highest historical level of NPP (Marin). Compost application had a reduced effect on NPP in the high emissions climate scenario compared to the reduced emissions scenario, likely due to increased precipitation and thereby decreased water stress in both control and compost simulations in the high emissions scenario.

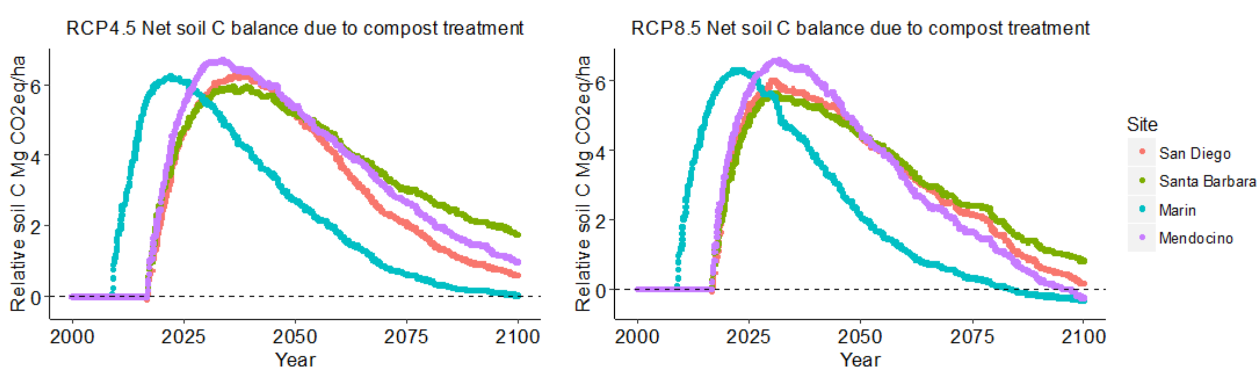

Figure 3.4: By the year 2100, the large amount of C sequestered in soil due to compost additions remains greater than cumulative greenhouse gas emissions of methane and nitrous oxide. This figure shows the net C balance between additional C sequestered and C lost through emissions at each site, and is a composite of figure A3.1 (See Appendix). The reduced emissions scenario (RCP4.5) has both greater amounts of C sequestered in soil and lower greenhouse gas emissions compared to the high emissions scenario (RCP8.5), pointing to a virtuous cycle of emissions reductions enhancing the benefit of mitigation practices.

Discussion and Conclusion

A one-time application of compost at rangeland sites along the coast of California resulted in a long-term increase in overall soil C storage and primary productivity. The overall climate benefit of the compost amendment was greatest in the first 30 years and peaks around 15 years after compost application; the benefit decreased over time, decreasing more quickly in the RCP8.5 high emissions scenario (Fig. 3.4**)**. In both scenarios, precipitation increased over time, resulting in higher methane and nitrous oxide emissions, especially in the RCP8.5 scenario. By 2100, there was a small source of 0.3 Mg C/ha in Mendocino (Fig. A3.1**)**. Ryals et al (2014) compared field observations and DayCent output for the Marin site and showed that the model overestimated N_2O fluxes from both the Marin site and an inland California grassland. We therefore assume that the model overestimates N_2O fluxes, and thus our C balance table likely underestimates the net C sink of the soil due to compost management. We emphasize that long-term trends in soil C are model estimates and thus not necessarily real outcomes.

Climate change in California is projected to increase variability of rainfall along these coastal sites, and under the CanESM2-ES model total rainfall is projected to increase as well; these changes are expected to impact greenhouse gas emissions and soil C sequestration. In the wetter sites of Marin and Mendocino, changes in precipitation lead to greater greenhouse gas emissions. Soil C sequestration rates are maximized within the first 15 years after addition, and more than offset greenhouse gas emissions for many decades longer. The two drier sites, Santa Barbara and San Diego, both had a more positive C balance (net sequestration) in both RCP scenarios, indicating that the climate benefit of compost amendments at drier sites are not as sensitive to the projected increase in both total precipitation and precipitation variability. The potential climate benefit of applying compost at each site is inversely related to the observed NPP at that site. Our results indicate that emissions reductions at a global scale (i.e. the RCP4.5 scenario) lead to longer term climate benefits of land-based mitigation strategies such as compost amendments, a virtuous cycle.

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