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Authors
Di Vittorio, Alan V
Simmonds, Maegen B
Jones, Andrew
et al.

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Soil management practices can contribute to net carbon neutrality in California

Alan V Di Vittorio[1,7,*], **Maegen B Simmonds**[1,2,7], **Andrew Jones**[1], **Whendee L Silver**[3], **Benjamin Houlton**[4], **Margaret Torn**[1], **Maya Almaraz**[5,6] and **Peter Nico**[1]

[1] Lawrence Berkeley National Lab, Berkeley, CA 94720, United States of America
[2] Now at: Regrow Agriculture, Inc., Durham, NH, United States of America
[3] Department of Environmental Science Policy and Management, University of California, Berkeley, CA 94720, United States of America
[4] Department of Ecology and Evolutionary Biology & Department of Global Development, Cornell University, Ithaca, NY 14850, United States of America
[5] Yale Center for Natural Carbon Capture, Yale University, New Haven, CT 06520, United States of America
[6] Institute of the Environment, University of California, Davis, CA 95616, United States of America
[7] Joint senior authorship.
[*] Author to whom any correspondence should be addressed.

E-mail: avdivittorio@lbl.gov

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Supplementary material for this article is available online

Abstract

Stabilizing climate requires reducing greenhouse gas (GHG) emissions and storing atmospheric carbon dioxide (CO_2) in land or ocean systems. Soil management practices can reduce GHG emissions or sequester atmospheric CO_2 into inorganic and organic forms. However, whether soil carbon strategies represent a viable and impactful climate mitigation pathway is uncertain. A specific question concerns the role that land-management practices and soil amendments can play in realizing California's ambition for carbon neutrality by 2045. Here we examine the carbon flux impacts of soil conservation (i.e., compost, reduced tillage, cover crop) and enhanced silicate rock weathering (EW) practices at different areal extents of implementation in cropland, grassland, and savanna in California under two climate change cases. We show that with implementation areas of 15% or 50% of private cultivated land, grassland, and savanna in California, soil conservation practices alone can contribute $1.4^{2.1}_{0.7}$% ($-1.8^{-2.7}_{-0.9}$ Mt CO_2eq y^{-1}) and $4.6^{6.9}_{2.3}$% ($-6.0^{-8.9}_{-3.0}$ Mt CO_2eq y^{-1}) of the additional emissions reduction needed (beyond previous targets) to meet the 2045 net neutrality goal (-129.3 Mt CO_2eq y^{-1}), respectively, on an average annual basis, including climate uncertainty. Including EW in these scenarios increases the total contributions of management practices to $4.1^{5.6}_{2.5}$% ($-5.2^{-7.3}_{-3.2}$ Mt CO_2eq y^{-1}) and $13.5^{18.6}_{8.2}$% ($-17.5^{-24.2}_{-10.7}$ Mt CO_2eq y^{-1}), respectively, of this reduction. This highlights that the extent of implementation area is a major factor in determining benefits and that EW has the potential to make a real contribution to net reduction targets. Results are similar across climate cases, indicating that contemporary field data can be used to make future projections. With EW there remains mechanistic uncertainties, however, such as rock dissolution rate and environmental controls on weathering products, which require additional field research to improve understanding of the technological efficacy of this approach for California's 2045 carbon neutrality goal.

1. Introduction

Atmospheric concentrations of carbon dioxide (CO_2) continue to rapidly increase primarily due to fossil fuel combustion and land use and land cover change (LULCC) (IPCC 2021). Limiting global warming to 1.5 °C to avoid increasingly dangerous climate change will require reducing net CO_2 emissions to zero (by reducing greenhouse gas (GHG) emissions and sequestering carbon) and aggressively mitigating emissions of other GHGs by 2050 (Rogelj *et al* 2018). California (CA) has been a leader in championing climate change mitigation policy through the CA Global Warming Solutions Act of 2006 (AB 32 2006) and later commitments (SB 1386 2016, SB 32 2016) to reduce gross GHG emissions by 40% and 80% below 1990 levels by 2030 and 2050, respectively. In 2018, a more ambitious target was set to achieve statewide carbon neutrality by 2045 (Executive Order B-55-18) and was recently codified in law (AB 1279 2022).

The majority of GHG emissions reductions must come from the energy, industrial, and transportation sectors, but LULCC will play a key role because the land sector produces ∼22% of global GHG emissions (Pathak *et al* 2022). Land-based strategies for GHG emissions reduction have been explored at the global (Griscom *et al* 2017, Mayer *et al* 2018), national (Fargione *et al* 2018, Drever *et al* 2021), and sub-national scales (Cameron *et al* 2017, Simmonds *et al* 2021), and have been included in all scenarios targeting the 1.5 °C warming limit. Land-based emissions reductions can be achieved through avoidance or through management practices that reduce emissions or sequester carbon. Alternative methods include bioenergy carbon capture and storage and direct air capture, but land management has been reported as the least expensive pathway for mitigating climate change, both in global (Griscom *et al* 2017) and sub-national modeling analyses (e.g. \$11 per tonne of CO_2 in CA (Baker *et al* 2020)).

Most land-based practices for mitigating climate change address organic carbon and have received more attention than practices addressing inorganic carbon. The net carbon flux impact of soil conservation practices (i.e., those affecting organic carbon; e.g., cover cropping, reduced tillage, and compost application), compared to conventional practices, has been estimated to range from 0.53 Mg CO_2e ha^{-1} y^{-1} to −5 Mg CO_2e ha^{-1} y^{-1} (increase in soil carbon) (Cameron *et al* 2017, Baker *et al* 2020, Graves *et al* 2020, Di Vittorio *et al* 2021). These increases are low compared to other land-based practices (e.g. woody restoration), thus requiring application across large areas to have significant impact (Di Vittorio *et al* 2021). In contrast, enhanced silicate rock weathering (EW) accelerates the accumulation of inorganic carbon in land or aquatic systems. Like organic carbon practices, accumulation of inorganic carbon may reduce emissions or sequester carbon, depending on the system. While EW field studies are rare, laboratory EW experiments and modeling suggest that under certain conditions it could have a relatively high rate of carbon accumulation on a per-area basis (Beerling *et al* 2018, Stler *et al* 2018).

EW of magnesium- and calcium-rich silicate rocks and minerals is a chemically and physically mediated process that can convert two moles of gaseous CO_2 to two moles of bicarbonate, per mole of base cation released (equation (1)). The fate of bicarbonate determines the net carbon accumulation rate: it is either transported to the ocean with residence times of potentially millions of years, or it precipitates as carbonate at half the bicarbonate conversion rate (equation (2)), in which case the residence time depends on site conditions (Koutsoukos and Kontoyannis 1984, Beerling *et al* 2018, Zamanian *et al* 2021),

$$CaSiO_3\,(s) + 2CO_2\,(aq) + H_2O\,(l) \rightarrow Ca^{2+}\,(aq) + 2HCO_3^-\,(aq) + SiO_2\,(s) \tag{1}$$

$$Ca^{2+}\,(aq) + 2HCO_3^-\,(aq) \rightarrow CaCO_3\,(s) + CO_2\,(g) + H_2O\,(l)\,. \tag{2}$$

Reactive surface area, temperature, water availability, and soil chemical properties are key variables in EW reaction rates. Simulations and laboratory studies have shown that dissolution and accumulation rates increase in controlled environments as grain size decreases (total surface area increases) (Hangx and Spiers 2009, Kelland *et al* 2020, Amann *et al* 2022). This suggests that finely pulverized rock may be applied to agricultural lands to capture CO_2. Furthermore, modeling indicates that the benefits of ultra-fine grains may not outweigh the additional costs of reducing grain diameter from 100 μm to 10 μm (Kantzas *et al* 2022). A recent study of EW in croplands reported that −25 to −100 Gt CO_2 could be converted globally over 50 years through sustained implementation, depending on the extent and suitability of the implementation area. The US contribution was −0.13 and −0.42 Gt CO_2 y^{-1}, requiring 10% and 55% of cropland area, respectively (Beerling *et al* 2020). EW also has potential co-benefits, such as increased plant nutrient availability and yield (Kelland *et al* 2020), improved soil physical properties, reduced cropland N_2O emissions (Blanc-Betes *et al* 2021), and reduced ocean acidification (Beerling *et al* 2018). The efficacy of EW has also been demonstrated under drought conditions (Holzer *et al* 2023). However, the magnitude of carbon accumulation and the long-term effects of continual rock amendment to agricultural soils are not well understood. Furthermore, a lifecycle assessment is needed to determine the availability of toxin-free rock substrate relative to farmland location and the associated GHG costs of production, transport, and application.

The State of CA includes natural and working lands (NWLs) management as contributing to its overall emissions reduction goals (SB 1386 2016) while meeting other needs such as wildfire mitigation (CA 2019). CA's 2030 NWL Climate Change Implementation Plan (CA 2019) estimates net GHG benefit for two suites of land management practices. Importantly, the small extent of alternative agricultural management limited benefits of both cases (Simmonds *et al* 2021). For example, 417 636 ha were dedicated to alternative agricultural management in the most ambitious scenario (CA 2019), yet there were over 4 Mha of cropland in 2010 (CALAND 2020). Another modeling study treated 1.3 Mha of croplands with soil conservation and conversion to grassland and 4.3 Mha of grassland with compost amendment to provide a 10 year mean annual benefit of -3.9 Tg CO_2e y^{-1}. They also estimated that an emissions reduction of -125 to -150 Tg CO_2e y^{-1} from the previous targets is needed to achieve carbon neutrality in 2045 (Baker *et al* 2020). CA's 2019 GHG emissions were estimated to be 418 Tg CO_2e y^{-1} (CARB 2021).

We examine the climate change mitigation potential of CA-field-tested soil conservation practices and EW in CA using the CA NWLs carbon and GHG model (CALAND; Di Vittorio and Simmonds 2019, CALAND 2020). We focus on private cropland and rangeland (grazed grassland, savanna, and woodland) as the most likely areas for these practices to be applied and explore uncertainties in implementation area, weathering fate of mineralized CO_2, and climate. Specifically, we address the following research questions: what are the potential carbon flux impacts of EW and soil conservation practices in CA? How much can these practices contribute to meeting California's 2045 target of statewide carbon neutrality?

2. Methods

2.1. Model description

The CALAND model simulates annual, terrestrial, net, carbon fluxes and stocks for 941 CA land units and eight carbon pools, including wood products and their decay. Species-specific carbon emissions (CO_2, CH_4, and optional black carbon) from biomass decay and burning (wildfire, controlled burning, bioenergy production) are also tracked. CALAND 3.0.1 (Di Vittorio and Simmonds 2019, CALAND 2020) has 16 distinct land management practices, plus variations, including soil conservation (cover cropping, reduced tillage, and compost application for cropland; compost application for rangeland). This study uses a modified version of CALAND 3.0.1 that adds rock amendment practices (text S1). We analyze the effects of land management on net ecosystem carbon fluxes by subtracting baseline outputs from management scenario outputs. Negative values represent increases in soil carbon due to alternative management that affects only soil CO_2 fluxes in the model, and indicate emissions reduction or carbon sequestration depending on whether the system is a carbon source or sink, respectively.

2.2. Scenario development and simulations

To explore the potential of soil management in CA cropland and rangeland to contribute to the state's GHG reduction goals, we developed 18 alternative land management scenarios and one baseline scenario that represents conventional or no management (table 1). All scenarios were simulated from 2010 through 2050, and alternative management was applied from 2021 through 2050. All scenarios assume mean levels of initial carbon densities and fluxes. We varied three factors: (1) management practice, (two of three options) (2) implementation area (three designations), and (3) per-area effects of each management practice based on their uncertainty (three levels) (tables 1, S1, text S1). The available practices are soil conservation (including compost amendment in rangeland), rock amendment, and both. Soil conservation is applied each year in cropland, compost is applied every 10 years in rangeland, and rock amendment is applied every three years. The annual average per-area effects of the two individual practices were estimated using 100% of the respective land type areas (to maximize spatial heterogeneity; table 2) and three uncertainty levels (table 1). Twelve scenarios correspond to treating 15% or 50% of privately owned cropland, grassland, and savanna (table 2) with soil conservation only or with both practices, at three uncertainty levels (table 1). These two extents were chosen to reflect the likelihood of implementation, uncertainty in source material availability, logistical challenges of application in woodland, and alignment of different practice areas for comparison. Plant and manure compost availability in CA has been estimated to be sufficient for application to 550 000 ha per year (DeLonge *et al* 2013), which is similar to 15% of private grassland and savanna (541 109 ha). More than tripling this area allows for considerable expansion of source material availability and does not assume that all grassland and savanna are grazed. Constant land type areas for determining implementation area were calculated as the average projected CALAND area from 2021 to 2050, and simulations were performed with constant 2010 CALAND land cover. These 12 scenarios were extended to 2070 to quantify when CA carbon neutrality may be reached if the state's previous emissions targets were met. Soil conservation and compost amendment input uncertainties are ± 2 * SD from the mean carbon flux of each practice, where SD is the variability in the effect of each practice. These values (without climate change effects) were derived from CA-specific estimates of net soil carbon change due to compost amendment or the average of soil conservation practices relative

Table 1. Summary of the management scenarios for sequestering soil carbon or reducing emissions in California cropland, grassland, savanna, and woodland. Land is segregated by private or non-private ownership. All scenarios were simulated using the CALAND model from 2010 to 2050, with management prescribed from 2021 to 2050, except for the baseline (first) scenario that had no management (or conventional management for cropland). The private land scenarios were extended to 2070. The prescribed management areas are based on fractions of the average total land type areas from 2021 to 2050 with projected land use-driven land cover change (table 2). All scenarios were duplicated for RCP 4.5 and RCP 8.5 climate change projection.

		Soil management practices			
				Silicate rock amendment in cropland, grassland, savanna, and woodland	
Alternative management area (%)	Ownership	Soil conservation in cropland[a]	Compost application[b] in grassland, savanna, woodland[c]	Annual dissolution of applied rock[d] ($Mg\ ha^{-1}\ y^{-1}$)	Bicarbonate to carbonate formation of dissolved rock (ratio)
0	NA				
100	All	mean	mean		
100	All	mean + 2SD	mean + 2SD		
100	All	mean − 2SD	mean − 2SD		
100	All			13.33	50:50
100	All			13.33	100:0
100	All			13.33	0:100
15	Private	mean	mean		
15	Private	mean + 2SD	mean + 2SD		
15	Private	mean − 2SD	mean − 2SD		
15	Private	mean	mean	13.33	50:50
15	Private	mean + 2SD	mean + 2SD	13.33	100:0
15	Private	mean − 2SD	mean − 2SD	13.33	0:100
50	Private	mean	mean		
50	Private	mean + 2SD	mean + 2SD		
50	Private	mean − 2SD	mean − 2SD		
50	Private	mean	mean	13.33	50:50
50	Private	mean + 2SD	mean + 2SD	13.33	100:0
50	Private	mean − 2SD	mean − 2SD	13.33	0:100

[a] Proxy for a range of regenerative agricultural practices, such as no-till, reduced tillage, cover crop, compost, but excluding practices that involve land cover change.
[b] Application rate of 14 $Mg\ C\ ha^{-1}\ y^{-1}$, C:N = 11:1, 10 y repeat frequency.
[c] Compost applied to woodland only for the 'All' ownership scenarios.
[d] Application rate of 40 $Mg\ ha^{-1}$ of ground basalt with 15% alkalinity applied once every three years, with complete dissolution over three years.

Table 2. Summary of California land-type specific and total land areas prescribed for the management scenarios listed in table 1.

Region	Ownership	Land type	Mean respective land type area from 2021 to 2050 (ha) by ownership	Proportion of mean total respective land type area (%)
All	All	Cropland	4105 456	100
All	All	Grassland	3834 628	100
All	All	Savanna	2144 848	100
All	All	Woodland[a]	4190 099	100
All	**All**	**Sum**	**14 275 031**	**100**
All	15% Private	Cropland	585 434	14
All	15% Private	Grassland	324 836	8
All	15% Private	Savanna	216 273	10
All	**15% Private**	**Sum**	**1126 543**	**11**
All	50% Private	Cropland	1951 447	48
All	50% Private	Grassland	1082 786	28
All	50% Private	Savanna	720 909	34
All	**50% Private**	**Sum**	**3755 142**	**37**

[a] For reference, this estimate of all private woodland is 1360 856 ha.

Table 3. Summary of the input uncertainties for changes in soil carbon flux due to alternative management.

Region	Land type	Soil carbon flux input	Description of values used in calculation of input SD	Publication source(s)
Non-Sacramento/San Joaquin River Delta	Cropland	SD of soil conservation effect	The propagated SDs of the effect at two sites are averaged. The effect at each site is calculated based on the published values, then averaged to get the final effect.	Kong *et al* (2005), Mitchell *et al* (2015)
Sacramento/San Joaquin River Delta	Cropland	SD of soil conservation effect	The non-Delta uncertainty value is used for the Delta due to lack of data in the Delta	NA
All	Grassland, Savanna, Woodland	SD of compost amendment effect	Propagated the published SD of modeled mean changes in carbon in the active, slow, and passive SOC pools, as these pool values are summed to get the effect.	Ryals *et al* (2015)
All	Cropland, Grassland, Savanna, Woodland	Silicate rock mechanism uncertainty	One-quarter of the range of specific carbon sequestration potential for basalt based on the endmembers of 100% bicarbonate or 100% carbonate	Beerling *et al* (2018)

to conventional management (table 3 and text S1). Rock amendment input uncertainty is characterized by three potential fates of mineralized CO_2 as bicarbonate and carbonate (mean = 50:50, minimum benefit = 0:100, maximum benefit = 100:0, respectively; table 3 and text S1). To account for interactions between climate change and land management, all scenarios were duplicated for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 estimated effects on soil and vegetation carbon fluxes. These cases range from more plausible to extreme and a previous CALAND study shows that their respective carbon flux responses to alternative land management bracket the no climate change case while being very similar to each other (Simmonds *et al* 2021). Therefore in the present study we use these two cases to represent climate uncertainty in our results. Differencing scenarios with the same climate reduces absolute climate change effects and isolates flux changes due to alternative management. The limited effects of dramatically different climates in this analysis preclude the need to explore additional climate cases, particularly if California's emissions reduction efforts do not align with those in the rest of world. Wildfire was not included because it is independent of managed soil carbon effects in CALAND.

A simplified equation summarizes the model estimate of total annual net soil carbon flux (Mg C y^{-1}) in each land category (region-ownership-land type combination) as the product of the total land category area and the climate-scaled, area-weighted average soil carbon flux (Mg C ha^{-1} y^{-1}) (equation (3)),

$$C_{x,r,o,l} = \sum_{r=1}^{9}\sum_{o=1}^{9}\sum_{l=1}^{15} a_{r,o,l} \cdot \frac{c_{r,o,l,x}\left(\bar{Y}_{M,r,o,l} \cdot f_{r,o,l,x} \cdot a_{r,o,l} + \bar{Y}_{B,r,o,l} \cdot a_{r,o,l}\left(1 - f_{r,o,l,x}\right)\right)}{a_{r,o,l}} \quad (3)$$

where $C_{x,r,o,l}$ is the simulated absolute net soil carbon flux (Mg ha^{-1} y^{-1}) in year x, located in region r, ownership o, and land type l; $a_{r,o,l}$ is the total land category area (ha by r, o, l), $f_{r,o,l,x}$ is the fraction of land category managed in year x; $c_{r,o,l,x}$ is the climate scalar in each land category (r, o, l) in year x, $\bar{Y}_{B,r,o,l}$ is the constant average annual baseline net soil carbon flux (Mg ha^{-1} y^{-1}) in each land category (r, o, l), and $\bar{Y}_{M,r,o,l}$ is the constant average annual net change in soil carbon flux due to alternative management (Mg ha^{-1} y^{-1}), which can be zero for the baseline or the mean, mean + upper bound, or mean − lower bound values.

3. Results and discussion

3.1. Net carbon flux impacts of individual practices on a per-area basis

To estimate the near-term (30 year) impacts of individual soil management practices across CA's landscape on a per-area basis, we analyzed CALAND simulations for 100% of cropland, grassland, savanna, and woodland, with and without each practice implemented from 2021 to 2050, under two climate change cases (table 1 and figure 1). Consistent with a previous study (Simmonds *et al* 2021), the different climate cases produced similar results with the main effect of adding interannual (figure 2, table S1) and spatial variability to a no climate change case. The 30 year average annual effect of soil conservation on cropland flux ranged from 0.49 Mg CO_2e ha y^{-1} to −2.24 Mg CO_2e ha y^{-1} (increase in soil carbon), including climate uncertainty, with an average across mean climate cases of −0.86 Mg CO_2e ha y^{-1} (figure 1, table S1). These are slightly lower carbon increases than those from a study including deeper soil profile measurements (0–200 cm) (Tautges *et al* 2019) at one of the field sites used for parameterizing CALAND. This suggests that cropland soil conservation practices may demonstrate greater carbon increases if deeper storage is considered. Compost amendment on rangeland had larger flux changes ranging from −2.19 Mg CO_2e ha^{-1} y^{-1} in grassland to −2.72 Mg CO_2e ha^{-1} y^{-1} in woodland, including climate uncertainty. Rock amendment showed the largest range of −1.64 Mg CO_2e ha^{-1} y^{-1} in cropland to −5.22 Mg CO_2e ha^{-1} y^{-1} in woodland, representing the lower and upper uncertainty bounds of these land types, including climate uncertainty. Changes in rock amendment fluxes across rangeland types were similar, with highest values in woodland and lowest values in grassland.

Uncertainty quantification for compost amendment in rangeland is limited by sparse field data (figure 1 and table S1). The CALAND input for this practice's impact (−1.9 ± 0.11 Mg CO_2e ha^{-1} y^{-1} over 10 years) (table S1) was derived from a single modeling study of long-term changes in organic carbon densities at three CA grassland sites following a single compost application (Ryals *et al* 2015) (see methods). In contrast, the combined temporal and spatial variability over the first three years at the same sites (Ryals and Silver 2013) was much greater than the modeled uncertainty. The short-term field impact (−2.35 ± 3.46 Mg CO_2e ha^{-1} y^{-1}), the mean of which is 24% greater than our mean input (by magnitude, table S1), was extrapolated in another study to estimate greater soil carbon increases and uncertainty due to compost amendments in CA grassland (Cameron *et al* 2017). We used the longer-term modeling data to represent the net impacts of compost amendment in rangeland because they more accurately reflected our 10 year reapplication period, and we accepted the smaller, modeled uncertainty associated with declining annual soil carbon increases over 10 years (Ryals and Silver 2013, Ryals *et al* 2015). A recent study with additional field sites also shows declining soil carbon increases over time for a single compost application (Mayer and Silver 2022). Additional studies with longer-term measurements may increase these modeled uncertainties.

While rock dissolution rate is a major source of uncertainty for EW, we assumed repeated rock amendment every three years with 100% dissolution during this period and focused on the fate of CO_2 as our primary source of uncertainty for simulations (figure 1 and table S1). This is a conservative approach that acknowledges the limited availability of experimental data (Almaraz *et al* 2022). Previous modeling studies have assumed 100% dissolution annually (e.g. Beerling *et al* 2020), while laboratory experiments indicate incomplete dissolution in the first year and declining amounts of rock dissolution over time (e.g. Amann *et al* 2022). In our framework the annual effects are distributed evenly across the dissolution period and thus our results scale linearly with the amount of annual rock dissolution. Hence, assuming 100% dissolution each year with annual reapplication would triple our results. The fate of CO_2 as carbonate or bicarbonate also contributes uncertainty to the estimates. Our mean estimate represents 50% carbonate and 50% bicarbonate, while the lower and upper accumulation bounds represent 100% carbonate and 100% bicarbonate, respectively. These results suggest that rock amendment practices be developed to maximize dissolution and bicarbonate production in order to maximize per-area benefits. Our findings highlight the need for additional field trials and model development with the aim of linking fundamental geochemistry to meteorological, soil, and management conditions to improve EW projections in California.

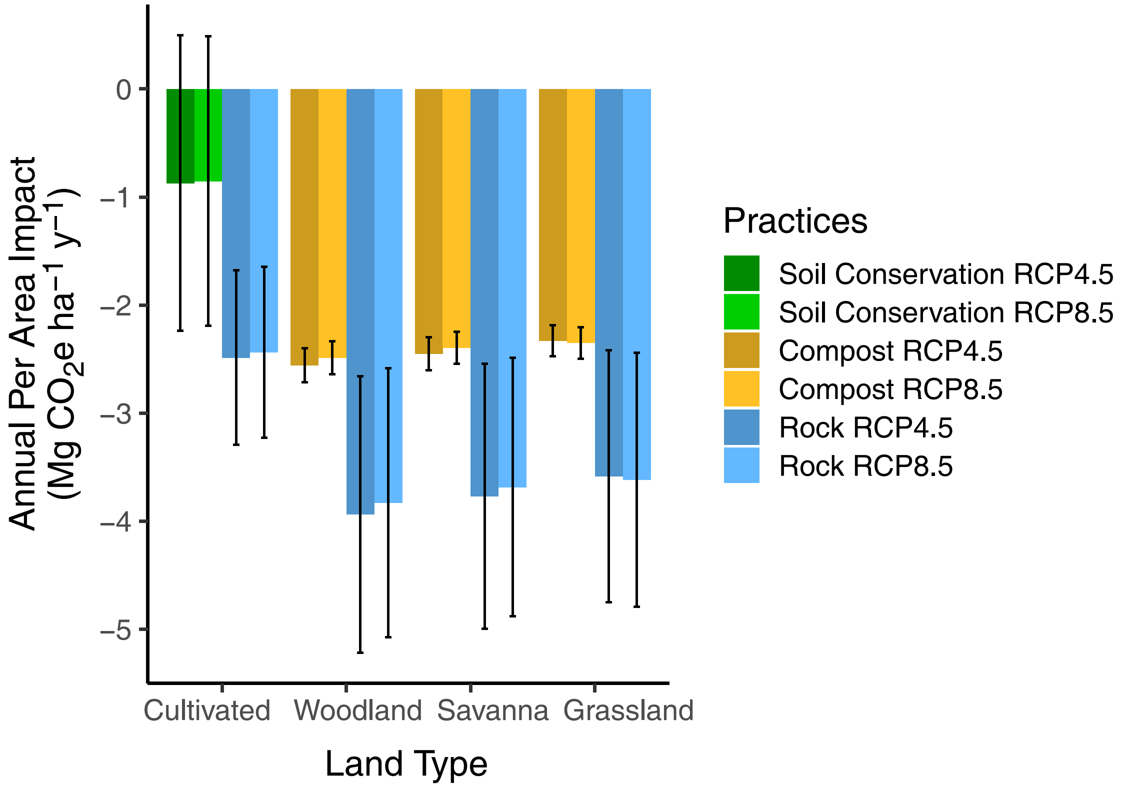

Figure 1. Simulated 30 year mean annual net soil carbon flux impacts on a per area basis of individual soil management practices from 2021 to 2050 in cropland, grassland, savanna, and woodland in California under Representative Concentration Pathways 4.5 and 8.5. Negative values represent reduced net soil carbon emissions or increased net soil carbon sequestration relative to a baseline of no treatment. Error bars are the uncertainty bounds for each technology, with the upper and lower bounds corresponding to the 30 year mean annual soil carbon flux difference from baseline of two additional scenarios per management-land type combination. For the soil conservation and compost application uncertainty bound scenarios, the inputs for the absolute net soil carbon flux were the mean net flux for the practice $\pm 2\sigma$ of the estimated effect of the practice. The rock application uncertainty bound scenarios were run with inputs for the absolute net soil carbon flux corresponding to the fate of the mineralized CO_2 as 100% carbonate (minimum benefit) or 100% bicarbonate (maximum benefit), while the mean scenario represented the fate as 50% carbonate and 50% bicarbonate.

a) Soil conservation and compost

b) Soil conservation and compost plus rock amendment

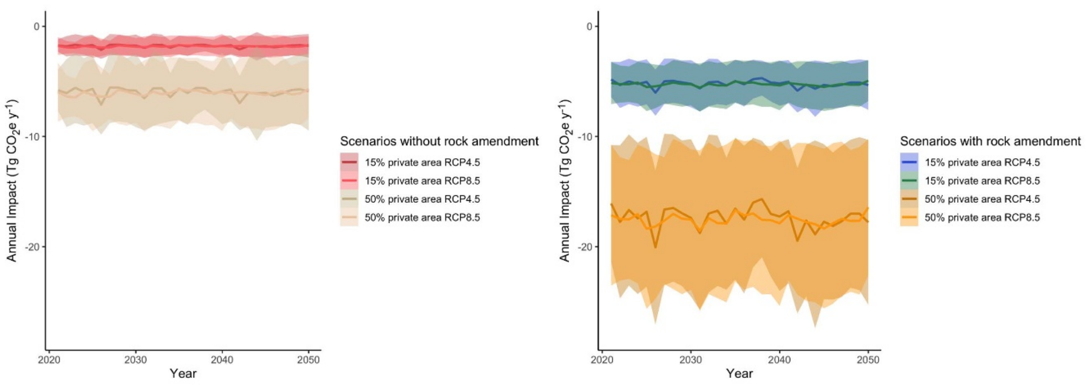

Figure 2. Simulated changes in annual soil carbon flux in California soils, relative to a baseline of no management, with (a) compost applications in grasslands and savanna and soil conservation in cultivated lands, and (b) the additional practice of applied rock amendment in these land types. Negative values represent decreased soil carbon emissions or enhanced soil carbon sequestration relative to a baseline of no management. Two climate cases (Representative Concentration Pathways 4.5 and 8.5) and two implementation extents (15% private, 50% private) are shown. The shaded areas are the uncertainty bounds for each scenario, which were generated using model inputs for the mean net soil carbon flux of each practice $\pm 2\sigma$ of the estimated effect of each practice, with the exception of rock amendment for which the central estimate represents the fate of the mineralized CO_2 as 50% bicarbonate and 50% carbonate and the uncertainty corresponds to 100% carbonate (minimum benefit) or 100% bicarbonate (maximum benefit).

3.2. Statewide changes in net carbon flux due to soil management

To estimate changes in net carbon flux due to soil conservation across CA, we simulated the impacts of aggregate practices in cropland and compost amendment in grassland and savanna for two proportions of private land area (15% and 50%) from 2021 to 2050 (tables 1 and 2, figure 2(a)), under two climate change cases. The results scale approximately linearly with implementation area and interannual variability reflects the spatially explicit interaction between climate change and management. Average annual flux changes ranged from −0.9 to −2.7 Tg CO_2e y^{-1} and −3.0 to −8.9 Tg CO_2e y^{-1} for 15% and 50% private land area, respectively. Another study reported that similar practices could change fluxes by −3.9 Tg CO_2e y^{-1} when applied to 1.5 Mha of cropland and 4.3 Mha of rangeland in CA (Baker *et al* 2020). This is within the range of our 50% private area scenarios, which have less implementation area (2 Mha of cropland and 1.8 Mha of savanna and grassland) but are based on CA-specific data while their analysis is based on a national farm model.

Scenarios with additional rock amendment and the 50:50 fate of mineralized CO_2 increase the magnitude of changes by a factor of 2.9 at both extents and climates (figure 2, table S2). For example, the mean RCP4.5 flux changed from −1.8 to −5.2 Tg CO_2e y^{-1} with the addition of rock amendments on 15% of private land. We assume that EW is independent of soil conservation because EW affects inorganic carbon while soil conservation affects organic carbon and potential interactions between these practices are unknown. The long-term stability of bicarbonate depends on it leaching through the soil and travelling through rivers to the ocean (Beerling *et al* 2018). Material remaining in the soil may precipitate as carbonate minerals with lifespans of thousands to millions of years in natural soils, but with shorter lifespans in agricultural soils (Zamanian *et al* 2021) because fertilizer could reduce soil pH sufficiently for carbonate dissolution to favor H_2CO_3 that can re-emit CO_2 to the atmosphere (Koutsoukos and Kontoyannis 1984).

3.3. Contributions of soil management to CA net carbon neutrality

The potential for soil conservation and rock amendment to contribute to CA's 2045 carbon neutrality goal depends on the implementation area and average annual per-area flux impacts of each practice (figures 3 and 4). The relative importance of these two factors depends on the range of per-area impacts (figure 3), which is partly based on data availability. We estimate that by 2045 an additional emissions reduction of −129.3 Tg CO_2e y^{-1}, with respect to previous targets, is required to meet the overall neutrality goal. Soil conservation on 15% and 50% private area of respective land types (tables 1 and 2) provides average annual flux changes of $-1.8_{-0.9}^{-2.7}$ and $-6.0_{-3.0}^{-8.9}$ Tg CO_2e y^{-1}, respectively, under RCP 4.5, corresponding to $1.4_{0.7}^{2.1}$% and $4.6_{2.3}^{6.9}$% of the additional reduction required to meet the neutrality goal, respectively (figure 4). The RCP 8.5 results are nearly identical (table S5). Compost amendment on grassland and savanna contribute most to overall emissions reduction because their mean, annual, per-area impacts (figure 1) are more than double those from soil conservation on cropland and the respective areas are similar.

Adding rock amendment to scenarios more than doubles the magnitude of flux change (figure 4(b)). Scenarios with all practices implemented on 15% and 50% private area of each respective land type change carbon flux by $-5.2_{-3.2}^{-7.2}$ and $-17.4_{-10.7}^{-24.1}$ Tg CO_2e y^{-1}, respectively, under RCP 4.5. These values correspond to $4.0_{2.5}^{5.6}$% and $13.4_{8.2}^{18.6}$% of the additional reduction required to meet the neutrality goal, respectively (figure 4(b)). Assuming California reduces fossil fuel and other industrial emissions following the trajectory set by the 2030 and 2050 targets, extended simulations of the mean scenarios show that the combined practices could help achieve carbon neutrality by 2060 or 2059 for 15% or 50% private area, respectively, regardless of climate case. While this does not meet the 2045 target, silicate rock amendments have the potential to contribute to overall emissions reduction. Field studies are needed to determine realistic dissolution rates, the fate of sequestered CO_2, and dependence on rock types, soil physical and chemical properties, and management, particularly with regards to tillage and water management. Thus, focusing research efforts on optimizing the rock sequestration potential on the most suitable land is warranted.

Regardless of practice or uncertainty, it is clear that increasing implementation area of these practices increases their impacts (figure 3). Our scenarios do not maximize the physical area because there are many physical, political, social, and economic barriers that limit implementation extent of these practices. However, our results can be scaled linearly with increasing area to estimate the effects of broader implementation, with caution. Cropland is inherently managed and 55% of potential rangeland in California is grazed, 46% percent of which is public land (Brown *et al* 2018; based on savanna, grassland, desert, shrubland, and conifer/hardwood woodlands). This provides a large base for alternative management, although compost amendment is most suitable for grass-dominated rangeland. Availability of source material for these practices will limit implementation area and may become more or less

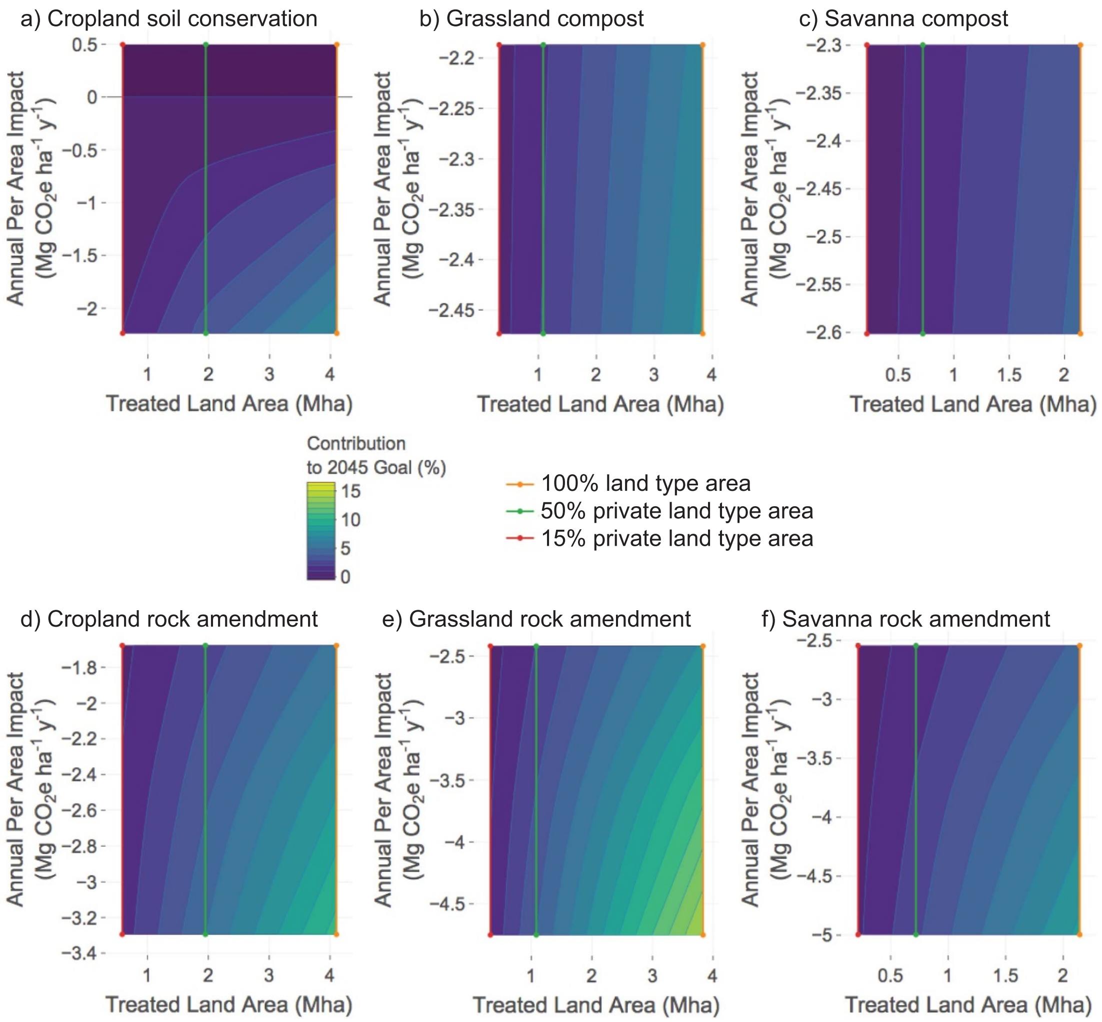

Figure 3. Potential contributions of individual soil conservation (a)–(c) and rock amendment (d)–(f) practices (relative to a baseline of no alternative management) to meeting California's 2045 statewide carbon neutrality goal (-129.3 Tg CO_2e y^{-1}) across the simulated uncertainty range of per area emissions benefits and potential treatment areas of cropland, grassland and savanna (figure 1). The data shown were derived from scenarios with 100% of each land type area treated and simulated from 2021 to 2050 under RCP 4.5 climate change. Note the different axis scales on each plot that reflect different levels of contribution and different available land areas (with the area limits determined by the scenarios). The uncertainty range for each soil-based strategy was generated using model inputs for the mean net soil carbon flux of each practice $\pm 2\sigma$ of the estimated effect of each practice, with the exception of the rock amendment inputs which correspond to the fate of the mineralized CO_2 as 100% carbonate (minimum effect) or 100% bicarbonate (maximum effect).

limited over time as demand grows. However, additional practices could boost implementation area; biochar soil amendment has been shown to increase soil organic carbon content at rates comparable to those of soil conservation (e.g. Blanco-Canqui *et al* 2020) and to improve soil health (Amonette *et al* 2021). Furthermore, incentives for alternative management in agricultural lands may be limited. For example, an ambitious CA Department of Food and Agriculture scenario estimates only 33 724 ha of agricultural land to be under alternative management annually through 2030 (CA 2019), which is only 5.8% of cropland under soil conservation in our 15% private land scenario. Ultimately, our 50% private land scenario may not be an accurate upper estimate of implementation, but it is reasonable given our current knowledge of governing factors.

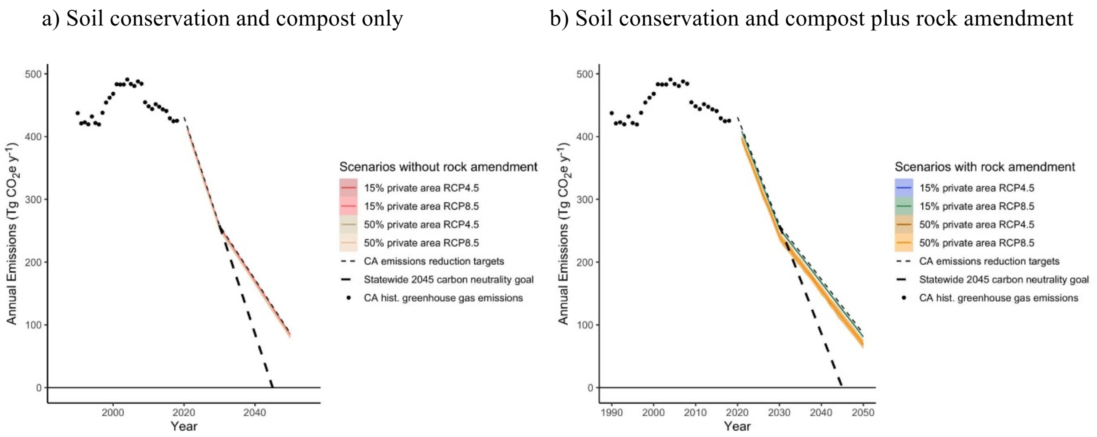

Figure 4. California statewide carbon neutrality goal in 2045 (thick dashed black line) and emissions reduction targets for 2020, 2030, and 2050 (thin dashed black line) compared to the estimated emissions reductions for practices implemented at varying area extents in cropland, grassland and savanna, as added to the 2020, 2030, and 2050 target projection. Note that RCP 4.5 and RCP 8.5 are indistinguishable from each other at this scale. The shaded areas are the uncertainty bounds for each scenario (and are also not clearly visible at this scale) which were generated using model inputs for the mean net soil carbon flux of each practice $\pm 2\sigma$ of the estimated effect of each practice, with the exception of the rock application inputs which correspond to the fate of the mineralized CO_2 as 100% carbonate (minimum benefit) or 100% bicarbonate (maximum benefit).

4. Conclusions

Alternative soil management practices have the potential to contribute to CA's 2045 carbon neutrality goal, with implementation area a major factor in determining the magnitude of contribution. The effects of alternative management are similar across climates, indicating that contemporary field data can be used to make future projections. EW, which increases inorganic carbon storage, is a promising contributor to this goal but mechanistic uncertainties, such as rock dissolution rate and environmental controls on weathering products, need to be further quantified through additional field research to improve understanding of the technological efficacy of this approach.

This study utilizes the best available data and a novel model to make estimates and characterize uncertainties, but several factors contribute to additional uncertainty that may not be represented here. Limited field data for many practices, including those not in this study, contribute to uncertainty in regional carbon flux estimates due to the inherent variability of soils, climate, management, and interactions across CA. Availability of source materials for amendment practices is highly uncertain and may limit implementation areas very differently than presented here. Climate uncertainty is based on only two cases from one Earth system model, and how the carbon accumulation rate of EW responds to changing conditions is not well known. Climate extremes can also reduce potential emissions reductions in particular years. Additional factors, such as economics or life cycle emissions, may also affect contributions to overall emissions reductions. Fortunately, the CALAND model has been shown to provide robust results at the landscape level given uncertainties in initial carbon state, carbon fluxes, and land use/cover change.

Data availability statement

CALAND source code for this study is available at https://github.com/aldivi/caland/tree/WLIC.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Maegen Simmonds conceived the study, modified CALAND, performed simulations and analysis, and wrote the first draft of the manuscript. Alan Di Vittorio updated the simulations and analysis and revised the manuscript accordingly. All authors provided feedback on the manuscript drafts, which improved the manuscript substantially.

ORCID iDs

Alan V Di Vittorio https://orcid.org/0000-0002-8139-4640
Andrew Jones https://orcid.org/0000-0002-1913-7870

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