Received: 9 March 2022 | Accepted: 20 May 2022

DOI: 10.1002/eap.2705

ECOLOGICAL APPLICATIONS
ECOLOGICAL SOCIETY OF AMERICA

ARTICLE

The climate change mitigation potential of annual grasslands under future climates

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Funding information
Betsy Taylor; California Climate Change 4th Assessment; California Coastal Conservancy; Lawrence Livermore National Laboratory, Grant/Award Number: DE-AC52-07NA27344; The Band Foundation; The Jena and Michael King Foundation; The Oak Creek Foundation; The Rathmann Family Foundation; The Trisons Foundation; The V.K. Rasmussen Foundation; US Department of Energy

Handling Editor: Hinsby Cadillo-Quiroz

Abstract

Composted manure and green waste amendments have been shown to increase net carbon (C) sequestration in rangeland soils and have been proposed as a means to help lower atmospheric CO_2 concentrations. However, the effect of climate change on soil organic C (SOC) stocks and greenhouse gas emissions in rangelands is not well understood, and the viability of climate change mitigation strategies under future conditions is even less certain. We used a process-based biogeochemical model (DayCent) at a daily time step to explore the long-term effects of potential future climate changes on C and greenhouse gas dynamics in annual grassland ecosystems. We then used the model to explore how the same ecosystems might respond to climate change following compost amendments to soils and determined the long-term viability of net SOC sequestration under changing climates. We simulated net primary productivity (NPP), SOC, and greenhouse gas fluxes across seven California annual grasslands with and without compost amendments. We drove the DayCent simulations with field data and with site-specific daily climate data from two Earth system models (CanESM2 and HadGEM-ES) and two representative concentration pathways (RCP4.5 and RCP8.5) through 2100. NPP and SOC stocks in unamended and amended ecosystems were surprisingly insensitive to projected climate changes. A one-time amendment of compost to rangeland acted as a slow-release organic fertilizer and increased NPP by up to 390–814 kg C ha^{-1} $year^{-1}$ across sites. The amendment effect on NPP was not sensitive to Earth system model or emissions scenario and endured through the end of the century. Net SOC sequestration amounted to 1.96 ± 0.02 Mg C ha^{-1} relative to unamended soils at the maximum amendment effect. Averaged across sites and scenarios, SOC sequestration peaked 22 ± 1 years after amendment and declined but remained positive throughout the century. Though compost stimulated nitrous oxide (N_2O) emissions, the cumulative net emissions (in CO_2 equivalents) due to compost were far less than the amount of SOC sequestered. Compost amendments resulted in a net climate benefit of 69.6 ± 0.5 Tg CO_2e 20 ± 1 years after amendment if applied to similar ecosystems across the state, amounting to 39% of California's rangeland. These results suggest that the biogeochemical benefits of a single amendment of compost to rangelands in California are insensitive to climate change and could contribute to decadal-scale climate change mitigation goals alongside emissions reductions.

KEYWORDS
California, CanESM2, carbon sequestration, compost, DayCent, HadGEM2-ES, nitrous oxide, RCP4.5, RCP8.5, soil organic carbon

INTRODUCTION

Rangelands are globally extensive, comprising 30%–50% of the world's ice-free land surface (Conant, 2012; White et al., 2000). These ecosystems generally occur in regions with periodic water deficits leading to high belowground allocation of biomass and the potential for carbon (C)-rich soils. Management has led to the loss of soil organic C (SOC) over time (Sanderman et al., 2016), making rangelands a key target for management improvements that could increase the movement of C from the atmosphere to the soil and replenish SOC stocks (Sanderson et al., 2020).

The large areal extent of rangelands means that changes in biogeochemical cycling in these systems due to climate change over the next century could have global-scale impacts. The effect of changing climate on C cycling in rangelands remains uncertain because shifts in soil moisture and temperature conditions could have simultaneous opposing and condition-dependent effects on biological C fluxes (Zhu et al., 2016). For example, warmer and wetter conditions could increase net primary productivity (NPP) and thereby C inputs (Wu et al., 2011). Warming could also stimulate microbial respiration and C outputs (Hicks Pries et al., 2017; Kirschbaum, 1995; Wu et al., 2011), or it could reduce soil moisture and thus slow belowground decomposition rates (Castanha et al., 2018). The balance between these fluxes is poorly understood. Furthermore, there is still uncertainty regarding how much the climate will change by the end of the century (Gershunov et al., 2019; Hartmann et al., 2013; Pierce et al., 2013), complicating the projection of ecosystem impacts.

Carbon sequestration in rangelands has been proposed as a mechanism to help mitigate climate change (Mayer et al., 2018; Smith et al., 2008; Soussana et al., 2010). Here we define SOC sequestration as the net additional organic C accumulated in soil (Jones & Donnelly, 2004). Compost amendments are one mechanism being explored to increase C sequestration in soils because they may increase the ratio of C inputs to C outputs. Carbon inputs to the soil in amended rangelands are greater than baseline inputs owing to both the direct addition of C in compost and the indirect addition of C due to enhanced primary productivity (Ryals & Silver, 2013). Nitrous oxide emissions from compost-amended soils can be greater than in unamended soils, although composting amendments prior to land application creates a slow-release fertilizer and tends to lower greenhouse gas emissions (i.e., N_2O) relative to uncomposted amendments. (Huang et al., 2006; Li et al., 2016; Lynch et al., 2006). Field research in California demonstrated that a single application of compost to grazed annual grassland soil significantly increased SOC sequestration over 1–3 years following the amendment (Ryals et al., 2014; Ryals & Silver, 2013; Silver et al., 2018). A modeling study at two annual grass rangeland sites demonstrated decadal-scale SOC sequestration following both single and multiple compost amendments, as well as amendments that differed in chemical composition (Ryals et al., 2015). A life cycle assessment of compost amendments to rangelands in California showed the feasibility of compost amendments to produce a net climate benefit, assuming compost was produced on the ranch it was applied to (∼5 km) and nonmanure materials were transported a standard distance of 20 km (DeLonge et al., 2013).

Questions remain about the long-term sensitivity of C cycling in these rangelands to climate change and about whether SOC sequestration following compost amendments will be resilient to potential future patterns in temperature and precipitation. The viability of SOC sequestration practices in a changing climate is debated (Bamminger et al., 2018; Dietzen et al., 2019; Luo et al., 2016) and often not accounted for in projections of SOC sequestration potential (Paustian et al., 2016; Smith et al., 2008). There is concern that warming will release vulnerable SOC back to the atmosphere (Crowther et al., 2016), negating the effect of C sequestration practices. Understanding how evolving environmental conditions could enhance or decrease SOC sequestration, and how these might vary by background environmental conditions, is important for determining the geographic scalability and the long-term suitability of these practices for climate change mitigation.

We used the DayCent biogeochemical model to explore long-term patterns in soil and plant C dynamics across annual grass-dominated rangelands in California under four projected future climates. We modeled ecosystem processes under current management (i.e., the background conditions) and following compost amendments. The aims of this study were to (1) elucidate the background effects of climate change on C cycling and greenhouse gas emissions across different rangeland bioclimatic zones, emissions scenarios, and climate models and (2) determine the spatial and temporal dynamics of ecosystem C and greenhouse gas fluxes following compost amendments to the same rangelands. We hypothesized that increased precipitation would drive SOC losses in a warmer world with greater proportional losses in drier regions, where we expected decomposition to outpace responses in NPP, at least initially. We hypothesized that compost amendments would increase both NPP and SOC storage at all sites and that compost amendments would buffer ecosystems from C losses in a changing climate due to enhanced inputs from NPP. We modeled the background condition and the effects of a single compost addition for 85 years to determine the timescale of climate change responses across sites.

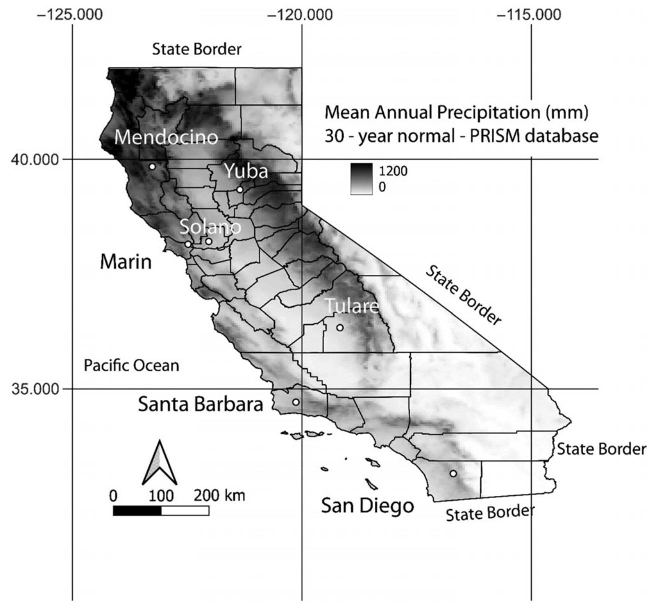

FIGURE 1 Map of rangeland sites analyzed in this study. Sites represent both coastal and inland ecosystems across a gradient of mean annual precipitation (1991–2020 year normal; PRISM Climate Group and Oregon State University, 2020). Sites are labeled by the county they represent, with counties delineated by black borders. All sites are within the state of California, which is bordered to the west by the Pacific Ocean (white).

METHODS

Site descriptions

We simulated biogeochemical cycling for seven grazed rangeland sites that were representative of a broad set of climates and geography within California's grassland ecosystems. These seven sites were part of a larger field experiment testing the effects of compost application on biogeochemical dynamics (Figure 1; Silver et al., 2018). The four coastal sites (Mendocino, Marin, Santa Barbara, and San Diego) and two inland sites (Solano and Yuba) fall within a generalized Mediterranean climate regime (cool, wet winters and warm, dry summers). The Tulare site had a semiarid climate regime (Kauffman, 2003). All sites were dominated by nonnative annual grass and forb species, typical of California annual grasslands (Heady, 1977). This is the dominant cover type in the region, which represents an important and expanding cover type in North America and globally (Bradley et al., 2006; Funk et al., 2016; Mack, 1989; Weber et al., 2008). Annual grasslands are less well studied and have a much shallower rooting system than deeply rooted perennial grasslands. Soil classifications according to the USDA included three Mollisols (Mendocino, Marin, Santa Barbara), three Alfisols (Solano, Yuba, San Diego), and one Inceptisol (Tulare). All sites were managed for cattle grazing for at least 100 years, with one hiatus in grazing of 14 to 20 years in the 1990s and 2000s at Yuba, Marin, Solano, and Tulare. Detailed site information, including grazing management and soil types, is given in Appendix S1 and Table 1.

Model description

The DayCent biogeochemical model (Parton et al., 1998) was used to simulate the effects of climate and management on C and greenhouse gas dynamics in each rangeland ecosystem. DayCent is a widely used and well-established complex process model, developed using ecological concepts of grassland soil C and nitrogen (N) dynamics (Parton et al., 1994). DayCent facilitates the simulation of explicit management practices, including grazing and compost amendments, and was originally developed and has been used extensively for modeling managed grassland and cropland ecosystems (Kelly et al., 2000; Parton et al., 1993; Parton et al., 1998; Ryals et al., 2015). The model is parameterized for initial conditions using site-specific historical climate data, annual NPP, and depth-specific measured values for soil texture and bulk density. The calibrated model provides a baseline from which the model can calculate trends with time and differences under changing conditions (e.g., climate and compost amendments in this study). DayCent partitions existing and added C into discrete soil pools based on estimated C turnover time: active (<1 year), slow (decadal), and passive (millennial). Dead plant material is partitioned into active or slow cycling pools initially, depending upon tissue chemistry (e.g., lignin:N ratio), using first-order kinetics. Carbon can move among pools through decomposition and stabilization. The movement among pools mimics microbial activity and the mineral association of organic matter; it includes a separate pool for microbial biomass, but DayCent does not explicitly model specific

TABLE 1 Characteristics of sites used to parameterize the model simulations, reported as mean values with standard errors (SE).

Site	Historic 30-years ANPP (Mg C ha^{-1} year^{-1}) Mean ± SE	Observed SOC 0–30 cm (Mg C ha^{-1}) Mean ± SE	Clay 0–30 cm (%) Mean ± SE	Sand 0–30 cm (%) Mean ± SE	Historic 30-year MAP (cm year^{-1})	Mean minimum daily temperature (°C)	Mean maximum daily temperature (°C)
Mendocino	0.8 ± 0.05	29.6 ± 4.2	15.6 ± 0.9	49.1 ± 3.0	108	4.6	22.3
Yuba	1.7 ± 0.1	22.3 ± 0.4	23.1 ± 1.3	38.6 ± 1.5	73	10.3	24.4
Solano	1.3 ± 0.05	23.8 ± 2.2	12.3 ± 0.8	56.5 ± 2.2	61	8.8	23.3
Marin	1.4 ± 0.05	40.9 ± 5.5	27.3 ± 0.9	44.1 ± 0.2	97	8.3	20
Tulare	1.2 ± 0.1	23.1 ± 1.1	10.2 ± 0.7	43.1 ± 2.6	28	10.8	24.1
Santa Barbara	1.8 ± 0.1	21.1 ± 0.1	8.8 ± 0.6	67.7 ± 0.4	38	8	25.1
San Diego	0.9 ± 0.1	15.0 ± 3.0	15.9 ± 0.6	66.1 ± 0.3	67	7.2	21

Abbreviations: ANPP, aboveground net primary productivity model output parameterized to reflect observations from ranchers; MAP, mean annual precipitation (1975–2005); SOC, soil organic carbon. Data are from Silver et al., 2018 (above) and local CalClim station data.

mechanisms of microbial interactions or mineral stabilization (Parton et al., 1994). Modeled SOC flows and NPP are both strongly dependent on soil water availability in DayCent, which has been shown to be an important driver of ecosystem C dynamics in grasslands (Burke et al., 1997; Harpole et al., 2007). The N gas submodel of DayCent uses a daily time step to simulate N_2O fluxes from nitrification and denitrification based on diffusivity parameters of soil (water-filled pore space, texture, bulk density, field capacity, temperature), pH, and soil NH_4^+ and NO_3^- concentrations (Parton et al., 2001). The grassland CH_4 oxidation submodel simulates methanotrophy at a daily time step as a function of soil water content, field capacity, porosity, and temperature (Del Grosso et al., 2000). DayCent also models soil respiration and microbial respiration of CO_2; here we report on total soil respiration, which is more comparable with field data.

Biogeochemical model inputs

Field observations of soil texture, total organic C, bulk density, and biomass production from pretreatment plots were used for the initial parameterization of the model for each site (Table 1). Total organic C was measured on five replicate soil cores along a transect at four depths down to 1 m or point of refusal. The point of refusal was below 1 m, except for a minority of cores in Mendocino, Marin, and Tulare, where the mean points of refusal were 95.7 ± 2.7, 92.2 ± 3.4, and 99.5 ± 0.5 cm, respectively. Soil texture was measured on three samples from each transect (first, third, and fifth core) from depths of 0 to 10 cm at each site. Soil texture data for soil depths of 10–100 cm were obtained from the SSURGO database (Soil Survey Staff et al., 2017). Bulk density samples were taken using a 6.35-cm-diameter metal corer at 10-cm-depth increments to 1 m or point of refusal from two soil pits per site. Aboveground NPP was measured by clipping vegetation at peak biomass from eight replicate 200 cm^2 subplots for both amended and unamended plots, oven drying at 65°C, and weighing; belowground NPP was measured in Marin and Yuba only by Ryals and Silver (2013). Soil subsamples were analyzed in duplicate for total C concentration at The University of California, Berkeley, on a Carlo Erba Elantech elemental analyzer (Lakewood, New Jersey, USA) using atropine as a standard at a rate of one per 10 samples. Samples were rerun if duplicates varied by more than 10%. Soils were tested for carbonates using 2M HCl; because no carbonates were found, the reported results reflect organic C concentrations. Bulk density was determined by calculating the rock volume and determining the oven-dry (105°C) mass of soil per unit volume. SOC stocks were calculated by multiplying the C concentrations (%) by the oven-dry mass of the fine fraction (<2 mm) and dividing by the bulk density and depth (Throop et al., 2012). Additional details can be found in Silver et al. (2018). Livestock effects on biomass and biogeochemical cycling were represented using scheduled time- and intensity-specific grazing events. Grazing management was simulated to reflect site-specific historic and current practices (Appendix S1: Site Descriptions).

Modeled climate conditions

Simulations of future conditions were driven by daily climate data from 2006 to 2100 extracted from the

CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK) Earth system models (ESMs). We chose not to simulate CO_2 fertilization in order to isolate the role of climate. There remains a debate as to which ESM most accurately represents future weather in California. We used CanESM2 and HadGEM2-ES because they yielded contrasting projections for future precipitation (see Figure 2). We used two Representative Concentration Pathway (RCP) scenarios: RCP4.5, which assumes some emissions reductions, and RCP8.5, which assumes business-as-usual societal behavior with minimal emissions reductions. We chose these two scenarios because California used RCP4.5 and RCP8.5 for emissions reduction targets in their 2018 assessment report (Franco et al., 2018). Data were extracted for the site-specific ($2.8° \times 2.8°$) geographical grid of CanESM2 and HadGEM2-ES.

A detailed presentation of modeled climate conditions is presented in Appendix S1. Briefly, future temperature increased at all sites in both climate models and the two scenarios, as expected (Appendix S1: Figure S1). There were no statistically significant differences between the two model outputs with regard to temperature, but there were effects of the different RCPs. For RCP8.5, the models predicted mean daily minimum temperatures would increase by 4.6°C (Tulare; HadGEM2-ES) to 5.8°C (Mendocino; HadGEM2-ES) and mean daily maximum temperatures would increase by 4.5°C (Mendocino; HadGEM2-ES) to 5.7°C (San Diego; HadGEM2-ES) by the end of the century. Under the reduced emissions scenario of RCP4.5, mean daily minimum temperature increased by 1.3°C (Mendocino; CanESM2) to 2.6°C (Mendocino; HadGEM2-ES), and mean daily maximum temperatures were limited to a 1.4°C (Mendocino; HadGEM2-ES) to 2.5°C (San Diego; HadGEM2-ES) increase, less than half of the warming seen in RCP8.5.

Predicted mean annual precipitation (MAP) at the seven sites was significantly different between the two ESM climate products over the 100-year period ($p < 0.001$, ANOVA), with generally greater MAP in the CanESM2 simulation than with HadGEM2-ES. Predicted MAP was significantly higher in RCP8.5 compared to RCP4.5 in the CanESM2 simulation ($p = 0.01$, ANOVA) (Figure 2). Mendocino and Tulare represented the wettest and driest extremes of sites, respectively ($p < 0.001$). Solano, Santa Barbara, and San Diego clustered among the drier end of the range, while Marin and Yuba were more mesic. Between the first and last decades of the century under RCP8.5, all sites saw a $28 \pm 7\%$ increase in precipitation under CanESM2, and six sites experienced a $22 \pm 7\%$ increase in precipitation under HadGEM2-ES. The only exception in the latter case was in Tulare, where MAP did not change significantly. Under RCP4.5, five sites (all but Marin and Solano) exhibited increased precipitation by $2 \pm 4\%$ with the CanESM2 output and a $6 \pm 5\%$ decrease in precipitation in all sites with HadGEM2-ES output. Further discussion of climate changes at the study sites can be found in Appendix S1.

DayCent model calibration and validation

The model simulations were run for an initial 3000-year period (e.g., spin-up) for each site using the measured soil parameters, extended historical daily climate data, and vegetation. This steady-state spin-up was used to initialize each of the subsequent model simulations beginning in the year 1800, assuming historical perennial grassland coverage until the approximate year of widespread annual grassland establishment in 1887 (Corbin & D'Antonio, 2004; Heady, 1977). The steady-state values for the SOC pools from 1-m profiles achieved from the spin-up runs were used as the baseline for each perturbation simulation, which began with the shift from perennial to annual grassland. Model parameters for annual grass water stress (wscoeff) and annual grass productivity (prdx) were adjusted so that the model output was within the range of observed annual NPP and within two standard deviations of bulk SOC stocks for each site under preamendment management conditions (Table 1). After parameterization, model results for NPP and SOC were validated using functional response metrics from the Marin and Yuba sites, including the relationship between NPP and MAP (Ryals Silver, 2013; Appendix S1: Figure S2), as well as SOC stocks in the slow cycling pool in DayCent, for which the occluded light fraction in density fractionated soils may provide a rough approximation (Ryals et al., 2014; Appendix S1: Figure S3). SOC at all seven sites was validated using data from the second year of the statewide field trial collected from 0 to 10 cm in 2017 and analyzed using the same methods as discussed earlier (Silver et al., 2022; Appendix S1: Figure S4). Nitrous oxide emissions simulated in the model were within one standard deviation of daily flux results from the Marin and Yuba sites, as reported in Ryals and Silver (2013) (Appendix S1: Figure S5).

For each ESM and climate scenario (four sets of climate data), we ran an unamended simulation assuming that current management continued throughout the century. We also ran an amendment simulation consisting of a one-time 6.4 mm. (0 addition of compost to the site. The compost was made from a mixture of green waste,

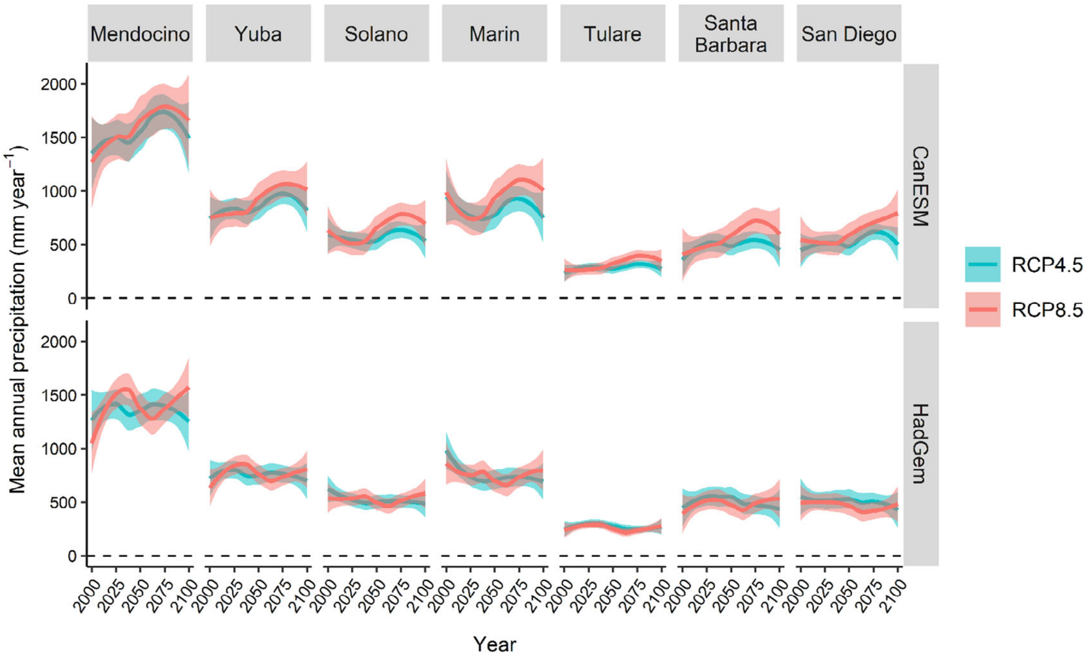

FIGURE 2 Projected mean annual precipitation (MAP) across each site. Lines are smoothed mean values using a generalized additive model for MAP in each emissions scenario, with colored bands representing 95% confidence intervals.

dairy manure, and livestock bedding typical for this region (Silver et al., 2018; Vergara & Silver, 2019) with a C:N ratio of 17.6, with a mean N concentration of 1.7%, a mean C concentration of 30%, and a mean lignin content of 40%. Further details on the chemistry of the compost can be found in appendix A of Silver et al. (2018). The compost amendment added C at a rate of 6.4 Mg C ha^{-1}, which replicated the application rate used in the field experiment (Silver et al., 2018) and was the rate recommended by rangeland managers. Nutrients from the compost amendment were prescribed to be allocated directly to the slow (decadal cycling) pool in DayCent due to the predecomposed state of compost. We traced the fate of the amendment in the model directly by simulating a ^{14}C label in the compost (Ryals et al., 2015). The baseline year for compost amendment was 2016 for all sites except for Marin and Yuba (baseline year 2008), which follows the actual field experiments conducted at all the sites.

DayCent model outputs and statistical analyses

We report ESM climate data for 100 years from 2000 to 2100 and results for soil and ecosystem C and greenhouse gas dynamics for an 85-year period from 2015 to 2100 for all sites except for Yuba and Marin, where we report the 85-year period 2008 (when compost was added) to 2093. We highlight the results for the year 2050 because a United Nations Special Report released by the Intergovernmental Panel on Climate Change (IPCC, 2018) projects 2045–2055 as the key period during which global anthropogenic emissions must reach net zero in order to avoid global warming of 1.5°C, a level of warming past which many ecological and social impacts and risks become more extreme. The year 2050 corresponds to 34 years after amendment for all sites except Yuba and Marin, where 2050 is 42 years after amendment. We explored the potential effects of climate change across the rangeland sites given current management (grazing only) as an unamended treatment and with compost application (grazing with compost treatment). Data analyses were conducted in R version 3.6.1 (R Core Team, 2019) using the stats, ggplot2, and plyr packages (R Core Team, 2019; Wickham, 2011, 2016). Owing to the high interannual variability typical of these ecosystems (Dettinger et al., 2011), we analyzed differences between mean NPP values of each decade from 2000 to 2100 to determine mean change over the century. The NPP data were smoothed for visualization using a generalized additive model, with colored bands representing 95% confidence intervals. General ANOVAs, including all predictor variables (global ANOVAs), were run on model data output from both the unamended and amended simulations to explore the relative differences within and across sites and over time. Variables that exhibited significant relationships within the global ANOVA were further tested using a pairwise *t*-test, with *p*-values adjusted using the Bonferroni method. For the compost amended soils, SOC and NPP results are reported as the relative difference between the compost-amended plot and the unamended plot at each site for each time point unless otherwise noted. Means, medians, and standard errors were calculated using the summarize function within the plyr package (Wickham, 2011).

To determine the net effect of compost amendments from DayCent simulations in terms of global warming potential (GWP), we calculated and compared the opposing responses of enhanced SOC and greenhouse gas emissions (N_2O and CH_4) in terms of the change in compost amended treatment relative to the unamended treatment. We converted the SOC sequestered into CO_2 equivalents (CO_2e) by assuming a 1:1 molar ratio and multiplying by the atomic mass ratio (44 g CO_2/12 g C). For N_2O and CH_4 we used the molar GWP ratios including climate feedbacks over 100 years of 298:1 and 34:1 (Myhre et al., 2014). We focus here specifically on soil C sequestration and thus do not include changes in vegetation biomass in the calculation of sequestration.

Upscaling exercise

We determined the potential impacts of compost amendments at a regional scale by applying results from each of the seven sites to its entire corresponding eco-subregion in California (Griffith et al., 2016). Taken together, the eco-subregion extent represented in this study accounted for 39% of California's rangeland area and 31 out of California's 58 counties (University of California Agriculture and Natural Resources, 2020). We included rangelands that are dominated by annual grasses in the understory, including grasslands, oak woodlands, and savannas. Results from each site were multiplied by the rangeland area within the same eco-subregion to calculate total climate benefit for each time period. We recognize that not all of the rangeland within these eco-subregions would be suitable for compost amendments, for a variety of reasons (e.g., access or landowner preference), so estimates should be considered as a first approximation of the potential area available in the state. It is also notable that ~61% of California's rangeland area was not represented climatically by the available field sites modeled in this study, so overall this upscaling exercise should be viewed as an estimate of only a subset of the statewide potential.

RESULTS

Climate model and scenario effects on unamended rangelands

Simulated NPP in the unamended rangeland soils were highly variable over space and time and differed significantly among sites ($p < 0.01$) and across decades ($p < 0.01$) (Appendix S1: Figure S6). There were no statistically significant main effects of ESM climate product or RCP scenario alone on predicted NPP, but NPP was impacted by interaction effects between ESM climate product and site ($p < 0.001$), decade and site ($p < 0.001$), and between site, ESM climate product, and decade ($p < 0.001$). Predicted annual NPP was similar in Marin and Solano, and Santa Barbara was similar to Yuba. Fluctuations in predicted annual NPP could be explained in part by modeled MAP (Appendix S1: Figure S7), especially in the drier sites of Tulare (adjusted $r^2 = 0.65$, $p < 0.001$) and Santa Barbara (adjusted $r^2 = 0.41$, $p < 0.001$). Modeled MAP was a significant but weak predictor of annual NPP in Solano (adjusted $r^2 = 0.31$, $p < 0.001$), Marin (adjusted $r^2 = 0.29$, $p < 0.001$), and San Diego (adjusted $r^2 = 0.27$, $p < 0.001$).

Total SOC in unamended soils varied over time by ESM climate product ($p = 0.06$), with HadGEM2-ES simulating $4.7 \pm 1.1\%$ greater mean total SOC stocks across all sites (0.6 Mg C ha^{-1} for RCP4.5 to 1.2 Mg C ha^{-1} for RCP8.5) relative to CanESM. Future SOC did not vary significantly by RCP scenario or decade. Total background SOC stocks were significantly different among all sites ($p < 0.001$) in the model, with the highest SOC stocks in Marin (38.8 ± 0.2 Mg C ha^{-1} in 2100) and the lowest stocks in San Diego (12.9 ± 0.2 Mg C ha^{-1} in 2100; Appendix S1: Figure S8). Modeled SOC was initialized to steady-state values under perennial grass vegetation until the simulated introduction of annual grasses in the 19th century, resulting in a long-term gradual decrease in SOC at all of the sites.

Average annual soil CO_2 emissions over the 85-year period ranged from 305 ± 9 mg CO_2-C g^{-1} $year^{-1}$ in San Diego to 1026 ± 11 mg CO_2-C g^{-1} $year^{-1}$ in Yuba; site was a significant predictor ($p < 0.001$) of modeled soil CO_2 flux. Of the total soil respiration, $20 \pm 1\%$ was heterotrophic respiration. Soil respiration was positively correlated with annual NPP (adjusted $r^2 = 0.55$, $p < 0.001$). Interannual variation in CO_2 emissions was greater than any mean site level trend in the model runs.

Mendocino had significantly higher N_2O fluxes ($p < 0.001$) compared to all other sites, with 79% greater mean annual emissions than the next highest site (Santa Barbara), and 276% higher emissions than Tulare, the site with the lowest emissions (Appendix S1:

Figure S9). Mean annual N_2O emissions for all sites were 21% higher in CanESM2 compared to HadGEM2-ES ($p < 0.001$; Appendix S1: Figure S10) and did not vary significantly across decades. Site was also a significant predictor of baseline CH_4 oxidation ($p < 0.001$), with the highest mean rate of CH_4 oxidation in Santa Barbara (0.46 ± 0.002 g CH_4-C m^{-2} $year^{-1}$) and the lowest rates of CH_4 oxidation in Yuba (0.15 ± 0.001 g CH_4-C m^{-2} $year^{-1}$). There were no effects of climate model or RCP scenario on CH_4 oxidation rates.

Climate model and scenario effects on compost-amended rangelands

A single addition of compost significantly increased modeled NPP compared to unamended rangelands ($p < 0.001$) across all sites and scenarios (Figure 3). The higher NPP in the compost amended rangelands persisted through the end of the century (85 years), with decadal NPP significantly higher in all decades after 2000 ($p < 0.001$) or the first full decade following amendment. Annual NPP was highly variable across sites; NPP peaked from 13 years (Solano, HadGEM2-ES, RCP4.5) to 47 years (Tulare, CanESM2, RCP8.5) after the single compost application. The mean effect on NPP, averaging across all sites and climate scenarios from both ESMs, peaked 26 ± 2 years after amendment with a mean maximum increase of 56.5 ± 2.0 g C m^{-2} $year^{-1}$ relative to unamended rangelands. Individual site peaks had maximum increases in NPP ranging from 39.0 g C m^{-2} $year^{-1}$ at the Marin site 16 years after amendment (HadGEM2-ES, RCP4.5) to 81.4 g C m^{-2} $year^{-1}$ at the Yuba site 16 years after amendment (HadGEM2-ES, RCP8.5). In 2050 the compost-amended plots had an average of 37.7 ± 2.8 g C m^{-2} $year^{-1}$ more NPP than unamended plots, and 85 years after amendment, Tulare and Santa Barbara had the greatest relative increases in NPP, with the mean difference across ESM climate products and scenarios of 30.8 ± 3.7 and 30.5 ± 2.7 g C m^{-2}, respectively. Compost amendment effects on NPP and other variables are summarized in Tables 2 and 3.

The addition of compost provided a direct, immediate pulse of organic C to the soil. The stimulation of NPP

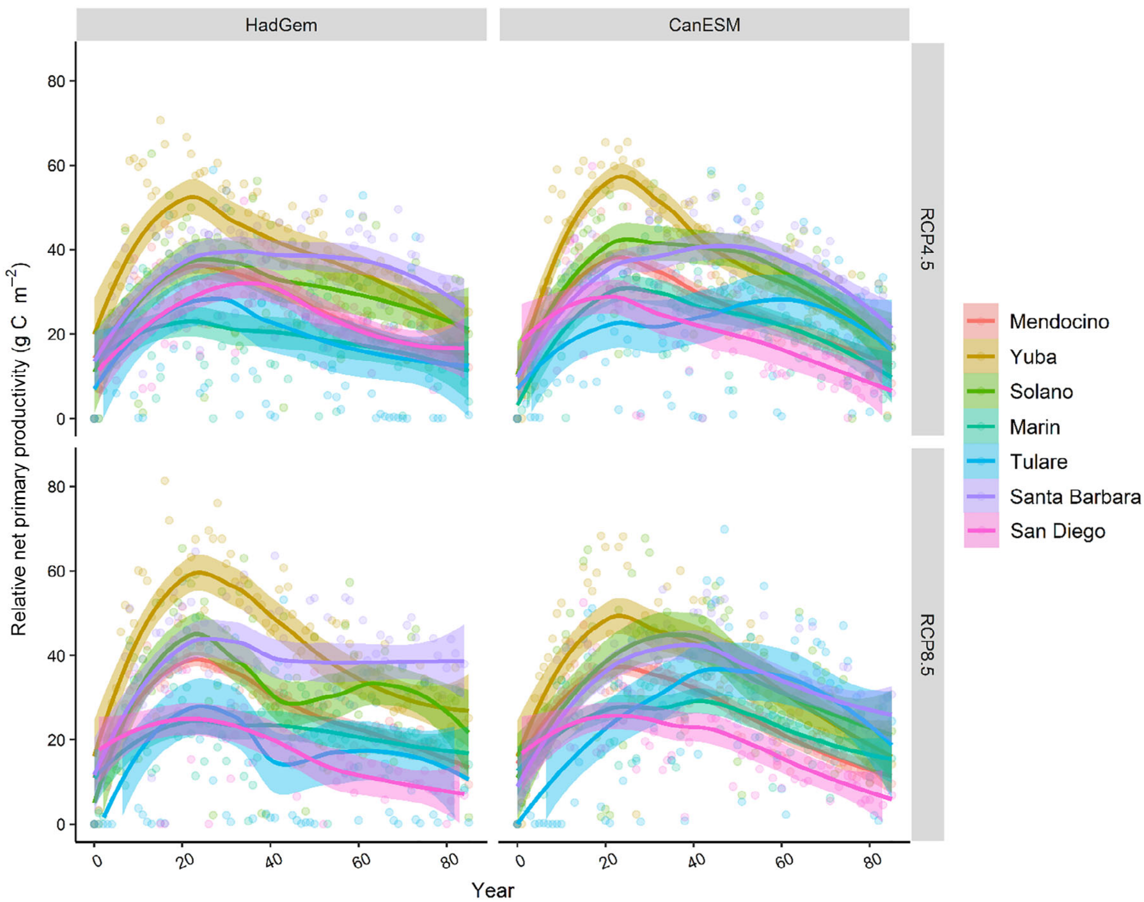

FIGURE 3 Relative (compost amended–unamended) net primary production (NPP) over time for both modeled climate projections and scenarios. Simulated differences for each year are represented by points. For visual clarity, lines are smoothed mean values using a generalized additive model for NPP at each site, with colored bands representing 95% confidence intervals.

after compost amendments provided a multidecade indirect effect on SOC sequestration. We estimated the indirect effects of compost amendment by differentiating the accumulation of new, plant-derived C from the simulated ^{14}C-labled compost C. The new, plant-derived C increased for the first 58 ± 2 years after amendment, peaking at a mean of 85.4 ± 3.6 g C m^{-2} of new C to the soil when averaged across sites. Though the Santa Barbara site continued to accumulate unlabeled C, the mean across sites of cumulative unlabeled C decreased after 59 years, resulting in an average increase across sites of 68.0 ± 4.5 g C m^{-2} in the 85th year after amendment. The amount of unlabeled SOC gained by 2050 in the compost amended soils was 62.8 ± 3.1 g C m^{-2} and ranged from 40.0 g C m^{-2} in Tulare (HadGEM2-ES, RCP8.5) to 99.0 g C m^{-2} in Yuba (HadGEM2-ES and RCP8.5) (Figure 4). Retention of the original labeled compost amendment was inversely related to annual precipitation over 22, 50, and 85 years ($r^2 = 0.16, 0.37, 0.17$ and $p < 0.05$, 0.001, 0.05 for the three respective time points) and clay concentrations (note that annual precipitation and clay concentration are correlated for these sites). The amendment effect on SOC was significant each decade from the year of addition through the end of the century ($p < 0.001$; Figure 5). The mean compost amendment effect was greater in RCP4.5 compared to RCP8.5 ($p < 0.05$) and had a greater range across sites for RCP8.5. The enhanced SOC sequestration in RCP4.5 was 14.6 ± 1.9 g C m^{-2} greater than RCP8.5 in the CanESM2 simulations in 2050. There was also a pronounced difference for the HadGEM2-ES simulation in San Diego and Mendocino, though not at the other sites (Appendix S1: Figure S11).

The total compost amendment effect increased mean annual SOC stocks relative to unamended soils until 20 years post amendment, with peaks ranging from 13 years (Yuba, CanESM2, both RCPs) to 40 years (Tulare, HadGEM2-ES RCP8.5) after amendment. At the peak effect of 22 ± 1 years after amendment, a single compost addition increased mean cumulative SOC relative to unamended soils by 195.6 ± 2.1 g C m^{-2} averaged across all sites and scenarios. By the year 2050, relative cumulative SOC ranged from 114.9 g C m^{-2} (Marin,

TABLE 2 Mean amendment effects averaged across all sites, Earth system models (ESMs) and scenarios.

Amendment effect	Years after amendment	SE	Mean effect	SE	Unit
NPP Peak	26	±2	0.56	±0.02	Mg C ha^{-1}
SOC Peak	22	±1	1.96	±0.02	Mg C ha^{-1}
CO_2 Peak	32	±4	1.13	±0.05	Mg CO_2-C ha^{-1}
Cumulative N_2O and CH_4	85		1.30	±0.08	Mg CO_2e ha^{-1}

Abbreviations: NPP, net primary productivity; SE, standard error; SOC, soil organic carbon.

TABLE 3 Mean amendment effects of a single compost amendment ($n = 7$ sites).

		Amendment effect on NPP (Mg C ha^{-1} $year^{-1}$)		Amendment effect on SOC (Mg C ha^{-1})		Amendment effect on soil respiration (Mg CO_2-C ha^{-1})		Amendment effect on cumulative N_2O and CH_4 (Mg CO_2e ha^{-1})		Amendment effect on net climate benefit (Mg CO_2e ha^{-1})	
Scenario	ESM	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
2050											
RCP4.5	HadGEM-ES	0.40	0.03	1.65	0.12	0.42	0.07	0.58	0.09	5.5	0.5
	CanESM2	0.28	0.07	1.70	0.12	0.60	0.10	0.66	0.11	5.6	0.5
RCP8.5	HadGEM-ES	0.44	0.06	1.58	0.12	0.64	0.07	0.65	0.10	5.1	0.5
	CanESM2	0.39	0.05	1.55	0.13	0.63	0.06	0.68	0.11	5.0	0.5
2100											
RCP4.5	HadGEM-ES	0.23	0.03	0.92	0.13	0.55	0.13	1.19	0.13	2.2	0.5
	CanESM2	0.23	0.03	0.86	0.14	0.38	0.06	1.39	0.17	1.8	0.6
RCP8.5	HadGEM-ES	0.23	0.04	0.84	0.13	0.30	0.06	1.30	0.14	1.8	0.5
	CanESM2	0.19	0.03	0.72	0.12	0.33	0.07	1.45	0.16	1.2	0.5

Abbreviations: ESM, Earth system model; NPP, net primary productivity; SE, standard error; SOC, soil organic carbon.

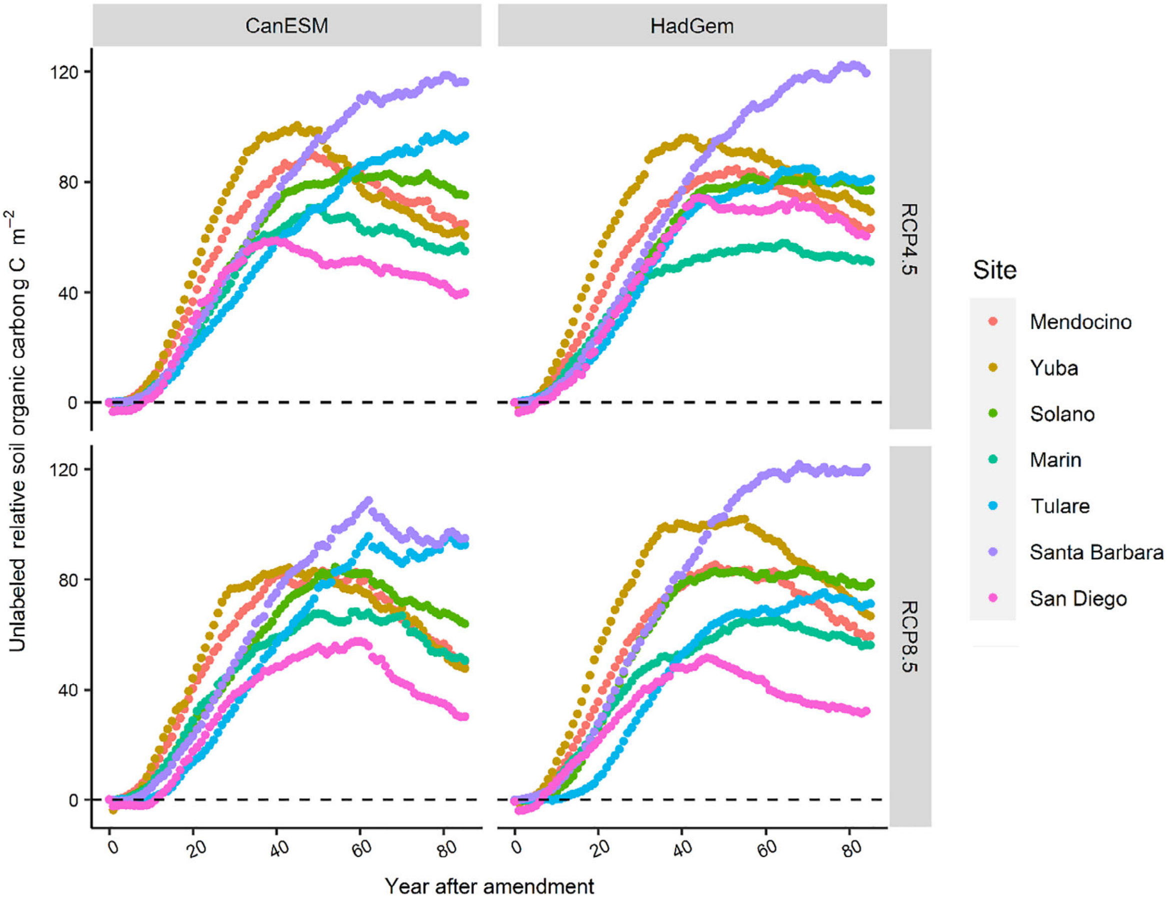

FIGURE 4 Relative (compost amended–unamended) unlabeled soil organic carbon (SOC) over time at each site for both models and scenarios. Data exclude any C added directly through the compost amendment. CanESM and HadGem refer to Earth System Model climate products CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK).

HadGEM2-ES RCP8.5) to 211.3 g C m^{-2} (Tulare, CanESM RCP4.5). The SOC effect within the northern sites (Mendocino, Yuba, Solano, Marin) were not distinct from one another and were lower than the other sites ($p < 0.05$). The relative increase in SOC stocks was greatest and persisted the longest in Santa Barbara and Tulare.

Compost amendments stimulated CO_2 emissions across all sites ($p < 0.001$). For RCP8.5, CanESM2 simulations in 2100 had higher rates of CO_2 emissions than the HadGEM2-ES simulations in the same year, when temperature and precipitation differences were most pronounced (means of 32.7 ± 3.0 and 28.4 ± 6.6 g CO_2-C m^{-2} year^{-1}, respectively). However, soil respiration did not differ significantly between scenarios or ESM climate products when the whole data set was considered. Amendment-induced soil respiration in the later decades was significantly different from the first two decades of the century by 24.0 to 48.5 g CO_2-C m^{-2} year^{-1} in RCP4.5 and 19.6 to 48.7 g CO_2-C m^{-2} year^{-1} in RCP8.5 ($p < 0.001$). The mean amendment effect on CO_2 emissions peaked at 32 ± 4 years post amendment across all sites and scenarios, with a mean maximum amendment effect of 112.9 ± 4.8 g CO_2-C m^{-2} year^{-1}.

Annual N_2O emissions also increased significantly in the compost-amended rangelands compared to the unamended fields ($p < 0.001$). The relative difference in N_2O emissions was twice as high in Mendocino as the next highest site, with emissions of 0.02 g N_2O-N m^{-2} year^{-1} after 9 years (RCP8.5) or 21 years (RCP4.5) post amendment (CanESM2; Figure 6). In contrast, emissions increased as little as 0.005 g N_2O-N m^{-2} year^{-1} in Tulare (70 years post amendment) and Solano (12 years post amendment). CanESM2 projections yielded higher N_2O emissions than the drier HadGEM2-ES projection ($p < 0.001$) and neither of which showed a significant difference overall between N_2O emissions in RCP4.5 and RCP8.5. We observed no significant amendment effects on CH_4 fluxes.

We estimated the net climate benefit of compost amendments by accounting for the changes in SOC sequestration and greenhouse gas emissions over time. Because emissions continued to accumulate while SOC accumulation slowed, the climate benefit decreased over time, though it remained positive. In 2050 the relative climate

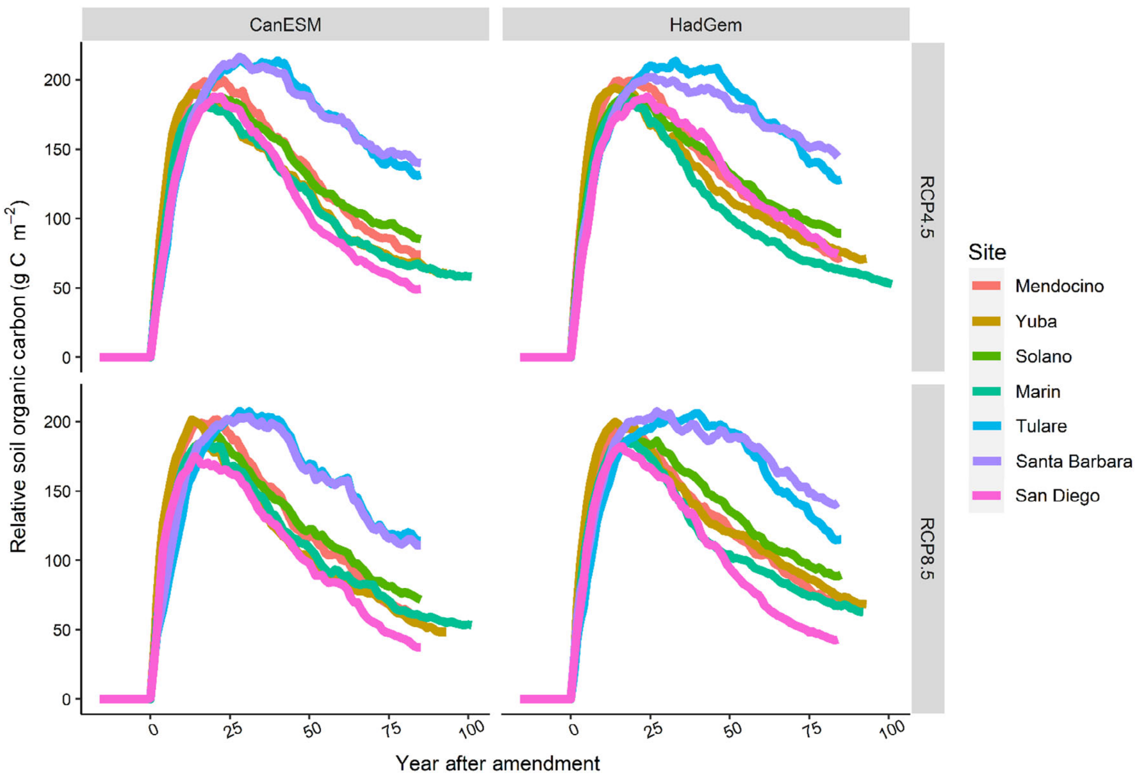

FIGURE 5 Relative (compost amended–unamended) total soil organic carbon (SOC) over time for both models and scenarios. RCP refers to Representative Concentration Pathway and CanESM and HadGEM refer to Earth System Model climate products CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK).

benefit was between 5.0 ± 0.5 Mg CO_2e ha^{-1} (CanESM2; RCP8.5) and 5.6 ± 0.5 Mg CO_2e ha^{-1} (CanESM2; RCP4.5; Figure 7a). The mean peak benefit across sites and scenarios was 6.9 ± 0.1 Mg CO_2e ha^{-1} and occurred at 20 ± 1 years after amendment (Figure 7b).

Scaling up to region

Rangelands in the eco-subregions represented by the seven sites simulated here accounted for 30 counties and 39% of the rangeland area in California. Applying a single compost amendment to the rangeland area in the eco-subregions represented by the field samples resulted in a peak climate benefit of 69.6 ± 0.5 Tg CO_2e by 20 ± 1 years after amendment and 57.1 ± 1.5 Tg CO_2e climate benefit for California by 2050 (Table 4).

DISCUSSION

Effects of projected climate changes on unamended annual grass rangelands

Simulated NPP in unamended annual grasslands was surprisingly insensitive to future climate at these sites, regardless of the climate scenario used. The lack of sensitivity of rangeland plant growth to future climate change may be due to the high background variability of NPP typical of these ecosystems, which is driven by high interannual variability in precipitation (Becchetti et al., 2016). The insensitivity of NPP at these sites contrasts to the work of Sleeter et al. (2019), who suggested that total NPP in California was likely to be differentially sensitive to CanESM2 versus HadGEM2-ES projections and particularly sensitive to the differences in predicted precipitation. Though we found a weak correlation with rainfall and simulated NPP, there was no trend over time. A greenhouse study of California annual grass species suggested that increased precipitation enhanced biomass production in dry and mesic sites, but not under conditions of higher background rainfall (between 1000 and 1250 mm) (St Clair et al., 2009), which might explain a lower response at the Mendocino site but not the lack of response elsewhere. A long-term multivariate field experiment on a California annual grassland similarly showed that NPP had a positive response to both warming and increasingly greater annual precipitation up to a threshold, but the NPP response decreased in very wet and in very warm conditions (Zhu et al., 2016). The interannual variability in precipitation can thus have differential effects on NPP response, highlighting the difficulty in

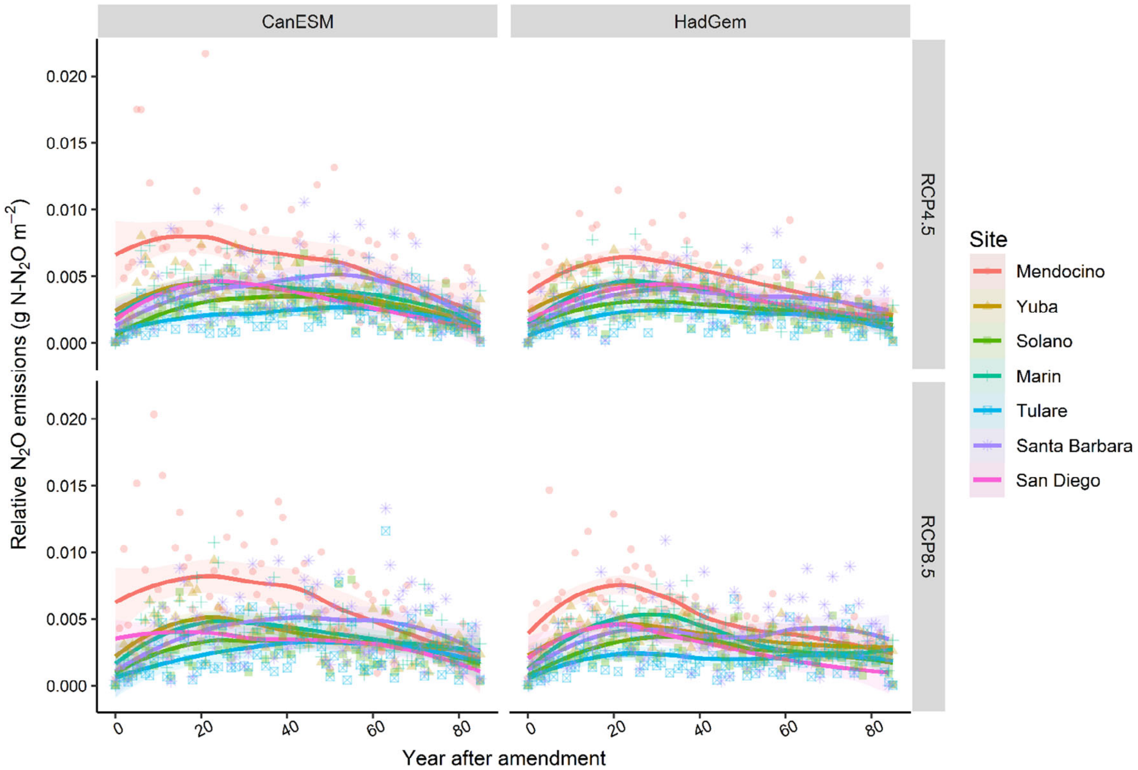

FIGURE 6 Relative (compost amended–unamended) treatment effect on annual N_2O emissions over time for both models and scenarios. Different point types and line colors represent different sites. Lines are smoothed mean values using a generalized additive model for annual N_2O at each site, with transparent colored bands representing 95% confidence intervals. RCP refers to Representative Concentration Pathway and CanESM and HadGEM refer to Earth System Model climate products CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK).

projecting future patterns in rangeland NPP and subsequent SOC stocks in relation to climate change.

SOC stocks, while different among sites, were also surprisingly unaffected by climate change in the unamended rangelands, and the SOC stocks were over two and a half times larger in the mesic Marin grasslands relative to the more arid annual grasslands in San Diego. Climate, soil type, and management history likely contributed to the significantly different baseline SOC stocks measured and simulated across sites, with variability slightly lower than expected based on a survey of California rangeland SOC stocks (Silver et al., 2010). The HadGEM2-ES model resulted in slightly larger SOC pools, possibly due to decreased total soil respiration under drier conditions. The lack of a temporal trend in SOC stocks with climate change was surprising and likely due to the lack of a trend in NPP. The DayCent model links SOC to NPP via transfer of C and N from vegetation to soil (Parton et al., 1987). Thus, the lack of a significant trend in NPP likely contributed to the lack of pattern in SOC pools. This lack of response in SOC stocks to warming could also result if the relative temperature sensitivities of decomposition and NPP maintain existing SOC stocks. Previous work in perennial grasslands suggested that soil systems acclimatize quickly to warming and decrease respiration, contributing to climate-resilient SOC stocks (Luo et al., 2001). At all sites, the gradual background loss of SOC was a result of decreasing residual SOC derived from historic perennial grasslands following the invasion of annual grasses in California in the late 1800s, as reported by others (Chou et al., 2008; Ryals et al., 2015).

Both soil CO_2 and N_2O emissions were correlated with temperature and precipitation in annual grass-dominated rangelands. In contrast to the Mediterranean rangelands within this study, a global-scale synthesis across climate types found that soil characteristics, such as texture, drainage, and original SOC content, rather than climate, predicted soil N_2O emissions (Stehfest & Bouwman, 2006). The DayCent model simulates higher N_2O production from denitrification in soils when soil has high water-filled pore space (Parton et al., 1996), suggesting that sites with more precipitation events would more frequently experience conditions conducive to N_2O production. Thus, Mendocino, the wettest site, had the greatest N_2O emissions, and Tulare (the driest site) had the least. Greenhouse gas emissions from these sites were not affected by the climate changes over times as expressed by climate model or anthropogenic emissions scenarios. Higher MAP projected in the CanESM2 model similarly resulted in higher N_2O emissions overall than projections from the drier HadGEM2-ES model, but we did not detect patterns over time in unamended rangelands.

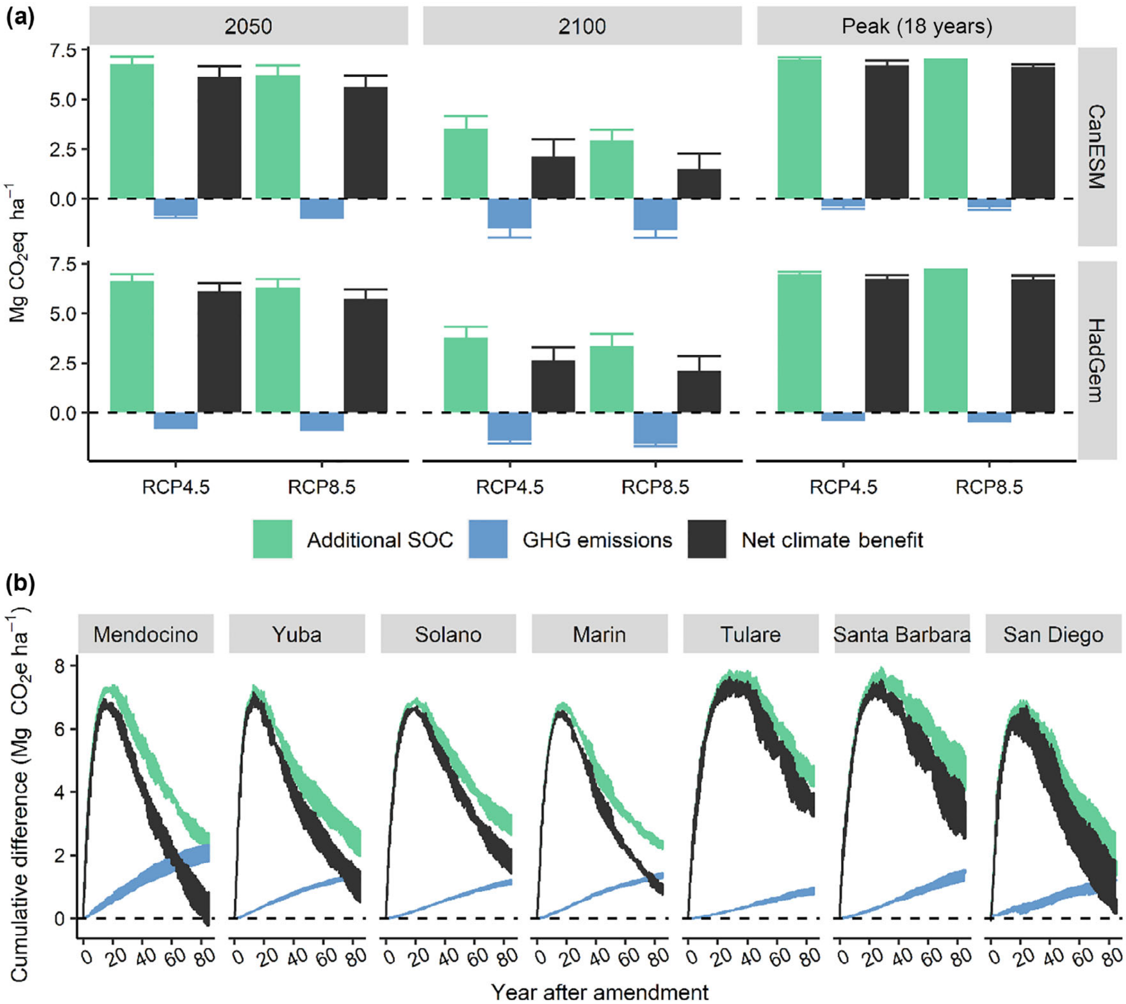

FIGURE 7 (a) Range of minimum and maximum values for relative (compost amended–unamended) soil organic carbon (SOC) (green), cumulative greenhouse gas emissions (blue), and the difference between the two as the net climate benefit (black) across both models and scenarios. Results shown were based on the four results for each site: CanESM2, HadGEM2-ES, each with RCP4.5 and RCP8.5 scenarios. (b) Bars indicate time-specific C balance at peak net C benefit (18 years after amendment at each site) in 2050 and in 2100. All values were converted to units of CO_2 equivalents for comparison. Emissions values (blue) represent a release of C from soil to atmosphere and are shown as negative values in plot (a) and absolute values in plot (b). Positive values in green and black indicate an uptake of SOC relative to unamended soil. RCP refers to Representative Concentration Pathway and CanESM and HadGEM refer to Earth System Model climate products CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK).

TABLE 4 Climate benefit (soil organic carbon sequestered minus N_2O and CH_4 emissions) of amendment scaled to representative regions, which together represent a total of 30 counties and 39% of California rangeland.

Time horizon	Area rangeland (Mha)	RCP4.5 CanESM2 (Tg CO_2e)	RCP4.5 HadGEM-ES (Tg CO_2e)	RCP8.5 CanESM2 (Tg CO_2e)	RCP8.5 HadGEM-ES (Tg CO_2e)
Total sequestered at peak effect	9.852	71	69	70	69
Total sequestered by 2050	9.852	61	57	56	54
Total sequestered by 2100	9.852	25	28	19	23

Abbreviation: RCP, Representative Concentration Pathway. CanESM and HadGEM refer to Earth System Model climate products CanESM2 (Canadian Centre for Climate Modeling and Analysis, Canada) and HadGEM2-ES (Met Office Hadley Centre, UK).

Effects of climate change on rangeland biogeochemistry following compost amendments

A single compost amendment acted as a slow-release organic fertilizer, which increased NPP relative to unamended soil across all sites and had an effect that endured through the end of the century. The peak increase in NPP ranged from an average of 390 to 814 kg C ha^{-1} $year^{-1}$. This level of biomass increase can be significant for ranchers, reducing the need for supplemental forage as well as the use of N-rich manure amendments or inorganic fertilizers. The pattern in NPP increase over time was nonlinear, with the greatest mean effects occurring by year 26 ± 2. DayCent may have underestimated the positive effect of compost on NPP. Ryals and Silver (2013) added twice the amount of compost as simulated here (0.5 in. vs. 0.25 in. or 12.7 mm vs. 6.4 mm) at the Marin and Yuba field sites but measured NPP that was 2.8 to 12.7 times higher than simulated for the Marin and Yuba sites over 3 years. This underestimation, in combination with the cascade of effects that NPP has on SOC and respiration, suggests that the results presented in this study may be a conservative estimate of the effect of compost in the field. The suite of climate scenarios and models used here did not have differential effects on NPP, likely due to the high variation of NPP interannually and among sites. We note that continued future emissions would likely lead to CO_2 fertilization, which could potentially further enhance NPP assuming sufficient water and nutrient availability (Dieleman et al., 2012). We chose not to simulate CO_2 fertilization in this study in order to isolate the effects of climate. DayCent does not account for the potential impact of increased soil moisture from the additional organic matter (Flint et al., 2018), which may further enhance productivity and SOC inputs in the field and support higher soil respiration rates. Added SOC sequestration in subsurface soil (below 1 m in this case) was not explored in this study but is also likely to be important over the long term (Tautges et al., 2019).

The compost amendments resulted in significant and enduring SOC sequestration. The amendment effect increased for two decades following additions, resulting in a maximum increase of 1.64–2.09 Mg C ha^{-1} relative to unamended rangelands. Though the compost effect gradually decreased after a mean of 22 ± 1 years, the total net sequestration effect remained positive through 2100. Long-term field studies that monitored the effects of a one-time organic amendment on a range of soil types and climates including Mediterranean and semiarid Alfisols confirmed sustained soil organic matter improvement after 15 years or more (Bastida et al., 2008; Diacono & Montemurro, 2010; García-Gil et al., 2004; Kätterer et al., 2014). The source of additional SOC shifted quickly from direct inputs from the compost amendment to indirect inputs from enhanced NPP. In DayCent, the rate of enhanced SOC storage depended on (1) the decomposition rate of the original material added and (2) the rate of increase in photosynthetic C uptake due to compost "fertilization." By 2100, the majority of the original compost amendment C had been respired, and 83% of the additional SOC sequestered in the compost-treated plots was due to enhanced NPP rather than protected or processed C added directly through the amendment.

In contrast to our hypothesis, a greater proportion of the original compost amendment was retained in drier sites, likely due to the greater water limitation of microbial decomposition. The amendment effect on SOC peaked on average 5 years after the peak in NPP, signaling a lag in the incorporation of C from plant biomass into SOC and the importance of higher NPP as an input of organic C to soil. Based on these results, we hypothesize that reapplying compost to soils once NPP peaks and begins to decline would likely strengthen the potential climate change mitigation benefit of the amended soil by prolonging the period of increased SOC sequestration. A previous analysis with DayCent at the Marin site showed that compost with the lowest C:N ratio, when applied annually rather than at a single time point, had the greatest climate benefit with regard to the balance of increased SOC and N_2O emissions. This suggested that rangelands are likely sensitive to both the quantity and quality of organic amendment (Ryals et al., 2015).

SOC sequestration was greater for RCP4.5 than RCP8.5 in the CanESM2 model results. Simulations driven by CanESM2 data had an average of 135 ± 7 kg C ha^{-1} more SOC sequestration in the reduced emissions scenario (RCP4.5) compared to the high emissions scenario (RCP8.5) at 22 ± 1 years, the maximum amendment effect ($p < 0.05$). Thus, global anthropogenic emissions reduction combined with SOC sequestration is a more powerful tool for climate change mitigation than SOC sequestration alone. The potential to maximize the climate change mitigation of improved agricultural management practices by combining SOC sequestration with simultaneous emissions reductions has been shown numerically at a global scale (Mayer et al., 2018).

Compost amendments stimulated CO_2 and N_2O emissions in the model, but not enough to outweigh the climate benefits of greater SOC sequestration. The net 100-year GWP of sites with composted amendments showed an overall climate benefit. Emissions of both CO_2 and N_2O are long-lived in the atmosphere, so the 20-year GWPs of compost amendment emissions are slightly lower than the 100-year GWP, making the overall climate benefit from a 100-year GWP reported here a more conservative estimate of climate benefit. This resulting climate benefit is consistent with the findings of a 3-year field study that measured a net C sink from a one-time compost amendment, even after omitting C gained directly from the compost amendment (Ryals et al., 2014). It is noteworthy that the field study did not detect a significant increase in N_2O emissions following compost applications at the Yuba and Marin sites (Ryals & Silver, 2013), suggesting that the model may be overestimating the N_2O emissions rates following compost amendments (Ryals et al., 2015). The continued climate benefit over time and across sites distinguished the use of a one-time compost amendment from continuous manure amendments: Though manure acted as a fertilizer and initially increased SOC stocks, the C sink declined within a few decades and later became a large net source (1.45 ± 0.52 CO_2e) to the atmosphere when accounting for N_2O emissions (Owen et al., 2015). The use of compost as a slow-release fertilizer likely lowers denitrification to N_2O and positions this practice as a climate-beneficial management strategy. One estimate suggested that composted soil amendments might contribute up to 9% of the cumulative emissions reductions needed to reach the state of California's climate mitigation goals by 2050 (Cameron et al., 2017). This study more conservatively estimates that the annual net negative emissions from the first 18 years of applying compost to 39% of California rangeland area would be equivalent to 118 ± 1% of California's annual emissions from agricultural fuel use (California Air Resources Board, 2019). This would account for 8% of California's 2030 target of reaching 40% below California's 1990 emissions rate (California Air Resources Board, 2015).

It is noteworthy that we simulated the effects of a one-time compost amendment over ~85 years. In practice, ranchers are likely to reapply compost within that time frame, which could increase the net C sequestration rate over time. In California, there is enough organic material to produce compost to apply to all of California's rangelands and croplands every 15 years (Breunig et al., 2019), falling slightly before the mean maximum SOC sequestration effect. In addition to the NPP and SOC benefits of applying compost, accounting for the alternative fates of waste used in compost amendments would also contribute to reaching targets for reduced emissions. Compost is partially decomposed organic matter (Lynch et al., 2006) often sourced from urban and agricultural byproducts including green waste, livestock manure or bedding material, foodwaste, or a combination thereof. The alternative fates of these waste products are in landfills or manure lagoons. Manure management and landfills contributed over 17% of annual CH_4 and N_2O emissions in the United States in 2019 (EPA, 2021), and ~5% of California's total greenhouse gas emissions in 2017 (California Air Resources Board, 2019). Diverting organic-rich waste to compost production and eventual use as a slow-release fertilizer on rangelands provides an additional benefit of avoided greenhouse gas emissions (DeLonge et al., 2013; Vergara & Silver, 2019), not accounted for in this analysis.

CONCLUSION

ESM projections suggest that California's annual grasslands will likely continue to warm significantly with climate change, though projected future precipitation was more variable. The different ESM climate projections for California did not significantly affect simulated background NPP in the unamended rangeland ecosystems examined across the state. Similarly, SOC stocks in unamended rangelands appeared to be relatively insensitive to projected climate change. It is notable that in unamended rangelands, background SOC stocks in all climate scenarios continue to decline following the shift to annual grasses as the dominant vegetation, as noted in other studies (Chou et al., 2008; Owen et al., 2015). Greenhouse gas emissions varied by background climate regime but did not change significantly over the course of the century.

A one-time compost amendment enhanced NPP and SOC across all sites. The augmented productivity and SOC stocks were resilient to climate change and persisted over time. The cumulative net GWP of greenhouse gas emissions stimulated by compost were less than the amount of SOC sequestered, leading to net savings of CO_2e. The cobenefits of compost addition, including enhancing water holding capacity (Flint et al., 2018; Hernandez et al., 2015), reducing run-off (Gravuer et al., 2019), and diverting waste from high emitting fates such as landfills and manure lagoons (DeLonge et al., 2013; Owen & Silver, 2014) were not included in this analysis but provide important incentives and potential additional greenhouse gas savings for the amendment of rangelands with compost. Finally, the greater sequestration rates under the more aggressive emissions reduction scenario provide additional justification for combining emissions reductions with strategies for increased SOC sequestration.

ACKNOWLEDGMENTS

We thank M. Hartmann and R. Ryals for help and guidance on using the DayCent model. Thanks go to J. Borum, J. Wick, and the Natural Resources Conservation Service for invaluable assistance fieldwork organization and facilitating connections and land managers and to S. Vergara, S. Grubinger, A. Haddad, S. Ahmed, and many others too numerous to name for collecting and processing samples used to parameterize the model. We are extremely grateful to the ranchers at each of these sites for allowing us to use their land and for sharing their land management history. We are grateful to L. Kueppers for a friendly review of this manuscript and to E. Díaz-Pinés and an anonymous reviewer for constructive suggestions for improving the manuscript. We are grateful for funding from Betsy Taylor, The Jena and Michael King Foundation, the Band Foundation, the V. K. Rasmussen Foundation, the Trisons Foundation, Oak Creek Foundation, Rathmann Family Foundation, California Coastal Conservancy, and California Climate Change 4th Assessment effort. A. Mayer was funded in part by the Lawrence Graduate Research Fellowship. A portion of this work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 (LLNL-JRNL-812399). We acknowledge that soil samples used for model parameterization were taken from the traditional homelands of the Northern Yukian, Nisenan, Coast Miwok, Patwin, Ineseño Chumash, Yokuts, and Kumeyaay Indigenous peoples and analyzed on the traditional homelands of the Chochenyo Ohlone Indigenous peoples.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data (Mayer & Silver, 2022) are available in Dryad at https://doi.org/10.6078/D1DD85.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mayer, Allegra, and Whendee L. Silver. 2022. "The Climate Change Mitigation Potential of Annual Grasslands under Future Climates." *Ecological Applications* e2705. https://doi.org/10.1002/eap.2705