INCREASING SOIL ORGANIC CARBON TO MITIGATE GREENHOUSE GASES AND INCREASE CLIMATE RESILIENCY FOR CALIFORNIA

A Report for:

California’s Fourth Climate Change Assessment

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Edmund G. Brown, Jr., *Governor*

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report advances understanding of multiple benefits, including increased climate resilience, of increasing the organic matter content of soils across California's working lands.

ABSTRACT

Rising air temperatures are projected to continue to drive up urban, agricultural, and rangeland water use, straining both surface and groundwater resources. Scientific studies have shown that managing farms, ranches, and public lands to increase soil carbon can increase soil water-holding capacity and increase hydrologic benefits such as increased baseflows and aquifer recharge, reduced flooding and erosion, and reduced climate-related water deficits. Coincident improvements in forage and crop yields are also indicated, while simultaneously sequestering carbon, reducing atmospheric greenhouse gases and mitigating climate change. This study was developed to consider the multiple benefits of increasing the organic matter content of soils across California's working lands.

Study results indicate that a one-time ¼" application of compost to rangelands can lead to carbon sequestration rates in soils that are maximized after approximately 15 years, and more than offset greenhouse gas emissions stimulated by the compost addition for at least five decades longer. Modeled increases in total soil organic matter of 3% enhanced hydrologic benefits across 97% of working lands, and reduced climate change impacts. Economic valuation indicated all benefits increasing over time, demonstrating a large potential for the California carbon market to support incentives in regionalizing the impacts in the coming decades. Socioeconomic and related land use pressures pose barriers to implementing management practices to increase soil organic matter by driving conversion of rangeland to urban or to more greenhouse-gas emission intensive agriculture. Results can be effectively used with land use change scenarios to identify where on California's working lands hydrologic benefits of soil organic matter enhancement coincide with development risk, highlighting counties in California in which there may be resilience to climate change when strategic soil management and land conservation are combined.

Keywords: compost, soil organic matter, land management, California, climate change, carbon sequestration, economic benefits

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HIGHLIGHTS

- Field and model results indicate that a one-time ¼″ application of compost to California's working lands (rangelands and crop lands) leads to carbon sequestration rates in soils that are maximized after approximately 15 years, and more than offset greenhouse gas emissions stimulated by the compost amendment for at least five decades longer. Regionalization of compost applications to only 6% of rangelands in California resulted in an estimate of 8.4 – 8.7 million metric tons of CO_2 equivalents at maximum sequestration, 15 years after compost amendment.
- Increases in total soil organic matter of 3% increased the soil water holding capacity by up to 4.7 million acre-feet across all working lands in California, with hydrologic benefits greatest in locations with enough precipitation to fill increases in soil storage capacity. The benefits of increasing soil organic matter included a reduction of climate change impacts to hydrologic variables in comparison to no-action soil management. Reductions in climate impacts averaged over the state for a wet future were 1-8% in comparison to baseline, and reductions for a dry future were 1-3% in comparison to baseline, but many locations had reductions in climate change impacts of up to 50% by the end-of-century.
- Economic valuation of benefits due to changes in soil organic matter included provisioning services associated with above-ground forage productivity, and regulating services associated with below-ground carbon sequestration and groundwater recharge. Estimated benefits from all services increased over time in the future, and analyses demonstrated a large potential for the California carbon market in the coming decades.
- Socioeconomic and related land-use pressures pose barriers to implementing management practices to increase soil organic matter by driving conversion of rangeland and cropland to development for more greenhouse gas emission intensive agriculture. Results can be effectively used with land-use change scenarios to identify where on California's working lands hydrologic benefits coincide with development risk, highlighting counties in California that may have locations providing resilience to climate change when strategic soil management and land conservation are combined.
- Analyses indicate potential hydrologic benefits from soil management on Williamson Act lands are an order of magnitude greater than potential losses related to future development, totaling over 700,000 acre-feet annually state-wide in a wet climate scenario. Existing barriers to management can potentially be overcome by strengthening existing efforts/infrastructure/programs, developing flexible and diverse funding mechanisms and tailored outreach programs to landowners.
- Increased soil organic matter can be achieved in multiple ways to increase soil water-holding capacity, forage and crop yields, increase baseflows and aquifer recharge, reduce flooding and erosion, increase carbon sequestration, and reduce climate-related water deficits, therefore developing hydrologic resilience to climate change while simultaneously reducing atmospheric greenhouse gases. Prioritized investment in California's working landscapes will yield multiple ecosystem service benefits by

targeting conservation and management actions on grasslands in locations or counties that can gain the most benefit.

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1: Introduction

1.1 Background

Climate change poses severe risks to working landscapes in California, those lands that are used for forest production, grazing or other production of food, and for this study include rangelands and croplands. Risks are posed to all the ecosystem services provided by these working lands, including not just food, but also habitat, carbon storage, and water supply for urban and rural communities, agriculture and wildlife. A healthy landscape offers increased resilience to climate change, increased water quality and net primary productivity, and buffers the impacts of environmental stress leading to forest die-off, wildfire, flood and drought (Rojas et al., 2016; Stocking, 2009; Flint et al., 2018; vanMantgem et al., 2013).

Rangelands and croplands, including publicly and privately managed lands, comprise a large portion of the land base in California (Figure 1.1). Increasing soil carbon can serve as a climate adaptation strategy due to its documented beneficial effects on soil erodibility, soil water-holding capacity, soil temperature and net primary productivity (Ryals and Silver, 2013). Enhancing soil carbon in working lands at scale has the potential to measurably reduce greenhouse gas levels in the atmosphere, increase the sustainability of working landscapes and ensure the provision of other ecosystem services, including water, food and wildlife habitat (Rojas et al., 2016).

Active management of working lands for enhanced carbon sequestration in soils and vegetation has a critical role to play in helping California develop resilience to climate change while simultaneously reducing atmospheric greenhouse gases. “Carbon farming” is a systems approach to land management that involves implementing practices that can improve the rate at which carbon dioxide (CO_2) is removed from the atmosphere and converted to plant material and/or soil organic matter (Evans et al., 2015; Lin et al., 2013). Carbon farming integrates ecological site assessment and mapping in conservation planning, uses dynamic ecosystem carbon models to predict and measure increases in farm-system terrestrial carbon stocks, and incorporates hydrologic modeling to evaluate potential long-term impacts to on-farm water resources. Benefits of carbon farming include: increased soil organic matter (SOM), increased forage and crop yields, increased soil water-holding capacity (WHC) and reduction in total landscape demand for water, carbon sequestration, reduction of atmospheric greenhouse gases (GHG) and diversion of urban and agricultural organic waste from methane-producing anaerobic disposal in landfills and manure lagoons, and from burning (Ryals et al., 2014).

Multiple benefits of increasing SOM include hydrologic benefits. Water that stays in the watershed as recharge can serve to preserve baseflows and riparian systems during low-flow periods and can potentially serve to sustain infiltration to the groundwater system (Flint et al., 2013). Increases in WHC can facilitate the reduction in climatic water deficit (calculated as potential minus actual evapotranspiration, the annual evaporative demand that exceeds available water) and increases in actual evapotranspiration, which implies greater soil moisture, less irrigation demand and landscape stress (Flint et al, 2013; Stephenson, 1998), an increase in net primary productivity (NPP, equivalent to actual evapotranspiration, see Section 3.3)), lower fire risk (vanMantgem et al., 2013), and increased drought resiliency (Flint et al., 2018) and carbon capture capacity (Ryals and Silver, 2013).

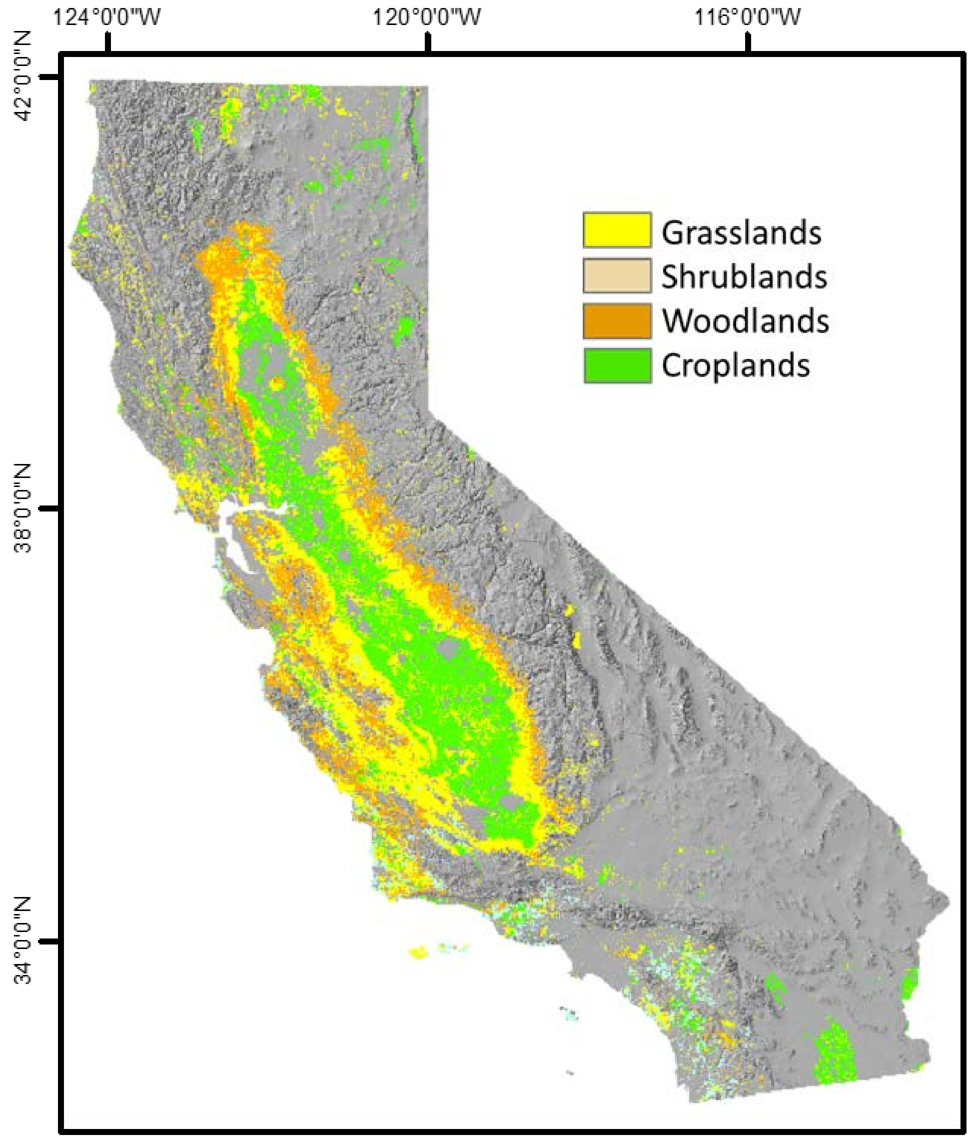

Figure 1.1: Map of working lands study area in California (from FRAP, 2014).

Rangelands and croplands have significant potential for sequestering additional carbon and improving hydrologic conditions with improved management. Successfully managing for enhanced terrestrial carbon storage will require understanding ecosystem dynamics in a changing climate, as well as identifying and overcoming economic and institutional barriers to managing working lands for enhanced carbon sequestration, hydrologic benefit, and climate change resilience.

1.2 Goals and Objectives

California's Fourth Climate Change Assessment (CCCA4) is intended to support and uphold California's leadership in climate change policy, which is built on a strong foundation of research addressing the impacts of climate change on the state, as well as strategies to dramatically reduce greenhouse gas emissions. In turn, the state's research responds directly to policy needs related to safeguarding California from these impacts. The research portfolio is designed to address near-term climate change research needs to ensure that the state stays on track to meet its climate goals. A win-win scenario is tested in this project, whereby addition of organic matter to soils on California's working lands can both sequester carbon to reduce greenhouse gas emissions, while at the same time introduce hydrologic benefits that increase sustainability of our state's hydrologic resources in the face of a changing climate.

While forests and rangelands (and, to a lesser extent, croplands) have been proven to have high potential for sequestering carbon, successfully managing these working lands for carbon storage requires developing California-specific understandings of ecosystem dynamics in a changing climate as well as economic dimensions of and institutional barriers to preserving working lands in a manner that provides adaptation benefits while sequestering carbon. This study is intended to focus on rangelands and croplands to assess threats from climate change and examine the benefits of increasing soil organic matter to sequester carbon and reduce greenhouse gas emissions, enhance ecosystem services, and increase resilience of the landscapes to climate change. Section 2 uses data generated from published and ongoing field and lab trials to simulate increased capacity for ongoing future sustainability of carbon sequestration. These data are also used to constrain water balance model estimates of soil moisture and evapotranspiration generated in Section 3 that quantifies the potential changes in soil water-holding capacity (WHC) and carbon sequestration for rangeland and cropland soils statewide in response to increases in SOM. Using this approach, Section 3 relies on current soil properties to calculate maximum potential benefit of increased SOM for all grasslands, pasture and arable lands in California. Limits to soil improvements are illustrated, as not all of these lands benefit hydrologically from increases in SOM (e.g. wetlands, vernal pools, serpentine or clayey soils). Benefits are calculated as increases in natural recharge (including no augmentation as used in California's Sustainable Groundwater Management Act, SGMA), increased actual evapotranspiration or net primary productivity, or decreased runoff and climatic water deficit (irrigation demand or landscape stress). Results from Sections 2 and 3 are used to quantify the potential benefits in ecosystem services—specifically, water (surface water, soil water, and groundwater), increases in actual evapotranspiration and forage, and GHG benefits—under current conditions and future climate scenarios, providing tools to prioritize soils statewide for SOM/SOC enhancement efforts. Additionally, results from Sections 2 and 3, including results from future climate simulations, are used in Section 4 to estimate the economic value of both no-action and management actions leading to SOM increases, with respect to system hydrology and carbon sequestration for a representative sample of agricultural crops and rangeland types. Finally, on the basis of results from Section 3, we identify in Section 5 the barriers to and incentives for farmland and rangeland carbon storage enhancement within a climate-smart land-use planning framework statewide under current and projected climate and land-use scenarios.

1.3 Study Area

The working lands of interest include all those identified as grasslands (annual grasslands, perennial grasslands, pasture), oak woodlands (blue oak-foothill pine, blue oak woodland, coastal oak woodland, valley oak woodland), shrublands (coastal scrub), and croplands (cropland, dryland grain crops, deciduous orchard, evergreen orchard, irrigated grain crops, irrigated row and field crops, irrigated hayfield, vineyard) in the Wildlife Habitat Response (WHR) class of the vegetation type map (California State Department of Forestry and Fire Protection GIS Data (FRAP) 2016). Section 2 analyses focus solely on annual grasslands, whereas statewide calculations done by Section 3 include all working lands. A mask was made to exclude all non-working land areas that wouldn't be suitable for strategic soil management, such as urbanized areas or low-rainfall deserts, and thus were not included in the analyses or calculations. Analyses on irrigated cropland soils assumed crops had actual evapotranspiration rates equal to annual grasslands as the water balance model used in Section 3 does not incorporate deliveries or pumping into water availability calculations. Analyses of croplands therefore emphasize the climate, existing soil properties, and energy loading occurring in these locations. The study area selected for analysis depicting California's working lands is 28% (93 million acres) of the total area of California, with grasslands making up 39% of the study area (36.5 million acres), oak woodlands 18% of the study area (17 million acres), shrublands 6% of the study area (6 million acres), and croplands 36% of the study area (33.6 million acres).

1.4 Climate Change Projections

This project used climate change projections evaluated by the CCCA4 technical advisory group (DWR-CCTAG, 2015) for use by project participants in evaluating impacts of climate change on the various sectors and environmental variables studied as part of the assessment. Ten Global Climate Models (GCMs) were selected from the full CMIP5 ensemble (DWR-CCTAG, 2015) based on GCM historical performance and to address specific needs for California water resource planning. These ten GCMs were statistically downscaled using the localized constructed analogs (LOCA) method (Pierce et al., 2014) from 2^{o} to 6-km resolution and the Livneh historical baseline climate dataset from 1979 to 2013 (Livneh, 2013) as a training dataset (Pierce et al., 2014). The LOCA method has been shown to produce better estimates of extreme events and reduces the common downscaling problem of too many light-precipitation days (Pierce et al, 2014). These 20 projections, available as daily data, were then spatially downscaled following methods described in Flint and Flint (2012) from 6-km spatial resolution to 270-m. The daily climate was applied to the DayCent model in Section 2, and it was aggregated to monthly and applied to the Basin Characterization Model to develop monthly hydrological surfaces for baseline conditions and future climates to inform this and other CCCA4 projects. A subset of four models were chosen by the technical advisory group to represent priority models that highlight the range of projected future conditions from wet and warm to hot and dry as noted below.

Table 1.1: Future climate models used in California's Fourth Climate Change Assessment.

Model name	Institute ID	Modeling center or group
ACCESS1.0	CSIRO-BOM	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia
CanESM2	CCCMA	Canadian Centre for Climate Modeling and Analysis, Canada
CCSM4	NCAR	National Center for Atmospheric Research, USA
CESM1-BGC	NSF-DOE-NCAR	Community Earth System Model National Science Foundation (NSF); Department of Energy (DOE), and National Center for Atmospheric Research (NCAR), USA

CMCC-CMS	CMCC	Centro Euro-Mediterraneo per I Cambiamenti Climatici, Italy
CNRM-CM5	CNRM-CERFACS	Centre National de Recherches Météorologiques (CNRM) / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS), France
GFDL-CM3	NOAA GFDL	National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), USA
HadGEM2-CC	MOHC	Met Office Hadley Centre, United Kingdom
HadGEM2-ES	MOHC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais), United Kingdom
MIROC5	MIROC	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan

This project used a subset of the priority scenarios for the various applications described in the subsequent sections. These included CanESM2 and HadGEM2-ES. The results of the annual changes in precipitation and average air temperature for 2007-2099 for representative concentration pathway (RCP) 8.5 (Figure 1.2, Table 1.2) indicate that these models have very similar increases in air temperature for future 30-year periods, increasing to 5.2°C (41.4°F) when averaged over the state. Precipitation differs between the models however, with the CanESM2 model increasing about 229 mm/year (9 inches/year) by the end-of-century, and the HadGEM2-ES model only increasing 89 mm/year (3.5°F) by end-of-century (although with a decline below historical in the mid-century). Notable, however is the difference in the variability of precipitation between the models with the CanESM2 having a much higher range of annual precipitation, many more above-historical-peak years and several years lower than the HadGEM2-ES model.

Section 2 used model CanESM2 for both RCPs to evaluate a warm-wet model for both mitigated and business-as-usual futures. Sections 3, 4, and 5 used CanESM2 and HadGEM2-ES, RCP 8.5 to evaluate differences in wet and moderately wet models for the business-as-usual emissions scenario. While Sections 3 and 5 included results from mid- and end-of-century, Sections 2 and 4 highlighted mid-century results as shorter-term planning resources. Results for CanESM2, RCP 8.5 are comparable for all sections of the project.

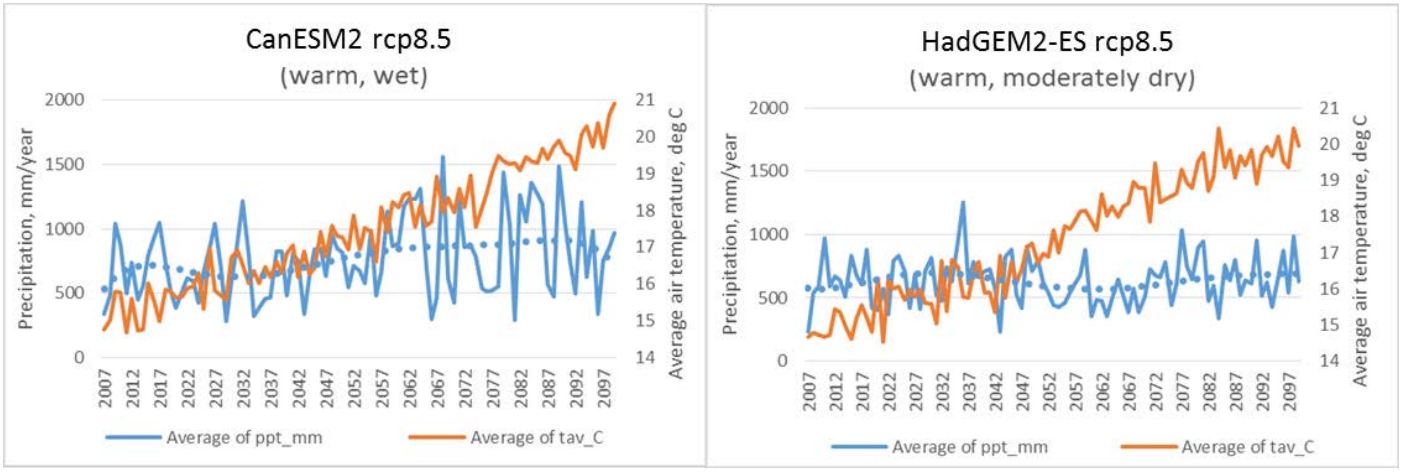

Figure 1.2: Annual time series of precipitation and average air temperature for two future climate models for representative concentration pathway 8.5.

Table 1.2: Precipitation and average air temperature for the historical baseline period 1981-2010 and three 30-year mean time periods for two future climate models for representative concentration pathway 8.5.

	Precipitation in mm/year					
	Historical		CanESM rcp 8.5		HadGEM-ES rcp 8.5	
	Mean	St Dev	Mean	St Dev	Mean	St Dev
1981-2010	587	206				
2010-2039			666	235	672	198
2040-2069			802	298	572	175
2070-2099			858	346	676	176
	Average air temperature, in deg C					
	Recent		CanESM rcp 8.5		HadGEM-ES rcp 8.5	
	Mean	St Dev	Mean	St Dev	Mean	St Dev
1981-2010	14.1	0.7				
2010-2039			15.9	0.6	15.6	0.7
2040-2069			17.5	0.7	17.4	1.0
2070-2099			19.3	0.8	19.3	0.6

2: The Potential for Carbon Sequestration in California from Compost Amendments to Rangelands

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2.1 Introduction and Objectives

2.1.1 Background

Grasslands cover 30% of Earth's ice-free terrestrial surface (White et al., 2000), and over 11% of California, while occupying 40% of California's working lands (Figure 1.1). Grassland soils are a major reservoir for carbon (Jobbagy & Jackson, 2000). This global expanse of grassland is largely degraded with respect to carbon (Bai et al., 2008), such that changes in environmental conditions through climate change or changes in land management could have a measurable impact on the global carbon budget.

Land management approaches that increase plant growth and/or add C directly to soils have been proposed as climate change mitigation strategies, as these practices have the potential to increase soil organic carbon (SOC) storage ("soil C sequestration"). 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 SOC storage (Ryals & Silver, 2013; Ryals et al., 2014). The long-lasting climate benefit is likely due to the enduring increase in plant productivity (especially belowground) due to the stimulation from the one-time compost application, as the amended compost particles decompose within a few years (Ryals *et al.*, 2015).

Here, we used the DayCent biogeochemical model to explore the effects of compost application across a latitudinal and climate gradient throughout 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.

2.1.2 Objectives

This study aims to explore the scalability of compost amendments on rangeland soils across space and time. In particular, the questions we seek to explore are:

- How does compost addition affect long-term net primary production and SOC storage in California rangelands?
- How do environmental variables affect biogeochemical cycling in rangelands, and how does background climate interact with compost impacts?
- How does projected future climate change influence soil carbon storage, and how does compost application impact C dynamics under potential future climate conditions?

2.2 Methodology

2.2.1 Site Descriptions

We parameterized the model using seven annual grassland sites that are representative of a broad range of California's grassland climates and geography. These seven 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 eight other sites (Figure A.1). Pilot compost application at the Marin and Yuba sites took place in 2008. Specific pre-compost field observations were used to parameterize the model for each site, and 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 (Mendocino, Marin, Santa Barbara, and San Diego) and two inland sites (Solano and Yuba) have a Mediterranean-type climate (cool, wet winters and warm, dry summers), and are dominated by non-native annual grass and forb species. The third inland site (Tulare) experiences a semi-arid climate, also with 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 Yuba site is at the Sierra Foothills Research and Education Center in Brown's Valley, CA (39.34°N, 121.35°W) with soil in the Aubern-Sobrante complex classified as Mollic Haploxeralfs (Alfisol and Inceptisol). 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 Solano site is in Suisun City, CA (38.21°N, 122.03°W) in the Antioch-San Ysidro Complex, with soils classified as a Typic Natrixeralf (Alfisol). 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 Tulare site is in Exeter, CA (36.33°N, 119.17°W); soils are in the Akers complex, and are characterized as Calcic Haploxerept (Inceptisol). The San Diego Site is in Santa Ysabel, CA (33.15° N, 116.69° W), at higher elevation (1,135 m) (3,724 ft) 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 2.1.

Table 2.1: Characteristics of modeled sites.

Site	Observed ANPP (Mg C/ha)	Observed bulk SOC (0-30 cm) (Mg C/ha)	% Clay (0-30 cm)	% Sand (0-30 cm)	Historical 30 yr MAP (1975-2005) (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	**1.8 – 2.0**	**21.07**	**9%**	**67%**	**38**	**8.0**	**25.1**
San Diego	**0.4 – 1.0**	**15.03**	**16%**	**66%**	**67**	**7.2**	**21.0**
Tulare	**0.9 – 2.0**	**23.12**	**10%**	**43%**	**28**	**10.8**	**24.1**
Solano	**1.0 - 1.5**	**23.75**	**12%**	**57%**	**61**	**8.8**	**23.3**
Yuba	**1.5 – 2.5**	**22.33**	**23%**	**39%**	**73**	**10.3**	**24.4**

Source: Silver Lab analyses and local CalClim station data, ANPP= aboveground net primary productivity; SOC= Soil Organic Carbon; MAP= Mean annual precipitation,

2.2.2 Model Simulation 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. DayCent partitions existing and added soil carbon into three pools: active (<1 year turnover), slow (decadal turnover), and passive (millennial turnover) carbon pools. Dead plant material is initially partitioned into active or slow cycling pools, depending on the structure of the material, and carbon can move between the pools through decomposition and stabilization. The movement between pools mimics microbial activity and mineral association of organic matter, but DayCent does not explicitly model mechanisms of microbial interactions or mineral stabilization (Parton et al, 1994). The C added directly from compost was traced in the model by simulating isotopically labeled compost. Soil C flows and NPP are both strongly dependent on water availability in DayCent. DayCent is a useful tool for this scenario because it allows the simulation of explicit management practices including grazing and compost amendments and was developed for and is highly utilized in grassland ecosystems. 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. Model parameters were adjusted such that the model output matched observed NPP for each site under current management conditions.

Simulations of future conditions were driven by daily climate data extracted from the CanESM2 Earth System Model. There remains debate as to which Earth System Model most accurately represents future weather in California. We used CanESM2-ES because it was one of the four models recommended by the Fourth Assessment for analyses of climate impacts in California. We used the Representative Concentration Pathway (RCP) 4.5 scenario (assuming some emissions reductions) and the RCP 8.5 scenario that assumes a business-as-usual scenario with minimal emissions reductions. Data were extracted for the site-specific (270-m) (886 ft) gridcell of the CanESM2 Earth System Model from the spatially downscaled datasets described in Section 1-4. The RCP 8.5 scenario differs from the RCP 4.5 scenario in that there is a pronounced increase in daily temperature, especially in daily minimum temperature across all of the sites. The RCP 8.5 scenario also results in increased annual precipitation and interannual precipitation variability in the last half of the century in the Southern California sites (Figure A.1). Thus, the RCP8.5 scenario as extracted from the CanESM2 model simulates a "warmer and wetter" climate for most sites.

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 6.5 mm (0.25 inch) addition of compost to the site. The compost addition replicated the actual management of the NRCS/UC Berkeley field experiment, which used a commercial 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^{-1}) with a C:N ratio of 17.6. The baseline year for compost amendment was 2016 for all sites except for Marin and Yuba (baseline year 2008), which follows the NRCS/UC Berkeley field trials.

2.3 Results and Discussion

2.3.1 Climate Change

Under the RCP 8.5 scenario of the CanESM2-ES climate model, projections for mean annual precipitation exhibit increases across the 21st century (comparing 2000-2010 to 2090-2100), ranging from an additional 3% increase (36 mm/yr, 1.4 in/yr, p=0.009) in Marin to an additional 33% increase (180 mm/yr, p=0.003) in San Diego (Figure A.2). The most significant increase in annual precipitation occurred in Tulare, with an additional 80 mm/yr by the end of the century (p=0.0003). Under RCP 8.5, four out of seven sites also experience a substantial increase in precipitation variability at the end of the century (Figure A.2**)**. The standard deviation of interannual precipitation increased by 50-70% in Tulare, Solano, San Diego, and Santa Barbara, while Yuba, Marin, and Mendocino experienced a change in standard deviation of interannual precipitation of 25-30% (Figure A.2). Mean annual precipitation did not increase significantly over the century under RCP 4.5. Mean temperatures were also affected by climate change (Figure 2.1). Mean minimum temperatures increased by 2.5°C (36.5°F) or less in the RCP 4.5 scenario (p<0.0001 for all sites), and between 3.6 and 6°C (38.5 to 42.8°F) in the RCP 8.5 scenario (p<0.0001 for all scenarios). Mean daily maximum temperatures also increased significantly at all sites, between 5.6 and 6.7°C (42.1 to 44.1°F) (p<0.0001). These increases in temperature and precipitation in RCP 8.5 affect ecosystem C cycling relative to the RCP 4.5 scenario.

2.3.2 Enhanced Productivity

A single addition of compost resulted in a relative increase in net primary production (NPP) in the compost treated plots relative to the otherwise identically managed control plots (Figure 2.2). These and the following results are reported as the relative difference between the compost-amended plot and the control plot at each site for each time point. Despite high interannual variability in NPP due to dependence of NPP on rainfall, the compost amendment increased NPP in all seven geographically diverse sites. This increase in above- and belowground productivity was largely responsible for the increased movement of C into soil (Figures 2.2, 2.3b). Because compost increases water holding capacity of soil and acts as a slow-release fertilizer (Diacono & Montemurro, 2010), vegetation growth receives an initial boost. This boost of productivity increases photosynthetic uptake of atmospheric C into vegetation and accumulation of C both above- and belowground, continuing a cycle of increased productivity and SOC storage more than a decade past the initial compost application. While productivity stops actively increasing 15 years after amendment, productivity in the compost amended simulations remained higher than the productivity in the control simulations until the end of the century.

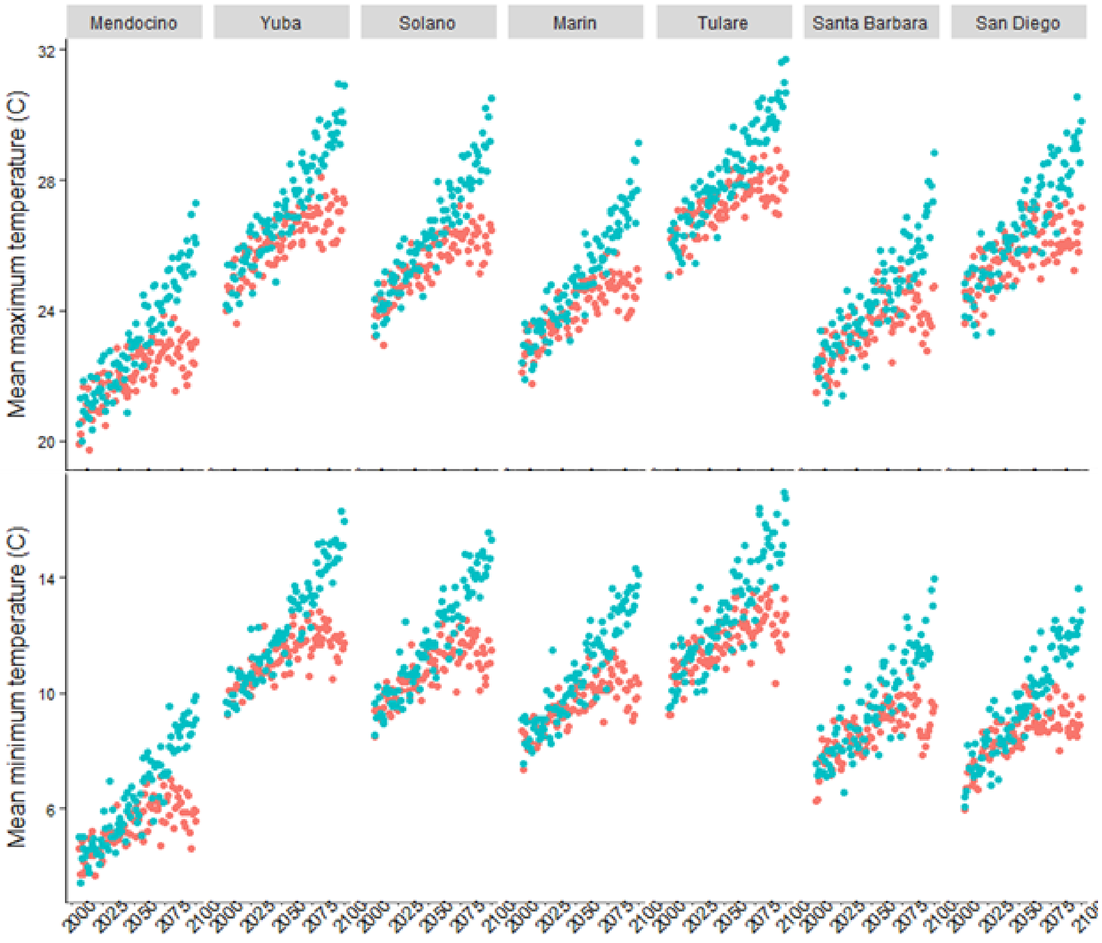

Figure 2.1: Mean daily temperature increased rapidly throughout the century in the RCP8.5 scenario (blue) compared to the RCP4.5 scenario (red).

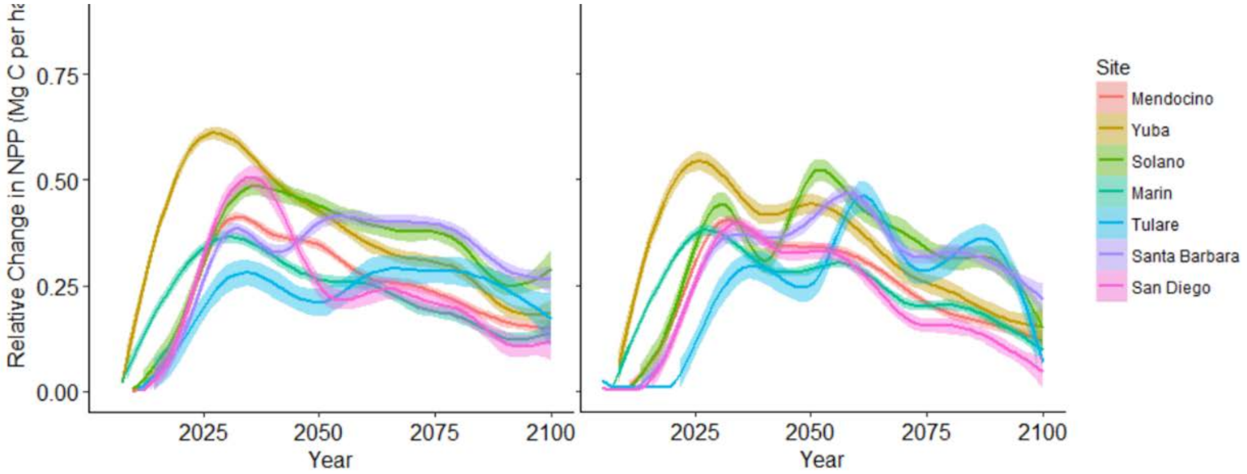

Figure 2.2: Aboveground net primary productivity increased in the compost treated plot relative to the control plot in all seven sites. The increase in primary productivity endures through the end of the century under both climate scenarios. The results presented are smoothed conditional means using a Generalized Additive Model to fit the data. The shaded areas represent 95% confidence intervals.

2.3.3 Enhanced soil Carbon Storage

A one-time application of compost 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 2.3a). The effect on bulk 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 (Figure 2.3a). 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, but the trend reversed as climate conditions diverged in the second half of the century.

The largest gain in SOC in 2031 was in Mendocino, where soils gained 1.91 Mg C ha^{-1} and 1.92 Mg C ha^{-1} more in the compost treated soils than in the control for the RCP 4.5 and 8.5 scenarios, respectively. The smallest increase in SOC was in San Diego. In the RCP 4.5 scenario, San Diego SOC gain peaked in 2031 with a maximum increase of +1.73 Mg C ha^{-1} in the composted compared to the control simulation. For the RCP 8.5 scenario, the peak C gain in San Diego decreased to 1.67 Mg C ha^{-1}. The San Diego site has the lowest initial soil C content, as well as one of the lowest average net primary productivity. Because the San Diego site is on a mountain pass, the higher altitude yields a cooler and wetter climate than the other southern California sites, making the results more comparable to the northern California sites than the South Central California sites.

The increase in soil C is due to both the direct addition of carbon through the compost amendment as well as an indirect increase in soil C inputs from the boost net primary productivity (Figure 2.3b). While the initial input of C from the compost provides a large increase in soil C, this directly added C has largely decomposed by the end of the century. The indirect benefit of compost to the ecosystem results in additional carbon drawdown of 0.3 Mg C ha^{-1} in San Diego mid-century, to 0.9 Mg C ha^{-1} by the end of the century. In the latter half of the century, the climate in most sites in RCP 8.5 is wetter and warmer than in RCP 4.5. At this point, the fraction of additional carbon allocated to the slow, decadally cycling pool is greater in RCP 4.5, while the fraction of additional passive pool C is higher in RCP 8.5. This change in C allocation from slow carbon to passive carbon in RCP 8.5 may be driven by accelerated decomposition of slow C due to the more preferable (warm, wet) conditions for decomposition, accelerating the movement of C from the slow pool to both the atmosphere and to passive, more stable C. The warmer, wetter conditions could accelerate movement of C through the mineral soil and increase instances of sorption to mineral surfaces or could facilitate passive C stabilization through greater soil aggregation from enhanced soil structure with more soil moisture.

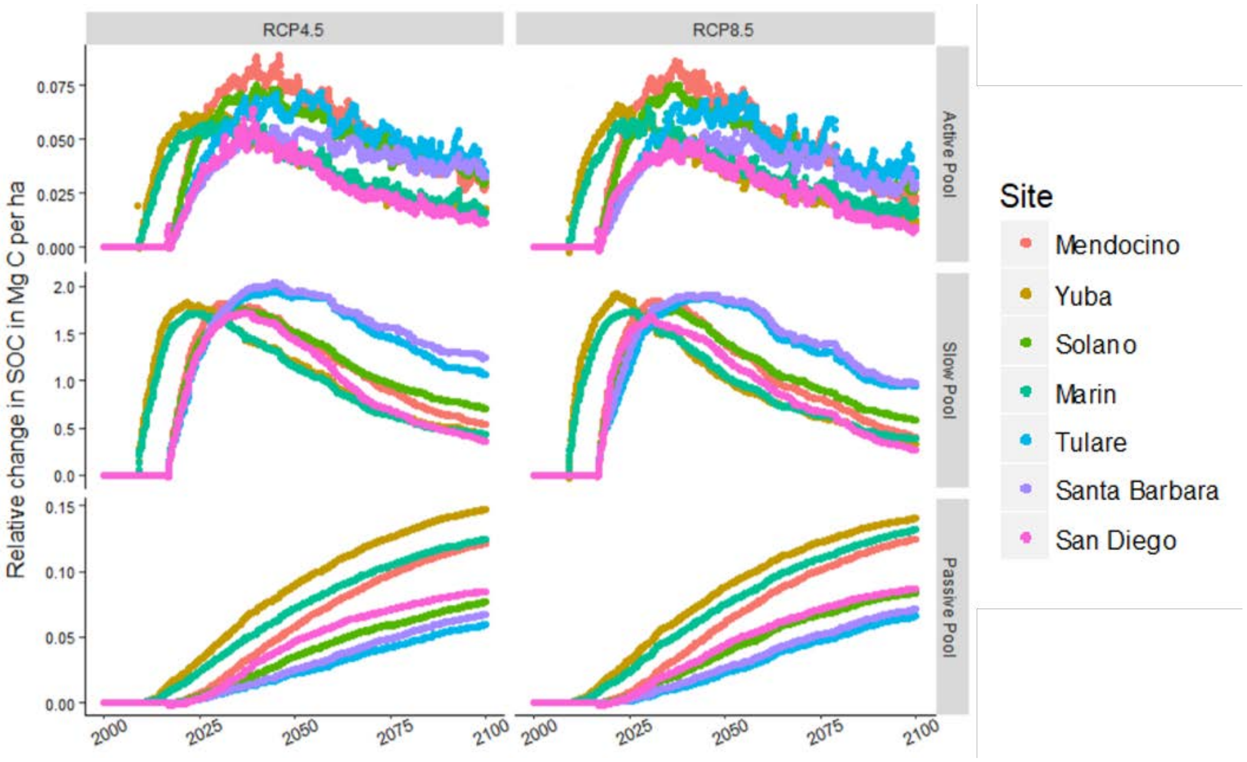

Figure 2.3a: Total soil organic C stock increased in the compost treatment relative to control in all three soil C pools. Soil organic C increased in all seven sites under both climate scenarios.

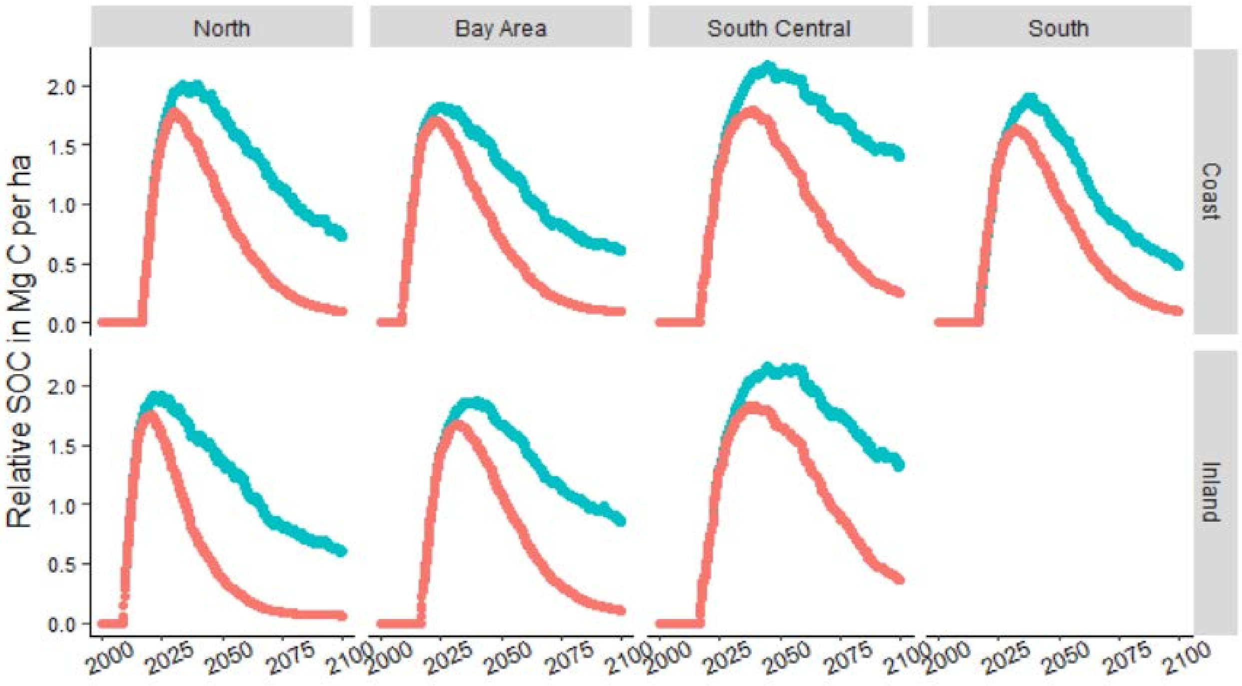

Figure 2.3b: Relative change in total soil organic C stock (blue lines) includes C added indirectly through the boost of ecosystem productivity, and the C added directly via compost (red lines).

2.3.4 Climate Change Mitigation Benefit

The increase in soil C due to compost was accompanied by a stimulation of greenhouse gas emissions, but the climate benefit of gross soil C inputs (measured in CO_2 equivalents) outweighed the emissions (Figure 2.4a). Loss of C through CO_2 emissions are accounted for in the total soil C stock, and DayCent for grasslands does not have a module to calculate methane emissions, as methane is normally consumed in grassland ecosystems. Therefore, the emissions represented here are cumulative nitrous oxide (N_2O) emissions due to the addition of compost. The net climate benefit (gross soil C inputs minus emissions) is maximized 15 years after compost application and remains positive through the end of the century in RCP4.5. The maximum net climate benefit for each site is reported in Table 3.4. The net climate benefit is highest in the two South-Central sites of Santa Barbara and Tulare, while the net climate benefit decreases more rapidly at the other sites, particularly at the wettest and Northern-most site of Mendocino (Figure 2.4b). Under the RCP 8.5 scenario, precipitation increased over time, resulting in higher N_2O emissions. By 2100, there was a small source of 0.3 Mg C/ha in Mendocino (Fig. A-3). Ryals et al. (2014) compared field observations from static flux chamber measurements every two to four weeks 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. Compared to the RCP4.5 scenario, the net climate benefit of compost application in the RCP8.5 scenario decreases more rapidly over time in all sites (Figure A.3). This indicates that a given C sequestration activity has a greater climate benefit when combined with emissions reductions, creating a positive feedback loop of mitigation activities and effect on climate, i.e., a virtuous cycle.

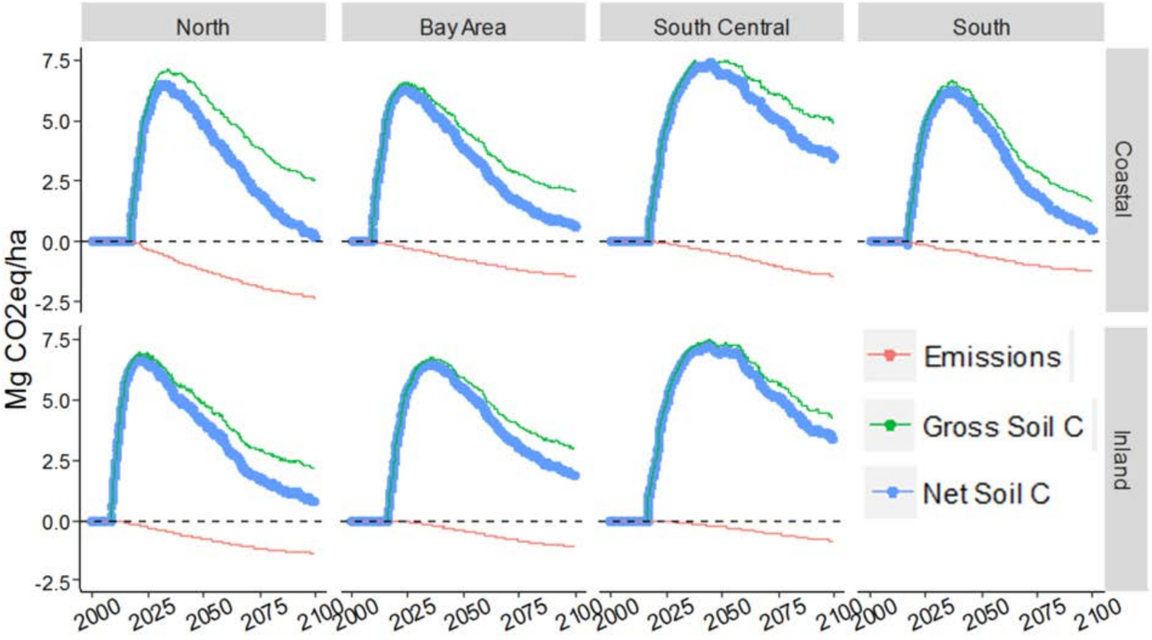

Figure 2.4a: Total enhanced soil C storage due to compost (Gross Soil C: green line) is greater than greenhouse gas emissions stimulated by compost application to soil (red line), resulting in a net climate benefit (Net soil C sequestration: blue line) for all sites through the end of the century (RCP4.5).

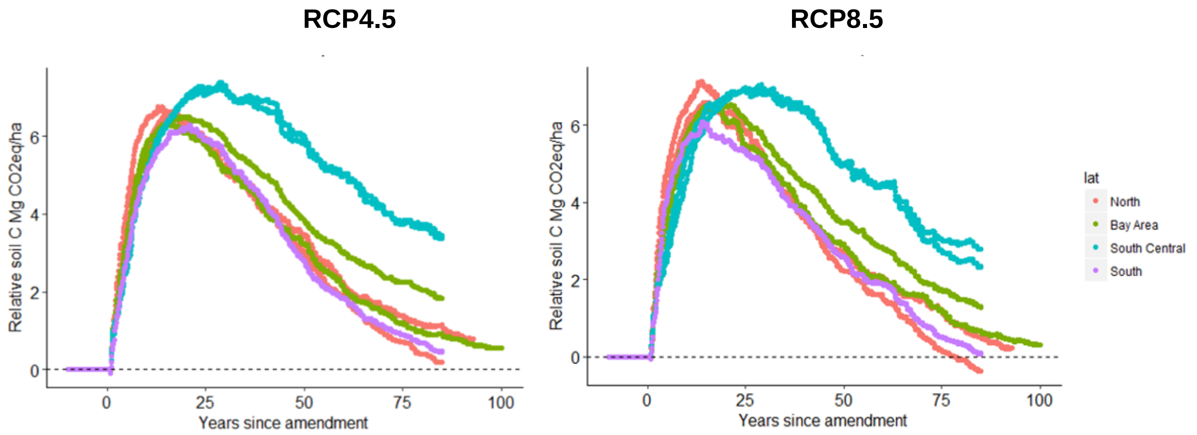

Figure 2.4b: Net climate benefit (gross soil C inputs minus greenhouse gas emissions in treatment relative to control sites) for all seven sites are positive through the end of the century under RCP4.5. The two northern sites (red), have a similar decreasing net climate benefit as San Diego in the south (purple), while the Bay Area sites (green) have a slightly longer lasting climate benefit. The two driest sites of Santa Barbara and Tulare in South-Central California (blue) have the largest and most enduring climate benefit due to compost. Under more climate change in the RCP8.5 scenario, all sites exhibit reduced climate benefit in the latter half of the century, and even a net loss of C from the system by the end of the century in the wet, Mendocino site (see Figure A.3).

Table 2.4: Model output shows increase in relative net climate benefit

Site	CanESM2 (2005-2025) Mean summer (JJA) maximum temperature (°C)	Model output mean annual aboveground NPP ± s.e. (Mg C ha^{-1})	RCP4.5 (15 y post compost) Maximum relative change in net climate benefit (Mg CO$_2$e ha^{-1})	RCP8.5 (15 y post compost) Maximum relative change in net climate benefit (Mg CO$_2$e ha^{-1})
Mendocino	30.4	0.81 ± 0.04	6.48	6.57
Yuba	35.4	1.59 ± 0.13	6.05	5.86
Marin	29.2	1.42 ± 0.05	6.3	6.36
Solano	32.5	1.25 ± 0.06	6.29	6.49
Santa Barbara	26.1	1.79 ± 0.13	6.34	6.36
Tulare	36.4	1.14 ± 0.12	6.27	6.02
San Diego	32.8	0.78 ± 0.08	5.88	6.02

JJA= June, July and August; NPP= Net Primary Productivity; Net climate benefit = C inputs – N$_2$O Emissions

2.4 Conclusions

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 NPP. The climate benefit of the compost amendment peaks around 15 years after compost application; the benefit decreased over time, decreasing more quickly in the RCP8.5 high emissions scenario (Figure 2.4b). We emphasize that long-term trends in soil C are model estimates and thus not necessarily real outcomes.

We used the U.S. Geological Survey Ecoregions to scale the climate benefit from each of these sites to other rangelands within the same sub-ecoregion using grasslands only (Griffith et al., 2016). The grassland sub-ecoregions represented by our seven modeled sites amount to 6% of California's grasslands. Assuming that the compost application would have the same climate benefit within each sub-ecoregion, we conservatively estimated that applying compost to only 6% of California rangelands (see Section 5), would sequester a cumulative 8.4 – 8.7 million metric tons of CO_2 equivalents at maximum sequestration, 15 years after compost amendment. Note that this does not include C and greenhouse gas savings from waste diversion. The C sequestration achieved through applying compost to this 6% of California rangelands would accomplish about half of the goal set by California's AB32 to avoid 15-20 million metric tons of CO_2 equivalents by 2030.

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 site of Mendocino, change 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 driest sites, Santa Barbara and Tulare, 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. We speculate that the large positive C balance in the drier sites is due to the relative benefit of increased soil moisture storage provided by compost (see Section 3). 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.

2.5 Acknowledgements

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3: Assessing the Benefits of Increasing Soil Organic Matter on Hydrology for Increasing Resilience to a Changing Climate

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3.1 Introduction

Climate change poses severe risks to working landscapes in California, including rangelands and croplands, and the ecosystem services they provide. These services include food, habitat, carbon storage, and water supply for urban and rural communities, agriculture and wildlife. A healthy landscape can increase resilience to climate change, increase water quality and net primary productivity, and buffer the impacts of environmental stress leading to forest die-off, wildfire, flood and drought.

Numerous scientific studies have shown that increasing soil organic matter (SOM) can have multiple benefits, including carbon sequestration and reduction of atmospheric greenhouse gases (GHG) (Ryals and Silver, 2013). Soil management strategies and active management of working lands for enhanced carbon sequestration, such as “carbon farming,” (Evans, et al., 2015; Lin et al., 2013) have a critical role to play in helping California develop resilience to climate change while simultaneously reducing atmospheric greenhouse gases. “Carbon farming” is a systems approach to land management that involves implementing practices that can improve the rate at which carbon dioxide (CO_2) is removed from the atmosphere and converted to plant material and/or SOM. Carbon farming integrates ecological site assessment and mapping in conservation planning, uses dynamic ecosystem carbon models to predict and measure increases in farm-system terrestrial carbon stocks, and incorporates hydrologic modeling to evaluate potential long-term impacts to on-farm water resources. Benefits of carbon farming include; improvement in soil health, increased forage and crop yields, increase in soil water holding capacity (Saxton and Rawls, 2006) and reduction in total landscape demand for water, increased carbon sequestration (Ryals et al., 2014), reduction of atmospheric GHG and diversion of urban and agricultural organic waste from methane-producing anaerobic disposal in landfills and manure lagoons, and from burning (Cabrera et al., 2009).

Water that stays in the watershed can serve to preserve baseflows and riparian systems during low-flow periods and can potentially serve to sustain infiltration to the groundwater system. Increasing soil water storage and recharge can reduce peak runoff that may carry excess sediment or water quality constituents, and may leave the watershed via rainy season streamflows. Enhancing water storage in the soil also results in less irrigation demand, an increase in net primary productivity (NPP, equivalent to actual evapotranspiration) (Ryals and Silver, 2013), lower fire risk (van Mantgem et al., 2013), and increased drought resiliency (Flint et al., 2018) and carbon capture capacity (Ryals et al., 2014).

This part of the overall project described in this report was intended to investigate the hydrologic benefits of enhanced soil organic matter (SOM) across all working lands in

California, including rangelands used for grazing (grasslands, oak woodlands, and shrublands), and croplands (Figure 1.1). We developed objectives to evaluate the range of possible hydrologic benefits to varying increases in SOM for 1981-2010, to explore a range of climates across the state, and evaluate where the same amount of management effort would result in more or less hydrologic benefit. Specifically, to represent the water supply benefit we evaluated increases in recharge, to represent the forage production benefit we analyzed increases in actual evapotranspiration, and to represent the benefits from reducing landscape stress or irrigation demand we evaluated the reduction in climatic water deficit. Additionally, we evaluated how soil management could ameliorate some of the negative impacts of climate change on our water resources.

3.2 Methods

3.2.1 Model Description and Calculation of Soil Properties

The tool used to calculate the changes in hydrologic response to climate as a result of increased SOM was the Basin Characterization Model (BCM; Flint et al., 2013). This model calculates the unimpaired water balance for the state of California at a monthly timestep at 270-m spatial resolution. The BCM has recently been revised to include soil organic matter in the calculation of soil water holding capacity from texture, and vegetation type-specific actual evapotranspiration (https://ca.water.usgs.gov/projects/reg_hydro/basin-characterization-model.html). Soil water holding capacity (WHC) is calculated in the model as water content at field capacity (-0.01 megapascals, MPa) minus water content at wilting point (-6 MPa) multiplied by soil depth. These are calculated on the basis of soil texture data (percent sand, silt and clay) and percent soil organic matter data (Figure 3.1) from the Natural Resource Conservation Service SSURGO dataset and accessed from Wieczorek (2014, 2015). Calculations of WHC are done using equations developed by Saxton and Rawls (2006), who evaluated the relation between SOM, porosity, field capacity and wilting point on the basis of thousands of laboratory-analyzed field samples (Figure 3.2). This figure illustrates the WHC as the difference between field capacity at -0.01 MPa and wilting point at -6 MPa for different additions of OM. The increase in WHC differs by textural class, with the biggest increase in silt loam and loamy fine sand, while there is the least increase in silty clay loam and sandy loam. Clay soils (silty clay and clay textural classes) do not benefit from addition of OM and are indicated by the calculations to reduce WHC with the addition of OM. Additionally, soils with a high percentage of fine sand have a negative impact with the addition of OM because the wilting point increases more than the field capacity, thus reducing the WHC. There are few places in California where very high clay or high sand soils occur, but these analyses serve to identify where strategic soil management may not result in hydrologic benefits.

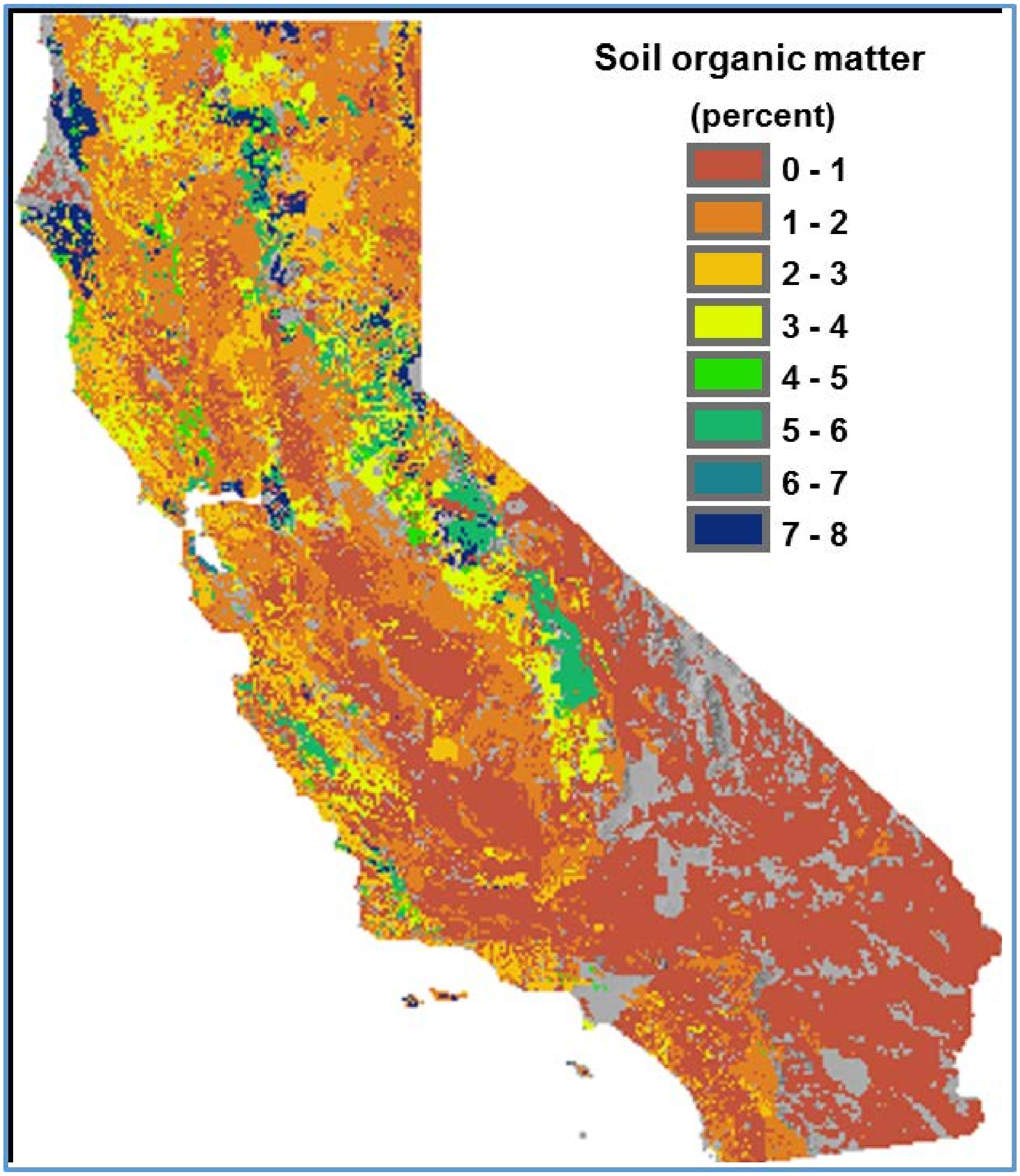


Figure 3.1: Map of soil organic matter from National Resource Conservation Service, SSURGO dataset (Wieczorek, 2014, 2015)

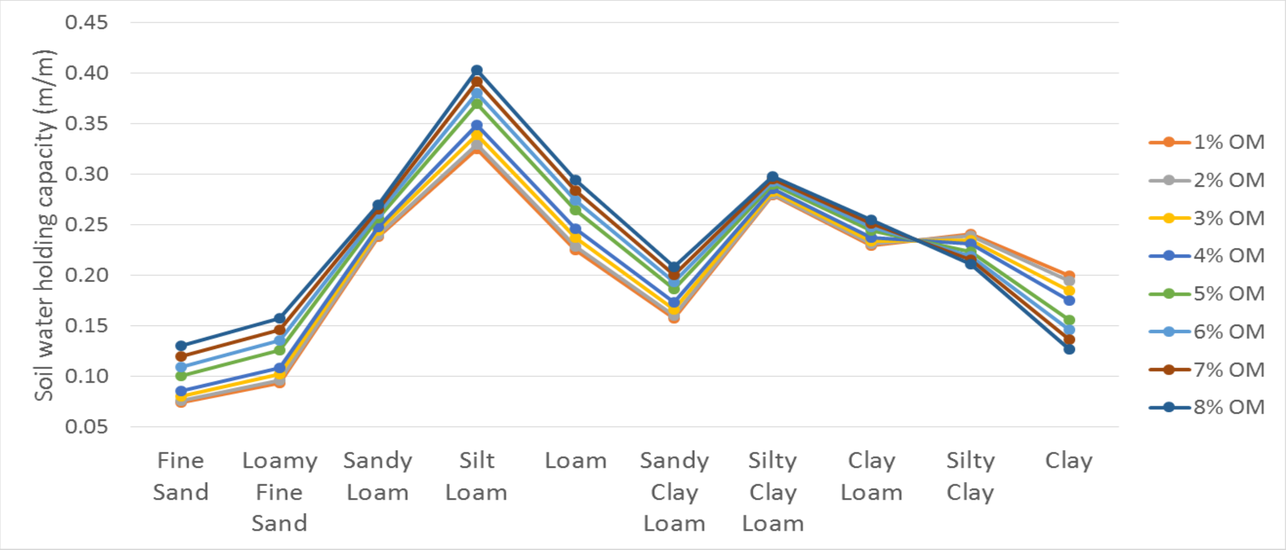
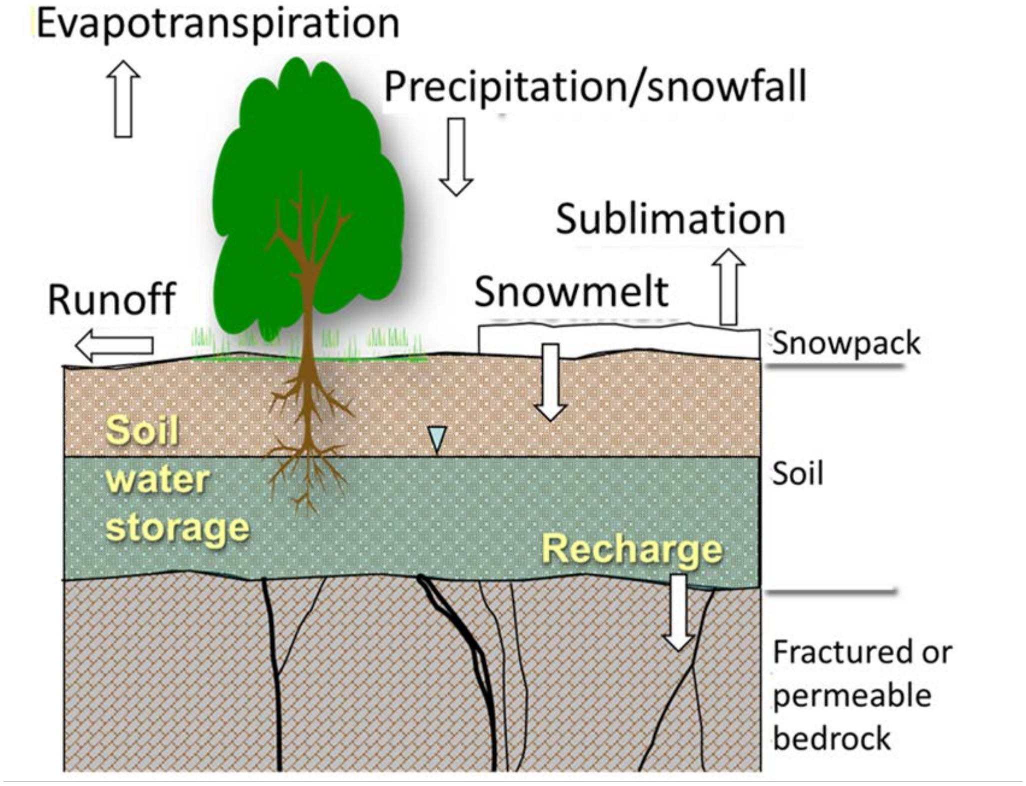


Figure 3.2: Calculations of soil water holding capacity (in meters of water per meter of soil) for different soil textural classes for different percentages of organic matter.

The BCM relies on climate (precipitation, minimum and maximum air temperature) from the historical dataset PRISM (Daly et al., 2008) and future climate scenarios that we spatially downscale to 270-m to calculate excess water that infiltrates into the soil for plant water use between FC and WP, to become recharge if the soil water content exceeds field capacity at the rate of spatially distributed bedrock permeability, and to run off if the soil is saturated. Therefore, recharge and runoff are approximately the inverse of each other, and recharge is defined, in this case, as water that makes it below the zone of evapotranspiration, not necessarily to the water table, depending on the thickness of the unsaturated zone. Water balance calculations illustrated in the schematic in Figure 3.3 indicate that if you increase the WHC, and depending on available water from precipitation, increases will occur in actual evapotranspiration (AET), which is correlated to net primary productivity and forage production (see Section 3-3). With increases in WHC, both recharge and runoff will decrease, but recharge less than runoff, especially in dry years. More soil water also leads to lower climatic water deficit (CWD), which is related to less irrigation demand, lower landscape stress, and typically less fire risk. However, as CWD goes down and AET increases there may be additional fuel loads that could change the level of risk due to wildfire, which warrants further study.

Uncertainties in model results are largely dependent on the underlying data layers, particularly the soil properties. The accuracy of baseline estimates of hydrologic variables is discussed at length in Flint et al. (2013). However, the key points to be made in this paper are relying heavily on changes in hydrologic variables as a result of the addition of SOM, so the underlying accuracy of the baseline calculations is not as critical. If we assume that the watershed properties and climate are correctly characterized, the BCM hydrologic outputs are based on properties that are spatially distributed throughout the study area, and the calculations are performed consistently across all basins, which provides a significant level of confidence in results for regional cross-comparisons of basins.



Precipitation – snowmelt – sublimation – evapotranspiration – runoff – recharge – change in soil water content = 0

Figure 3.3: Schematic of water balance processes used in the Basin Characterization Model.

3.2.2 Sensitivity Analyses

Sensitivity analyses were developed to calculate the hydrologic benefits of increased SOM under a no-action baseline and under a range of percent increases in SOM (+1%, +2%, +3%, and +8%), assuming the achievement of each level of SOM increase to be attainable under a variety of approaches, including compost addition or strategic farming or ranching strategies (Zomer et al. 2017; Lal, 2015; Machmuller et al, 2015). The +3% increase in SOM above baseline conditions was considered generally attainable, although an upper end, and the +8% scenario was considered generally unattainable across most working lands, but potentially attainable on croplands with intensive management, thus was included as an extreme possible condition. Reporting was done on a map basis, statewide averages, and county-wide averages for hydrologic variables CWD, AET, recharge, and runoff, averaged over historical (1981-2010) and future (2010-2039, 2040-2069, 2070-2099) time periods (see sub-section 3.2.5 below), and for decades (1990-1999, 2000-2009, 2010-2019, 2020-2029, 2030-2039, 2040-2049). Additionally, calculations were also averaged separately for rangelands (grasslands, oak woodlands, and shrublands), and croplands.

3.2.3 Calculation of Weighted Average Benefit Map

A calculation to represent the hydrologic benefit across the state using a single index was done using the 1981-2010 average condition for +3% increase in OM above baseline for recharge, actual evapotranspiration (AET), and climatic water deficit (CWD). These three variables represent the increase in water supply benefit, increase in forage production benefit, and reduction in landscape stress/irrigation demand benefit, respectively. The absolute values of all three were normalized to 0 to 1, and CWD was multiplied by -1 to represent a positive benefit as it went down in value. They were then summed and cells where all three were zero benefit were given a "no benefit" value, the remaining values were binned equally into three bins with "minimum benefit," "moderate benefit," and "maximum benefit." Locations with no hydrologic benefit given strategic soil management still may have benefit from carbon sequestration (see Sections 2 and 4 in this report).

3.2.4 Future Climate Scenarios

Descriptions of the GCMs used are in Section 1.4. This Section used both selected GCMs and applied them to the BCM. The two projections are for the business-as-usual RCP 8.5, which was chosen to represent current trajectories of GHG emissions. The 'warm and moderately dry' model is HadGEM2-ES, and the 'warm and wet' model is CanESM2.

3.3 Analyses and Results

Modeled increases in SOM of 3% resulted in calculated soil moisture storage for all working lands in California of up to 4.7 million acre-feet per year (Table 3.1), with decreases in CWD of over half a million acre-feet and decreases in runoff of over a million acre-feet. Increases in AET and recharge were over half a million acre-feet each for a 3% increase in SOM. The changes were very different for the different locations in California, depending on climate, baseline soil properties and percent soil organic matter however, and increases in recharge of from 0.4 inches to 2.8 inches were found when averaged over counties in California (Figure 3.4; Table B.1).

Table 3.1: Hydrologic results from the Basin Characterization Model run using 1, 2, and 3% increases in soil organic matter for 1981-2010, averaged over all rangelands and croplands in California.

Management application	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff	Soil moisture storage
	Acre-feet per year				
Base case	25,164,842	38,176,609	7,139,557	11,233,201	46,799,831
+1 % OM	24,956,384	38,385,101	7,422,953	10,760,406	48,317,979
+2 % OM	24,769,893	38,570,545	7,641,958	10,381,837	49,735,485
+3 % OM	24,622,868	38,726,298	7,770,454	10,097,544	51,188,814
	Change in acre-feet per year				
+1 % OM	-208,457	208,492	283,396	-472,794	1,518,148
+2 % OM	-403,032	403,033	489,832	-856,636	3,108,975
+3 % OM	-584,017	584,053	613,304	-1,147,040	4,710,746
	Percent change from base case				
+1 % OM	-0.83	0.55	3.97	-4.21	3.24
+2 % OM	-1.60	1.06	6.86	-7.63	6.64
+3 % OM	-2.32	1.53	8.59	-10.21	10.07

Some counties had soil conditions that were far more sensitive to the addition of **organic** matter than others. Because there was more soil storage, there was also more water for AET, which was greater for all counties, but ranged dramatically among all counties. For example, in Imperial County there was a big increase in soil storage capacity, but precipitation is low, and the increase provides no advantage on average, so the AET increase was minimal. Alternatively, in locations with higher rainfall where increases in soil storage could be an advantage, such as Mariposa or Monterey Counties, the AET increases were larger. Recharge generally increased the most in counties with both larger increases in soil storage capacity and more precipitation, with the largest increases in Butte, El Dorado, Lake, Shasta, Sonoma, and Tehama Counties.

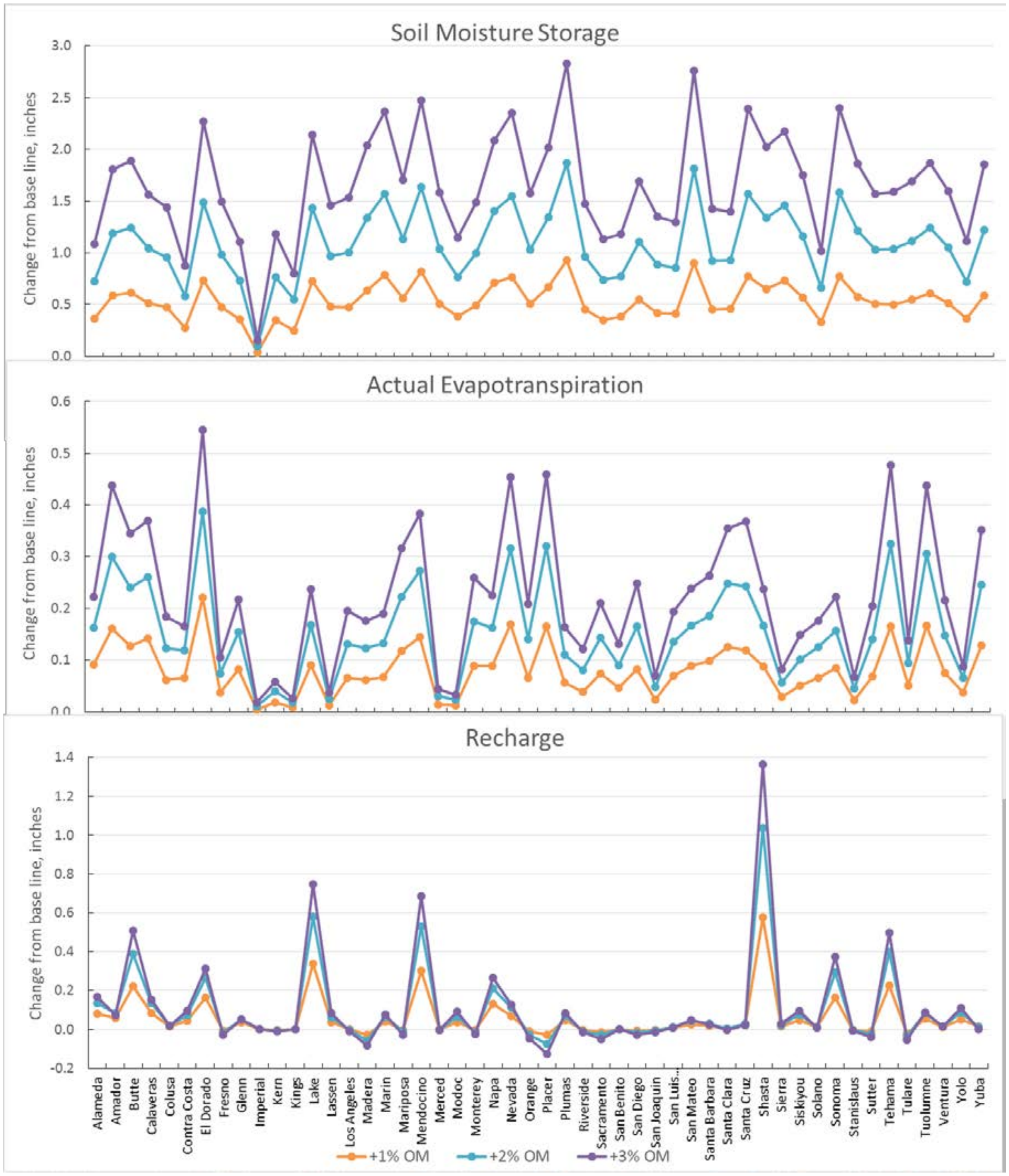


Figure 3.4: County averaged results for 1981-2010 as a change from baseline soil organic matter to an increase of 3% for soil water holding capacity, actual evapotranspiration, and recharge. Counties with more than 85% mask are not included.

Some locations with very high sand or very high clay soils had reductions in recharge with increases in SOM, and those counties with small percentages of working lands that have these conditions, when averaged over the whole county are shown to decline in recharge (e.g. Madera, Placer, Sacramento) (Figure 3.4). Net primary production (NPP) is calculated using the DayCent model parameterized on the basis of soil, climate, and forage field data at eight sites ranging across California (see Section 2 in this report) (Table 3.2). Comparisons of NPP calculated by DayCent were made with AET calculated using the BCM to determine if AET was a reasonable proxy for NPP or forage production. Two steps were followed to make the comparison: first to substantiate that percentages of NPP were of similar magnitude to AET, and secondly to determine if the application rate to increase soil organic carbon (SOC) that is modeled by DayCent is comparable to the increases in SOM that is used in BCM calculations of changes in hydrologic variables. Because simulated NPP from field applications of organic matter in the form of compost includes the addition of nutrients such as nitrogen, we assume that BCM AET estimates, which only assume physical changes to soil properties, should be low in comparison to NPP estimates. Measurement of % soil organic carbon (SOC) increased across all sites from 1.1 to 2.5% as a result of compost addition. Soil scientists often use the ratio of 1:1.724 for comparisons of SOC to SOM (Howard and Howard, 1990; Loveland and Webb, 2003), therefore bracketing the range of field SOC values with modeled estimates of AET on the basis of 1 and 3% increase in SOM. In comparison, the BCM AET also bracketed the NPP values for four of the sites, was low for two sites, and high for one site. Generally, however, the calculation of AET was considered to be a reasonable proxy for NPP, allowing us to conclude that increases in AET from the addition of SOM was a hydrologic benefit as a result of increases in forage production.

Table 3.2: Comparison of net primary productivity calculated using the DayCent biogeochemical model and ¼" of compost addition, and actual evapotranspiration calculated using the Basin Characterization Model for eight field sites in California.

	Length of Study	DayCent NPP	BCM Actual ET	
Field Site/County	years	2031	+1% OM	+3% OM
Marin	9	18%	7%	19%
Yuba	9	19%	19%	19%
Mendocino	4	35%	14%	38%
Solano	4	10%	17%	17%
Santa Barbara	4	16%	10%	26%
Tulare	4	35%	8%	8%
San Diego	4	35%	8%	25%

Statewide results for these four hydrologic variables are shown in Figure 3.5 for the change from baseline (1981-2010) SOM to an increase of 3% for all working lands. Climatic water deficit and runoff decrease over much of the state, and AET and recharge increase in all but a few, very small locations (see Appendix B, Figures B.1 through B.2 for close ups of these results for selected counties). The largest increases in hydrologic benefit occur in the perimeter locations of the Central Valley, where the precipitation is the highest, and thus, the increases in soil storage capacity as a result of increased SOM can be realized. This is most evident in the northern parts of the Central Valley in Tehama and Shasta counties, whereas the southern central valley obtains much less of a benefit for all variables. These results represent natural climatic conditions and do not reflect the addition of irrigation to valley floor soils that are primarily croplands. However, with intensive management on cropland soils, it has been shown that up to 8% increase in SOM can be attained (Lickacz and Penny, 2001; Spain et al., 1983), and our model simulations result in the additional hydrologic benefit of reducing CWD on all croplands (Figure 3.1) of up to 241,000 acre-feet/year. This increased AET by 518,000 acre-feet/year and recharge by 42,000 acre-feet/year, and reduced runoff by 98,000. The combined hydrologic benefit index is shown in Figure 3.6 and shows a similar benefit of adding 3% OM to soil of moderate to maximum benefit throughout the foothills and higher elevation locations of the working lands in California, including much of the coastal areas. These locations account for 36% of the working lands. The central and inland valleys that have less precipitation have minimum hydrologic benefit with increased SOM, accounting for 60% of working lands. All of these valley locations would however have the benefit of carbon sequestration (see sections 2 and 4) with increased SOM. Locations with no calculated hydrologic benefit account for 3.5% of the working lands and are interspersed throughout the state notably in the organic-rich soils of the Sacramento-San Joaquin Delta, but also in locations with very high clay or very high sand soils, and some with moderate climate and low AET. A county that has a range of hydrologic benefits, Sonoma County, is highlighted in Figure 3.6 in the top right panel. This shows that the annual grasslands in the southwest portion of the county have no hydrologic benefit from increases of 3% SOM, due to a combination of properties and factors. There are already high amounts of organic matter in these silt loam soils, approximately 3.5% SOM, with high water holding capacity (0.17 m/m), as well as a coastal climate with low levels of stress. Field tests in these locations, however, were shown to have a high benefit of soil management to sequester carbon (see Section 2). Alternatively, there are many locations in this county, including grasslands and croplands, where the models suggest strategic soil management resulting in an increase of +3% SOM will result in maximum hydrologic benefit. These results serve to illustrate where on the ground strategic soil management is likely to result in the most or leas benefit with regard to hydrologic processes as ecosystem services.

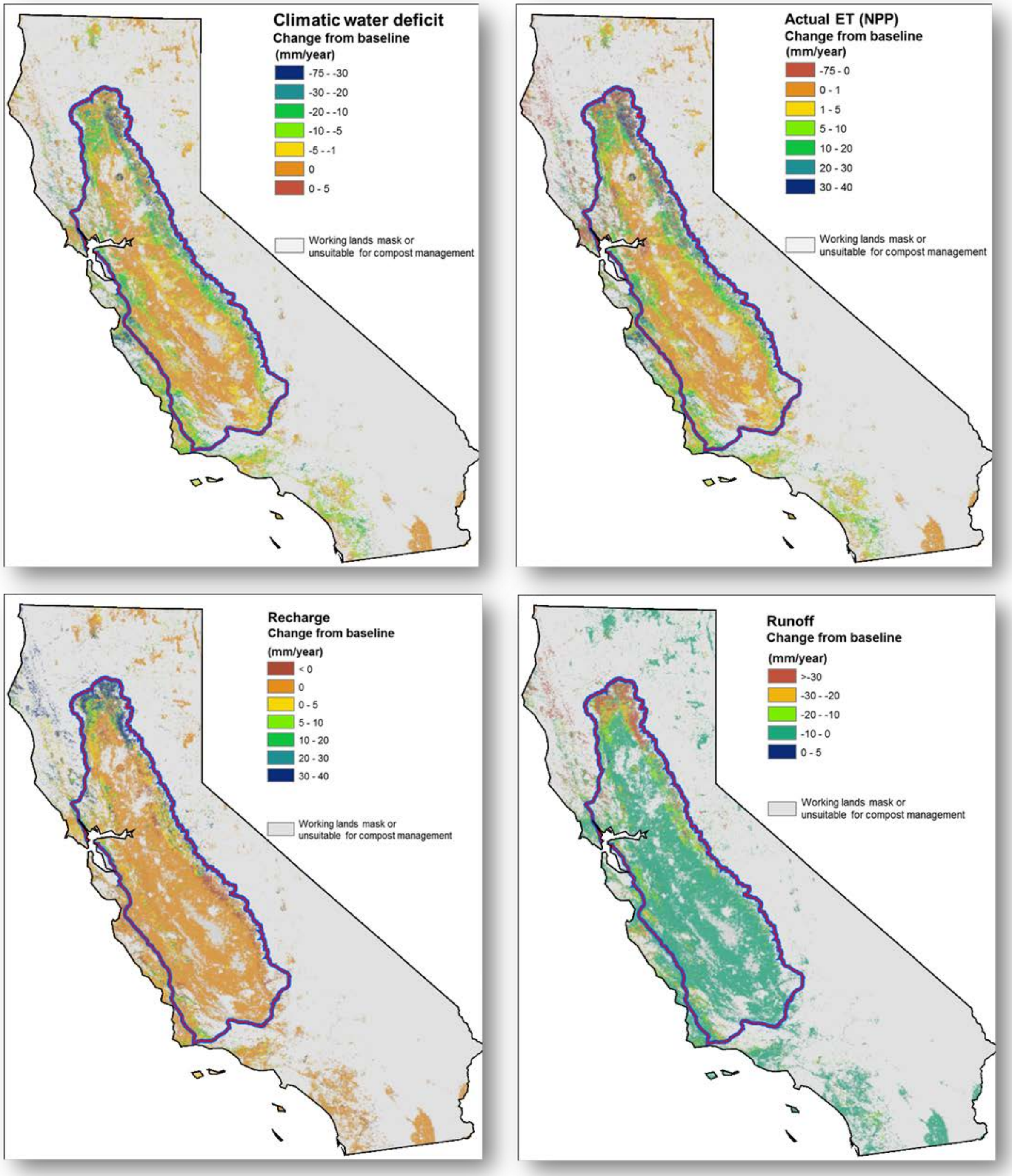


Figure 3.5: Hydrologic benefits of increasing 3% soil organic matter in comparison to baseline using the Basin Characterization Model for 1981-2010.

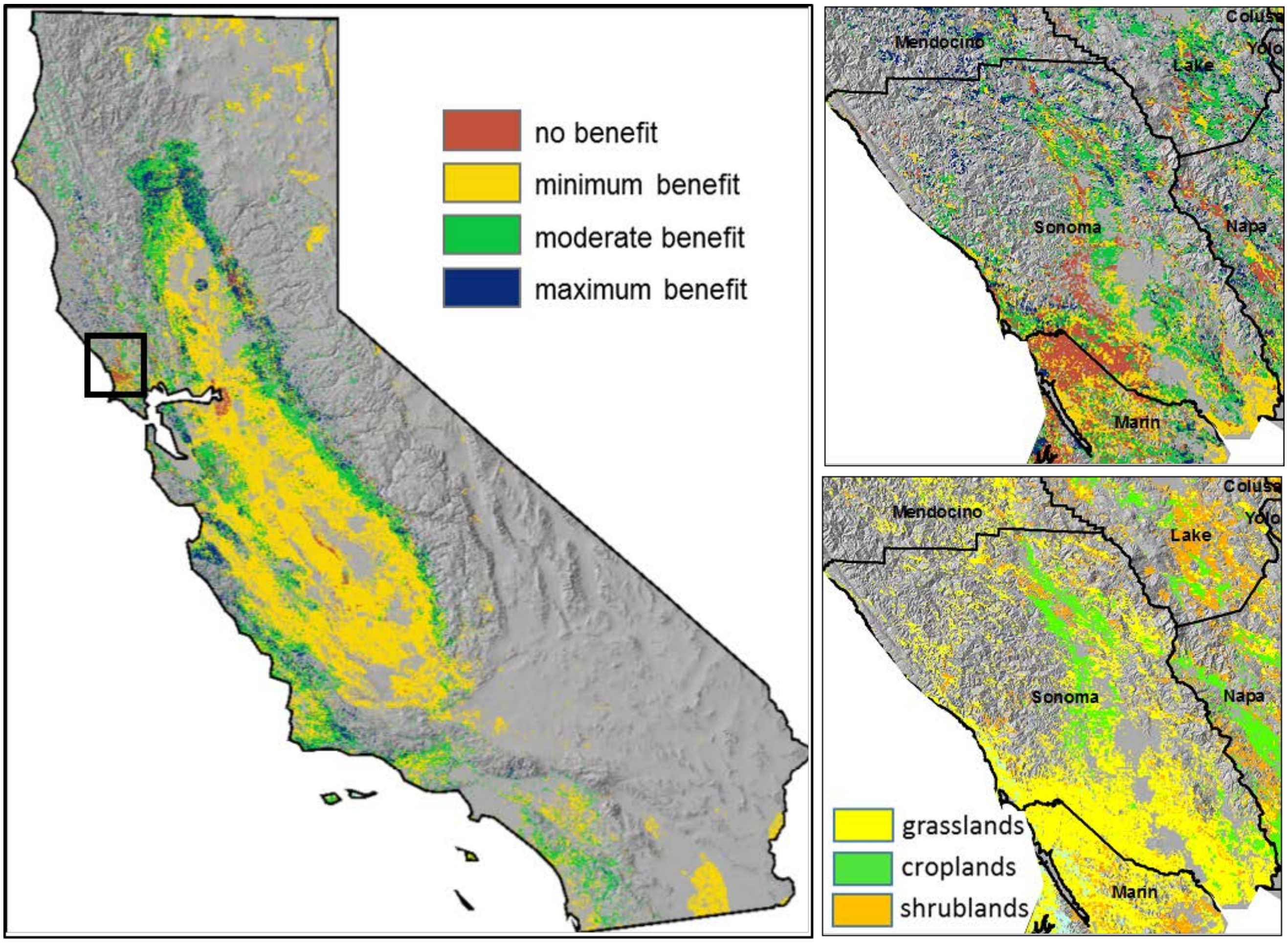


Figure 3.6: Hydrologic benefit from addition of 3% soil organic matter using an index combining AET, recharge and CWD. Included is a blow up of Sonoma County with both hydrologic benefit and vegetation types.

Table 3.3: Hydrologic results from the Basin Characterization Model run using 3% and 8% increases in soil organic matter for 1981-2010, averaged for rangelands and croplands separately.

Grasslands (32,723,717 acres)

Management application	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
	Acre-feet per year			
Baseline	21,793,996	40,421,972	5,854,818	13,119,484
+3% SOM	21,193,892	40,762,948	6,571,976	11,914,910
+8% SOM	20,442,303	41,558,835	6,779,328	11,181,319
	Change in acre-feet per year			
+3% SOM	-600,104	340,976	717,158	-1,204,573
+8% SOM	-1,351,693	1,136,863	924,509	-1,938,165
	Percent change from baseline			
+3% SOM	-0.03	0.01	0.12	-0.09
+8% SOM	-0.06	0.03	0.16	-0.15

Croplands (11,091,777 acres)

Management application	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
	Acre-feet per year			
Baseline	17,355,323	8,170,942	214,441	353,088
+3% SOM	17,284,686	8,605,370	241,246	296,692
+8% SOM	17,114,403	8,688,559	256,843	254,732
	Change in acre-feet per year			
+3% SOM	-70,637	434,428	26,805	-56,396
+8% SOM	-240,920	517,616	42,402	-98,356
	Percent change from baseline			
+3% SOM	0.00	0.05	0.13	-0.16
+8% SOM	-0.01	0.06	0.20	-0.28

In order to evaluate the outcome from potentially achieving a higher OM content with intensive management on croplands, we applied +8% SOM to the soil properties and ran the BCM for the historical time period 1981-2010. We then averaged the results for rangelands (grasslands, oak woodlands, and shrublands) and croplands. Results show greater benefit for rangeland soils than for cropland soils for CWD, but higher changes for croplands for AET, recharge, and runoff. While CWD relates to diminished irrigation demand, advantages in croplands could include improved crop yield and water supply in the form of recharge, which is very important for most croplands in the central valley that rely heavily on groundwater extractions.

Analyses of future climate impacts on hydrologic variables were done for a hot and wet future (CanESM2) and a hot and moderately dry future (HadGEM2-ES) for the business-as-usual emissions scenario, RCP 8.5. The results of the annual changes in precipitation and average air temperature for 2007-2099 (Figure 1.2, Table 1.2) indicate that these models have very similar increases in air temperature for future 30-year periods, increasing to 5.2°C when averaged over the state. Precipitation differs between the models however, with the CanESM2 model increasing about 229 mm/year by the end-of-century, and the HadGEM2-ES model only increasing 89 mm/year by end-of-century (although with a decline below historical in the mid-century). Notable, however, is the difference in the variability of precipitation between the models with the CanESM2 having a much higher range of annual precipitation, many more above historical peak years and several years lower than the HadGEM2-ES model.

Table 3.4: Hydrologic results for baseline conditions and with the addition of 3% soil organic matter, for two future climate projections. Management impact is the difference in future climate impacts as a result of adding organic matter.

Warm, wet scenario (CanESM2, rcp8.5)

Units in % change

BASELINE	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	0.9%	-3.9%	7.9%	15.7%
2040-2069	-0.5%	11.2%	29.4%	73.9%
2070-2099	11.9%	12.5%	18.0%	113.8%

+3% SOM	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	0.1%	-2.8%	6.7%	15.7%
2040-2069	-2.9%	12.9%	29.7%	75.3%
2070-2099	8.7%	14.9%	20.0%	117.2%

Management impact	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	-0.8%	1.1%	-1.2%	0.0%
2040-2069	-2.4%	1.8%	0.3%	1.4%
2070-2099	-3.2%	2.4%	1.9%	3.4%

Warm, moderately dry scenario (HadGEM2-ES, rcp8.5)

Units in % change

BASELINE	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	-1.3%	1.5%	6.9%	8.6%
2040-2069	11.0%	-11.4%	-10.7%	-22.6%
2070-2099	0.5%	2.3%	1.8%	18.5%

+3% SOM	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	-2.1%	2.6%	6.0%	7.7%
2040-2069	11.0%	-10.5%	-12.7%	-23.9%
2070-2099	-0.9%	3.6%	0.1%	18.4%

Management impact	Climatic water deficit	Actual evapotrans-piration	Recharge	Runoff
2010-2039	-0.9%	1.1%	-0.9%	-0.9%
2040-2069	0.0%	0.9%	-2.0%	-1.2%
2070-2099	-1.4%	1.3%	-1.8%	-0.1%

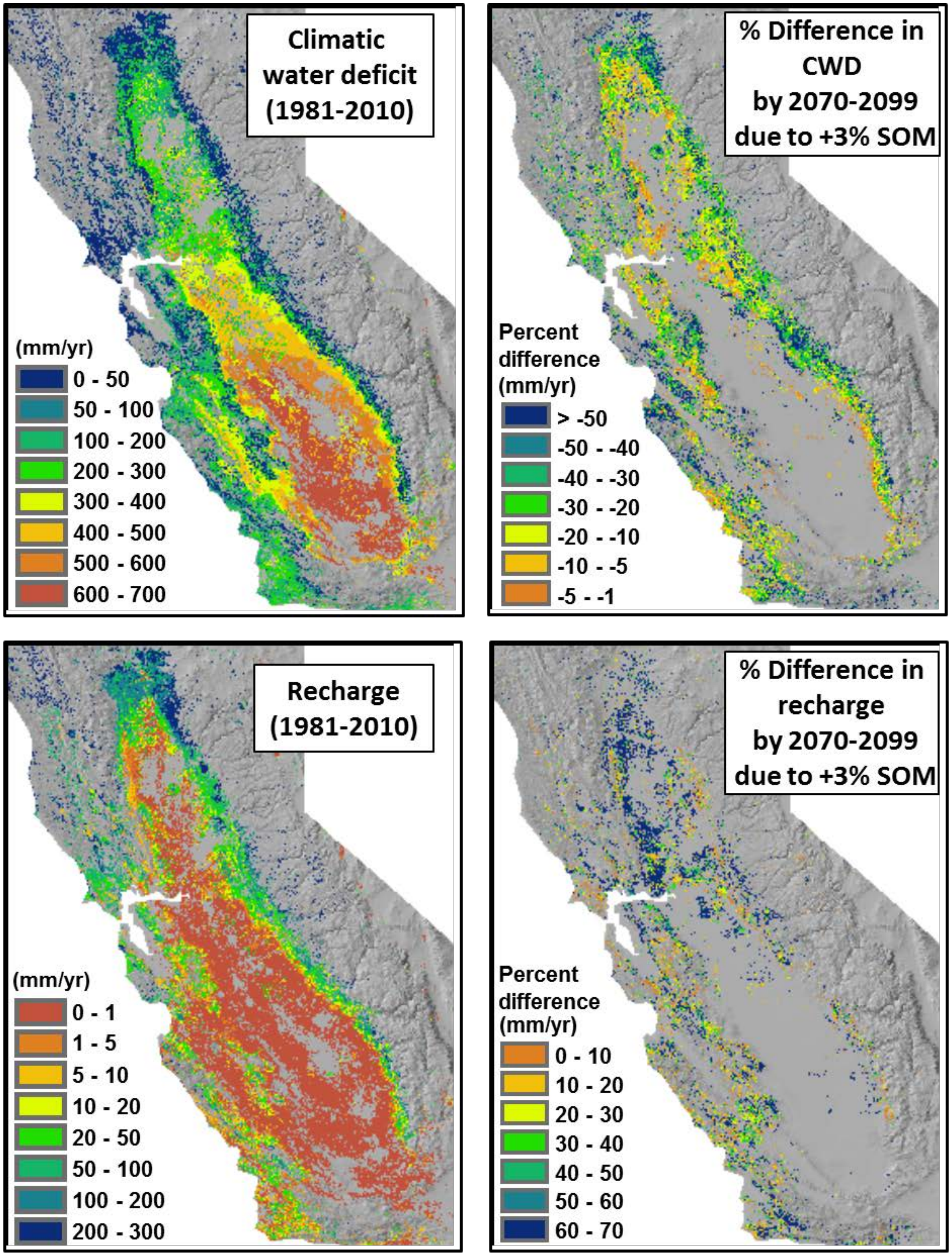


Figure 3.7: Baseline climatic water deficit (CWD) (top left) and recharge (bottom left) and percent difference (right) by end of century due to a +3 % increase in soil organic matter for the CanESM2 RCP8.5 climate projection. Gray background is masked area.

Analyses were done to compare (1) the historical baseline (1981-2010) to the future hydrologic conditions with no increases in SOM, (2) the historical baseline (1981-2010) to the future hydrologic conditions with increases of 3% SOM, and (3) the difference between these to assess if increases in 3% SOM provides any hydrologic benefit or resilience to climate change. Table 3.4 provides the results averaged over the state for future 30-year periods indicating the change in hydrology from historical climate for both baseline soil management and the increase in SOM. Climate change alone impacts the hydrology differently for the two models, with the CanESM2 resulting in more recharge and runoff than the HadGEM2-ES for all time periods, and larger increases in AET. Small changes in CWD are evident between the models, as similar air temperature increases combine with differences in precipitation with the mid-century dry periods for the HadGEM2-ES shown as an increase in CWD and decrease in AET. The benefit of adding OM is shown as the management impact in the bottom portion of the table, where +3% SOM is subtracted from BASELINE for each variable. When averaged over the whole State, there are small reductions in CWD and increases in AET, indicating some advantage to adding OM for future resilience on the basis of these two models. By the end-of-century, there is a larger impact on water supply for the wet scenario if recharge and runoff are combined, but minimal impact on hydrologic processes in the dry scenario.

However, there are much larger differences in the amelioration of climate change impacts as a result of increases in SOM in many locations, as indicated in Figure 3.7. In this example using the CanESM2 RCP8.5 future projection for CWD and recharge, there are large reductions in CWD, especially in oak woodland and grassland regions in the Sierra Nevada foothills and coastal ranges, where the baseline CWD ranges from 50-200 mm/year but is projected to increase with future warming. Decreases in CWD of 30 to > 50% occur as a result of adding SOM to ameliorate the impacts of climate change. CWD is reduced in more locations than recharge is increased as a result of adding SOM by the end-of-century, and the effects of climate change alone outweigh any impacts from adding SOM through most of the working lands in California, but there are locations where recharge increases by up to 60-70 percent over end-of-century without addition of SOM.

3.4 Discussion and Conclusions

Our objective was to test the impacts of increasing soil organic matter on hydrologic conditions and to consider various hydrologic processes as ecosystem services provided by carbon rich healthy soils. We did this with a regional water balance model that represents all water balance components and their associated processes and calculates the change in those components on the basis of changes in soil water holding capacity as a function of organic matter content. The equations used to calculate changes in soil water holding capacity were developed on the basis of thousands of soil samples with field and lab measurements that were used to correlate the soil texture and organic matter content to hydraulic properties. A small portion of textural classes, those with very high clay content, did not increase WHC with increase in OM.

The hydrologic process variables considered valuable ecosystem services are recharge, actual evapotranspiration, and climatic water deficit. The rationale for considering recharge, which in this characterization does not include artificially augmented groundwater, more valuable than runoff is that recharge is the water that stays in the watershed, contributes to late season baseflows, may penetrate to the groundwater aquifer, and is generally more resilient to changes in climate than runoff (Micheli et al., 2016). Runoff, while it fills reservoirs and is certainly valuable for water supply, generally runs off in the wet season, and may create peak flows that transport sediment and other water quality constituents and threaten or damage water management infrastructure. For these reasons, we are considering an increase in recharge relative to runoff the primary hydrologic benefit, while coincident reductions in runoff may result in less opportunity for flooding or water quality issues. Applications of this approach, however, should consider the tradeoffs given what the local hydrology and resources actually are. Actual evapotranspiration (AET) is calculated by the model as losses in soil moisture at the rate of monthly vegetation-specific evapotranspiration, until soil moisture reaches a wilting point limit. AET is often considered to be tightly correlated to above-ground net primary production (Knapp and Smith, 2001; Sims and Singh, 1978; Webb et al., 1978), which in the case of grazing lands equates to the production of forage. In our study, AET related well to the field measurements of increased forage following compost application indicated in Section 2. Climatic water deficit is well correlated to landscape stress and irrigation demand, and therefore, reductions in CWD are also a hydrologic benefit.

The variability of hydrologic benefits across the State, assuming the increase of 3% SOM on all working lands soils, is a result of the baseline soil organic matter and the differences in changes in soil water holding capacity across textural classes with increases in organic matter. Additionally, soils that could respond well to increases in SOM may not be in a climatic zone where there is enough precipitation to take advantage of the increase in soil water holding capacity and therefore do not benefit hydrologically. This is notable in southern Central Valley counties. One final consideration is the decline in soil water holding capacity with increase in SOM in soils that are very clayey, although they are minimally present in the state. Our analyses describe the spatial details of these calculations and identify soils that would not be suitable for compost application as a management strategy, if the objective is to enhance hydrology as an ecosystem service.

Modeled hydrologic benefits of increasing soil organic matter were greatest in locations with ample precipitation to fill increases in soil water holding capacity, and therefore, also had greater amelioration of climate change impacts for the wet future scenario, reducing the climate change impacts in comparison to historical climate by 1-8% when averaged over the entire state, whereas the climate change impacts were only reduced for the dry scenario by 1-3%. When evaluated spatially, many locations in the state had locations with greater than 50% change (decrease in CWD or increase in recharge) by the end-of-century, where adding SOM ameliorated climate change impacts. These were generally in northern or coastal regions, or Sierra Nevada foothill locations. These locations are particularly important to consider for CWD reduction in these fire-prone regions where California experienced massive die-off following the recent drought. Valley floor locations benefitted little in recharge but had some benefit for reducing CWD in some locations, therefore reducing irrigation demand on croplands. An additive index combining all three variables described a range of benefits across all working lands. Very few locations (3% of all working lands) had no modeled hydrologic benefit, although addition of organic matter provides carbon sequestration benefits even in the absence of hydrologic benefit. Locations with no calculated hydrologic benefit include sites high in organic matter, those with little climatic stress or little precipitation, and/or sites with unsuitable soil textures as described above. Given the future climate projections considered and the percentages of SOM analyzed, modeled hydrologic benefit from increases of SOM was attained on 97% of working lands in California.

3.5 General Application Recommendations and Guidance

Soil management to achieve the results presented here at a large scale could have important ramifications for the use of compost and other strategies to enhance soil organic matter throughout the state. Management strategies should be considered on the basis of local conditions; tradeoffs between recharge and runoff, soil properties, ongoing land management practices, and the desired benefit, whether it be for increased hydrologic resilience to climate change, forage production, reduced landscape stress and agricultural demand, mitigation of greenhouse gas emissions, or all of these outcomes. Additionally, these management strategies could be considered as part of the implementation of the Sustainable Groundwater Management Act in locations across the state where increased SOM resulted in increased recharge, and most certainly can be applied to achieve goals of California's Healthy Soils Initiative.

The results presented here rely on data layers for soil properties that may not accurately represent local conditions and should be evaluated on a case-by-case basis. Data layers of model inputs and results are available at a 270-m spatial resolution, but should be considered in concert with local characterization (Flint et al., 2013). Model uncertainty associated with various input layers and calculations results in recommendations that variables most closely associated with energy loads (AET and CWD) could be applied at the hillslope scale, but application of water supply derivatives (RCH and RUN) are recommended for spatial scales no smaller than planning watersheds.

At a regional scale, these results provide guidance as to the general landscape and climatological conditions where strategic soil management could play a big role in increasing resilience to climate change and providing hydrologic benefits and inform the prioritization of management strategies and resource allocation.

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4: Selected Economic Benefits of Increasing Soil Organic Matter on California Rangelands and Croplands

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4.1 Introduction: Purpose, Approach, and Data Constraints

The purpose of this Section is to build upon and provide a preliminary economic analysis of the biogeochemical and hydrological modelling results presented in Sections 2 and 3 for two business-as-usual (BAU) climate change scenarios (warm-wet and warm-dry), given increases in soil organic matter (SOM)[1]. This section serves as a transition piece between the technical analyses in Sections 2 and 3 and policy analyses presented in Section 5. This preliminary economic analysis of impacts due to changes in SOM include provisioning services associated with above-ground forage productivity and regulating services associated with below-ground carbon sequestration, and groundwater recharge. General results are discussed for the state for recharge, with more detailed findings presented for the four selected California counties (Tehama, Tulare, Santa Barbara, and San Joaquin). For forage production and below ground carbon sequestration we provide preliminary estimates of the economic benefits for seven experimental plots in San Diego, Tulare, Santa Barbara, Marin, Mendocino, Yuba, and Solano counties. For forage production and carbon sequestration, the financial analyses are dependent on the results of the CanESM2 model for RCP8.5 (high emissions reduction) and RCP 4.5 (low emission reduction) scenarios employed in Section 2. For hydrological impacts the analysis builds upon the results of the BCM model in Section 3 that uses only RCP 8.5 scenario applied to a “hot and dry” HadGEM2-ES climate model and the “hot and wet” CanESM2 climate model.

While the analysis presented in this Section flows from the biophysical modelling results previously reported, placing a monetary or non-monetary value on the changes in the key biogeochemical (above ground forage production and carbon sequestration) and the hydrological variables (groundwater recharge) is dependent on two important factors. First, there must be data on the production response to changes in SOM, whether through compost application or through other management practices. Such data exist for forage production and are based on past and current composting field trials, but there is a dearth of reporting for crop production response to management practices designed to augment SOM. In addition, individual row or tree crop response will depend on soil type and characteristics, climate, and geography. Thus, given time and data constraints, it is not possible to assess state-wide values for these types of crops at this time. To the extent that there exist secondary SOM amendment production data and analysis for specific locations and crops we report on those in Section 4.2

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[1] For estimating the value of hydrologic impacts (recharge) we use an increase in SOM of 3%. For the biogeochemical impacts due to addition of ¼ inch compost (carbon sequestration and forage production) we equate this to approximately an increase in SOM of 1%.

(Literature Review), and if possible, report on any type of economic analysis that might be available.

The remainder of this Section is organized along the following lines. Sub-section 4.2 provides a literature review on the economic and/or financial impacts of SOM increases on range and croplands, either in California or other comparable areas. Section 4.3 lays out a general analytical framework to underpin the identification and valuation of the selected ecosystem services and the types of market or non-market benefits that may accrue due to increases in SOM. Section 4.3 also lays out the types of economic and/or financial methods used in valuing these services, such as forage production that can be estimated using avoided supplemental feeding costs, or price of hay. Likewise, changes to groundwater recharge may be valued by using avoided water irrigation costs as a proxy.[2] Supporting services such as carbon sequestration can be valued by estimating market values (assuming a private or administered market for carbon credits exists) and the public social cost of carbon (SCC)[3] from avoided greenhouse gas (GHG) emissions. Other potentially impacted ecosystem services such as benefits associated with pollination or increases in native forage species are not addressed here because of the lack of adequate production functions that link SOM to these services.

Sub-section 4.4 will present the methods and results of our research and analysis and the potential economic benefits of increasing SOM through management actions on working agricultural lands. In collaboration with the Carbon Cycle Institute, Section 4.5 will discuss specific policy questions related to the establishment and operation of carbon credit markets. Section 4.6 will summarize our conclusions and provide recommendations for future directions for policy and further research.

4.2 Literature Review

The value of increased soil organic matter (SOM) can be estimated by the change in flow of impacted ecosystem service benefits provided to individual producers and to society. These benefits, derived from selected potential soil-related ecosystem services, are based on evidence and data of preferences from which values can be assessed, estimated, and sometimes monetized. Some studies have attempted to value ecosystem services derived from increases in SOM in California range and croplands and elsewhere (Martínez-Blanco et al., 2013). This review will discuss some of these studies, as well as studies that are more biophysical in nature and address carbon sequestration, crop and forage productivity, and groundwater recharge.

4.2.1 Carbon Sequestration

With abundant resources being funneled into climate change research in the last few decades, the ecosystem service of carbon sequestration has been well studied and analyzed in

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[2] See more details in Section 4.4.3 on valuing groundwater recharge.

[3] The social cost of carbon (SCC) is a monetary estimate of the net societal damage caused by a 1-metric ton increase in carbon dioxide emissions. Net damages equal the costs minus the benefits associated with climate change impacts, such as GDP loss, agricultural productivity, risks to human health, damage from floods, among other parameters (NAS, 2017). For more on the social cost of carbon see National Academies of Sciences (2017).

biogeochemical terms[4]. However, the economic literature for assessing economic benefits of carbon sequestration on California range and agricultural lands is scarce. Most economic studies have used two types of valuation approaches. The first is an assessment of the private benefits of carbon sequestration via carbon credit markets or payments for ecosystem services (PES) (Alexander et al., 2015; Bremer et al., 2016). The second approach examines the public benefits derived from avoided CO_2 emissions based on the SCC, a well-established metric that calculates the value of avoided GHG emissions (Alexander et al., 2015). In a recent report discussing the biophysical and economic benefits of healthy soils in the United States, The Nature Conservancy (2016) estimated the SCC of avoided GHG emissions from crop agriculture in 2004 to be US$12.4 billion (using a 2015 SCC estimate of US$36 per ton of CO_2). In a comprehensive economic analysis of agricultural soil carbon sequestration in U.S. Northern Plains, Antle et al. (2001) demonstrated soil carbon values could vary dramatically from US$12 to US$500 per ton depending on the type of payment mechanism or credit contract employed.

4.2.2 Cropland Productivity

The biogeochemical and hydrologic underpinnings laid out in Sections 2 and 3, which sustain ecosystem processes and functions that in turn provide economic and financial benefits related to plant productivity, are very similar for both agricultural and rangelands. Most assessments to date attempting to quantify the relationship between increases in SOM and plant productivity have only examined the biogeochemical connections between these variables. Studies on crop productivity responses to increases in SOM have received much more attention than forage productivity. In a recent study, Agegnehu et al. (2016) found that agricultural soils amended with biochar and compost significantly increased maize grain yield by 10 to 29% in Queensland, Australia. In Nova Scotia, Canada, Warman (1998) also found compost-amended soils to positively influence onion plant growth, producing higher yields as compared to conventionally fertilized vegetable plots over an 11-year period.

Some studies have monetized improvements in crop productivity resulting from the application of SOM. In the Salinas Valley, California, researchers studied the effects of using municipal compost on intensive vegetable production systems. They found that application of compost increased lettuce and broccoli yields in three different trials, resulting in increased financial returns of US$1,732 per acre for plots treated with minimum tillage and compost compared to control plots that did not receive compost (Jackson et al., 2004). The same study reports that there were cost savings related to reductions in fuel use, reduced labor and equipment ownership costs in comparison to only conventional tillage operations (Jackson et al., 2004). In another California study, Karp et al. (2016) reported higher lettuce yields for compost-amended plots compared to non-amended plots. Using the replacement cost of fertilizer as a proxy for valuing increases in SOM, Hoorman and Islam (2010) estimated a value of US$68/ton for SOM nutrients, which, according to the researchers, would equal about US$680 per acre assuming 2,000,000 pounds of soil in the top six inches. Also using a replacement cost of fertilizer as a proxy, Wander and Nissen (2004) found increases in SOM to have an annual value of US$140 per hectare for corn.

Halloran et al. (2013) conducted a cost-benefit analysis of compost amendments and demonstrated that the costs of purchasing and applying compost were quite significant when

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[4] Please refer to Section 2 for more on the literature available.

compared with the benefits of compost for potato production in Maine. The authors found that rain-fed, compost-amended plots achieved higher net revenues when compost costs were US$9.43 per ton or less, when compared to irrigated, non-composted plots. However, they concluded that using compost was not economically feasible when potato crop productivity was taken into account, given that market costs of compost in Maine varied between US$30 and US$40 per ton (Halloran et al. 2013). With this important caveat in mind, Weindorf et al. (2011) presented a review that examines different assessments around the world pertaining to the several benefits derived from compost use in agricultural settings, including the avoided cost of fertilizers in Cuba, soil erosion mitigation in Chile, and improvement in water quality through decreases in nutrient run-off in Europe.

4.2.3 Forage Quantity and Quality

Although the positive correlation between forage productivity and quality associated with increases in SOM has been demonstrated (Ryals et al., 2016; Ryals and Silver, 2013; DeLonge et al., 2013), very few studies have placed a monetary value on this relationship. Although not due to an increase in SOM, in a recent analysis, Craine et al. (2017) quantified an increase in dietary nutritional status of North American cattle due to an increase in forage quality. In this 22-year study, researchers found that due to a reduced protein provision in cattle forage over the past two decades, ranchers would have to pay US$1.9 billion to compensate for declines in protein, based on the market price for soy meal at US$0.36/kg. Also in regards to forage quality and productivity for a dairy farm, Daley (2012) found compost amended soils significantly increased both forage yield and quality in a two-year study performed in Chico, California. Based on the cost of replacing the increased amount of hay produced per season (1,440 pounds) in comparison to the non-amended soils, the research team found the value of increased forage production on composted plots to be US$253.5 per acre. It would cost a rancher about US$6,400 to compensate for the loss in forage productivity on non-amended soils. Compost amended soils improved relative forage quality (RFQ)[5] by 19.6% as compared to non-amended soils. This improvement resulted in higher milk production per ton of forage consumed, generating about an additional US$199 per cow or about US$17,912 for a 90-cow herd, based on a US$30 cost of milk per hundredweight (Daley, 2012).

4.2.4 Hydrologic Impacts

As discussed in detail in Section 3, the hydrologic benefits of SOM increases have been well documented in the literature (Ryals et al., 2013; Huntington, 2005; Rawls et al., 2003). However, there have been few economic analyses associated with these benefits. On a general level, one USDA conservation study found that increases in SOM reduced soil erosion from runoff and had a positive impact on water quality. Ribaudo (1989) examined the public benefits from avoided soil erosion from agricultural lands and estimated an avoided cost of about US$2.33 per ton of eroded sediment (in 2017 dollars), based on impacts of runoff on recreation, navigation, water storage, irrigation, flooding, commercial fishing, municipal and industrial water use, and municipal water-treatment. Given the 40 to 45 million acres of highly erodible

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[5] Relative Forage Quality (RFQ) is an index for ranking forages based on a more comprehensive analysis that includes Crude Protein (CP) content, Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF), fat, ash, and Neutral Detergent Fiber Digestibility (NDFD) calculations. The higher the RFQ, the better the quality (Daley, 2012).

cropland analyzed by the study, those benefits could result in an estimated US$7 to US$8 billion in water quality benefits (Ribaudo, 1989).

By analyzing the benefits of compost application on soil erosion and water quality, Crohn (2011) – in a study done for the California Department of Resources Recycling and Recovery (CalRecycle) – found that compost application reduced water runoff by 80%. Soil erosion was also found to be effectively reduced in compost-amended soils, with sediments, total suspended solids (TSS), and total dissolved solids (TDS) being reduced by 95, 94 and 65% respectively (Crohn, 2011).

Regarding the benefits of water recharge derived from increases in SOM, The Nature Conservancy (2016) estimated the value of water supply, based on agricultural irrigation costs in the U.S. western states, to be US$1.17 billion (based on average water costs of US$66.28/acre for western states). To put into perspective how scarcer – and therefore valuable – water is in western states, the rest of the U.S. has a per acre average cost of purchased water of *only* US$10. This is an important implication – increases in SOM in western states like California may have significant economic benefits related to improvements in both water supply and quality.

4.3 Conceptual Frameworks for Defining and Valuing Ecosystem Services

This brief overview of how ecosystem services have been characterized, and the economic conceptual framework used to value those services, underpins the types of rangeland ecosystem services that may be affected through the application of SOM and whether or not monetary valuations are possible. As a general approach, this study utilizes the Millennium Ecosystem Services Assessment (MEA, 2005) categorization of ecosystem services. The MEA classified ecosystem services into four basic categories: provisioning, regulating, supporting, and cultural.[6] As applied to California rangelands, an example of a provisioning service resulting from additional SOM amendments would include increased forage production and quality, and, therefore, increased animal production for consumption. Regulating services would include carbon sequestration and potential flood mitigation. Rangelands also provide services that "support" pollinators and other species' populations. Examples of cultural services provided by rangelands include recreation (e.g. fishing and hunting), but also aesthetic and spiritual benefits. Table 4.1 provides a list of selected benefits and associated ecosystem services derived from rangelands.[7]

Economists use the term Total Economic Value (TEV) to describe the range of benefits provided by a particular landscape. TEV is broken into two categories: use and non-use values (see Figure 4.1). In our analysis of the benefits associated with increasing, SOM we only address direct and in direct use values, and therefore provide a partial economic value rather than the entire TEV.

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[6] For alternative conceptual frameworks or classification systems for ecosystem services, see Brown et al., 2007, Boyd and Banzaff (2007), Wallace (2007) and EPA (2015). A classification system specific to rangelands can be found in Maczko et al. (2011).

[7] See Kroeger et al. (2010).

Table 4.3: Selected benefits and associated ecosystem services provided by rangelands.

Benefit	Ecosystem Service
Livestock harvest	Forage production and water availability
Crop harvests (nearby properties)	Pollinator populations
Recreation – hunting and fishing	Relevant species populations; natural land cover
Recreation – wildlife viewing	Relevant species populations
Wildlife passive use benefits	Relevant species populations (threatened/ endangered/rare species and habitats)
Drinking water provision – Avoided treatment cost	Aquifer and surface water quality (run-off nutrient retention)
Drinking water provision – Avoided pumping/transport cost	Aquifer and surface-water availability (aquifer infiltration)
Aesthetic benefits (open space property value premiums and outdoor recreation)	Natural land cover in view shed
Damage avoidance – Health benefits	Drinking-water quality (nutrient and bacterial control)
Damage avoidance – Property	Natural land cover (trees and grasses), soils, and wetlands (climate change and rain storm events)
Damage avoidance – Harvests (forage)	Native plants resistant to invasion by unpalatable weeds (for example, cheat grass)
Damage avoidance – stream channel dredging	Reservoirs and natural land cover

Sources: Boyd and Banzhaf (2007); Maczko and Hidinger (2008); Valerie Eviner, Department of Plant Sciences, University of California at Davis (oral commun., 2010). Adopted from Kroeger (2010).

Rangelands are the source of both use and non-use values. Use values generally pertain to values derived from direct interaction, whether something is actually consumed or not, now or in the future. For use values, the ecosystem services provided by rangelands include "direct use" values (forage provisioning, recreation, aesthetics, and so forth), for which market prices can be observed. However, rangelands also provide indirect use values, such as ecosystem supporting and regulating services (e.g. flood protection, carbon sequestration). These services are more difficult to value monetarily given the complexity in the biophysical relationships (especially at the margin), limitations of aggregation, lack of data pertaining to specific management actions, and, ultimately, deriving economic values in comparable units.

Rangelands also support non-use benefits in the form of existence values as well as cultural/spiritual values. Non-use values include the value people place on simply knowing something exists now or into the future, regardless of actual interaction. For ranchers, cultural and bequest values can be high and are integral to quality of life. In common with use and non-use values is the dependence on the quality and/or quantity of the resource in question. Some ecosystem services can be valued in monetary terms using a variety of economic methods, depending on the availability of biophysical response data and the type of value (use or non-use) that is being estimated. Table 4.2 lists selected valuation methods applied to various ecosystem services, some of which are not strictly economic methods (damage costs avoided, averting behavior, replacement costs, and public pricing), but maybe accepted for public policy decision makers). Most typologies group defensive and damage cost methods under revealed preference techniques. We separate them here because they are more weakly grounded in economic theory than other approaches. (See Champ et al, 2003; National Research Council, 2005; U.S. Environmental Protection Agency (EPA), Science Advisory Board, 2009).

For example, the value of a provisioning service (e.g., forage) is estimated most often using revealed market prices (the price of hay, for example). Supporting and regulating services, such as aquifer recharge and carbon sequestration, respectively, rely on the production function method that attempts to elicit the ecosystem services' specific contribution to the production process of a marketable good (e.g., agricultural commodities), in this case from the increase in SOM. There is a dearth of production function data and models that reliably estimate many, if not most, of the supporting and regulating services resulting from increasing SOM on California rangelands and crop lands.[8] The same data and research constraint applies to information on stated preferences for non-use values, whether through contingent valuation surveys or choice modeling experiments. The methods to estimate a monetary benefit of these types of values are usually described as "Willingness to Pay" (WTP), or stated preferences, which is solicited through contingent valuation or choice modelling survey methods.

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[8] In cases where production function data models do not exist for regulating and supporting services, one could use a replacement value if the service is lost.

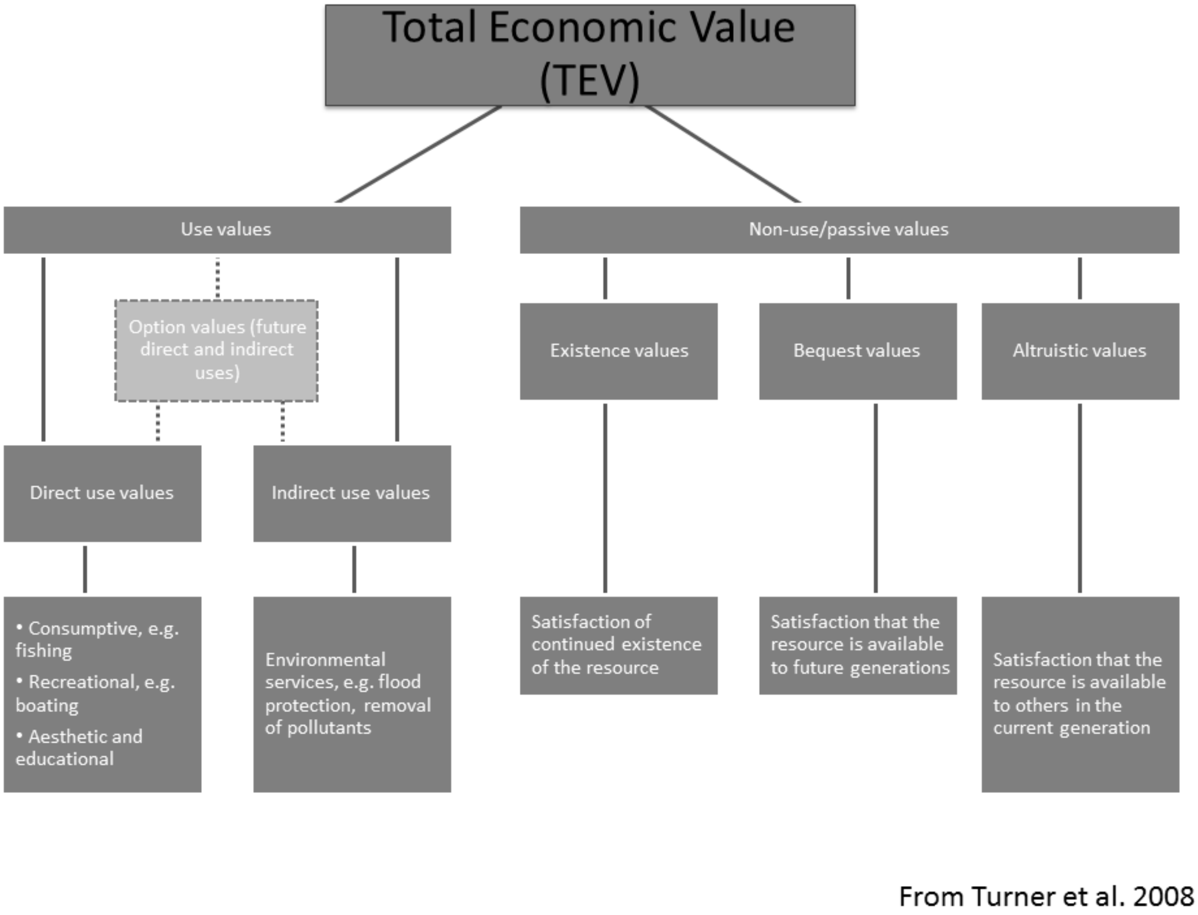

Figure 4.1: Components of Total Economic Value (presented by the National Ecosystem Services Partnership, 2014).

Table 4.4: Valuation methods for ecosystem services)

	Valuation Method	Description	Examples of Ecosystem Services Valued
Market Valuation[9]	Market Analysis and Transactions	Derives value from household's or firm's inverse demand function based on observations of use	Fish Timber Water Other raw goods
	Production Function	Derives value based on the contribution of an ecosystem to the production of marketed goods	Crop production (contributions from pollination, natural pest control) Fish production (contributions from wetlands, sea grass, coral)
Revealed Preferences	Hedonic Price Method	Derives an implicit value for an ES from market prices of goods	Aesthetics (from air and water quality, natural lands) Health benefits (from air quality)
	Recreation Demand Methods	Derives an implicit value of an on-site activity based on observed travel behavior	Recreation value (contributions from: Water quality and quantity Fish and bird communities Landscape configuration Air quality)
Defensive and Damage Costs Avoided[10]	Damage Costs Avoided	Value is inferred from the direct and indirect expenses that would have otherwise been incurred as a result of damage to the built environment or people.	Flood protection (costs of rebuilding homes) Health and safety benefits (treatment costs)
	Averting Behavior/Defensive Expenditures	Value is inferred from costs and expenditures incurred in mitigating or avoiding damages	Health and safety benefits (for example, cost of an installed air filtration system suggests a minimum willingness-to-pay to avoid discomfort or illness from polluted air)
	Replacement/ Restoration Cost	Value is inferred from potential expenditures incurred from replacing or restoring an Ecosystem Service.	Drinking water quality (treatment costs avoided) Fire management
	Public Pricing	Public investment serves as a surrogate for market transactions (for example, government money spent on purchasing easements).	Non-use values (species and ecosystem protection) Open space Recreation
Stated Preference	Contingent Valuation (open-ended and discrete choice)	Creates a hypothetical market by asking survey respondents to state their willingness-to-pay or willingness-to-accept payment for an outcome (open-ended), or by asking them whether they would vote for or choose particular actions or policies with given outcomes and costs (discrete choice).	Non-use values (species and ecosystem protection), Recreation Aesthetics
	Choice Modeling/ Experiments	Creates a hypothetical market by asking survey respondents to choose among multi-attribute bundles of goods and derives value using statistical models.	Non-use values (species and ecosystem protection), Recreation Aesthetics

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[9] Some typologies consider market valuation a type of revealed preference analysis.

[10] Most typologies group defensive and damage cost methods under revealed preference techniques. We separate them here because they are more weakly grounded in economic theory than other approaches. (See Champ et al, 2003; National Research Council, 2005; U.S. Environmental Protection Agency (EPA), Science Advisory Board, 2009).

Source: National Ecosystem Services Partnership, 2015

4.4 Methods and Results

This section describes the methods and results for estimating the market and non-market benefits of specific ecosystem services associated with increasing SOM on California rangelands. The ecosystem services to be assessed include provisioning, supporting, and regulating services: increased "natural" above ground forage production[11]; below ground carbon sequestration; and groundwater recharge. For example, the change in net primary productivity (NPP) from increased soil water holding capacity or decreases in climate water deficit (CWD) could be used to estimate the economic value of increased production and/or avoided irrigation water costs for selected high value crops *if* sufficient individual crop production response data from increased SOM were available.

To estimate the economic and financial benefits associated with forage production and below ground carbon sequestration and storage, we build upon the biogeochemical modelling results described in Section 2. Benefits are estimated relative to the control plots at each of the seven sample sites investigated by the UC Berkeley team, which include four coastal sample sites located in the San Diego, Santa Barbara, Marin, and Mendocino counties, and three inland sample sites located in Tulare, Solano, and Yuba.

For estimating the economic benefits associated with water recharge from increasing SOM, we utilize the modeling results from Section 3. For groundwater recharge, methods and results are described at two geographic scales: at the state level and for selected counties. Four counties were selected that represent a diversity of California grassland production and include Tehama, Tulare, Santa Barbara and San Joaquin.

The benefits of increasing SOM are discussed in the context of two climate scenarios. In the case of the hydrological modelling, the two scenarios correspond to a warm-wet and warm-dry futures climate. However, for the biogeochemical modelling, only the warm-wet future climate is analyzed using high and low carbon emissions scenarios.

4.4.1 Forage Production

For each 10-year (decadal) period, the average difference in forage production per ha/year, between the control plots and the plots that received increased SOM through compost addition, is calculated for each of the climate change scenarios (Table 4.3). The ten-year periods that reflect the impacts of composting include 2010-2019, 2020-2029, 2030-2039, and 2040-2049. As stated previously, however, we caution that estimating the value of forage production beyond 2030 becomes more problematic because several variables related to climate, availability of substitutes, and technology change are difficult to predict.

We estimate two values for forage production. The first value depicts a private value attributed to the landowner and is represented by the avoided cost of having to purchase hay (Table 4.3, columns 2 and 4 for each climate scenario). We assume that the rancher will need to purchase less hay given the increase in forage production over the years after the application of compost. We arrive at the avoided costs of purchased hay by multiplying the average difference in dry

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[11] While directly increasing SOM on grasslands may be considered a management practice and result in a managed ecosystem, the biogeochemical processes resulting from increasing SOM on forage production are entirely natural.

tons of forage production per ha/year by an average estimated price per ton of commercial hay for each of the seven counties.[12] For statewide results, the biophysical difference of dry tons of aboveground forage production between control and compost plots was multiplied by the average price of hay in California for each decade. The results are presented as decadal annual averages for each of the four decades from 2010 to 2049 for each respective decade.[13]

The second value depicts a public market value and is represented by benefit of increased hay production (Table 4.3, columns 3 and 5 for each climate scenario) at the county level. This value is estimated by multiplying the increase of aboveground forage production from the control and compost plots by the annual hay production for each county, which is then multiplied by the avoided cost of purchased hay for each respective decade.[14] The county annual hay production data provides a market value representative to the actual total average production for each county, as different counties may have strikingly different production patterns for hay. This market value takes the entire annual production of hay for the county and accounts for the biophysical increase in forage production for each respective county. The results, demonstrated below in Table 4.3, are annual averages for each respective decade from 2010 to 2049.

Although the monetary values vary substantially among some counties, all county plot data show that an increase in forage production via compost application has the potential to provide ranchers steady and increasing monetary benefits over time. As an estimate of statewide impacts, the seven site average illustrates this positive relationship. For instance, under the high emissions scenario, the average private savings a landowner would incur from avoided hay purchase increases from $14 to $64 per ha/yr from 2010 to 2049 – a 357% increase, based on the 7-county average values. This illustrates how a one-time compost application can lead to increases in the value of forage production over time. In general, with the exception of the Solano County test site, the monetary benefits from increased hay production are higher under the reduced emissions scenario.

Table 4.5: Value of forage production for two emissions scenarios by county for 2010-2049.

		Forage Production			
		High Emissions Scenario (CanESM-ES rcp8.5)		**Reduced emissions scenario (CanESM-ES rcp4.5)**	
		Avoided costs of purchased hay ($/ton/ha/yr)	**Benefit of increased county hay production ($/yr)**	**Avoided costs of purchased hay ($/ton/ha/yr)**	**Benefit of increased county hay production ($/yr)**
San Diego	***2010-2019***	$2	$350	$2	$619
	2020-2029	$14	$23,000	$30	$59,423
	2030-2039	$29	$98,846	$36	$95,163
	2040-2049	$41	$131,496	$40	$103,698
Santa Barbara	***2010-2019***	$3	$948	$2	$769
	2020-2029	$25	$102,711	$42	$221,739
	2030-2039	$24	$94,745	$61	$447,094

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[12] All hay price data were collected from the USDA National Agricultural Statistics Service (NASS). See Table C.1 in Appendix C.

[13] Forecasted hay prices (2017-2050) were calculated via simple linear regression analysis based on historical price received data (1949-2016) for California.

[14] County hay production data was only available for the years 2002, 2007, and 2012. We used the 3-year average to account for hay production in each county.

	2040-2049	$61	$356,610	$79	$596,435
Marin*	***2010-2019***	$28	$16,438	$9	$1,857
	2020-2029	$10	$2,182	$21	$10,344
	2030-2039	$21	$13,472	$20	$12,301
	2040-2049	$22	$8,739	$36	$23,577
Mendocino	***2010-2019***	$5	$3,068	$4	$1,210
	2020-2029	$41	$214,252	$49	$247,770
	2030-2039	$35	$209,578	$49	$321,889
	2040-2049	$68	$414,180	$83	$526,700
Yuba	***2010-2019***	$56	$49,848	$51	$41,979
	2020-2029	$89	$169,902	$93	$188,599
	2030-2039	$79	$124,961	$110	$210,310
	2040-2049	$100	$146,606	$102	$163,971
Solano	***2010-2019***	$5	$25,558	$2	$3,434
	2020-2029	$50	$2,360,306	$51	$2,325,380
	2030-2039	$54	$2,815,501	$81	$5,118,246
	2040-2049	$97	$6,039,558	$88	$5,260,867
Tulare	***2010-2019***	$2	$9,024	$2	$10,587
	2020-2029	$13	$652,977	$27	$2,248,774
	2030-2039	$46	$5,785,911	$43	$5,529,038
	2040-2049	$58	$7,538,864	$60	$8,833,539
7 County avg.	***2010-2019***	$14	$15,034	$10	$8,636
	2020-2029	$35	$503,619	$45	$757,433
	2030-2039	$41	$1,306,145	$57	$1,676,292
	2040-2049	$64	$2,090,865	$70	$2,215,541

4.4.2 Below Ground Carbon Sequestration

For each 10-year (decadal) period, the average difference in CO_2 equivalents/ha/year between the control plots and the plots which received increased SOM through compost application is calculated for the high and low emissions climate change scenarios (Table 4.4.). The four 10-year periods that reflect the measured impacts of compost include 2010-2019, 2020-2029, 2030-2039, and 2040-2049. To derive the potential benefit using prices set by the California Air Resources Board (CARB), we use the value of carbon sequestration only up to 2030, in accordance with the current legislative mandate for the California cap-and-trade program.[15] Values for the Social Cost of Carbon (SCC), which are employed to estimate the societal value of avoided GHG emissions via increases in SOM, have been estimated for several decades into the future under different discount rate scenarios through 2049.[16]

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[15] California legislature passed legislation SB 32 (2006) and AB 398 (2017), which extend GHG emissions reduction targets and the cap-and-trade program through 2030 (CARB, 2017).

[16] For more on technical details regarding the development and use of the SCC, please refer to the Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis created by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government (IWGSCGG, 2016).

Carbon sequestration values in the form of CO_2 equivalents can be used to estimate administered compliance market value of sequestered carbon (CARB, 2017) and/or the *public* social cost of carbon (SCC) from avoided GHG emissions over a given period (IWGSCGG, 2016). The societal value of avoided GHG emissions was represented by the difference or additional tons of carbon sequestered between control and compost plots, which was then multiplied by the discounted SCC average value for all respective decades.[17]

The market value of avoided GHG emissions is represented by the product of increased carbon sequestration after the application of compost – the difference between control and compost plots – and the market price of carbon.[18] Table 4.4 provides results for the two carbon sequestration values – the public societal value, calculated via the SCC, and the CARB administered compliance market price for CO_2 equivalents.

Using the SCC, the two different emissions scenarios affect different counties in distinct ways depending on geographical location. However, the results in Table 4.4 generally indicate that the stream of benefits increases over the assessed 40-year period at each test site. The seven site average results provide estimates for the state as a whole for both the SCC and the administered markets under both climate scenarios. This assumes that the sites studied adequately represent the diversity of regions throughout the state. Although estimates of CARB compliance market values are provided for only two decades, the results show a substantial increase in the average value of carbon credits between 2010 and 2029.[19]

Table 4.4: Valuation of carbon sequestration based on the social cost of carbon and CARB administered prices for two climate scenarios, 2010-2049.

		Carbon sequestration			
		High emissions scenario (CanESM2 rcp8.5)		Reduced emissions scenario (CanESM2 rcp4.5)	
		Societal value of avoided GHG emissions (ton/ha/1%)*	Market value of avoided GHG emissions (ton/ha)	Societal value of avoided GHG emissions (ton/ha/1%)*	Market value of avoided GHG emissions (ton/ha)
San Diego	***2010-2019***	$16.68	$4.94	$13.02	$3.86
	2020-2029	$278.64	$91.50	$238.89	$78.45
	2030-2039	$235.72	-	$262.10	-
	2040-2049	$386.13	-	$434.40	-
Santa Barbara	***2010-2019***	$16.34	$4.84	$14.01	$4.15
	2020-2029	$245.47	$80.61	$241.28	$79.23
	2030-2039	$303.08	-	$318.57	-
	2040-2049	$524.60	-	$554.56	-
Marin*	***2010-2019***	$184.11	$54.57	$177.46	$52.60

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[17] SCC data was collected from the Interagency Working Group on Social Cost of GHG (2016), United States Government. A 3% discount rate was used, for additional values and different discount rates please refer to Table C.2 in Appendix C.

[18] Carbon price data (2012-2017) was retrieved from the California ARB auction prices for carbon. Linear regression analysis was used to forecast prices up to 2030. Please refer to Table C.3 in Appendix C for the price data.

[19] For more details on policy considerations, please refer to Section 4.5 and Section 5.

	2020-2029	$345.12	$113.33	$341.81	$112.25
	2030-2039	$209.91	-	$218.91	-
	2040-2049	$329.59	-	$351.55	-
Mendocino	***2010-2019***	$23.05	$6.83	$16.91	$5.01
	2020-2029	$297.11	$97.57	$277.33	$91.07
	2030-2039	$260.34	-	$263.47	-
	2040-2049	$411.69	-	$426.24	-
Yuba	***2010-2019***	$223.56	$66.26	$208.75	$61.87
	2020-2029	$365.95	$120.18	$360.61	$118.42
	2030-2039	$202.39	-	$218.73	-
	2040-2049	$312.66	-	$356.97	-
Solano	***2010-2019***	$16.43	$4.87	$18.45	$5.47
	2020-2029	$262.89	$86.33	$271.81	$89.26
	2030-2039	$278.90	-	$271.50	-
	2040-2049	$463.54	-	$442.74	-
Tulare	***2010-2019***	$15.21	$4.51	$14.21	$4.21
	2020-2029	$221.55	$72.76	$235.23	$77.25
	2030-2039	$304.56	-	$313.21	-
	2040-2049	$533.14	-	$549.29	-
7 county avg.	***2010-2019***	$70.77	$20.98	$66.12	$19.60
	2020-2029	$288.10	$94.61	$281.00	$92.28
	2030-2039	$256.41	-	$266.64	-
	2040-2049	$423.05	-	$445.11	-

* 3% discount rate (See Appendix C.2 for calculations using 5% and 7% discount rates)

4.4.3 Groundwater Recharge

Section 3 reported on the results for four hydrologic variables (climatic water deficit (CWD), actual evapotranspiration (AET), recharge, and runoff) at the state level and four counties and for two future climate scenarios. The measure of water supply reported in Section 3 is a combination of recharge and runoff. Depending on the climate change scenario, water supply varies. For the warm-wet scenario, water supply increases in all counties and across all time periods, although the relative shares of recharge and runoff vary.

In this section, we only attempt to value water recharge. There appears to be a lack of studies and data that estimate both the positive (increased reservoir capacity) and negative values (sedimentation, water quality impairment, infrastructure damage) associated with runoff. The recharge variable represents late season baseflow and groundwater recharge – the amount of water that seeps into the ground and ultimately recharges aquifers. Section 3 demonstrated that an increase in SOM facilitates the infiltration and recharge of water through the ground in comparison with baseline plots without the respective increases in SOM. The estimated irrigation water cost ($45.36 acre/ft) was chosen as a proxy value for groundwater recharge because of the extensive use of groundwater in selected rangelands and croplands for irrigation.[20] To arrive at the monetary value of water recharge, water costs for irrigation uses per acre-foot were multiplied by the increase of groundwater recharge from baseline to

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[20] Data for water costs for irrigation uses in California were collected from USDA NASS (NASS, 2017). Data on cost of water irrigation per acre-feet was only available for year 2013.

increased SOM scenarios (i.e. difference in recharge between a baseline and a 3% SOM increase scenario).[21]

Results from Table 4.5 demonstrate how differences in soil type and climate from each county may affect how an increase in SOM influences the regional hydrology[22]. However, statewide estimated average values maintain a stable stream of benefits over the years[23]. Based on these results for both climate scenarios, landowners in the state of California could avoid spending about $1.6 billion over 50 years (2000-2049), based on the value of the cost of irrigation water alone.

At the county level, both Tehama and Santa Barbara Counties show positive values for groundwater recharge compared to the 2000-2009 period. However, these values vary from year to year, sometimes significantly. Both San Joaquin County (Figure B.3) and Tulare County gain little benefit in recharge. This is the reason why the entries for Tulare and San Joaquin show NS (not significant). Foothill locations with sandy soils in these counties have a reduction in recharge due to larger soil water holding capacity with increases in soil organic matter, leading to enhanced AET and decreased CWD, rather than recharge. Increasing WHC in locations with inadequate precipitation to take advantage of the extra storage also fails to increase recharge (see explanation in Section 3.3). There are some locations within place in the counties that may have increased recharge, but when averaged over the county negative values average economic benefits are considered negligible.

Table 4.5: Value of groundwater recharge at the state level and for selected counties under a 3% SOM enhancement scenario.

		Value of Groundwater Recharge ($/yr)	
	Decade	**Warm, wet: CanESM2 rcp8.5**	**Warm, dry: HadGEM2-ES rcp8.5**
Statewide	**2000-2009**	$34,980,936	$34,980,936
	2010-2019	$41,496,774	$33,323,755
	2020-2029	$22,046,364	$23,504,414
	2030-2039	$31,037,723	$39,176,799
	2040-2049	$35,444,794	$35,377,979
Tehama	**2000-2009**	NS	NS
	2010-2019	$4,421,759	$3,097,341
	2020-2029	$1,551,164	$2,068,711
	2030-2039	$3,239,625	$3,404,881
	2040-2049	$3,577,756	$3,701,025
San Joaquin	**2000-2009**	NS	NS

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[21] Water costs for irrigation were used as a proxy for the value of the estimated water recharged into aquifers and does not directly represent the financial benefit a landowner would incur (solicited through a Willingness to Pay for irrigation water by producer surveys) nor a public benefit enjoyed by society. The intention here is to provide a figurative monetary value to a vital ecosystem service in California. A more comprehensive analysis is beyond the scope of this section.

[22] For details on the hydrological results and modelling, please refer to Section 3.

[23] Tables C.4a and C.4b in Appendix C show more detailed data on how water supply values for recharge were calculated for the warm-wet scenario and the warm-dry scenario, respectively.

	2010-2019	NS	NS
	2020-2029	NS	NS
	2030-2039	NS	NS
	2040-2049	NS	NS
Santa Barbara	**2000-2009**	NS	NS
	2010-2019	$238,946	$329,497
	2020-2029	$84,935	$48,352
	2030-2039	$282,122	$456,894
	2040-2049	$216,611	$131,099
Tulare	**2000-2009**	NS	NS
	2010-2019	NS	NS
	2020-2029	NS	NS
	2030-2039	NS	NS
	2040-2049	NS	NS

4.5 The Viability of Carbon Markets

In Section 4.4.2 we reported on monetary estimates of increased below ground carbon sequestration resulting from a 1% increase in SOM at seven experimental sites. Two monetary estimates were discussed for each of the climate change scenarios (high and reduced emissions for a warm-wet climate). These two monetary estimates represented the SCC and an offset market administered by the CARB. The offset market represents a potential source of increased income for ranchers and crop producers, if current barriers to participation could be mitigated. The purpose of this section is to describe what those barriers are and to offer some recommendations for resolving them.

Several carbon sequestration protocols are available to California farmers and ranchers including: Rice Cultivation (ARB), Compost Application on Grazed Grassland (American Carbon Registry [ACR]), Livestock (ARB), Avoided grassland and shrub land conversion (ACR/CAR [Climate Action Reserve]), and wetland restoration (ACR). However, these protocols are not yet being adopted by California producers for several reasons. AB398, which extended California's cap and trade program, invokes agriculture through two limited means. First, revenue from the extended cap and trade program (via greenhouse gas reduction fund, [GGRF]) would be earmarked for GHG reduction projects, with the potential for some of those to be agricultural in nature (via state agency programs such as Healthy Soils implemented by the California Department of Food and Agriculture, and the Sustainable Agricultural Lands Conservation (SALC) implemented by the Strategic Growth Council.24 At this time there is no way of estimating the amount that would potentially go to agriculture, in general, nor the frequency and duration. Second, AB398 sets up an advisory panel to advise ARB on developing offset protocols for the cap and trade, including those for agricultural offsets. Agricultural protocols are listed as one of many sectors to be considered; however, upon review, AB398 provides no guidance on deadlines or milestones nor the type or number of agricultural protocols that would allow anyone to estimate the impact for CA agriculture.

While the Social Cost of Carbon (SCC) and the CA offset market represent two potential sources of increased income for ranchers and crop producers, the significant difference between these

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[24] See Section 5 for a more detailed description of the Healthy Soils and SALC programs.

values - currently over $31/metric ton for the SCC (Nordhaus 2017) vs $15.10 as of March 29, 2018, on the California offset market; http://calcarbondash.org/), - reflects a significant barrier to producer participation that must be overcome if producers are to be engaged in soil carbon enhancement activities at scale. SCC value estimates are typically significantly higher than carbon market prices, ranging between $11 and $105 per ton in 2007 dollars (EPA 2016), with most states placing that value above $40 per metric ton, or about three times higher than recent carbon prices on the California Cap and Trade market. Producers are unlikely to engage in carbon markets in which compensation for sequestered carbon resulting from implementation of on-farm practices is significantly undervalued.

Several carbon sequestration protocols are available to California farmers and ranchers; however, these protocols are not yet being adopted by California producers for two primary reasons:

First, the low price of carbon credits compared to the costs of various management practices. Currently, the price on the voluntary market for one ton of sequestered CO2e ranges between $3-5, well below the cost of implementation. High upfront costs, combined with the lack of robust financing mechanisms, discourages producers from participating in these markets.

Second, estimates of the current and projected market value of avoided GHG emissions, shown in Table 4.4, are based on the offset market administered by the ARB, at an average value of about $5 and $7 per MT for the 2010-2019 decade across the two climate scenarios, while for the 2020-2029 decade, the average price of a GHG offset credit increases to between about $70 and $120 per MT. These higher values are likely to be attractive to producers, but even these may not be enough to meet implementation and transactions costs under an offset framework.

The combination of low prices for carbon credits and high transaction costs[25] requires projects on large tracts of land (10,000 acres or more), well above the size of a typical California agricultural operation. Aggregating multiple smaller projects could overcome the issue of scale as a barrier to project implementation. Questions around additionality, leakage and permanence remain important obstacles to developers of terrestrial carbon sequestration projects and thus to participation by agriculture. These concepts, and carbon markets generally, remain too complicated and opaque for most landowners. Increased transparency could lead to more participation in carbon markets by producers.

Institutional barriers to integrating working agricultural landscapes into GHG offset and cap-and-trade programs include the lack of an agreed upon GHG accounting platform for on-farm soil and land management practices. The use of models can reduce quantification costs; for example, ARB's recent acceptance of COMET-Planner (Swan et al., 2017) for GHG accounting under the CDFA Healthy Soils Initiative (CARB 2017). Existing GHG accounting and economic valuation approaches are geared toward emissions reductions, not sequestration. The State of California lacks a strategy for carbon sequestration on agricultural lands even though terrestrial sequestration was identified as one of the five pillars in the California Climate Action Strategy. A clear terrestrial carbon sequestration strategy and significant funding through the state GGRF

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[25] Transactions costs consist of those costs associated with assessing, validating, and verifying carbon mitigation credits by third party.

program for research, planning, outreach, education and monitoring are needed to advance this work.

While individual producers express interest in participating in climate change mitigation activities, the agricultural sector as a whole remains reluctant to engage in climate change policy despite widespread acknowledgement that climate is affecting agriculture and rural communities both more quickly and more significantly than other sectors (IISD, 2017). Government regulation is of greater concern for California ranchers than the impacts of climate change (Roche et al 2015). An incentive-based, rather than regulatory, program framework is essential to engage agricultural interests in working land climate policy discussions and programs (Chambers et al., 2016, Lal et al., 2015, Lal, 2014, Kroeger et al., 2010, Casey et al., 2006, Lal et al., 2004)[26].

Agriculture is broadly viewed as a net contributor to climate change through emissions, rather than as an important contributor to a climate change solution. This perspective results in onerous measurement and data requirements for agricultural GHG projects that are not required in other sectors (e.g., energy efficiency), even as quantification of uncertainty is an explicit component of terrestrial sequestration models (Swan et al 2017). Similarly, the dominant preservation paradigm of the conservation community often results in pitting land conservation strategies against land management strategies in the allocation of limited resources. Focusing on conservation of above-ground carbon stocks (particularly trees and forests) while ignoring the magnitude of both soil carbon stocks and the potential for enhancement of soil carbon stocks through management, contributes to the failure to support the adoption of soil-based strategies. Widespread social recognition and policy support are essential to engage producers and realize the full potential of terrestrial sequestration on the State's working lands.

Several local jurisdictions (towns, cities and counties) across California have instituted mechanisms requiring project developers to mitigate GHG emissions above a given threshold under the authority of CEQA. On average, local jurisdictions charge over $200/metric ton CO2e for off-site mitigation fees. The range of local mitigation projects is fairly wide (from energy efficiency to public transit and bicycle paths), and increasingly includes agriculture-related projects. In addition, the CA Air Pollution Control Officers Association (CAPCOA) has approved several protocols for agricultural-related mitigation projects. Many local jurisdictions are increasingly interested in having local climate mitigation projects originate from local working lands to capture the multiple environmental and economic co-benefits that come with carbon farming projects.

Valuing terrestrial carbon and creating effective financing mechanisms is essential to the expansion of terrestrial sequestration efforts. Federal programs (e.g. Farm Bill) remain the main incentive mechanism, but these programs remain underfunded (Follet and Reed, 2010). The development and marketing of "climate beneficial" products provides an alternative source of value that could drive adoption of GHG reduction/mitigation practices on working landscapes while helping to revitalize rural economies. Supporting and expanding the concept of climate beneficial agriculture to include producers and consumers across the state could significantly

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[26] For a more in-depth discussion of various natural resource market approaches see Pindilli and Casey (2015)

advance terrestrial carbon capture on California's working lands. Two emerging initiatives are underway in California and are described here.

4.5.1 Fiber Systems[27]

Fibershed is a working example of a non-profit organization operating in Northern California, the U.S. and the world, marketing Climate Beneficial Wool. Climate Beneficial Wool is derived from farms and ranches that have participated in development and initial implementation of a Carbon Farm Plan. Using a carbon farm plan as a framework, Fibershed supports ranchers and farmers in building higher value, direct, regionally-based markets for climate-beneficial fibers, while simultaneously supporting producers in both understanding and utilizing carbon as an organizing principle in land management. During the spring of 2017, Fibershed was able to develop and implement agreements with manufacturers so that 19,000 pounds of fine-grade California wool was sold at a Climate Beneficial price premium. This equates to the ranchers directly receiving between 70% to 85% higher prices for their wool (based on commodity pricing), with an additional 60 cents per pound paid specifically for Climate Beneficial land-management. A portion of the funds generated are pooled into a Carbon Farm Fund and are returned to the ranches where the price premium for the fine-grade wool was established. These funds are used to implement more carbon farming practices, guided by the Carbon Farm Plan. If we were to scale this economic model to the largest wool producers within the state of California, we could generate over $2 million annually for Carbon Farm implementation. Scaling the program nationally for a multitude of fibers and natural dyes would offer considerable support towards transforming our textile system into one that internalizes environmental costs through building soil organic carbon while stabilizing our climate and enhancing the economies of rural communities.

4.5.2 Food Systems

Straus Family Creamery is a USDA-certified organic creamery working with the Marin Carbon Project on the implementation of a Carbon Farm Plan to produce Climate-Beneficial milk and advertises their carbon farming philosophy on their product labels. Although there is no direct financial gain, the information provided aims to increase consumer awareness and acceptance of the potential for agriculture to engage in climate beneficial practices.

The Perennial restaurant in San Francisco, CA features Climate-Beneficial beef on their menu. The beef comes from a ranch in Marin that has a Carbon Farm Plan and is implementing climate beneficial practices over time, using the Plan as a guide. The Perennial has recently created a non-profit organization, the Perennial Farming Initiative, to combat climate change by promoting climate beneficial practices within food systems, including compost applications, among others.

For California to realize the monetary and co-benefits presented above, policy decisions would be necessary that facilitate the participation of producers in implementing carbon sequestration practices and creating carbon market mechanisms, rules, and policies that result in monetary benefits that exceed costs.

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[27] For further information, see www.fibershed.com.

4.6 Conclusions and Future Directions

This section, through a literature review and an economic analysis of the hydrological and biogeochemical impacts from increased SOM, has illustrated that the monetary benefits, or costs avoided, can be substantial for forage production, below ground carbon sequestration, and groundwater recharge. Forage production and below ground carbon sequestration benefits result from a 1% increase in SOM; groundwater recharge impacts result from a 3% increase in SOM.

Forage production benefits (Table 4.3), measured in terms of the value of increased hay production, were estimated for two warm-wet climate scenarios (high and reduced emissions). Although the benefits varied amongst the seven experimental sites, the average decadal benefit across the seven sites increases from about $760,000 for 2020-2029 to approximately $2 million for the 2040-2049 period for the reduced emissions scenario. Although the monetary benefits for the high emissions scenario are not quite as large, they are nonetheless substantial.

Again, referring to the seven-county average, the ARB administered offset market (Table 4.4) increases from an average of about $21 per ton/ha from the 2010-2019 period to nearly $95 per ton/ha during the 2020-2029 decade for the high emissions scenario. For the reduced emissions scenario, the value increases from about $20 per ton/ha to about $92 per ton/ha across the same time period. Values are similar across all sites except for the Yuba site. Whether or not these values are sufficient to encourage ranchers to participate in the ARB carbon market is dependent on the costs of implementing SOM-enhancing practices and the transaction costs associated with complying with market rules. Increasing market opportunities at a more local level could alleviate some of these costs.

Although there is a great deal of variability between counties and for each county over time for the societal value of avoided GHG emissions (Table 4.4, columns 2 and 4), the seven-county average value for each emissions scenario is very similar. For example, societal values across the seven counties increase from about $71/ha for the 2010-2019 period to nearly $423/ha for the 2040-2049 period for the high emissions scenario. Values for the low emissions scenario are nearly the same.

The value of groundwater recharge, estimated using a proxy value of irrigation water costs, varies widely between counties (Table 4.4), depending on soil characteristics. Across the state, the total value of groundwater recharge ranges between about $41 million and $22 million for the warm wet scenario and between $39 million and $23 million for the warm dry scenario, depending on the decade over the 2020-2049 period.

Future directions for individual producers and/or for society in California to actually realize the estimated monetary benefits presented here will depend on policy decisions that facilitate the participation of producers in implementing carbon sequestration practices and creating carbon market mechanisms, rules, and policies that result in monetary benefits that exceed costs. To expand the potential biophysical and economic benefits associated with enhancing additional ecosystem services (pollination, water quality, decreased erosion, control of invasive species, etc.), more research is needed on the impacts of increasing SOM on these other services. Finally, to obtain better estimates of the value of groundwater recharge, we recommend that further data collection and research on the actual value of water at the local irrigation or water supply district level be pursued.

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5: Using Land Use Change Scenarios to Identify Risks and Opportunities for Climate Benefits from Management of Soils on Working Lands

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5.1 Introduction

In an era of increased risk due to climate change, the State of California seeks to determine how conservation investments combined with management activities can increase long-term, agricultural sustainability. In particular, the State seeks quantitative information on what may be achieved if conservation programs should evolve to provide enhanced ecosystem services and climate benefits related to soil management. To fulfil this need, this section provides an assessment of barriers to and incentives and opportunities for both working lands conservation and management for increased soil carbon sequestration and climate resilience. Objectives of this section are (1) to provide a review of barriers to management of soils on working lands; and (2) to apply a land-use-change scenario analysis to identify risks and opportunities for achieving climate benefits on protected working lands. Here, climate benefits are quantified using model outputs on soil carbon sequestration and N_2O emissions (Section 2) and related changes in hydrology (Section 3). The section concludes with a discussion of programs to incentivize land management practices for climate change mitigation.

5.2 Barriers to Working Land Carbon Sequestration

In addition to the barriers that prevent producers from accessing carbon markets (see Section 4) and the challenges surrounding land conservation, additional barriers could prevent producers from implementing soil health practices in California. These may include: insufficient financing mechanisms and technical assistance for land managers, the lack of practical quantification methods, a lack of understanding of the role of carbon in rangeland ecosystem dynamics on the part of producers, consumers and policymakers and institutional barriers such as permitting requirements.

5.2.1 Financial Barriers

Financial barriers are one of the main obstacles that could explain the low-adoption rate of practices that improve soil health. The high up-front cost of implementation of practices was mentioned by farmers in the Central Valley of California (Haden et al. 2012). Maintenance costs of practices, lack of access to specialized equipment and opportunity costs are also important factors explaining low adoption rates of practices that increase soil health (Carlisle, 2016). The lack of information about costs and benefits of implementing practices and the high, upfront cost of changing practices were also identified as barriers for ranchers interested in participating in carbon markets (Gosnell et al., 2011). Despite the fact that agriculture is among those human activities most impacted by climate change (COP 23, Bonn, Germany, 12 November 2017;

http://enb.iisd.org/climate/cop23/agriculture-action-day/), there is limited funding for the nevertheless extensive social infrastructure needed to deploy conservation on-farm. Much of this infrastructure emerged during and in response to the ecological crisis of the Dustbowl, yet funding remains insufficient to address current challenges faced by working landscapes.

5.2.2 Socio-economic Barriers

In addition to financial barriers, socio-economic constraints are also the source of significant risk and uncertainty that hinder producer's participation in incentive programs for climate change mitigation and adaptation (Niles et al., 2013, Cheatum et al. 2011, Gosnell et al 2011, Carlisle, 2016; Ma and Coppock 2012). These reveal limited social innovation infrastructure to educate and deploy conservation on farms. Farmer's awareness, beliefs and attitudes also affect their willingness to implement practices that would help them adapt to or mitigate against climate change (Haden et al., 2012; Ma and Coppock, 2012). Many ranchers have concerns about the role of government in voluntary or compliance carbon markets, raising questions about which agency should be responsible for regulating a carbon offset program (Gosnell et al., 2011, Cheatum et al., 2011, Niles et al., 2013). In California, a survey of ranchers' knowledge and attitudes toward payments for ecosystem services showed that federal or private organizations were the preferred administrator of a potential program with state agencies being the least preferred. (Cheatum et al. 2011).

To overcome these social barriers to participation, a strong communication and implementation support system for farmers and ranchers seeking to explore carbon-friendly management strategies is needed in order to fully realize the potential of working landscape to contribute significantly to achieving climate change mitigation and resilience goals.

5.2.3 Land-Use Change and Land Economics

Socioeconomic challenges and related land-use pressures pose barriers to implementing soil management practices on working lands, as evidenced by historical conversion of rangeland and cropland to development or more GHG emission-intensive agriculture. Approximately 678,433 acres (274,553 ha) of farmland were converted to development between 2002 and 2012 (FMMP 2004-2015). The proportion of rangelands in private ownership and tendency for lower profits on rangelands compared to other land types make rangelands also subject to conversion. Between 1984 and 2008, over 481,855 acres (195,000 ha) of rangeland in the California Central Valley and Coast Range were converted to residential development, more intensive agriculture, or lands for mineral extraction, while Williamson Act contracts protected approximately 6.9 M acres (2.8 M ha) of rangeland from conversion to development (Cameron et al., 2014). Rangeland conversions, combined with a changing climate, can lead to substantial loss in ecosystem services in California, including water supply (groundwater recharge and runoff), soil carbon, and wildlife habitat (Byrd et al., 2015a). In addition, conversion of cropland to urban development can increase GHG emissions 70 times and conversion of rangelands could increase GHG emissions by as much as 200 times (Jackson et al. 2012).

5.3 Land-Use Change Scenarios to Identify Risks and Opportunities of Climate Benefits from Conservation and Management of Soils

For this section objective, we developed future land-use and conservation scenarios based on historical land-change data, population projections, and incremental levels of conservation investment representative of current conservation programs. One State of California program that incentivizes farmland conservation is the Department of Conservation’s (DOC) Land Conservation (a.k.a. Williamson) Act of 1965. The Williamson Act enables local governments to enter into 10-year renewable contracts with private landowners that restrict land to agricultural or related open-space use in return for lower property tax assessments. While subvention payments from the state to counties for the program have stopped, more than 18 million acres are under contracts that restrict development, though conversions to other agricultural land uses are allowed (DOC, 2017). DOC and other agencies and land trusts implement conservation easement programs that also incentivize farmland conservation. Historically, approximately 32,000 acres of conservation easements have been placed on California working lands annually since 1988 (NCED, 2017). A relatively new program, the Sustainable Agricultural Lands Conservation Program (SALC) administered by DOC and the Strategic Growth Council, funds both conservation easements and strategic plans for agricultural lands that prevent development and reduce greenhouse gas emissions through reduced vehicle miles driven. In 2017 the Strategic Growth Council awarded nearly $34 million in easements and strategy and outcome grants, which will protect over 46,000 acres of agricultural land (DOC press release, Dec. 5, 2017; http://www.conservation.ca.gov/index/Documents/2017-12-SALC-ag-easements.pdf).

This land-use-change scenario analysis for California working lands addresses two main questions: (1) What are the risks to preserving climate benefits, in particular hydrologic benefits, of working lands? and (2) To what extent can teaming conservation programs with soil management practices increase climate benefits? We focus our scenario analysis on modeled spatially explicit hydrologic benefits of groundwater recharge, reduction in climatic water deficit, and increase in actual evapotranspiration, described in Section 3. Land use change scenarios were modified from two growth scenarios developed for the California Fourth Climate Change Assessment and modeled using the Land Use and Carbon Scenario Simulator (LUCAS) state and transition simulation model (Sleeter et al., 2017a). Given growth scenarios, we conducted a sensitivity analysis of benefits associated with incremental areal and spatial allocation of land for conservation (Byrd et al., 2015b). Through scenario analysis, we identified where and the extent to which soil management activities that increase soil organic matter can maximize climate benefits. We identified regions with high development risk/high potential for hydrologic benefits, and opportunities for soil management (land area available) and hydrologic benefits when Williamson Act and other easement programs are implemented at varying intensities. While modeled GHG reduction benefits (soil carbon sequestration) were not spatially explicit, we also provide estimates of potential GHG reduction benefits on grasslands within Williamson Act lands based on results from Section 2 of this report.

5.3.1 Methods: Scenario Development and Analysis

Scenarios were developed with input from DOC staff to simulate current and projected levels of growth in conservation programs (Table 5.1). We developed nine 270m resolution land use/conservation scenarios from 2001 – 2100 representing variable levels of conservation land acquisition. For each scenario, we ran 10 Monte Carlo iterations to develop uncertainty estimates for the area of land cover conversion. Baseline model land use/land cover was derived from the National Landcover Dataset, with classes for development, annual agriculture (cropland), perennial agriculture (orchards/vineyards), wetland, shrubland, grassland, and forest (i.e. conifer and oak woodland) (2017). The model restricted land use change on current protected land as indicated by the USGS Protected Areas Database (GAP, 2016), though these existing protected lands were not evaluated for hydrologic climate benefits in our analysis.

Scenarios represented permutations of: (1) One business as usual (BAU) population/development projection (Wilson et al. 2016) and one moderate population projection (PopMed) (Sleeter et al, 2017a). The moderate population growth scenario is based on county-level population projections from California Department of Finance. The BAU scenario represents a higher growth rate based on historical data from the California Farmland Mapping and Monitoring Program (Sleeter et al., 2017a). Rates of agricultural expansion and contraction in each case were based on historical trends from 1992 – 2012 for each scenario. (2) Implementation of the Williamson Act in which all contract lands NOT indicated as non-renewal in the DOC Williamson Act geodatabase (DOC, 2017) are maintained from 2020 to 2100. (3) Implementation of a simulated easement program based on historical and future acquisition rates starting in 2020 with zero, low (30,000 acres/year for 15 years), medium (30,000 acres/year for 30 years) and high (60,000 acres/year for 30 years) acquisition rates. In addition, we included a baseline BAU scenario with no Williamson Act lands after 2020 or other new easements to compare outcomes (BAU_noWA).

We integrated conservation scenarios with development projections in the LUCAS model. The model preferentially targeted conservation easements on working lands that provide maximum hydrologic benefits from soil management, as measured by the Hydrologic Benefits Index (Section 3). Easements were allocated annually based on the rates provided above. Easement sizes ranged from 50 to 3700 acres (20 to 1500 hectares), which represent a typical size distribution of California easements in the National Conservation Easement Database (NCED 2017). As a result of these scenario criteria, the easement scenarios represent a "best case" for hydrologic benefits in each level of conservation land acquisition. The easement locations in the model outputs represent places with high potential for hydrologic benefits from soil management.

Easements could also occur on Williamson Act lands. While conversions between grassland, annual and perennial agriculture were allowed on Williamson Act lands, no land change was permitted on easements after they were established in the model. On all Williamson Act lands and new easements, we assumed adoption of soil management activities on working lands that increase soil organic matter (SOM) by 3% from baseline, which also represents a "best case" in hydrologic benefits (see Section 3).

Table 5.1: Scenario definitions, PopMed is moderate population projection, BAU is business-as-usual population development projection, and WA is Williamson Act.

PopMed_EH	PopMed; Easements 240 km (~60k acres)/year for 30 years, WA lands present
PopMed_EM	PopMed; Easements 120 km (~30k acres)/year for 15 years, WA lands present
PopMed_EL	PopMed; Easements 120 km (~30k acres)/year for 15 years, WA lands present
PopMed	PopMed; no easements. WA lands present
BAU_EH	BAU; Easements 240 km (~60k acres)/year for 30 years, WA lands present
BAU_EM	BAU; Easements 120 km (~30k acres)/year for 15 years, WA lands present
BAU_EL	BAU; Easements 120 km (~30k acres)/year for 15 years, WA lands present
BAU	BAU; no new easements. WA lands present
BAU_noWA	BAU; no new easements; no WA lands after 2020

For each scenario we calculated by county: (1) area of development on working lands and lost potential for hydrologic benefits from soil management due to development and (2) total area of conservation lands by land cover class and opportunities for hydrologic benefits on conservation lands. Benefits of soil management (i.e. SOM is increased by 3% from baseline) on conservation lands were also summarized for: (1) Williamson Act lands, (2) easements, and given likely overlaps in land area, (3) combined Williamson Act and easement lands. Hydrologic benefits were calculated as average annual total gain in water [increased actual evapotranspiration (AET) +reduced climatic water deficit (CWD) +increased groundwater recharge (RCH)] from soil management. Mean annual hydrologic benefits were calculated from 10 Monte Carlo iterations of land use change, specifically from new development and easements. We report results for two climate scenarios: relatively wet CanESM2 and relatively dry HadGEM2-ES (see Section 1.4), both RCP 8.5 for years 2050 (based on the 2040-2070 climate average) and 2100 (based on the 2070-2100 climate average).

5.3.2 Results

5.3.2.1 Development risks

The BAU and PopMed growth projections are similar for year 2050, with approximately 2 million acres subject to development in both cases. By 2100, losses of California working lands to development were approximately 4.3 million acres in the BAU projection and approximately 2.76 million acres in the PopMed projection (Table D.1). Total lost potential for hydrologic benefits on these lands due to urbanization ranges from 27,465 to over 71,000 acre-feet in 2050 and from 49,949 to over 177,000 acre-feet by 2100 (Table D.2). Figure 5.1 illustrates the distribution of lost potential for hydrologic benefits across counties for three hydrology variables; AET, CWD and RCH, where development is likely to occur in 2050 (See Appendix Figure D.1 for year 2100 outcomes). Figures 5.1 and D.1 do not account for lost potential for hydrologic benefits due to land conversion alone such as groundwater recharge that would occur without the increase in impervious surfaces. For example in a case study of the Lower Cosumnes Watershed, the watershed transitions from a recharge dominated system to a runoff dominated system as a result of future projected development that is likely to occur on deep soils (Byrd et al., 2015a).

In this report's scenarios, future development in general leads to lost potential for reduced CWD and increased AET; development occurs more often on the Central Valley floor, where groundwater recharge potential is low. However, on modeled developed land, lost potential for groundwater recharge increases in a wet climate scenario, compared to the dry scenario. The distribution of potential losses in hydrological benefits is not even across the state, where a small number of counties experience the greatest potential losses. Counties with the greatest potential losses include Sacramento, Riverside, San Diego and Santa Clara (Figure 5.2). Overall, the development projection is more influential than the conservation acquisition rate in controlling lost hydrologic benefits; however, in 2050 in the PopMed projection, a small increase in easement lands does slightly reduce the risk of lost opportunity for groundwater recharge.

5.3.2.2 Opportunities on conservation lands; Williamson Act lands

By 2050 overall opportunity for hydrologic benefits on all Williamson Act lands varies from an annual average of 373,052 acre-feet in a dry climate to 718,830 acre-feet in a wetter climate. By 2100, these values increase to 509,587 acre-feet in a dry climate to 878,332 acre-feet in a wetter climate (Table D.3). Hydrological and climatic benefits on Williamson Act lands are an order of magnitude greater than potential losses related to future development. As with development, water benefits are unevenly distributed across California, with a limited number of counties providing a majority of the benefits. Counties with the highest potential for hydrologic benefits on Williamson Act lands include Tehama, Shasta, Santa Barbara, San Luis Obispo, Mendocino and Humboldt (Figure 5.3). These are high ranking counties in part because of the land area in contract and in part because of soil properties on these lands; for example, the ratio of acre-feet of hydrologic benefits to acres of Williamson Act lands range from 0.01 in Fresno County, with over 1 million acres of working land in contract, to 0.16 in Shasta County, with 161,495 acres of working land in contract (Table D.4). However, while development does not occur on Williamson Act lands, changes in agriculture, such as conversions from grassland (i.e. rangeland) to perennial agriculture (orchards/vineyards) can occur.

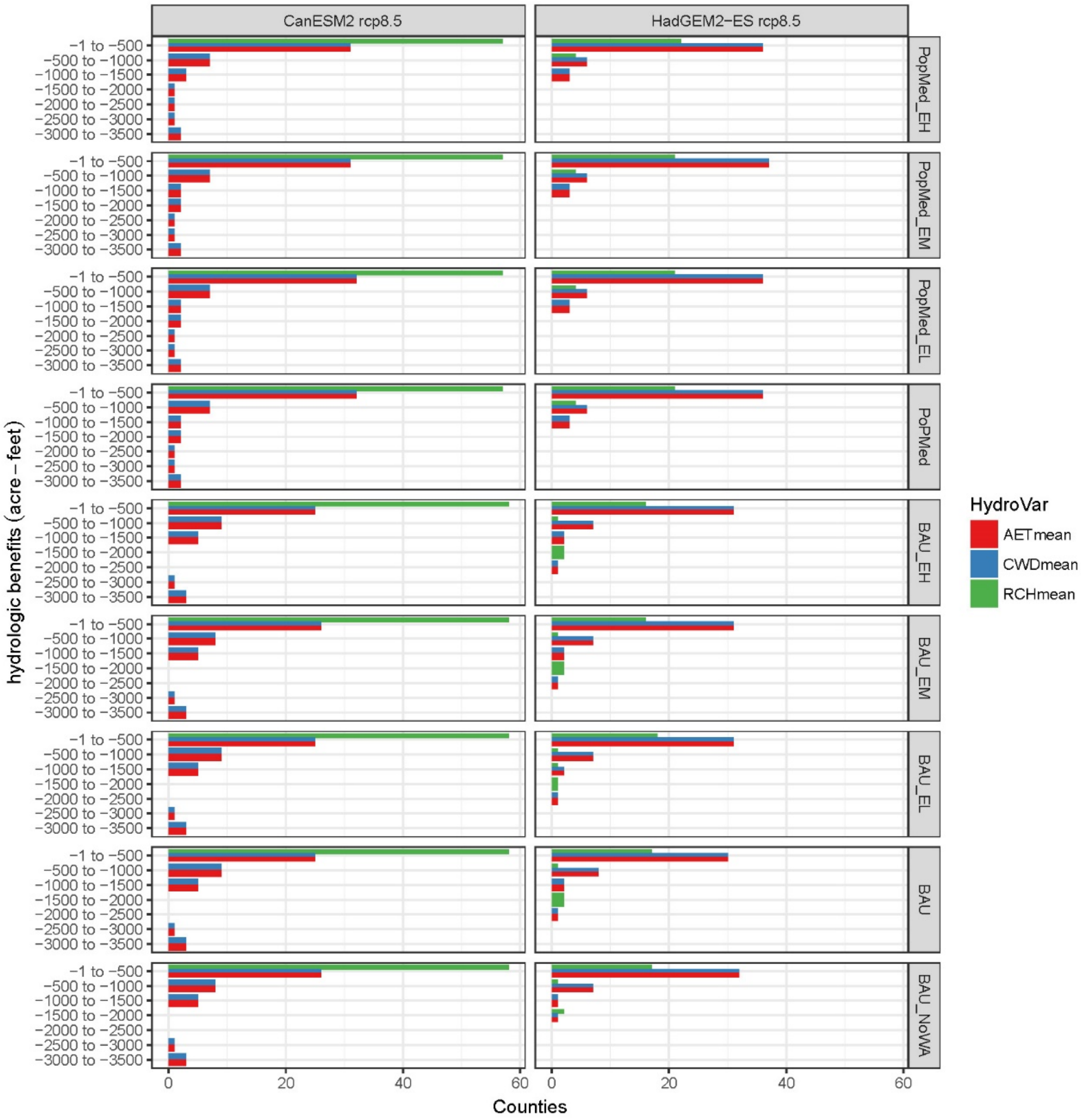

Figure 5.1: For year 2050, two climates and nine scenarios, lost potential for hydrologic benefits on working lands from soil management alone, as a result of land conversion to development. See Figure D.1 in Appendix for Year 2100.

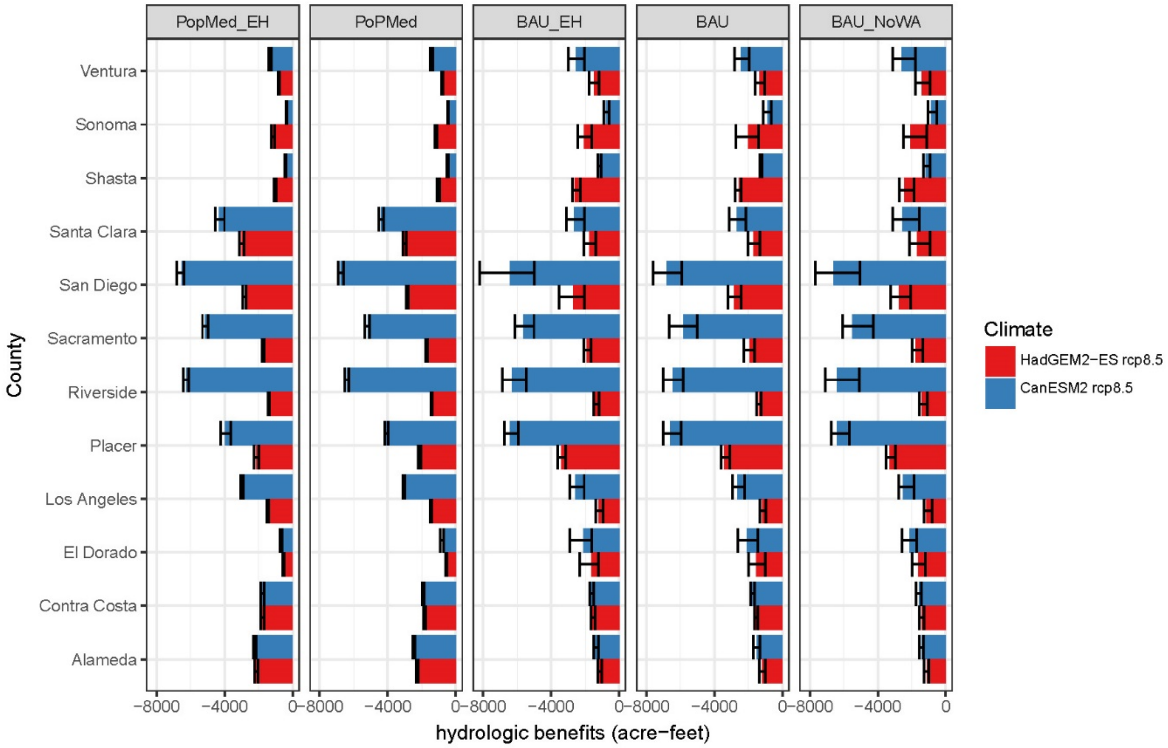

Figure 5.2: For year 2050, top 12 counties where lost potential for hydrologic benefits due to development is highest. Values represent total average, plus minimum and maximum values based on 10 Monte Carlo iterations per scenario. See Figure D.2 in Appendix for year 2100.

While soils can still be managed on these converted agricultural lands, we consider the extent to which this land conversion could occur, as loss of soil carbon due to grassland conversion could be substantially greater than gains from soil management (Sanderman et al 2017). Most of the land area on Williamson Act lands (4.6 million acres) is grassland and remains grassland by 2100 in a BAU scenario without additional easements (Table 5.2), though approximately 632,000 acres are subject to conversion to another form of agriculture. In comparison to forest (e.g. oak woodland), soil management practices are more feasible on grassland, and likely to be even more feasible on agricultural land intensively managed to increase soil organic carbon (Chambers et al., 2016, Minasny et al., 2017).

Table 5.2: Land cover and land use changes (acres) from 2001 to 2100 on Williamson Act working lands for the business-as-usual (BAU) growth scenario, with values based on 10 Monte Carlo iterations.

Class	Mean Area	Min Area	Max Area
forest, no change	3,376,379	3,355,153	3,387,506
grassland, no change	4,598,096	4,566,610	4,622,237
annual ag, no change	1,680,951	1,615,239	1,817,716
perennial ag, no change	1,552,679	1,544,264	1,562,512
grass to annual ag	103,591	93,637	112,209
grass to perennial ag	527,524	512,677	551,101
annual to perennial ag	1,206,726	1,131,997	1,307,597

Greenhouse gas reduction benefits may also be estimated for grasslands within Williamson Act lands for select counties where data is available (Section 2). For the counties where field trials were located, maximum GHG reduction benefits from compost application to grazed grassland may be scaled to the area of grassland in Williamson Act lands. Given grassland area likely to remain grassland by 2100, for county data available, GHG reduction benefits can range from approximately 34,000 to over 580,000 Mg CO_2e per county after considering N_2O emissions (Table 5.3).

Table 5.3: Estimated GHG reduction benefits on Williamson Act grassland likely to remain grassland by 2100 for select counties. Benefits are based on maximum modeled benefits from C sequestration minus N_2O emissions occurring in 2031, 15 years after compost application, for the CanESM2 RCP 8.5 scenario. Mean, min and max climate benefits are based on 10 Monte Carlo iterations of change in grassland cover in the business-as-usual (BAU) growth scenario.

	C seq. minus N2O	Mean	Min	Max
County	Mg CO_2e/ha	Mg CO_2e	Mg CO_2e	Mg CO_2e
Tulare	6.49	561,000	515,000	589,000
Marin	6.36	148,000	147,000	150,000
Santa Barbara	6.36	335,000	319,000	345,000
Solano	6.49	174,000	167,000	177,000
San Diego	6.02	34,000	33,000	36,000
Mendocino	6.57	243,000	242,000	243,000

5.3.2.3 Opportunities on conservation lands; conservation easements

Given the model placement of easements with the highest potential for hydrologic benefits, results can illustrate how the spatial allocation of conservation easements across California's working lands can maximize opportunities for hydrologic benefits through soil management (Figure 5.4) (See data release: Sleeter et al. 2017b). In our scenario analysis, hydrologic benefit outcomes on easements were similar for BAU and PopMed growth scenarios. As with Williamson Act lands, hydrologic climate benefits on future conservation easements are unevenly distributed across California, with a limited number of counties providing a majority of the benefits. Counties with the highest potential for hydrologic benefits on easement lands include Tehama, Shasta, Monterey, Mendocino, Humboldt and Butte (Figure 5.5). Hydrologic benefits on easements are similar in magnitude to potential losses from development. Counties with high benefits on easement lands that are also subject to high losses from development include Santa Clara and Shasta counties. By 2050, for all scenarios the dominant land covers within the total area of conservation easements is grassland and forest (Table D.5). However, soil management activities are more feasible on grassland than on forest or oak woodland. Tehama and San Luis Obispo are the two counties with the greatest proportion of grassland area within their modeled easement locations (Figure 5.6).

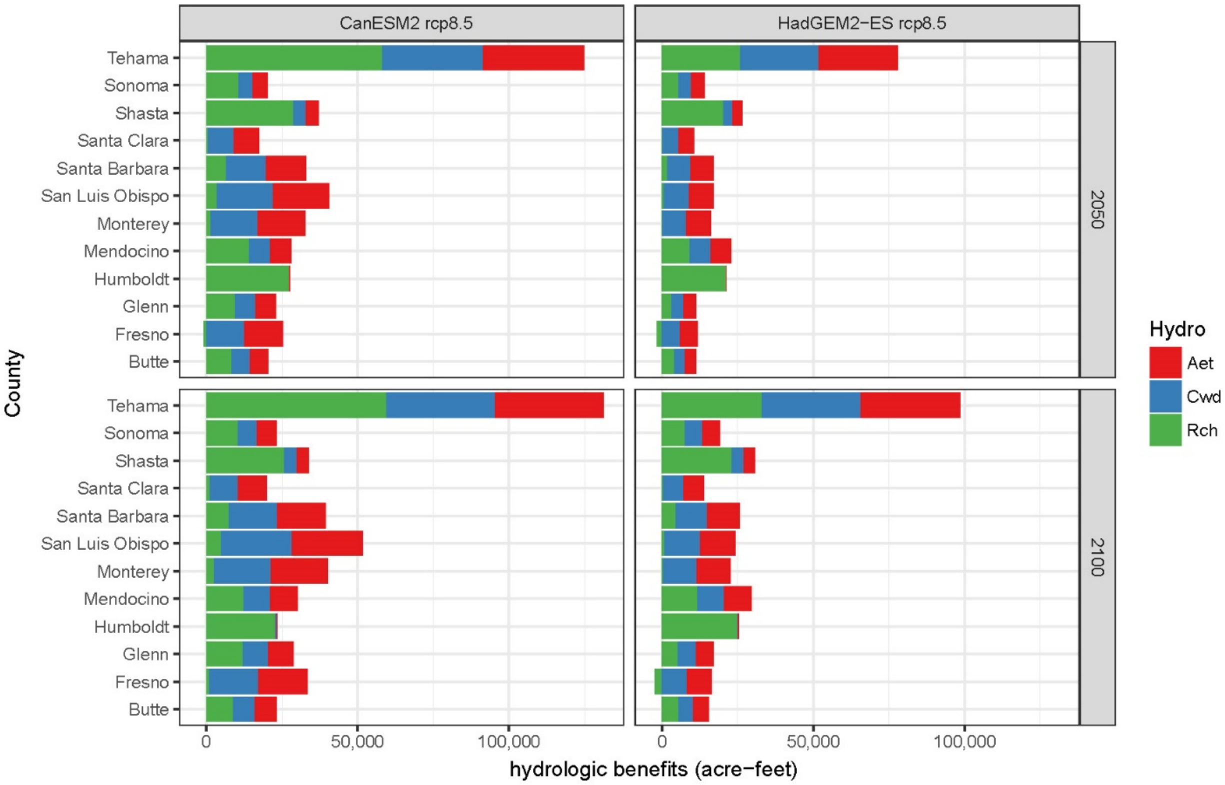

Figure 5.3: Future potential hydrologic benefits on Williamson Act lands by hydrologic variable for the top 12 counties, for 2050 (top) and 2100 (bottom), for two climate scenarios.

5.3.2.4 Opportunities on conservation lands: Easements and Williamson Act lands

Given easement locations may often occur on Williamson Act lands, we calculated overall combined potential hydrologic climate benefits on conservation lands across scenarios. Despite substantial overlap in land area between the two programs, in 2050 for a dry climate scenario, there is approximately a 20,000 acre-feet increase in hydrologic benefits between the zero to low and low to medium easement scenarios, and a 30,000 acre-feet increase between the medium and high easement scenarios (Table D.3). These opportunities increase to 30,000 acre-feet between the zero to low and low to medium easement scenarios and 47,000 acre-feet from a medium to high easement scenario in a wet climate. Associated with this increase in hydrologic climate benefits is an overall increase of 500,000 acres of protected working lands between the zero and high easement scenarios (Table D.6).

5.3.3 Main Findings of Land Use Scenario Analyses

Future development poses more risk of lost potential for reduced CWD and increased AET resulting from soil management, since development generally occurs on the floor of the Central Valley where the potential to increase groundwater recharge is low. The uneven distribution of hydrologic benefits resulting from soil management across California drive an uneven distribution in the potential losses from development and gains on conservation lands. A limited number of counties provide a majority of the benefits. Santa Clara and Shasta Counties are two areas where future development is likely to occur on soils with high hydrologic benefit potential.

Potential hydrologic benefits on Williamson Act lands are an order of magnitude greater than potential losses related to future development, totaling over 700,000 acre-feet annually state-wide in a wet climate scenario. On these and other protected working lands and open space, it is more feasible to implement soil management activities on grassland than forest or oak woodland. Based on a BAU scenario, approximately 4.6 million acres of grassland will remain as Williamson Act lands by 2100. Potential hydrologic benefits from easements alone are similar in magnitude to potential losses that could be experienced from development. Despite many easements co-occurring on Williamson Act lands, a high easement acquisition rate could increase hydrologic benefits over those on just contract lands by approximately 100,000 acre-feet annually in a wet climate scenario. Easements can also offset potential conversion of grassland to more intensive agriculture; in a BAU scenario, over 600,000 acres of Williamson Act grassland may be converted to perennial or annual agriculture.

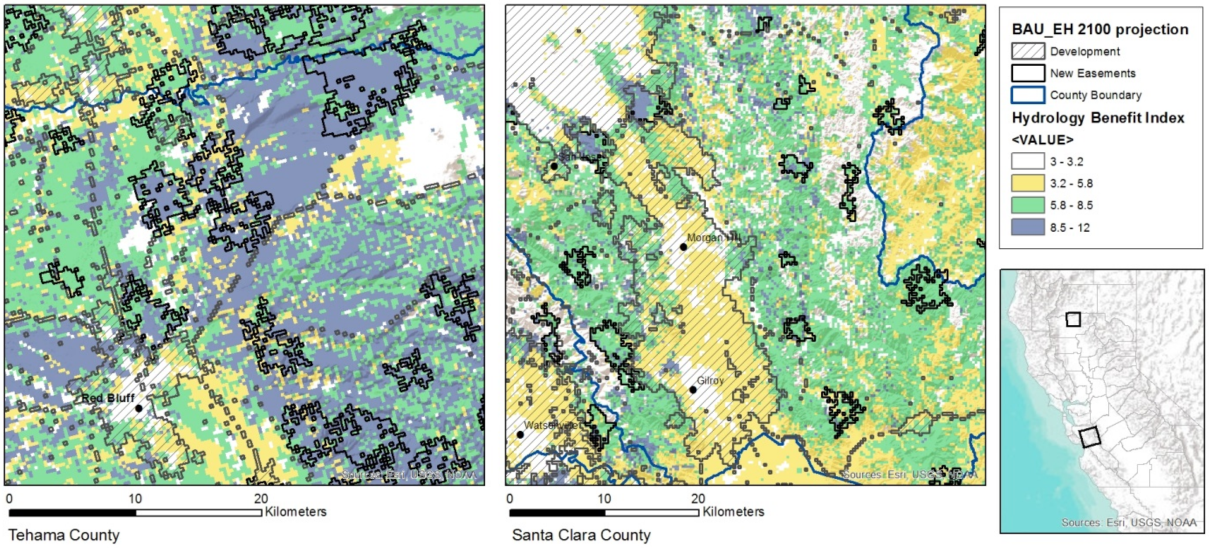

Figure 5.4: Land use projections for a Business as Usual, High Conservation Easement (BAU_EH) scenario in 2100. Left: Future conservation easements targeted for hydrologic benefits in Tehama County; Right: Projected development in Santa Clara County on working lands with moderate to high potential for hydrologic benefits.

5.4 Opportunities for increased carbon sequestration through land management

Despite the barriers to land management mentioned above, several programs and organizations are working to incentivize land management practices for climate change mitigation and resilience. Existing programs that are aimed at reducing GHGs and increasing carbon sequestration in the agricultural sector through climate-beneficial agricultural practices, can play a key role in reducing atmospheric GHG. At the same time these programs can increase the productivity, resilience and ecological sustainability of agricultural landscapes and improve environmental health.

5.4.1. Federal programs

Several USDA policies and programs aim to enhance soil carbon sequestration through farmland protection and management. Two of the main USDA-Natural Resources Conservation Service (NRCS) programs through which eligible farmers and ranchers can receive financial assistance for implementation of SOM-enhancing practices on working lands are the Environmental Quality Incentives Program (EQIP) and the Conservation Security Program (CSP). EQIP provides landowners financial assistance (cost-share) for technical assistance for conservation planning and practice implementation. Under CSP, farmers receive financial assistance for maintaining conservation enhancements that build on and leverage the performance of existing NRCS-approved conservation practices. The Agricultural Conservation Easement Program (ACEP) provides financial and technical assistance to help conserve agricultural lands and wetlands and their related benefits.

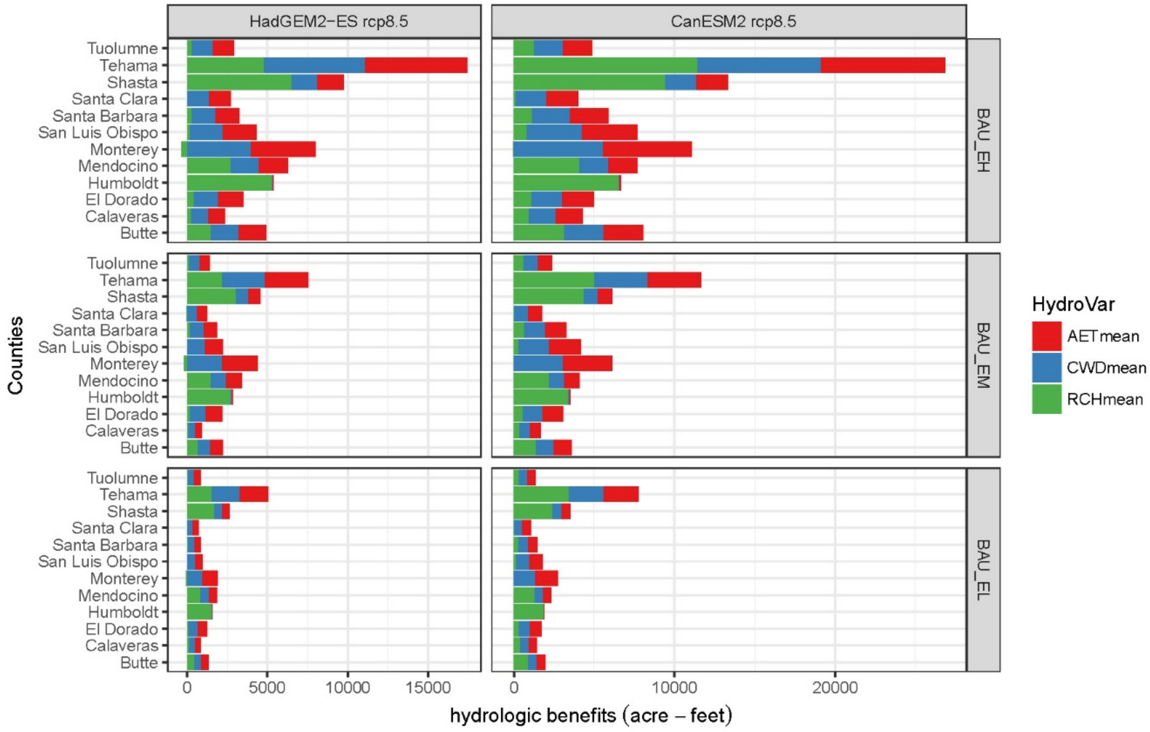

Figure 5.5: For year 2050 and two climates, hydrologic benefits by hydrologic variable within new modeled easements for the top 12 counties. Hydrologic benefits are average based on 10 Monte Carlo iterations of easement locations.

The EQIP remains the number one funding source for conservation practices on working lands and provides a solid platform for achieving C sequestration nationally, albeit currently on relatively few acres overall (Chambers et al., 2016). Chambers and others (2016) have estimated the potential for implementation of NRCS conservation practices on working lands in the US to achieve carbon sequestration goals consistent with the French Ministry of Agriculture's Four Per Thousand (4PT) Initiative (Minasny 2017; Lal 2016). Meeting the 4PT goal of increasing soil organic carbon by 0.4% annually, - 68 MMT of C per year, equivalent to 250 Tg CO_2e - by 2025, would require enrolling an additional 10 M acres of cropland and 20 M acres of grasslands in NRCS conservation programs each year at a cost of $3 to 5 billion per year (Chambers et al., 2016).

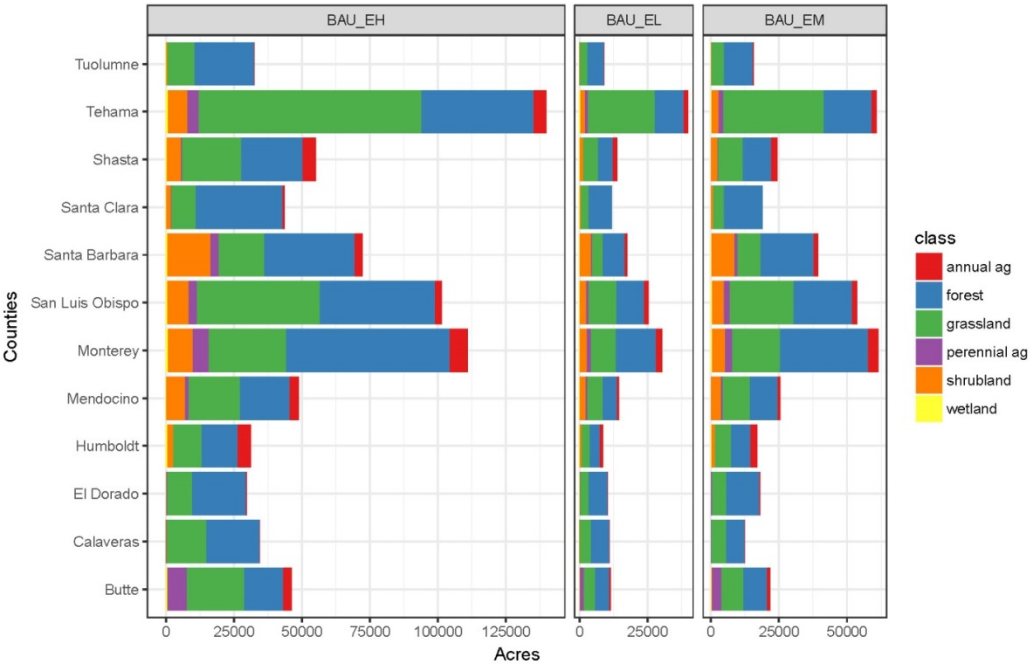

Figure 5.6: Land area in easements (acres) for the top 12 easement counties, at 2050, for three easement scenarios. Values are averaged from 10 Monte Carlo iterations of easement locations.

5.4.2 State Programs

In California, multiple programs incentivize land conservation strategies and practices that could have climate change benefits. CDFA's Healthy Soils Program provides financial assistance for the implementation of conservation agricultural management practices that sequester carbon, reduce atmospheric greenhouse gases and improve soil health on farms and ranches. The California Air Resources Board (CARB) has approved an increasing number of management activities under the Healthy Soils Program to promote reduced GHG emissions and increased carbon sequestration on natural and working lands. For information on approved management practices and implementing agencies, readers are referred to the most recent CARB funding guidelines.

In addition, the State Water Efficiency and Enhancement Program (SWEEP) provides financial assistance for the implementation of irrigation systems that reduce water use and greenhouse gas emissions on agricultural operations. As described in Section 5.3, SALC supports the protection and management of California's agricultural lands through planning and permanent protection of farm and ranch lands through the purchase of agricultural easements. Other state land preservation programs, such as the Williamson Act or the Rangeland, Grazing Land and Grassland Protection Program and Oak Woodlands Conservation Program administered by the Wildlife Conservation Board have the potential to achieve climate benefits by avoiding conversion of working landscapes to other land uses that are net GHG emitters. The Coastal Conservancy's Climate Ready Program supports planning, project implementation and multi-agency coordination on strategies that will increase the resilience of coastal communities and natural systems. Philanthropic organizations such as the Jenna and Michael King Foundation, the Leonardo diCaprio Foundation, 11thth hour, and several others also provide financial support for land-based, climate change strategies.

Establishing a soil organic carbon (SOC)[28] increase goal for California's working lands may help to implement the Governor's 2014 Healthy Soils Initiative. Offsetting ***all*** of the State's agricultural emissions (36,744,000 metric tons of CO_2e per year) with equivalent increases in SOC would require 1.67 metric tons of CO_2e, or just under 0.5 metric tons C per acre per year across ***all*** of the State's 22 million cropland and grazed grassland acreage. This goal could be achieved over time through voluntary implementation of a suite of incentive-based NRCS and other soil carbon-sequestration based conservation practices, including compost applications, across agricultural lands on an ongoing basis. How long this rate of annual increase in SOC could be maintained is uncertain, however 20 to 30 years is probably realistic (Chambers et al., 2016; Lal 2016; Ryals et al., 2015).

Alternatively, California might choose to become a signatory to the French 4PT initiative (http://4p1000.org/join). Taking the national average baseline for topsoil (0-20 cm) organic C of 51.56 metric tons C per hectare, or 23 short tons of C per acre (Chambers et al., 2016) as representative of California working land soils, an annual increase of 4/1000 (0.4%) is equivalent to 0.20624 metric tons C per hectare per year, or 0.092 short tons C per acre per year. Applied across the 22 million cropland and grazed grassland acres of California, this is equivalent to 6,741,627 metric tons of CO_2e per year, or just over 18% of the State's annual agricultural emissions of 36,744,000 metric tons of CO_2e.

5.4.3 Non-profit Organizations

Several non-profit organizations are involved in engaging agricultural producers in climate change mitigation strategies. Examples include The Nature Conservancy's jurisdictional accounting tool that helps quantify and prioritize land-based conservation and management strategies and the California Climate and Agriculture Network (CalCAN) that works on state and federal policies that help farmers transition to adoption of climate-beneficial practices. Point Blue Conservation Science Rangeland Watershed Enhancement Program provides technical assistance to ranchers for implementation of conservation practices that enhance carbon sequestration, water capture and wildlife habitat on grazing lands. The Community Alliance with Family Farms (CAFF) provides outreach and technical assistance to small farms

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[28] OM is approximately 50% OC (Pribyl 2010). One unit of C equals 3.67 units of CO_2e.

on climate-smart farming practices. The Carbon Cycle Institute (CCI) through its Ag Carbon Program is helping build local partnerships for planning and implementation of carbon farming initiatives across California.

5.4.4 Carbon Farming: A Framework for Achieving Climate Mitigation Goals on Working Landscapes

Carbon farming involves implementing practices like those described above that are known to improve the rate at which CO_2 is removed from the atmosphere and converted to plant material and/or soil organic matter (see Sections 3 and 4). Carbon farming is successful when carbon gains resulting from enhanced land management and/or conservation practices exceed carbon losses. The process starts with the creation of a Carbon Farm Plan (CFP), which involves a comprehensive assessment of the land's resources and capacity to capture and sequester GHG, developed by a technical advisor in conjunction with the landowner.

Carbon farming can address many environmental impacts related to agriculture, including GHGs: reducing groundwater degradation and air quality issues associated with nitrogen fertilizer use; improving soil health, fertility and long-term productivity through increasing soil organic matter content and reducing the need for synthetic fertilizers; converting manure and other agricultural wastes into high-quality compost, avoiding methane and air quality issues of conventional on-farm nutrient and waste management (Delonge et al., 2013).

5.4.5 Scaling Carbon Farming

Resource Conservation Districts (RCDs) are the local partner best positioned to plan, implement, and scale carbon farming across California. Formed during the Dust Bowl Era, RCDs have been working with farmers, ranchers, and foresters for decades to implement conservation practices, many of which help improve soil quality, increase SOM and restore and enhance vegetation. RCDs have knowledge of local ecological conditions, conservation strategies, and the needs of the local agricultural community; they have a long history of creating successful partnerships with local, state and federal agencies to implement on-the-ground conservation projects. There are ninety-six (96) RCDs across California, providing technical assistance to farmers and land managers and leading implementation of on-farm conservation practices. Currently, there are 32 RCDs encompassing a multitude of different climatic regions, ecosystems and soil types, engaged in development of a carbon farming network to create a broad scientific knowledge base and realize the potential for scaling carbon farming across the State (Carbon Cycle Institute, 2018).

By working with existing infrastructure, California has the capacity to deliver climate change and soil impacts at scale on its working landscapes. Carbon Farm Plans developed on farms and ranches, from Modoc to Santa Barbara County, include estimates of the GHG (as CO_2e) and water benefits of implementing those plans. A Carbon Farm Plan CCI and NRCS developed for a 4,500-acre ranch in Modoc County showed a potential to sequester 111,581 metric tons of CO_2e over 20 years, with an associated potential increase in soil water holding capacity of over 520 acre-feet. Similarly, a Carbon Farm Plan developed by CCI and the Cachuma RCD for an 8,000-acre ranch in Santa Barbara County showed a 20-year sequestration potential of over 500,000 metric tons of CO_2e, with an associated potential increase in soil water holding capacity of over 900 acre-feet. On average, each acre of land subject to SOC-increasing practices would be capable of holding at least one additional acre-inch of water (27,152 gallons). On a "typical" 500-

acre ranch, this represents roughly 13.5 million gallons, or 41.6 acre-feet, each water year, which equals the average annual water use of over 140 homes in California.

5.4.6 Strategies to Reduce Barriers

The social and technical barriers to implementing carbon-focused, working land programs may be addressed by strengthening program delivery infrastructure and increased coordination for organizations that currently provide technical assistance and engage agricultural producers in conservation practices. Implementation of conservation practices at the scale needed to render enhanced management of working lands a significant element in climate change mitigation will also require a ramping up in the capacities of those doing the actual work on the ground.

Effective outreach strategies can include sharing of data documenting both the biophysical and economic benefits of implementing climate-beneficial practices and their associated co-benefits. Haden et al. (2012) suggest that adoption of mitigation practices by farmers is motivated more by their concern for long-term risk to society rather than their near-term, personal risk, which, by contrast, is one of the goals of adaptation. Therefore, incentive and outreach programs may benefit by addressing both the producer's willingness to be part of the solution to global problems (mitigation) and their concerns about local impacts (adaptation).

5.5 Conclusions and Future Directions

The potential to achieve carbon sequestration increases and associated water benefits through land preservation or management varies across California soils, geography, and working land cover types. This analysis specifically evaluates the potential for soil management on protected working lands to increase hydrologic and GHG reduction benefits, as well as losses in potential benefits due to lost management opportunities. It does not consider change in GHG stocks or flux due to land conversion, nor change in water balance. Conversely, it does not consider avoided loss of carbon or avoided loss of water supply from land protection. Changes in land management and land conservation can play a large role in contributing to California emission reduction targets (Cameron et al., 2017). Next steps should include calculation of combined hydrologic and GHG reduction benefits that result from co-occurring avoided conversion and land management on protected lands.

Multiple socio-economic, technical and policy barriers hinder the development of effective, conservation strategies aimed at increasing carbon sequestration on working landscapes. A multi-faceted strategy that includes: strengthening the existing infrastructure (i.e. financial and technical assistance), modifying existing programs to incentivize land conservation and implementation of climate-beneficial practices with robust and diverse financing mechanisms could potentially remove the existing barriers to the conservation and management of working landscapes for climate change mitigation in California.

Data and analysis derived from this study are key to understanding the scale and scope of potential State programs and investments needed to accomplish Carbon Sequestration in the Land Base (Natural and Working Lands) under the Governor's Climate Change Pillars/2030 GHG Goals. The information contained in this report could be used in the following programs/initiatives:

- Natural and Working Lands section of the AB32 Scoping Plan Update currently underway as mandated by Governor Brown Executive Order B-30-15.

- Implementation and refinement of the goals and targets of the Natural Resource and Solid Waste Diversion investment category of the Second Investment Plan for Cap and Trade Auction Proceeds.
- Development of the goals, targets and strategies for the Carbon-Rich Healthy Soils program by CDFA in collaboration with DoC, NRA, CalRecycle, and ARB in 2016-2017 and beyond.
- Development of the guidelines for and implementation of the second (Agricultural Easements) and third (Land Management Incentives) component of the Sustainable Agriculture Lands Conservation Program under the Strategic Growth Council.
- Scoping and creation of the Third Investment Plan for Cap and Trade Auction Proceeds (as well as FY 2016-2017 and FY 2018-2019 GGRF investments through the State budget process).
- Development of new and/or refinement of existing farmland conservation programs, including Williamson Act.
- Inform the development of local climate action plans, local adaptation plans (with specific focus on working lands), and regional climate plans (such as those being developed by Bay Area Air Quality Management District and Joint Policy Committee).
- Greenhouse Gas Reduction Fund investment

5.5 Acknowledgements

This work was conducted in collaboration with the State of California Department of Conservation, Division of Land Resource Protection.

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6: Conclusions and Future Directions

An often-overlooked resource to help California meet its ambitious greenhouse gas and water conservation goals is right beneath our feet. Soils can be significant sinks for atmospheric carbon, while at the same time, increasing soil organic matter can increase California's water storage capacity. The State of California has developed goals to increase carbon in soil and establish long term goals for carbon levels in all of California's agricultural soils, though these remained undefined.

Rising air temperatures are projected to continue to drive up urban, agricultural, and rangeland water use, straining both surface and groundwater resources. Scientific studies have shown that managing farms, ranches, and public lands to increase soil carbon can have multiple benefits. These soil management activities to increase capacity to sequester carbon in soils and vegetation also increase water-holding capacities and crop yields, reduce erosion, and reduce climate-related water deficits. Although healthy soils with increased soil organic matter can be achieved in multiple ways, whole-farm management strategies such as "carbon farming" can play a critical role in helping to optimize achievement of those goals and aid California in developing resilience to climate change while simultaneously reducing atmospheric greenhouse gases. This study was developed to address the multiple benefits of increasing the organic matter content, generally recognized as an indicator of the "health" of soils, across California's working lands.

A simulated one-time application of compost at rangeland sites across a range of California climates resulted in a long-term increase in overall soil C storage (between 1.6 to 2.0 Mg C per ha), and primary productivity (ranging from 0.20 to 0.60 Mg C per ha). On the basis of future climate simulations, the overall climate benefit of the compost amendment peaked around 15 years after compost application, with the benefit decreasing over time. The long-term net C sequestration due to compost application was highest in the drier sites of Tulare and Santa Barbara counties, indicating that the compost effect at drier sites is less sensitive to climate change than the northern sites. 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, at the local scale. Regionalization of compost applications to only 6% of rangelands in California resulted in an estimate of 8.4 – 8.7 million metric tons of CO_2 equivalents at maximum sequestration, 15 years after a single compost application.

Increases in soil organic matter of 1-3%, representative of the rangeland compost field trial increases (Ryals et al 2014), were added to a regional water balance model to increase soil water holding capacity and enable calculation of concomitant changes in hydrologic components. Increasing the amount of soil water storage reduces climatic water deficit (CWD), which has multiple benefits, including reducing demand (the need for irrigation), reducing wildfire risk, reducing vegetation stress and vulnerability to disease. It also increases actual evapotranspiration (AET), which represents net primary productivity, with hydrologic model results comparing well with DayCent GHG model results indicating increasing forage and crop yields. Recharge is the water that stays in the watershed, contributes to late season baseflows, may penetrate to the groundwater aquifer, and is generally more resilient to changes in climate than runoff. Runoff, while it fills reservoirs and is valuable for water supply, may run off in the wet season, and may create peak flows that transport sediment and other water quality constituents and damage water management infrastructure. For these reasons we considered an increase in recharge relative to runoff the primary hydrologic benefit, while coincident reductions in runoff may result in less opportunity for flooding, water quality, and infrastructure issues.

Benefits of increasing soil organic matter were as high as 4.7 million acre-feet of increased soil moisture storage per year with an increase in SOM of 3% across all working lands in California, with a high degree of variation across the state. Hydrologic benefits were greatest in locations with ample precipitation to fill increases in soil water holding capacity; amelioration of climate change impacts thus was also greater for the wet future scenario (1-8%) than the dry scenario (1-3%). These were generally in northern or coastal regions, or Sierra Nevada foothill locations. Valley floor locations benefitted little in recharge, but had more benefit from reduced CWD, therefore reducing irrigation demand on croplands. Many locations on working lands benefitted by decreased CWD or increased recharge as a result of adding SOM to reduce the impacts of climate change by the end-of-century by over 50%. An additive index combining all three variables described a range of benefit across all working lands, with no hydrologic benefit in only 3% of working lands. All locations were deemed to have benefits of carbon sequestration, even in the absence of hydrologic benefit. Locations with no calculated hydrologic benefit are already high in organic matter, with little climatic stress, low precipitation, or with unsuitable soil textures.

Application of strategic soil management to achieve the results presented here at a large scale could have important ramifications for the use of compost or other strategies to enhance soil organic matter throughout the state. However, SOM-enhancing practices should be considered on the basis of local conditions, soil properties, ongoing land management strategies, and the desired benefit, whether it be for increased hydrologic resilience to climate change, forage production, reduced landscape stress and agricultural demand, or mitigation of greenhouse gas emissions.

Hydrologic and carbon sequestration results, given a 3% increase in SOM, were considered in an economic analysis. This preliminary analysis includes provisioning services associated with above ground forage productivity, and regulating services associated with below ground carbon sequestration and groundwater recharge. The value of increased SOM can be estimated by the change in flow of impacted ecosystem service benefits provided to individual producers and to society. These benefits, derived from selected potential soil-related, ecosystem services, are based on evidence and data of preferences from which values can be assessed, estimated and sometimes monetized.

For forage production, the monetary values vary substantially among counties; all county plot data show that an increase in forage production via composting may provide ranchers steady and increasing monetary benefits over time, with landowners being able to save on average $64/ton/ha/year for the high emissions scenario in the 2040-2049 decade, a 357% increase when compared to the cost savings from 2010-2019, showing how the benefits from composting actually increase over time.

Carbon sequestration values, in the form of CO_2 equivalents, were used to estimate administered market value of sequestered carbon and the *public* social cost of carbon (SCC) from avoided GHG emissions. Using the SCC, the two emissions scenarios affected different counties variably depending on geographical location. However, the results generally indicate that the stream of benefits increases over the assessed 40-year period, demonstrating the large potential for the California carbon market in the coming decades.

The recharge variable represents the amount of water that seeps into the ground, becoming either baseflows or recharging aquifers. It was demonstrated that an increase in SOM increases recharge. The estimated cost of irrigation was chosen as a proxy value for groundwater recharge. Results demonstrate how differences in soil type and climate between counties may affect how an increase in SOM influences the regional hydrology. However, statewide estimated average values maintain a stable stream of benefits over the years.

Socioeconomic and related land use pressures pose barriers to implementing management practices to increase soil organic matter (SOM) by driving conversion of rangeland and cropland to development or more GHG emission-intensive agriculture. The final section of this study sought to answer questions of risks to preserving climate resilience benefits on working lands, and to what extent teaming conservation programs with soil management practices can enhance climate resilience benefits for California. Land use and growth scenarios were used to analyze the sensitivity of benefits associated with incremental areal and spatial allocation of land conservation. Analyses identified where and the extent to which soil management activities could maximize climate benefits. We identified regions with high development risk/high potential for hydrologic resiliency to climate change, and opportunities for hydrologic benefit when conservation programs are present.

Future development posed more risk of lost potential for reduced CWD and increased AET resulting from soil management than loss of recharge, since development generally occurs on the floor of the Central Valley, where potential for increased recharge from increased SOM is low. Since potentials for hydrologic benefits resulting from soil management are unevenly distributed across California, potential losses from development and gains on conservation lands are also unevenly distributed; a limited number of counties provide a majority of the benefits. Santa Clara and Shasta Counties are two areas where future development is likely to occur on soils with high hydrologic benefit potential.

In consideration of two conservation programs, potential hydrologic benefits on Williamson Act lands are an order of magnitude greater than potential losses related to future development, totaling over 700,000 acre-feet annually state-wide in a wet climate scenario. Potential hydrologic benefits from easements alone are similar in magnitude to potential losses that could be experienced from development. Despite many easements co-occurring on Williamson Act lands, a high easement acquisition rate could increase hydrologic benefits over those on just Williamson Act contract lands by approximately 100,000 acre-feet annually in a wet climate scenario. Easements can also offset potential conversion of grassland to more GHG-intensive agriculture; in a business as usual scenario, over 600,000 acres of Williamson Act grassland may be converted to perennial or annual agriculture without stipulation as to its management for GHG or hydrologic benefits.

Combined implications of these analyses indicate that strategic soil management to increase soil organic matter can indeed sequester carbon, increase soil water holding capacity, increase above ground productivity in the form of forage, increase recharge relative to runoff, and reduce the climatic water deficit. Benefits vary across the state's working lands, with greater benefit in locations with more precipitation; but these analyses allow for prioritization of available locations and resources, and optimization of benefits. These benefits can be economically valued to help prioritize locations and incentivize land managers and policy makers. Results can be effectively used to inform State land conservation programs and future land use scenarios to identify where on California's working lands hydrologic benefits coincide with development risk, highlighting counties in California that may provide the greatest resilience to climate change with strategic soil management and land conservation.

APPENDIX A: Results from Analyses Conducted for Section 2.

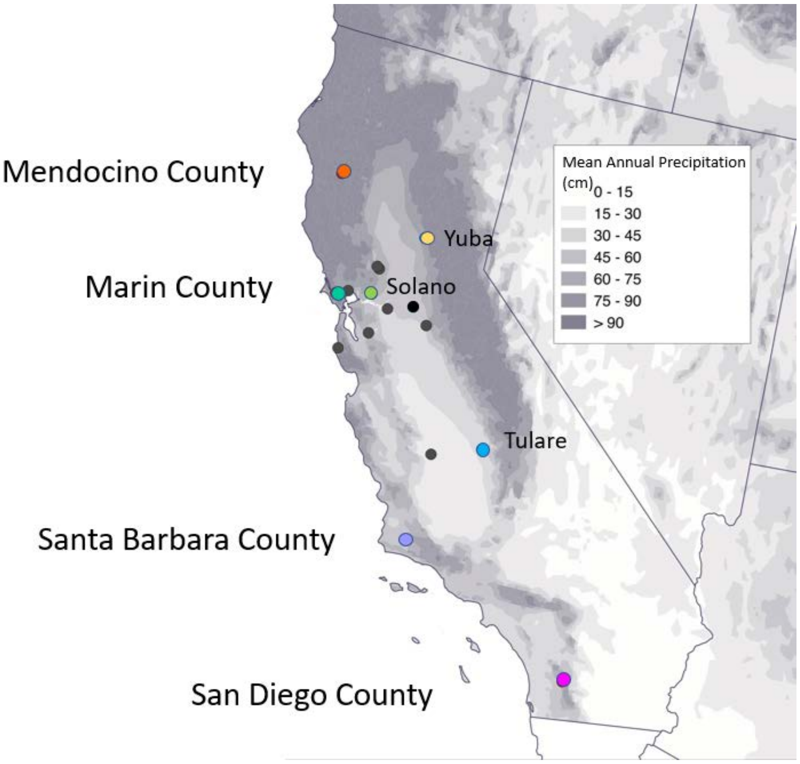

Figure A.1: Site locations for the Statewide Compost Addition Experiment. The seven modeled sites are color coded; the black dots are field sites that were not modeled. Map created by S. Grubinger.

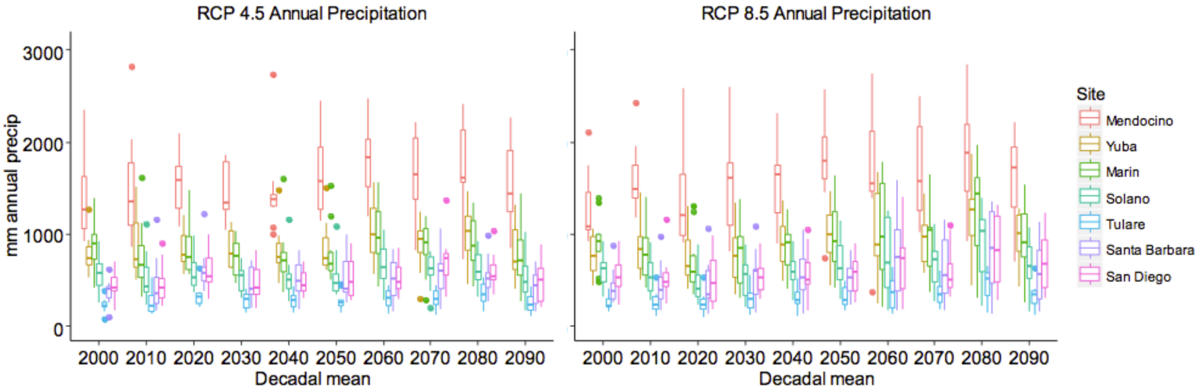

Figure A.2: Projected climate change under CanESM2-ES results in an increase of mean annual precipitation by decade. Annual precipitation varies more in the last half of the century under the high emissions scenario (RCP8.5) compared to the reduced emissions scenario (RCP4.5).

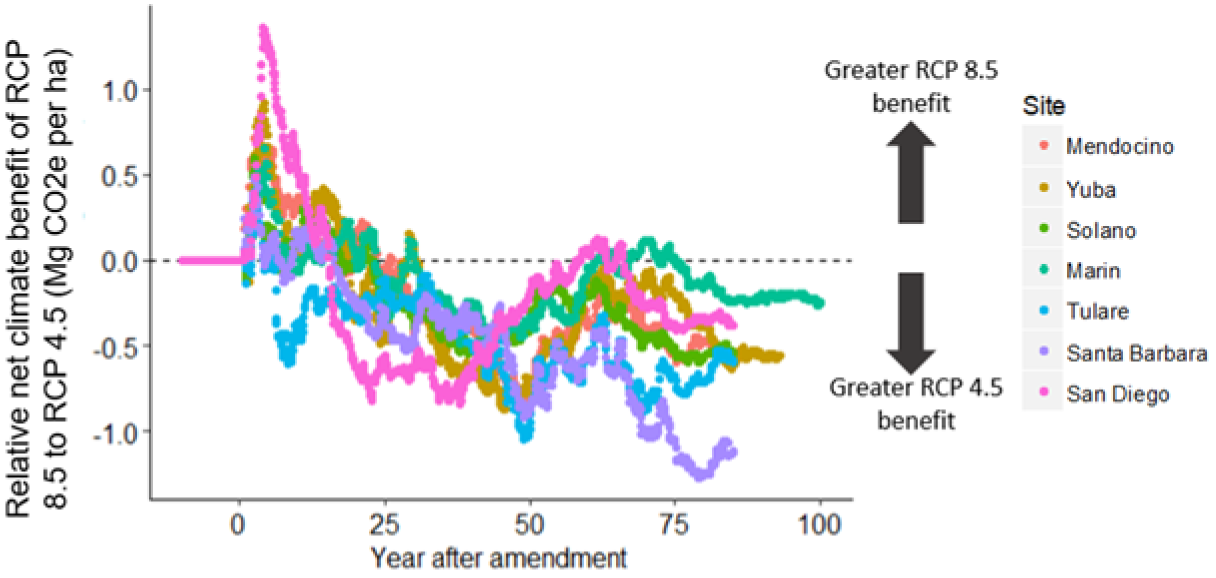

Figure A.3: The same compost amendment results in a greater climate benefit if combined with emissions reduction (RCP4.5) then in a high emissions scenario (RCP8.5). We calculated the difference between the climate benefit of compost for RCP8.5 and RCP4.5 and found that the benefit from RCP4.5 was larger than the benefit from RCP8.5 (points below the dotted line) in all sites throughout most of the century.

APPENDIX B: Results from Analyses Conducted for Section 3.

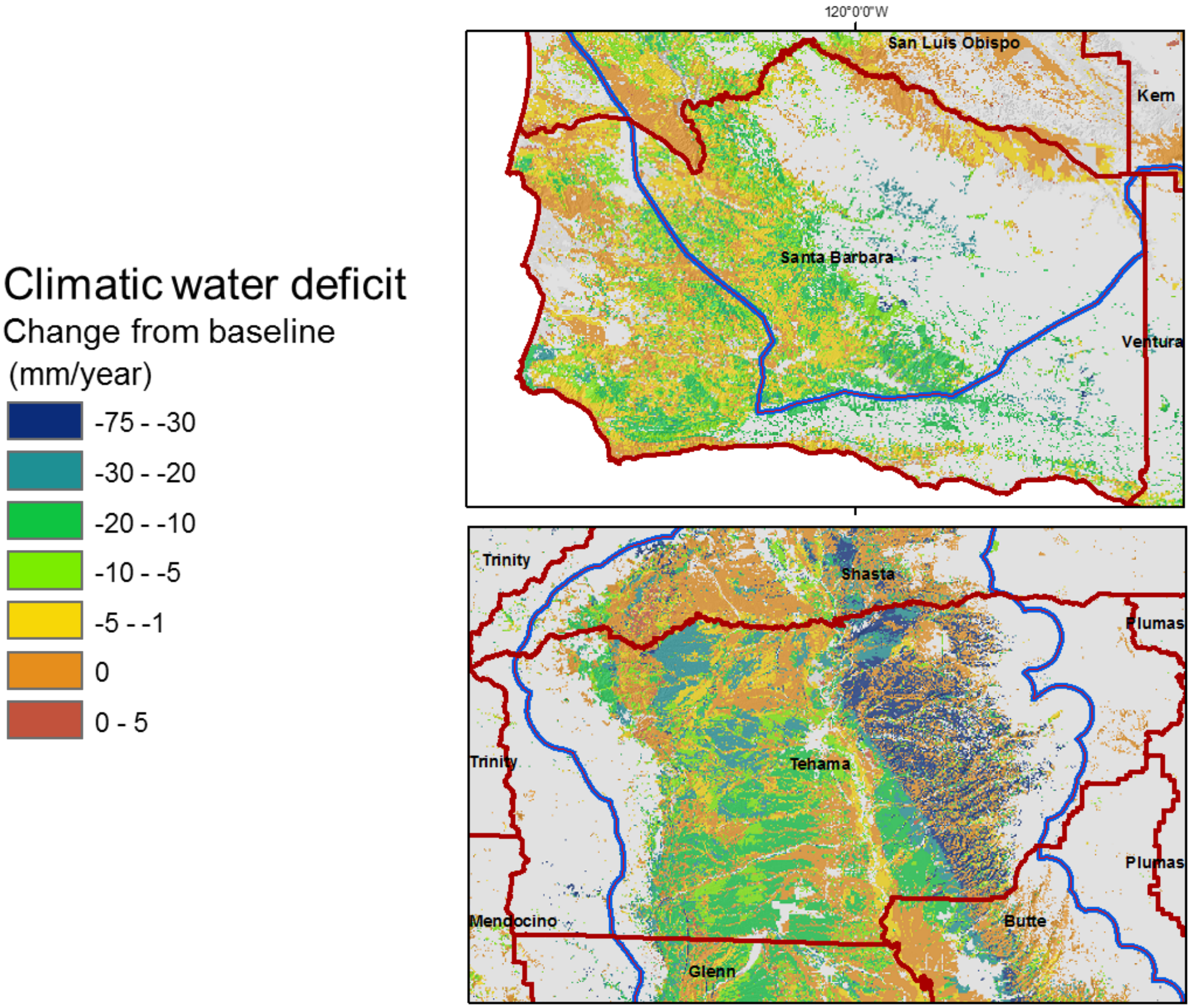

Figure B.1: Close up for results of change in climatic water deficit (CWD) by adding 3% soil organic matter to baseline conditions, averaged for 1981-2010 for Santa Barbara and Tehama Counties, illustrating decreases in CWD for most locations, and especi

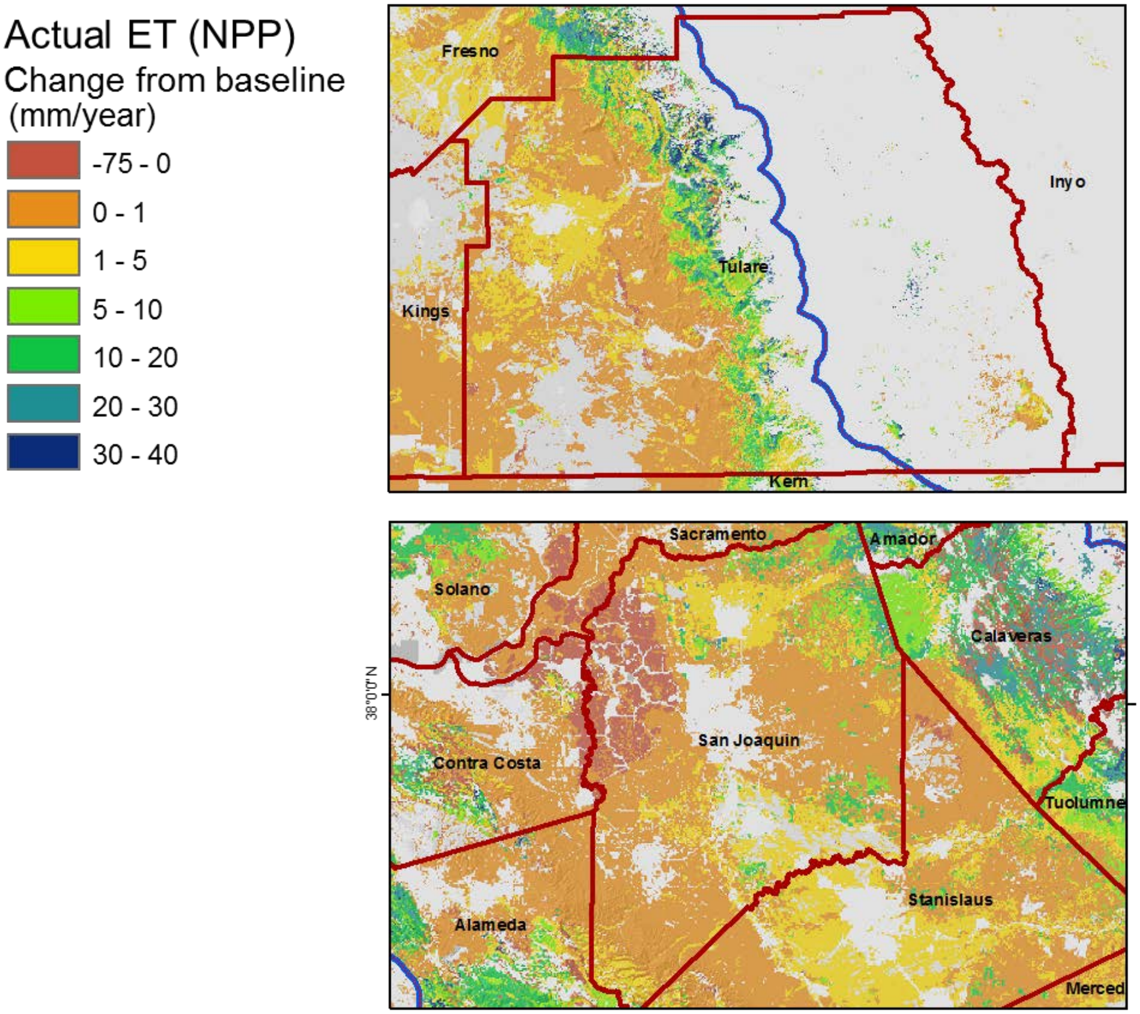

Figure B.2: Close up of results of change in actual evapotranspiration (AET), proxy for net primary productivity, by adding 3% soil organic matter to baseline conditions, averaged for 1981-2010 for Tulare and San Joaquin and Tehama Counties, illustration.

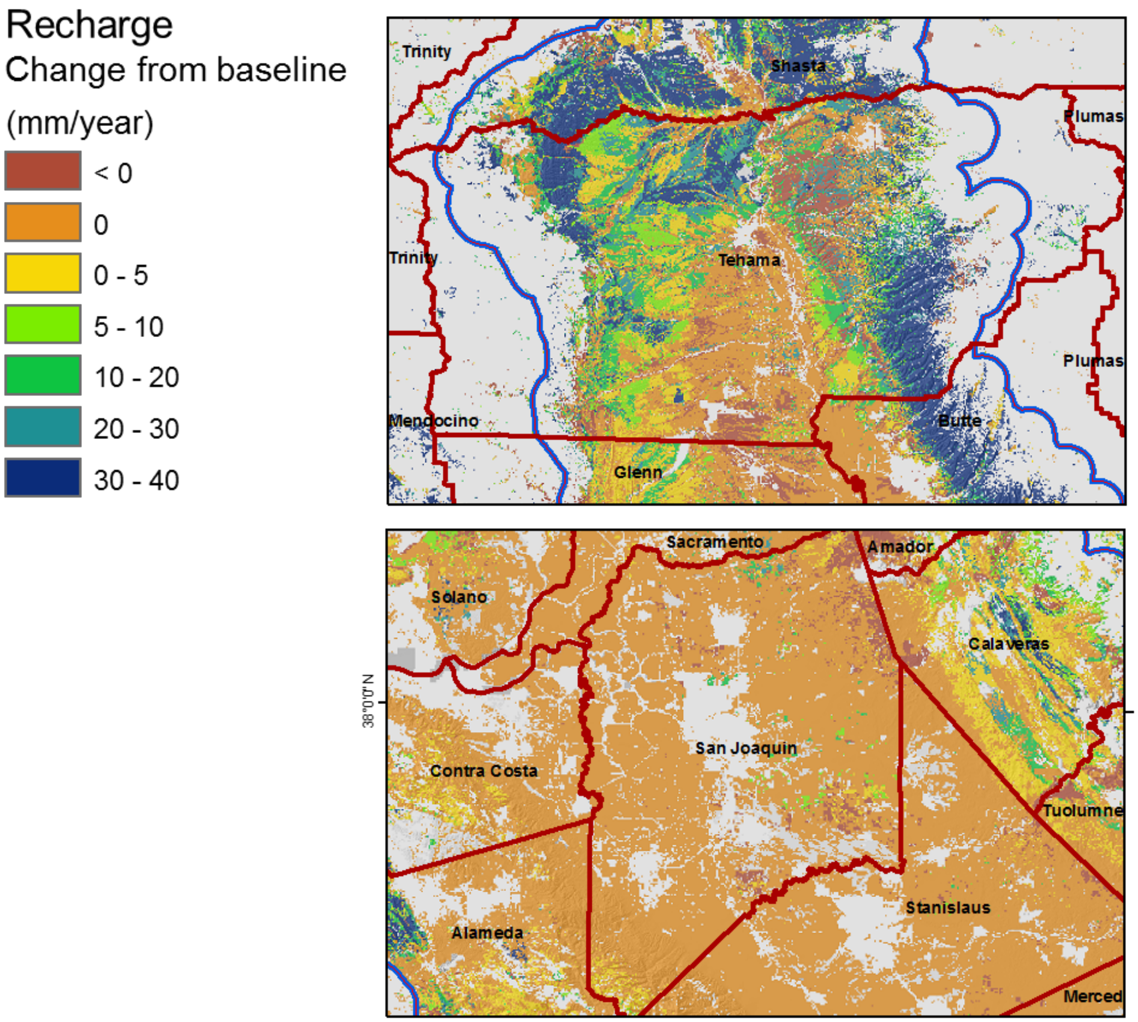

Figure B.3: Close up of results of change in recharge by adding 3% soil organic matter to baseline conditions, averaged for 1981-2010 for Tehama and San Joaquin Counties, illustrating little change in recharge on the valley floor of San Joaquin County, and large changes in Tehama County.

Table B.1: Values of hydrologic benefit with three levels of added soil organic matter for counties in California with less than 85% mask, for (a) treated, and (b) baseline for each treatment level. Cwd is climatic water deficit, aet is actual evapotranspiration, rch is recharge, run is runoff, and str is soil storage, all values are in inches of water, modeled unmasked area and county area are included.

(a)

County	Modeled unmasked area (acres)	County area (acres)	% masked	+1% soil organic matter					+2% soil organic matter					+3% soil organic matter				
				cwd (in)	aet (in)	rch (in)	run (in)	str (in)	cwd (in)	aet (in)	rch (in)	run (in)	str (in)	cwd (in)	aet (in)	rch (in)	run (in)	str (in)
Alameda	275,577	463,337	41%	6.2	15.4	0.8	1.7	19.9	6.1	15.5	0.9	1.6	20.2	6.1	15.5	0.9	1.5	20.6
Amador	189,561	380,185	50%	4.5	18.8	3.5	3.0	15.4	4.4	18.9	3.6	2.8	15.9	4.3	18.9	3.6	2.7	16.4
Butte	439,919	1,048,826	58%	4.2	19.9	4.1	5.4	21.1	4.1	20.0	4.3	5.1	21.7	4.0	20.1	4.4	4.9	22.3
Calaveras	325,710	639,189	49%	3.9	18.3	2.9	3.6	15.1	3.8	18.4	2.9	3.4	15.6	3.7	18.5	2.9	3.3	16.2
Colusa	412,628	738,302	44%	7.6	16.1	0.6	1.4	22.7	7.5	16.1	0.6	1.4	23.0	7.4	16.2	0.6	1.3	23.5
Contra Costa	293,663	457,428	36%	7.5	15.4	0.5	1.8	24.3	7.5	15.3	0.6	1.8	24.2	7.5	15.3	0.6	1.7	24.3
El Dorado	220,437	1,092,402	80%	1.9	20.7	4.9	5.8	18.0	1.7	20.9	5.0	5.5	18.8	1.6	21.0	5.0	5.3	19.6
Fresno	2,230,488	3,815,788	42%	19.2	6.3	0.4	0.3	15.9	19.1	6.4	0.4	0.3	16.5	19.1	6.4	0.3	0.3	16.9
Glenn	511,542	844,602	39%	7.7	17.1	0.9	1.2	20.6	7.6	17.1	0.9	1.1	21.0	7.5	17.2	0.9	1.0	21.3
Imperial	506,751	2,657,851	81%	29.1	0.3	-	-	1.7	29.1	0.3	-	-	1.8	29.1	0.3	-	-	1.9
Kern	2,697,049	5,212,212	48%	23.4	3.1	0.1	0.0	7.3	23.4	3.2	0.1	0.0	7.7	23.4	3.2	0.1	0.0	8.1
Kings	835,631	888,971	6%	25.6	1.4	0.0	0.1	15.9	25.6	1.4	0.0	0.1	16.5	25.6	1.4	0.0	0.0	16.5
Lake	283,810	802,792	65%	0.9	19.9	4.6	8.1	28.1	0.9	20.0	4.8	7.8	28.8	0.8	20.0	5.0	7.5	29.5
Lassen	539,014	2,975,437	82%	15.9	7.8	0.9	0.5	15.2	15.9	7.8	0.9	0.4	15.6	16.0	7.8	0.9	0.4	16.1
Los Angeles	696,239	2,533,537	73%	14.0	9.5	0.3	0.8	10.9	14.0	9.5	0.3	0.8	11.4	14.0	9.5	0.3	0.7	11.9
Madera	757,721	1,370,988	45%	15.7	9.5	0.6	0.4	9.7	15.7	9.6	0.6	0.4	10.5	15.6	9.6	0.6	0.4	11.2
Marin	214,870	324,647	34%	0.5	19.2	2.4	12.5	28.2	0.4	19.2	2.5	12.4	29.0	0.3	19.3	2.5	12.3	29.8
Mariposa	388,795	927,142	58%	7.0	15.8	1.7	1.9	14.3	6.9	15.9	1.7	1.8	14.9	6.8	16.0	1.7	1.8	15.4
Mendocino	365,431	2,237,207	84%	0.9	21.6	6.3	17.9	26.1	0.8	21.7	6.5	17.5	26.9	0.7	21.8	6.7	17.3	27.8
Merced	1,101,661	1,246,566	12%	17.8	7.3	0.0	0.1	16.5	17.8	7.3	0.0	0.1	17.0	17.7	7.3	0.0	0.1	17.5
Modoc	750,263	2,571,690	71%	11.1	8.7	0.4	0.3	16.5	11.1	8.7	0.4	0.3	16.9	11.1	8.7	0.5	0.3	17.3
Monterey	1,569,862	2,101,796	25%	9.2	12.4	0.5	2.4	15.9	9.1	12.4	0.5	2.3	16.3	9.1	12.5	0.5	2.2	16.7
Napa	230,200	480,901	52%	1.1	19.8	2.3	7.2	26.3	1.1	19.9	2.4	7.0	26.9	1.0	19.9	2.5	6.9	27.5
Nevada	141,518	614,474	77%	1.4	19.3	5.4	10.1	19.7	1.3	19.4	5.4	9.9	20.4	1.1	19.5	5.4	9.8	21.3
Orange	152,812	502,013	70%	12.8	10.1	0.3	0.6	12.0	12.7	10.2	0.3	0.5	12.2	12.6	10.3	0.3	0.5	12.6
Placer	181,310	899,995	80%	6.9	18.5	2.4	2.8	16.2	6.7	18.7	2.3	2.7	16.8	6.6	18.8	2.3	2.6	17.5
Plumas	276,911	1,632,875	83%	10.3	15.3	2.4	1.4	16.1	10.2	15.3	2.4	1.3	17.1	10.2	15.4	2.4	1.2	18.0
Riverside	846,314	4,614,365	82%	19.4	6.2	0.1	0.3	6.8	19.3	6.2	0.1	0.2	7.2	19.3	6.2	0.1	0.2	7.7
Sacramento	370,961	621,914	40%	11.9	15.7	0.4	0.3	18.0	11.8	15.8	0.4	0.3	18.4	11.8	15.9	0.4	0.3	18.8
San Benito	744,535	889,151	16%	10.5	12.0	0.1	0.5	17.8	10.5	12.1	0.1	0.5	18.2	10.5	12.1	0.1	0.5	18.6
San Diego	963,188	2,657,545	64%	11.4	10.4	0.3	0.9	10.8	11.2	10.5	0.3	0.9	11.3	11.2	10.6	0.2	0.8	11.8
San Joaquin	763,557	903,094	15%	14.1	10.9	0.1	0.1	19.4	14.1	10.9	0.1	0.1	19.9	14.1	11.0	0.1	0.1	20.4
San Luis Obispo	1,676,649	2,095,581	20%	11.0	11.7	0.5	1.7	14.8	10.9	11.7	0.5	1.7	15.2	10.9	11.8	0.5	1.6	15.4
San Mateo	112,911	277,217	59%	0.8	20.2	2.4	6.5	25.0	0.7	20.3	2.4	6.4	25.9	0.6	20.3	2.4	6.3	26.9
Santa Barbara	1,193,352	1,722,224	31%	7.8	13.9	0.5	1.8	15.2	7.7	14.0	0.5	1.8	15.4	7.7	14.0	0.6	1.7	15.5
Santa Clara	498,932	825,363	40%	4.0	15.7	0.7	5.0	15.9	3.9	15.8	0.7	4.9	16.3	3.8	15.9	0.7	4.8	16.8
Santa Cruz	80,648	276,712	71%	4.0	18.7	3.2	7.7	20.9	3.9	18.8	3.2	7.6	21.7	3.7	18.9	3.2	7.5	22.5
Shasta	601,720	2,418,013	75%	1.6	18.3	7.3	7.9	24.5	1.5	18.4	7.8	7.4	25.1	1.4	18.5	8.1	6.9	25.8
Sierra	102,481	608,836	83%	13.2	14.5	1.3	1.0	17.1	13.2	14.6	1.3	1.0	17.9	13.2	14.6	1.3	1.0	18.6
Siskiyou	700,851	4,020,625	83%	7.4	13.5	1.9	1.6	16.4	7.3	13.6	2.0	1.5	16.9	7.3	13.6	2.0	1.5	17.4
Solano	376,942	528,583	29%	9.8	17.1	0.4	0.8	27.3	9.7	17.1	0.4	0.7	27.4	9.7	17.2	0.4	0.7	27.8
Sonoma	406,845	1,012,438	60%	0.6	21.1	4.0	11.4	33.2	0.6	21.1	4.2	11.2	33.7	0.5	21.2	4.3	11.1	34.5
Stanislaus	855,231	963,116	11%	13.8	10.2	0.1	0.2	15.2	13.8	10.2	0.1	0.2	15.8	13.8	10.2	0.1	0.2	16.4
Sutter	216,041	389,101	44%	10.6	16.6	0.3	0.5	23.1	10.6	16.7	0.3	0.4	23.5	10.5	16.7	0.3	0.4	24.0
Tehama	1,154,839	1,890,510	39%	4.5	18.2	4.8	3.4	17.4	4.3	18.3	5.0	3.1	17.9	4.2	18.5	5.1	2.9	18.4
Tulare	1,487,340	3,087,844	52%	17.2	7.9	0.5	0.4	12.4	17.2	7.9	0.5	0.4	12.9	17.2	7.9	0.5	0.3	13.4
Tuolumne	259,959	1,426,597	82%	3.5	18.3	4.7	3.7	14.4	3.3	18.4	4.7	3.5	15.1	3.2	18.5	4.7	3.4	15.7
Ventura	609,610	1,159,666	47%	8.8	13.8	0.3	1.2	15.6	8.7	13.9	0.3	1.1	16.1	8.7	14.0	0.3	1.0	16.5
Yolo	497,077	653,186	24%	8.7	17.0	0.3	1.0	30.7	8.7	17.0	0.3	0.9	30.5	8.7	17.1	0.4	0.9	30.5
Yuba	212,150	405,422	48%	5.2	19.1	1.5	5.6	18.7	5.1	19.2	1.5	5.4	19.1	5.0	19.3	1.5	5.3	19.7

(b)																		
				base case for 1%					base case for 2%					base case for 3%				
County	Masked area (acres)	Unmasked area (acres)	% masked	cwd (in)	aet (in)	rch (in)	run (in)	str (in)	cwd (in)	aet (in)	rch (in)	run (in)	str (in)	cwd (in)	aet (in)	rch (in)	run (in)	str (in)
Alameda	275,577	476,033	42%	6.3	15.3	0.7	1.8	19.6	6.3	15.3	0.7	1.8	19.5	6.3	15.3	0.7	1.8	19.5
Amador	189,561	386,989	51%	4.6	18.6	3.4	3.2	14.8	4.7	18.6	3.5	3.2	14.7	4.7	18.5	3.5	3.2	14.6
Butte	439,919	1,073,605	59%	4.3	19.8	3.9	5.7	20.5	4.3	19.8	3.9	5.7	20.5	4.3	19.8	3.9	5.7	20.5
Calaveras	325,710	663,261	51%	4.0	18.2	2.8	3.8	14.6	4.0	18.2	2.8	3.8	14.6	4.0	18.2	2.8	3.8	14.6
Colusa	412,628	740,142	44%	7.6	16.0	0.6	1.5	22.2	7.6	16.0	0.6	1.5	22.1	7.6	16.0	0.6	1.5	22.0
Contra Costa	293,663	486,357	40%	7.5	15.3	0.5	1.9	24.0	7.7	15.1	0.5	1.9	23.6	7.7	15.1	0.5	2.0	23.5
El Dorado	220,437	1,144,425	81%	2.1	20.5	4.7	6.1	17.3	2.1	20.5	4.7	6.1	17.3	2.1	20.5	4.7	6.1	17.3
Fresno	2,230,488	3,851,544	42%	19.2	6.3	0.4	0.3	15.5	19.2	6.3	0.4	0.3	15.5	19.2	6.3	0.4	0.3	15.4
Glenn	511,542	849,234	40%	7.7	17.0	0.8	1.3	20.3	7.7	17.0	0.8	1.3	20.2	7.8	17.0	0.8	1.3	20.2
Imperial	506,751	2,868,281	82%	29.1	0.3	-	-	1.7	29.1	0.3	-	-	1.7	29.1	0.3	-	-	1.7
Kern	2,697,049	5,223,310	48%	23.4	3.1	0.1	0.1	7.0	23.4	3.1	0.1	0.1	6.9	23.4	3.1	0.1	0.1	6.9
Kings	835,631	890,517	6%	25.6	1.4	0.0	0.1	15.6	25.6	1.4	0.0	0.1	16.0	25.7	1.4	0.0	0.1	15.7
Lake	283,810	850,833	67%	1.0	19.8	4.3	8.5	27.4	1.0	19.8	4.3	8.5	27.4	1.0	19.8	4.3	8.5	27.4
Lassen	539,014	3,021,078	82%	15.9	7.8	0.9	0.5	14.7	16.0	7.8	0.9	0.5	14.7	16.0	7.8	0.8	0.5	14.6
Los Angeles	696,239	2,616,087	73%	14.1	9.4	0.3	0.9	10.4	14.1	9.4	0.3	0.9	10.4	14.2	9.3	0.3	0.9	10.4
Madera	757,721	1,377,917	45%	15.8	9.5	0.7	0.4	9.1	15.8	9.5	0.7	0.4	9.1	15.8	9.5	0.7	0.4	9.1
Marin	214,870	336,047	36%	0.5	19.1	2.4	12.6	27.5	0.5	19.1	2.4	12.6	27.4	0.5	19.1	2.4	12.6	27.4
Mariposa	388,795	935,330	58%	7.1	15.7	1.7	2.0	13.7	7.1	15.7	1.7	2.0	13.7	7.1	15.7	1.7	2.0	13.7
Mendocino	365,431	2,247,631	84%	1.1	21.4	6.0	18.4	25.3	1.1	21.4	6.0	18.3	25.3	1.1	21.4	6.0	18.3	25.3
Merced	1,101,661	1,261,144	13%	17.8	7.2	0.0	0.1	16.0	17.8	7.2	0.0	0.1	16.0	17.8	7.2	0.0	0.1	15.9
Modoc	750,263	2,690,199	72%	11.1	8.7	0.4	0.4	16.2	11.1	8.7	0.4	0.4	16.2	11.1	8.7	0.4	0.4	16.1
Monterey	1,569,862	2,121,178	26%	9.3	12.3	0.5	2.4	15.4	9.3	12.2	0.5	2.4	15.3	9.3	12.2	0.5	2.4	15.2
Napa	230,200	504,738	54%	1.2	19.7	2.2	7.4	25.6	1.2	19.7	2.2	7.4	25.5	1.2	19.7	2.2	7.4	25.4
Nevada	141,518	623,740	77%	1.6	19.1	5.3	10.4	18.9	1.6	19.1	5.3	10.4	18.9	1.6	19.1	5.3	10.4	18.9
Orange	152,812	511,724	70%	12.9	10.0	0.3	0.6	11.5	12.8	10.1	0.3	0.6	11.2	12.8	10.0	0.3	0.6	11.1
Placer	181,310	961,193	81%	7.0	18.3	2.4	2.9	15.5	7.0	18.3	2.4	2.9	15.5	7.0	18.3	2.4	2.9	15.5
Plumas	276,911	1,672,476	83%	10.3	15.2	2.3	1.4	15.2	10.3	15.2	2.3	1.4	15.2	10.3	15.2	2.3	1.4	15.2
Riverside	846,314	4,674,083	82%	19.4	6.1	0.1	0.3	6.3	19.4	6.1	0.1	0.3	6.3	19.4	6.1	0.1	0.3	6.2
Sacramento	370,961	636,946	42%	12.0	15.6	0.4	0.4	17.7	12.0	15.6	0.4	0.4	17.7	12.0	15.6	0.4	0.4	17.6
San Benito	744,535	889,958	16%	10.6	12.0	0.1	0.6	17.4	10.6	12.0	0.1	0.6	17.4	10.6	12.0	0.1	0.6	17.4
San Diego	963,188	2,712,892	64%	11.5	10.3	0.3	1.0	10.3	11.4	10.4	0.3	1.0	10.2	11.4	10.4	0.3	1.0	10.1
San Joaquin	763,557	912,037	16%	14.1	10.9	0.1	0.1	19.0	14.1	10.9	0.1	0.1	19.0	14.2	10.9	0.1	0.1	19.0
San Luis Obispo	1,676,649	2,124,670	21%	11.1	11.6	0.5	1.8	14.4	11.0	11.6	0.5	1.8	14.3	11.1	11.6	0.5	1.8	14.1
San Mateo	112,911	291,305	61%	0.9	20.1	2.4	6.6	24.1	0.9	20.1	2.4	6.6	24.1	0.9	20.1	2.4	6.6	24.1
Santa Barbara	1,193,352	1,760,046	32%	7.9	13.8	0.5	1.9	14.7	7.9	13.8	0.5	1.9	14.5	7.9	13.7	0.5	1.9	14.0
Santa Clara	498,932	831,091	40%	4.1	15.6	0.7	5.1	15.4	4.1	15.6	0.7	5.1	15.4	4.1	15.6	0.7	5.1	15.4
Santa Cruz	80,648	285,849	72%	4.1	18.6	3.2	7.9	20.2	4.1	18.6	3.2	7.9	20.2	4.1	18.6	3.2	7.9	20.1
Shasta	601,720	2,462,536	76%	1.7	18.3	6.8	8.6	23.8	1.7	18.3	6.8	8.6	23.8	1.7	18.3	6.8	8.6	23.8
Sierra	102,481	615,709	83%	13.3	14.5	1.3	1.0	16.4	13.3	14.5	1.3	1.0	16.4	13.3	14.5	1.3	1.0	16.4
Siskiyou	700,851	4,062,380	83%	7.4	13.5	1.9	1.7	15.8	7.4	13.5	1.9	1.7	15.7	7.4	13.5	1.9	1.7	15.7
Solano	376,942	569,317	34%	9.9	17.0	0.4	0.9	26.9	9.8	17.0	0.4	0.9	26.8	9.8	17.0	0.4	0.9	26.8
Sonoma	406,845	1,017,662	60%	0.7	21.0	3.9	11.6	32.4	0.7	21.0	3.9	11.7	32.1	0.7	21.0	4.0	11.7	32.1
Stanislaus	855,231	968,827	12%	13.9	10.2	0.1	0.2	14.6	13.9	10.2	0.1	0.2	14.6	13.9	10.2	0.1	0.2	14.6
Sutter	216,041	389,414	45%	10.7	16.5	0.3	0.5	22.6	10.7	16.5	0.3	0.5	22.5	10.7	16.5	0.3	0.5	22.4
Tehama	1,154,839	1,895,556	39%	4.6	18.0	4.6	3.8	16.9	4.6	18.0	4.6	3.8	16.8	4.7	18.0	4.6	3.8	16.8
Tulare	1,487,340	3,096,720	52%	17.3	7.9	0.6	0.4	11.8	17.3	7.8	0.6	0.4	11.8	17.3	7.8	0.5	0.4	11.7
Tuolumne	259,959	1,458,370	82%	3.6	18.1	4.6	3.9	13.8	3.6	18.1	4.6	3.9	13.8	3.6	18.1	4.6	3.9	13.8
Ventura	609,610	1,188,753	49%	8.9	13.8	0.3	1.2	15.1	8.9	13.8	0.3	1.2	15.0	8.9	13.8	0.3	1.2	14.9
Yolo	497,077	654,955	24%	8.7	17.0	0.2	1.0	30.3	8.7	17.0	0.2	1.1	29.8	8.7	17.0	0.2	1.1	29.4
Yuba	212,150	411,854	48%	5.3	19.0	1.5	5.7	18.1	5.3	19.0	1.5	5.6	17.9	5.3	19.0	1.5	5.6	17.9

Table B.2: Hydrologic benefits of baseline and added 3% soil organic matter under historical climate and two future scenarios. Results are averaged statewide for (a) grasslands and (b) croplands.

(a) Grasslands

Hot, wet scenario (CanESM2 rcp8.5)

	Units in Inches per year				Units in Acre-feet per year			
+3% SOM	cwd	aet	rch	run	cwd	aet	rch	run
1981-2010	7.77	14.95	2.41	4.37	12,252,222	23,565,125	3,799,270	6,888,028
2010-2039	7.78	14.54	2.57	5.05	12,260,837	22,916,957	4,053,699	7,968,643
2040-2069	7.55	16.88	3.13	7.66	11,901,564	26,616,439	4,929,173	12,074,726
2070-2099	8.45	17.18	2.89	9.49	13,317,422	27,076,320	4,557,842	14,959,840
BASELINE								
1981-2010	7.99	14.82	2.15	4.81	12,599,143	23,368,006	3,384,680	7,584,394
2010-2039	8.07	14.25	2.32	5.57	12,714,297	22,463,424	3,651,896	8,774,025
2040-2069	7.95	16.48	2.78	8.37	12,540,630	25,976,828	4,380,478	13,190,064
2070-2099	8.94	16.68	2.53	10.29	14,099,348	26,294,323	3,994,644	16,214,010

Hot, moderately dry scenario (HadGEM2-ES, rcp8.5)

	Units in Inches per year				Units in Acre-feet per year			
+3% SOM	cwd	aet	rch	run	cwd	aet	rch	run
1981-2010	7.77	14.95	2.41	4.37	12,252,222	23,565,125	3,799,270	6,888,028
2010-2039	7.61	15.34	2.55	4.70	11,990,106	24,177,664	4,025,511	7,415,961
2040-2069	8.63	13.37	2.10	3.33	13,602,102	21,083,053	3,315,479	5,244,394
2070-2099	7.70	15.49	2.41	5.17	12,143,405	24,418,954	3,802,567	8,156,538
BASELINE								
1981-2010	7.99	14.82	2.15	4.81	12,599,143	23,368,006	3,384,680	7,584,394
2010-2039	7.89	15.05	2.29	5.22	12,441,007	23,726,729	3,617,659	8,234,104
2040-2069	8.87	13.13	1.92	3.72	13,983,578	20,701,623	3,022,013	5,867,586
2070-2099	8.03	15.16	2.19	5.70	12,660,519	23,901,327	3,446,943	8,985,029

(b) Croplands

Hot, wet scenario (CanESM2 rcp8.5)

	Units in Inches per year				Units in Acre-feet per year			
+3% SOM	cwd	aet	rch	run	cwd	aet	rch	run
1981-2010	18.70	9.23	0.27	0.32	17,284,686	8,531,425	249,565	295,781
2010-2039	18.14	8.72	0.37	0.49	16,769,872	8,059,255	338,339	455,155
2040-2069	18.90	11.12	0.53	0.87	17,464,983	10,278,439	486,227	808,227
2070-2099	19.74	11.73	0.57	1.20	18,249,172	10,846,360	526,817	1,104,773
BASELINE								
1981-2010	18.78	8.84	0.23	0.38	17,355,323	8,170,942	214,441	353,088
2010-2039	18.20	8.66	0.33	0.59	16,821,256	8,007,875	300,764	546,343
2040-2069	19.00	11.02	0.47	1.04	17,559,770	10,183,579	429,938	961,443
2070-2099	19.89	11.59	0.49	1.42	18,380,986	10,714,449	456,693	1,310,369

Hot, moderately dry scenario (HadGEM2-ES, rcp8.5)

	Units in Inches per year				Units in Acre-feet per year			
+3% SOM	cwd	aet	rch	run	cwd	aet	rch	run
1981-2010	18.70	9.23	0.26	0.32	17,284,686	8,531,425	241,246	296,692
2010-2039	18.63	9.01	0.32	0.41	17,221,097	8,324,502	293,052	374,367
2040-2069	18.84	7.31	0.24	0.25	17,414,515	6,754,511	223,832	235,418
2070-2099	18.41	9.05	0.31	0.48	17,013,770	8,362,380	283,818	443,483
BASELINE								
1981-2010	18.78	8.84	0.23	0.38	17,355,323	8,170,942	214,441	353,088
2010-2039	18.68	8.96	0.28	0.49	17,265,205	8,280,409	261,040	451,647
2040-2069	18.87	7.28	0.22	0.31	17,443,493	6,725,534	199,906	288,637
2070-2099	18.46	8.99	0.27	0.57	17,063,483	8,312,676	250,720	529,254

APPENDIX C: Results from Analyses Conducted for Section 4.

Table C.1: California Hay Production and Prices, 2000-2049

CALIFORNIA - HAY PRODUCTION (TONS)		Avg. decadal hay production (tons, 1990-2049)
Year	Value	
2049	7,908,941	7,963,762
2048	7,921,123	
2047	7,933,306	
2046	7,945,488	
2045	7,957,671	
2044	7,969,853	
2043	7,982,036	
2042	7,994,218	
2041	8,006,400	
2040	8,018,583	
2039	8,030,765	8,085,586
2038	8,042,948	
2037	8,055,130	
2036	8,067,313	
2035	8,079,495	
2034	8,091,678	
2033	8,103,860	
2032	8,116,042	
2031	8,128,225	
2030	8,140,407	
2029	8,152,590	8,207,411
2028	8,164,772	
2027	8,176,955	
2026	8,189,137	
2025	8,201,320	
2024	8,213,502	
2023	8,225,684	
2022	8,237,867	
2021	8,250,049	
2020	8,262,232	
2019	8,274,414	7,899,680
2018	8,286,597	
2017	9,395,791	

2016	6,576,000	
2015	6,891,000	
2014	7,513,000	
2013	7,646,000	
2012	8,130,000	
2011	7,980,000	
2010	8,304,000	
2009	8,890,000	9,197,000
2008	9,414,000	
2007	9,042,000	
2006	9,568,000	
2005	9,206,000	
2004	9,220,000	
2003	9,485,000	
2002	9,774,000	
2001	8,775,000	
2000	8,596,000	
1999	8,782,000	8,256,500
1998	8,554,000	
1997	8,408,000	
1996	8,008,000	
1995	8,341,000	
1994	8,210,000	
1993	7,590,000	
1992	7,755,000	
1991	8,610,000	
1990	8,307,000	

Hay Prices	
Avg. decadal prices*	
(1990-2049)	
1990-1999	$97.85
2000-2009	$119.45
2010-2019	$180.44
2020-2029	$182.42
2030-2039	$206.96
2040-2049	$231.49
Source: USDA NASS (2017)	

Table C.2: The Social Cost of Carbon (SCC)

Social Cost of Carbon (inflated to current USD)								
Inflation Factor (2007 to 2017)			1.21		**Decadal avgs.**			
Discount Rate	5.00%	3.00%	2.50%	3.00%	5.00%	3.00%	2.50%	3.00%
Year	Avg	Avg	Avg	95th	Avg	Avg	Avg	95th
2010	$12.10	$37.51	$60.50	$104.06				
2011	$13.31	$38.72	$61.71	$108.90				
2012	$13.31	$39.93	$64.13	$112.53				
2013	$13.31	$41.14	$65.34	$117.37				
2014	$13.31	$42.35	$66.55	$122.21				
2015	$13.31	$43.56	$67.76	$127.05				
2016	$13.31	$45.98	$68.97	$130.68				
2017	$13.31	$47.19	$71.39	$135.52				
2018	$14.52	$48.40	$72.60	$140.36				
2019	$14.52	$49.61	$73.81	$145.20	$13.43	$43.44	$67.28	$124.39
2020	$14.52	$50.82	$75.02	$148.83				
2021	$14.52	$50.82	$76.23	$152.46				
2022	$15.73	$52.03	$77.44	$156.09				
2023	$15.73	$53.24	$78.65	$159.72				
2024	$15.73	$54.45	$79.86	$163.35				
2025	$16.94	$55.66	$82.28	$166.98				
2026	$16.94	$56.87	$83.49	$170.61				
2027	$18.15	$58.08	$84.70	$173.03				
2028	$18.15	$59.29	$85.91	$176.66				
2029	$18.15	$59.29	$87.12	$180.29	$16.46	$55.06	$81.07	$164.80
2030	$19.36	$60.50	$88.33	$183.92				
2031	$19.36	$61.71	$89.54	$187.55				
2032	$20.57	$62.92	$90.75	$191.18				
2033	$20.57	$64.13	$91.96	$194.81				
2034	$21.78	$65.34	$93.17	$198.44				
2035	$21.78	$66.55	$94.38	$203.28				
2036	$22.99	$67.76	$95.59	$206.91				
2037	$22.99	$68.97	$98.01	$210.54				
2038	$24.20	$70.18	$99.22	$214.17				
2039	$24.20	$71.39	$100.43	$217.80	$21.78	$65.95	$94.14	$200.86
2040	$25.41	$72.60	$101.64	$221.43				
2041	$25.41	$73.81	$102.85	$225.06				
2042	$26.62	$73.81	$104.06	$228.69				
2043	$26.62	$75.02	$105.27	$232.32				
2044	$27.83	$76.23	$106.48	$234.74				
2045	$27.83	$77.44	$107.69	$238.37	$27.83	$77.08	$107.45	$237.04

2046	$29.04	$78.65	$108.90	$242.00
2047	$29.04	$79.86	$111.32	$245.63
2048	$30.25	$81.07	$112.53	$249.26
2049	$30.25	$82.28	$113.74	$252.89
2050	$31.46	$83.49	$114.95	$256.52

3 percent discount rate based on U.S. Office of Management and Budget guidelines discount rate over a horizon of 30+ years (OMB. 1992. "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. " circular no A-94, revised) (2014 rate is 3.9%)
Source: Bureau of Labor Statistics. (2014). *Consumer Price Index.* Available at: http://www.bls.gov/cpi/cpifact8.htm.

Table C.3: Projected California ARB Auction Prices

Auction annual avg.	Auction Settlement Price ($/ton)	Decadal avg. ($/ton)
2029	$20.68	$18.08
2028	$20.10	
2027	$19.53	
2026	$18.95	
2025	$18.37	
2024	$17.79	
2023	$17.21	
2022	$16.63	
2021	$16.06	
2020	$15.48	
2019	$14.90	$12.87
2018	$14.32	
2017	$14.04	
2016	$12.73	
2015	$12.44	
2014	$11.65	
2013	$12.83	

Table C.4: Decadal results for baseline recharge and +3% SOM for historical through mid-century for 2 futures for grasslands for (a) a warm, wet future climate scenario, and (b) a warm dry future climate scenario.

	(a) Warm, wet scenario (CanESM2 rcp8.5), recharge values in ac-ft/yr					
	Decade	Baseline	+3%	Difference	% change	Water supply value
Statewide	1990-1999	5,574,700	6,440,760	866,060	16%	$39,284,473
	2000-2009	5,912,852	6,684,036	771,185	13%	$34,980,936
	2010-2019	6,988,840	7,903,672	914,832	13%	$41,496,774
	2020-2029	6,033,901	6,519,932	486,031	8%	$22,046,364
	2030-2039	5,928,404	6,612,657	684,253	12%	$31,037,723
	2040-2049	6,902,134	7,683,545	781,411	11%	$35,444,794
Tehama	1990-1999	389,901	535,938	146,037	37%	$6,624,228
	2000-2009	494,541	284,050	(210,491)	-43%	-$9,547,865
	2010-2019	523,464	620,946	97,481	19%	$4,421,759
	2020-2029	408,077	442,274	34,197	8%	$1,551,164
	2030-2039	397,852	469,272	71,420	18%	$3,239,625
	2040-2049	473,361	552,236	78,875	17%	$3,577,756
San Joaquin	1990-1999	5,699	4,940	(759)	-13%	-$34,430
	2000-2009	3,540	2,279	(1,261)	-36%	-$57,198
	2010-2019	10,892	9,849	(1,044)	-10%	-$47,336
	2020-2029	5,481	4,229	(1,252)	-23%	-$56,777
	2030-2039	7,366	6,503	(863)	-12%	-$39,162
	2040-2049	7,014	5,684	(1,330)	-19%	-$60,328
Santa Barbara	1990-1999	53,990	58,516	4,526	8%	$205,302
	2000-2009	38,379	38,160	(219)	-1%	-$9,924
	2010-2019	40,938	46,206	5,268	13%	$238,946
	2020-2029	35,567	37,440	1,872	5%	$84,935
	2030-2039	52,441	58,661	6,220	12%	$282,122
	2040-2049	63,917	68,693	4,775	7%	$216,611
Tulare	1990-1999	68,603	29,863	(38,740)	-56%	-$1,757,239
	2000-2009	50,004	21,186	(28,817)	-58%	-$1,307,161
	2010-2019	77,999	71,961	(6,038)	-8%	-$273,866
	2020-2029	45,862	41,063	(4,800)	-10%	-$217,721
	2030-2039	73,467	66,514	(6,953)	-9%	-$315,399
	2040-2049	84,315	77,604	(6,711)	-8%	-$304,396

	(b) Warm, dry scenario (HadGEM2-ES rcp8.5), recharge values in ac-ft/yr					
	Decade	Baseline	+3%	Difference	% change	Water supply value
Statewide	1990-1999	5,574,700	6,440,760	866,060	16%	$39,284,473
	2000-2009	5,912,852	6,684,036	771,185	13%	$34,980,936
	2010-2019	6,499,902	7,234,553	734,651	11%	$33,323,755
	2020-2029	5,200,410	5,718,584	518,175	10%	$23,504,414
	2030-2039	7,073,164	7,936,850	863,686	12%	$39,176,799
	2040-2049	6,626,561	7,406,499	779,938	12%	$35,377,979
Tehama	1990-1999	389,901	535,938	146,037	37%	$6,624,228
	2000-2009	494,541	284,050	(210,491)	-43%	-$9,547,865
	2010-2019	466,245	534,528	68,284	15%	$3,097,341
	2020-2029	392,428	438,034	45,607	12%	$2,068,711
	2030-2039	466,279	541,343	75,064	16%	$3,404,881
	2040-2049	536,916	618,508	81,592	15%	$3,701,025
San Joaquin	1990-1999	5,699	4,940	(759)	-13%	-$34,430
	2000-2009	3,540	2,279	(1,261)	-36%	-$57,198
	2010-2019	5,928	4,757	(1,172)	-20%	-$53,150
	2020-2029	2,322	1,549	(773)	-33%	-$35,070
	2030-2039	10,481	9,360	(1,120)	-11%	-$50,822
	2040-2049	6,650	5,570	(1,080)	-16%	-$48,989
Santa Barbara	1990-1999	53,990	58,516	4,526	8%	$205,302
	2000-2009	38,379	38,160	(219)	-1%	-$9,924
	2010-2019	55,905	63,169	7,264	13%	$329,497
	2020-2029	22,180	23,246	1,066	5%	$48,352
	2030-2039	67,144	77,217	10,073	15%	$456,894
	2040-2049	35,574	38,464	2,890	8%	$131,099
Tulare	1990-1999	68,603	29,863	(38,740)	-56%	-$1,757,239
	2000-2009	50,004	21,186	(28,817)	-58%	-$1,307,161
	2010-2019	58,391	53,249	(5,141)	-9%	-$233,209
	2020-2029	37,202	33,017	(4,185)	-11%	-$189,828
	2030-2039	95,779	89,648	(6,131)	-6%	-$278,115
	2040-2049	53,803	47,164	(6,639)	-12%	-$301,163

APPENDIX D: Results from Analyses Conducted for Section 5.

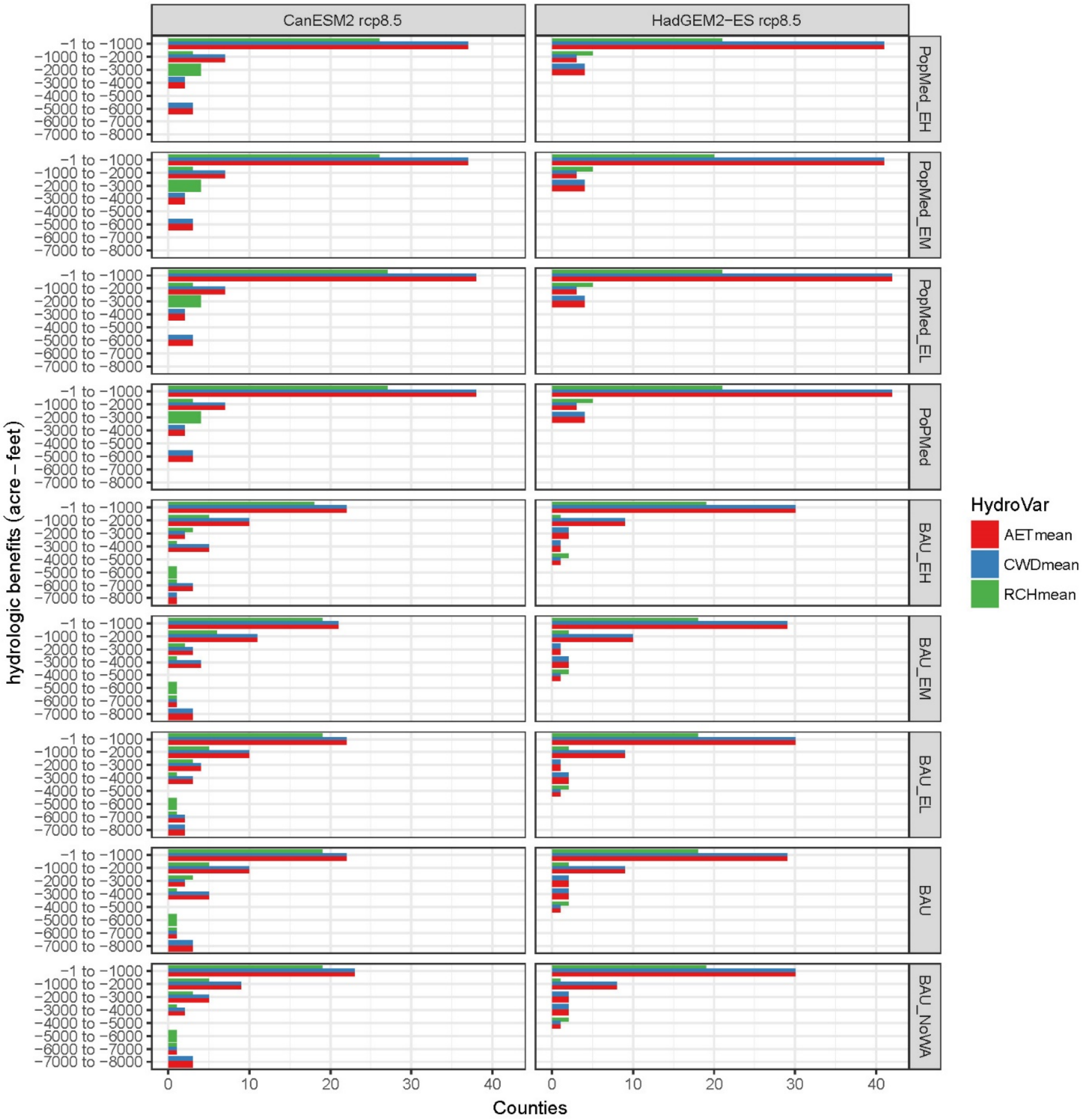

Figure D.1: For year 2100, two climates and nine scenarios, lost potential for hydrologic benefits on working lands from soil management alone, as a result of land conversion to development

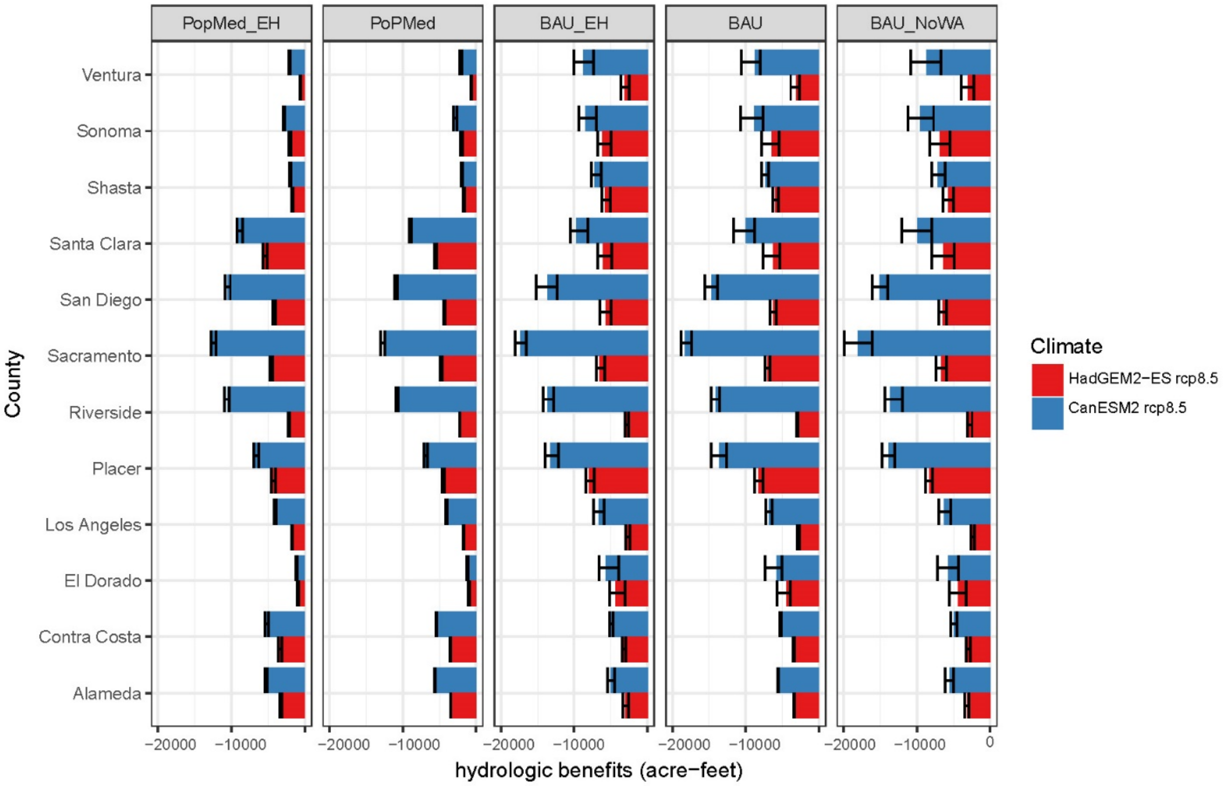

Figure D.2: For year 2100, top 12 counties where lost potential for hydrologic benefits (in acre-feet) due to development is highest. Values represent total average, with error bars representing minimum and maximum values based on 10 Monte Carlo iterations per scenario.

Table D.1: Working land area developed per scenario (acres) in 2050 and 2100. Values are based on 10 Monte Carlo iterations of land use change per scenario.

2050

Scenario	Area mean	Area min	Area max
PopMed_EH	1,988,548	2,001,530	1,978,941
PopMed_EM	1,993,129	2,000,432	1,983,462
PopMed_EL	1,993,936	1,999,153	1,980,814
PoPMed	1,996,115	2,004,845	1,990,128
BAU_EH	2,208,705	2,315,514	1,999,639
BAU_EM	2,172,297	2,288,295	2,058,112
BAU_EL	2,176,976	2,335,563	2,046,619
BAU	2,186,447	2,334,302	2,014,789
BAU_NoWA	2,159,520	2,300,904	1,780,463

2100

Scenario	Area mean	Area min	Area max
PopMed_EH	2,751,758	2,767,646	2,744,552
PopMed_EM	2,759,012	2,767,646	2,748,119
PopMed_EL	2,763,141	2,770,780	2,751,145
PoPMed	2,764,670	2,771,627	2,756,946
BAU_EH	4,330,937	4,595,702	4,007,330
BAU_EM	4,289,162	4,575,580	4,104,083
BAU_EL	4,272,607	4,387,533	4,123,124
BAU	4,359,597	4,560,034	4,221,822
BAU_NoWA	4,296,321	4,566,483	3,815,932

Table D.2: Potential average hydrologic benefits *lost* (acre-feet) on developed lands by scenario and climate in the year 2050 (top) and 2100 (bottom). Values are based on 10 Monte Carlo iterations.

2050 Scenario	Climate	RCHmean	AETmean	CWDmean	Total mean	Total min	Total max
PopMed_EH	HadGEM2-ES rcp8.5	-2,757	-12,354	-12,354	-27,465	-27,073	-27,599
PopMed_EM	HadGEM2-ES rcp8.5	-2,752	-12,440	-12,440	-27,631	-27,357	-27,972
PopMed_EL	HadGEM2-ES rcp8.5	-2,773	-12,483	-12,483	-27,739	-27,454	-27,934
PoPMed	HadGEM2-ES rcp8.5	-2,801	-12,534	-12,534	-27,868	-27,672	-28,111
BAU_EH	HadGEM2-ES rcp8.5	-3,610	-14,188	-14,188	-31,987	-28,270	-34,108
BAU_EM	HadGEM2-ES rcp8.5	-3,567	-14,001	-14,001	-31,570	-29,646	-34,101
BAU_EL	HadGEM2-ES rcp8.5	-3,564	-13,949	-13,949	-31,462	-28,636	-34,355
BAU	HadGEM2-ES rcp8.5	-3,544	-14,090	-14,090	-31,725	-27,568	-34,897
BAU_NoWA	HadGEM2-ES rcp8.5	-3,521	-13,642	-13,642	-30,804	-23,612	-34,102
PopMed_EH	CanESM2 rcp8.5	-839	-26,354	-26,354	-53,547	-52,742	-54,141
PopMed_EM	CanESM2 rcp8.5	-2,470	-26,519	-26,519	-55,509	-54,486	-56,246
PopMed_EL	CanESM2 rcp8.5	-4,096	-26,575	-26,575	-57,247	-56,523	-58,018
PoPMed	CanESM2 rcp8.5	-5,647	-26,645	-26,645	-58,936	-58,261	-59,715
BAU_EM	CanESM2 rcp8.5	-7,383	-29,179	-29,179	-65,742	-62,902	-69,518
BAU_EL	CanESM2 rcp8.5	-8,569	-29,075	-29,075	-66,720	-61,782	-70,376
BAU	CanESM2 rcp8.5	-10,851	-29,436	-29,436	-69,723	-63,350	-74,713
BAU_NoWA	CanESM2 rcp8.5	-9,667	-28,631	-28,631	-66,929	-54,924	-71,691

2100 Scenario	Climate	RCHmean	AETmean	CWDmean	TOTmean	TOTmin	TOTmax
PopMed_EH	HadGEM2-ES rcp8.5	-5,559	-22,195	-22,195	-49,949	-49,455	-50,453
PopMed_EM	HadGEM2-ES rcp8.5	-5,632	-22,497	-22,497	-50,626	-50,128	-50,975
PopMed_EL	HadGEM2-ES rcp8.5	-5,642	-22,641	-22,641	-50,924	-50,400	-51,209
PoPMed	HadGEM2-ES rcp8.5	-5,691	-22,817	-22,817	-51,324	-50,888	-51,558
BAU_EH	HadGEM2-ES rcp8.5	-10,407	-37,686	-37,686	-85,779	-77,620	-91,755
BAU_EM	HadGEM2-ES rcp8.5	-10,743	-37,976	-37,976	-86,696	-81,084	-95,162
BAU_EL	HadGEM2-ES rcp8.5	-10,497	-37,575	-37,575	-85,647	-82,362	-88,943
BAU	HadGEM2-ES rcp8.5	-10,766	-39,093	-39,093	-88,952	-83,887	-97,412
BAU_NoWA	HadGEM2-ES rcp8.5	-10,965	-37,751	-37,751	-86,468	-74,782	-95,798
PopMed_EH	CanESM2 rcp8.5	-16,695	-43,346	-43,346	-103,387	-102,738	-103,994
PopMed_EM	CanESM2 rcp8.5	-16,864	-43,769	-43,769	-104,401	-103,739	-104,901
PopMed_EL	CanESM2 rcp8.5	-16,910	-43,965	-43,965	-104,841	-104,118	-105,485
PoPMed	CanESM2 rcp8.5	-16,958	-44,240	-44,240	-105,438	-104,805	-105,983
BAU_EH	CanESM2 rcp8.5	-29,411	-71,319	-71,319	-172,048	-157,737	-181,933
BAU_EM	CanESM2 rcp8.5	-29,849	-71,549	-71,549	-172,947	-163,964	-187,252
BAU_EL	CanESM2 rcp8.5	-29,369	-71,026	-71,026	-171,420	-165,662	-177,329
BAU	CanESM2 rcp8.5	-30,280	-73,409	-73,409	-177,098	-168,595	-191,428
BAU_NoWA	CanESM2 rcp8.5	-30,416	-71,733	-71,733	-173,882	-152,375	-189,101

Table D.3: Overall hydrologic benefits (acre-feet) by scenario for all Williamson Act lands and easements combined, for the BAU and PopMED development projections. Values are based on 10 Monte Carlo iterations of easement locations.

2050 Scenario	Climate	RCHmean	AETmean	CWDmean	TOTmean	TOTmin	TOTmax
PopMed_EH	HadGEM2-ES rcp8.5	109,718	164,296	164,296	438,310	435,246	440,693
PopMed_EM	HadGEM2-ES rcp8.5	102,386	152,721	152,721	407,828	404,821	411,458
PopMed_EL	HadGEM2-ES rcp8.5	97,835	146,531	146,531	390,898	389,450	392,047
PoPMed	HadGEM2-ES rcp8.5	93,606	139,723	139,723	373,052	373,052	373,052
BAU_EH	HadGEM2-ES rcp8.5	109,250	164,390	164,390	438,030	432,357	441,144
BAU_EM	HadGEM2-ES rcp8.5	101,645	152,223	152,223	406,091	402,755	409,326
BAU_EL	HadGEM2-ES rcp8.5	98,102	146,366	146,366	390,835	389,145	393,059
BAU	HadGEM2-ES rcp8.5	93,606	139,723	139,723	373,052	373,052	373,052
PopMed_EH	CanESM2 rcp8.5	222,630	299,435	299,435	821,499	817,048	824,543
PopMed_EM	CanESM2 rcp8.5	209,065	282,036	282,036	773,137	769,521	778,083
PopMed_EL	CanESM2 rcp8.5	200,630	272,865	272,865	746,361	744,393	748,190
PoPMed	CanESM2 rcp8.5	192,981	262,925	262,925	718,830	718,830	718,830
BAU_EH	CanESM2 rcp8.5	221,936	299,458	299,458	820,853	813,538	825,454
BAU_EM	CanESM2 rcp8.5	207,499	281,459	281,459	770,416	766,380	774,670
BAU_EL	CanESM2 rcp8.5	201,090	272,737	272,737	746,563	743,137	749,269
BAU	CanESM2 rcp8.5	192,981	262,925	262,925	718,830	718,830	718,830

2100 Scenario	Climate	RCHmean	AETmean	CWDmean	TOTmean	TOTmin	TOTmax
PopMed_EH	HadGEM2-ES rcp8.5	137,437	228,267	228,267	593,971	589,714	596,584
PopMed_EM	HadGEM2-ES rcp8.5	128,409	213,097	213,097	554,603	550,946	558,965
PopMed_EL	HadGEM2-ES rcp8.5	122,873	204,879	204,879	532,631	530,936	534,066
PoPMed	HadGEM2-ES rcp8.5	117,724	195,931	195,931	509,587	509,587	509,587
BAU_EH	HadGEM2-ES rcp8.5	136,865	228,556	228,556	593,978	587,277	597,621
BAU_EM	HadGEM2-ES rcp8.5	127,419	212,397	212,397	552,212	548,750	555,778
BAU_EL	HadGEM2-ES rcp8.5	123,125	204,673	204,673	532,472	530,277	535,114
BAU	HadGEM2-ES rcp8.5	117,724	195,931	195,931	509,587	509,587	509,587
PopMed_EH	CanESM2 rcp8.5	234,027	378,942	378,942	991,911	987,279	995,942
PopMed_EM	CanESM2 rcp8.5	220,115	359,167	359,167	938,448	934,009	943,722
PopMed_EL	CanESM2 rcp8.5	211,524	348,512	348,512	908,548	906,520	910,356
PoPMed	CanESM2 rcp8.5	203,685	337,324	337,324	878,332	878,332	878,332
BAU_EH	CanESM2 rcp8.5	233,495	379,054	379,054	991,604	985,892	996,901
BAU_EM	CanESM2 rcp8.5	218,442	358,451	358,451	935,344	931,602	939,486
BAU_EL	CanESM2 rcp8.5	211,937	348,561	348,561	909,060	905,569	911,775
BAU	CanESM2 rcp8.5	203,685	337,324	337,324	878,332	878,332	878,332

Table D.4: Overall hydrologic benefits (acre-feet) and Williamson Act working land area (acres) for the Business as Usual scenario for 12 counties with highest hydrologic climate benefits, for two climate scenarios and years 2050 and 2100. “Water per acre” represents the ratio of total acre-feet of water to land area.

	Land Area (acres)	Aet	Cwd	Rch	Total water	Water per acre	Aet	Cwd	Rch	Total water	Water per acre
2050		**CanESM2 rcp8.5**					**HadGEM2-ES rcp8.5**				
Butte	150,218	6,046	6,046	8,395	20,487	0.14	3,587	3,587	4,064	11,239	0.07
Fresno	1,125,422	12,695	12,695	-807	24,584	0.02	5,864	5,864	-1,704	10,024	0.01
Glenn	360,117	6,706	6,706	9,693	23,105	0.06	4,115	4,115	3,089	11,318	0.03
Humboldt	136,456	75	75	27,379	27,528	0.20	57	57	21,200	21,314	0.16
Mendocino	210,889	6,936	6,936	14,133	28,005	0.13	6,801	6,801	9,205	22,807	0.11
Monterey	706,471	15,534	15,534	1,566	32,633	0.05	8,020	8,020	51	16,092	0.02
San Luis Obispo	728,340	18,558	18,558	3,475	40,591	0.06	8,190	8,190	694	17,074	0.02
Santa Barbara	456,366	13,195	13,195	6,487	32,877	0.07	7,663	7,663	1,788	17,114	0.04
Santa Clara	216,258	8,406	8,406	632	17,444	0.08	5,223	5,223	139	10,585	0.05
Shasta	161,495	4,192	4,192	28,733	37,117	0.23	3,076	3,076	20,280	26,431	0.16
Sonoma	172,195	4,707	4,707	10,765	20,179	0.12	4,353	4,353	5,378	14,084	0.08
Tehama	708,741	33,325	33,325	58,215	124,865	0.18	25,984	25,984	25,854	77,821	0.11
2100											
Butte	150,218	7,253	7,253	8,780	23,287	0.16	5,009	5,009	5,403	15,422	0.10
Fresno	1,125,422	16,203	16,203	968	33,373	0.03	8,233	8,233	-2,339	14,128	0.01
Glenn	360,117	8,266	8,266	12,178	28,710	0.08	5,961	5,961	5,225	17,146	0.05
Humboldt	136,456	265	265	22,891	23,420	0.17	139	139	25,018	25,296	0.19
Mendocino	210,889	8,972	8,972	12,252	30,196	0.14	8,915	8,915	11,667	29,496	0.14
Monterey	706,471	18,814	18,814	2,553	40,181	0.06	11,083	11,083	329	22,495	0.03
San Luis Obispo	728,340	23,478	23,478	4,849	51,805	0.07	11,734	11,734	814	24,283	0.03
Santa Barbara	456,366	15,929	15,929	7,612	39,471	0.09	10,490	10,490	4,575	25,555	0.06
Santa Clara	216,258	9,434	9,434	1,169	20,037	0.09	6,762	6,762	271	13,795	0.06
Shasta	161,495	4,016	4,016	25,868	33,900	0.21	3,808	3,808	23,142	30,758	0.19
Sonoma	172,195	6,359	6,359	10,508	23,225	0.13	5,762	5,762	7,619	19,144	0.11
Tehama	708,741	35,876	35,875	59,648	131,399	0.19	32,756	32,756	32,971	98,483	0.14

Table D.5: Total area of land (acres) per class across all future easements, for three Business as Usual easement scenarios at 2050. Mean, minimum and maximum land areas are based on 10 Monte Carlo iterations of easement locations per scenario.

	BAU_EL			**BAU_EM**			**BAU_EH**		
Class\Scenario	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**
annual ag	62,971	73,857	53,159	116,606	125,918	107,615	242,617	257,113	223,427
forest	161,859	178,356	153,173	313,291	329,944	288,926	622,487	664,949	569,583
grassland	166,489	182,337	154,506	322,396	348,408	302,797	644,273	674,875	613,735
perennial ag	38,366	45,215	33,380	83,390	96,213	69,498	167,332	179,923	156,848
shrubland	40,333	47,143	35,271	75,922	80,775	67,714	145,173	151,569	129,845
wetland	3,923	5,260	2,540	6,287	7,512	5,620	13,813	16,771	11,799

Table D.6: Area of protected working lands per scenario (acres), Williamson Act and easement lands combined, for eight conservation scenarios. Values for mean, min and max area are based on 10 Monte Carlo iterations of easement locations.

Scenario	Area mean	Area min	Area max
PopMed_EH	16,714,136	16,688,614	16,745,322
PopMed_EM	16,215,090	16,195,896	16,239,742
PopMed_EL	15,960,421	15,943,809	15,983,368
PoPMed	15,695,685	15,695,685	15,695,685
BAU_EH	16,715,579	16,671,897	16,733,487
BAU_EM	16,206,591	16,184,169	16,232,122
BAU_EL	15,967,843	15,951,519	15,979,711
BAU	15,695,685	15,695,685	15,695,685