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Key Points:

- Combined organic and inorganic amendments had the highest rates of enhanced weathering and organic carbon accumulation
- Inorganic ground rock (GR) amendments reduced nitrous oxide (N₂O) and methane fluxes but decreased aboveground net primary production
- Scaling to 8% of California's rangeland area suggest combining organic and inorganic amendments could contribute net CO₂e benefits up to $-51.7 \text{ Mt CO}_2\text{e yr}^{-1}$

Supporting Information:

Supporting Information may be found in the online version of this article.

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Supplementing Enhanced Weathering With Organic Amendments Accelerates the Net Climate Benefit of Soil Amendments in Rangeland Soils

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Abstract Carbon dioxide (CO₂) removal (carbon dioxide removal (CDR)) that combines decreased greenhouse gas emissions with atmospheric CO₂ reduction is needed to limit climate change. Enhanced rock weathering (ERW) of ground silicate minerals is an emerging CDR technology with the potential to decrease atmospheric CO₂. However, there are few multi-year field studies and considerable uncertainty in field-rates of ERW. We explored combining finely ground metabasaltic rock with other soil CDR technologies (compost and biochar amendments) to stimulate carbon (C) sequestration. The combined ground rock (GR), compost, and biochar amendment had the greatest increases in soil C stocks over 3 years ($15.3 \pm 4.8 \text{ Mg C ha}^{-1}$). All other treatments slowed or reversed background C losses, with GR-only treatments reducing rates of soil C loss relative to the control but still losing soil C over time. Ground rock amendments lowered nitrous oxide (N₂O) emissions by $11.0 \pm 0.6 \text{ kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ and increased methane (CH₄) consumption by 9.5 ± 3.5 to $18.4 \pm 4.4 \text{ kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$; while significant, emissions reductions were an order of magnitude smaller than organic C sequestration with compost amendments. The combined amendment yielded the greatest estimated net ecosystem benefit (3 year relative changes in soil C, estimated ERW rates, and greenhouse gas emissions) of $-86.0 \pm 24.7 \text{ Mg CO}_2\text{e ha}^{-1}$. Benefits were dominated by soil organic C gains, directly from organic amendments and indirectly from increased plant growth. Weathering rates were <10% of the theoretical potential. Combined ERW and organic amendments increased estimated weathering rates and stimulated soil organic C sequestration.

Plain Language Summary To combat climate change, we need strategies that both reduce greenhouse gas emissions and remove existing greenhouse gases. One proposed method is to add organic (compost and biochar) and inorganic (GR) substances to soils, which may increase plant growth and transfer atmospheric carbon into the soil. Most studies look at amendments separately, but this study quantified what happens when used together. The researchers found that using a mix of compost, GR, and biochar led to the most carbon being stored in the soil. All treatments that included compost increased the amount of carbon in the soil. The researchers also measured greenhouse gas emissions and found that adding GR reduced emissions of N₂O (a potent greenhouse gas) and increased the ecosystem's ability to consume methane (another potent greenhouse gas). The combination of compost, GR, and biochar had the greatest net benefit, reducing the equivalent of 86.0 {plus minus} 7.2 tons of CO₂-equivalents per hectare after 3 years. All treatments showed net benefits, including slowing or reversing losses in soil carbon. This suggests using a combination of soil amendments could lead to increases in organic carbon in the soil, and reduced greenhouse gas emissions in grazed grassland soils.

1. Introduction

Land management practices offer significant potential as a nature-based pathway to help mitigate climate change by lowering greenhouse gas emissions and/or sequestering atmospheric carbon dioxide (CO₂). Rock dust amendments are an emerging CO₂ removal (CDR) technology that has the potential to remove atmospheric CO₂ via enhanced weathering and subsequent formation and leaching of inorganic carbonates and bicarbonates (Beerling et al., 2018). These compounds are assumed to leave the ecosystem and eventually be deposited deep in the ocean where they will be protected from degassing for long (e.g., millennial) time periods (Hartmann et al., 2013). There are few field trials of enhanced weathering and those show highly variable rates of CO₂ removal (Deng et al., 2023). This high variability is likely due to environmental and biogeochemical factors that

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can alter the formation and behavior of carbonates and bicarbonates in soils including soil pH, moisture content, and the concentrations of nitrate (NO_3^-) which can favor strong acid weathering over carbonic acid weathering (Knapp & Tipper, 2022).

Most of the field research exploring enhanced weathering in working lands has focused on single mineral amendments. The combination of mineral (GR) and organic (compost, biochar) amendments has the potential to ameliorate some of the conditions that lower inorganic C removal via enhanced weathering (e.g., unfavorable pH, low moisture content) while stimulating organic C sequestration from organic C addition and subsequent increases in plant productivity. The application of existing CDR technologies, such as compost or biochar soil amendments, have been shown to contribute to atmospheric C capture by stimulating plant growth and associated deposition of organic matter in soils (Kutos et al., 2023; Mayer et al., 2018; Mayer & Silver, 2022; Smith, 2008; Smith et al., 2016; Soussana et al., 2010), and decrease greenhouse gas emissions from high emitting waste streams (Almaraz et al., 2023; DeLonge et al., 2013; Owen & Silver, 2015; Pérez et al., 2023; Rubin et al., 2023). Combining inorganic and organic amendments could provide multiple pathways for CO_2 removal, but there are caveats. For example, adding GR amendments in combination with organic material may augment weathering rates as organic acids produced by decomposing organic matter can accelerate the chemical weathering and dissolution of applied soil minerals (Drever & Stillings, 1997), although it could decrease rates of weathering if pH becomes unfavorably high (Dietzen & Rosing, 2023). Concomitantly, inorganic amendments may provide more surface area for organo-mineral bonding that could increase the amount and the lifetime of organic C in soils (Calabrese et al., 2022; Song et al., 2018), but organo-mineral bonding can slow rates of mineral weathering by coating mineral surfaces and limiting direct contact with weathering agents like water and acids, or by reducing reactive surface area available for dissolution reactions. Biochar amendments may also increase organic soil C storage while concomitantly reducing net soil greenhouse gas emissions (Borchard et al., 2019; He et al., 2017), although both soil C and emissions are often dependent on soil type and biochar characteristics (Joseph et al., 2021). Applying biochar and compost with GR amendments could increase soil aeration and nutrient availability which could drive greater soil C losses via decomposition (Schmidt et al., 2011; Xu et al., 2021). These organic amendments could also increase C capture by stimulating net primary productivity (Ding et al., 2010; Laird et al., 2010; Vijay et al., 2021). Applying soil amendments in combination may decrease application costs per unit of total C sequestered by providing multiple synergistic pathways (Sevilla-Perea et al., 2016) for greenhouse gas emissions reductions and organic plus inorganic C sequestration. However, this potential has not been thoroughly explored in field-scale trials, particularly in grasslands.

Existing research on enhanced weathering in working lands has predominantly occurred in croplands and forests (Almaraz et al., 2022; Beerling et al., 2018; Calabrese et al., 2022). Managed grasslands cover over 30% of the terrestrial land surface (White et al., 2000), and are widely recognized for their potential to sequester soil carbon (C) due to their extensive land area and high belowground allocation of biomass (Conant et al., 2001; Conant & Paustian, 2002; Lorenz & Lal, 2018). Rangelands are particularly appealing for nature-based climate solutions because they are widely distributed across the globe and may experience co-benefits for food and fiber production (Beerling et al., 2018). As rangelands are generally managed without tillage, nature-based climate solutions in these ecosystems are likely to exhibit longer-term C storage than in cropping systems with frequent soil disturbance (Mayer & Silver, 2022; Mehra et al., 2018; Ryals et al., 2015).

Multi-year field experiments comparing single and combined amendments are needed to identify antagonistic or synergistic effects of mixed amendments, as well as quantify the net climate benefits of various amendment types under the same set of soil and environmental conditions and management approaches. Few field-scale soil amendment experiments have quantified both the effects on plant and soil C stocks alongside the net impacts on greenhouse gas emissions, let alone annual budgets of ecosystem greenhouse gas fluxes. Continuous multi-year ecosystem-scale measurements of CO_2 , CH_4 , and N_2O are needed to ensure amendments do not shift the timing or magnitude of emissions: if emissions are unexpectedly shifted outside of typical sampling periods, then non-continuous flux measurements may systemically over- or under-estimate the net impacts on the ecosystem greenhouse gas budget (Anthony & Silver, 2021, 2023). Thus, continuous measurements can capture potentially important leading or lagging scale-emergent effects of soil amendments on greenhouse gas fluxes and are necessary to truly quantify the ecosystem-scale impacts of soil amendments on soil C stocks, plant productivity, and other co-benefits.

Table 1

Application Rate, Number of Applications, and Total Soil Amendment Applied, and Associated Abbreviations for All Treatment Combinations

Treatment	Abbreviation	Application rate (MT ha ⁻¹ yr ⁻¹)	Number of applications over 3 years	Total biochar amendment applied (MT ha ⁻¹)	Total compost amendment applied (MT ha ⁻¹)	Total ground rock amendment applied (MT ha ⁻¹)
Control	CT	N/A	N/A	N/A	N/A	N/A
Compost	CP	36.8	1	N/A	36.8	36.8
Ground rock	GR	37.8	3	N/A	N/A	113.4
Ground rock, Compost	GR + CP	CP: 36.8 GR: 37.8	CP: 1 GR: 3	N/A	36.8	113.4
Ground rock, Compost, Biochar	GR + CP + BC	CP: 36.8 GR: 37.8 BC: 9.9	CP: 1 GR: 3 BC: 1	9.9	36.8	113.4

Using *in-situ* field applications, we explored the effects of separate and combined amendments of rock dust with and without compost and biochar amendments on ecosystem soil organic and inorganic C stocks, porewater dissolved inorganic C, aboveground biomass, and greenhouse gas emissions in a rangeland ecosystem. We measured continuous greenhouse gas fluxes on single amendment plots and used these values together with soil and plant sampling on all plots to determine effects on ecosystem greenhouse gas budgets, nutrient cycling, aboveground biomass, and soil C stocks over three growing seasons. We estimated the net ecosystem climate benefit (sum of relative increases in organic and inorganic carbon, increases in aboveground biomass, and reduction in N₂O and CH₄ emissions) using a simple upscaling exercise to determine the potential impact of combined inorganic and organic amendments in California rangelands. Our work tested the hypothesis that rock dust treatments would increase soil inorganic C pools and soil porewater dissolved inorganic carbon (DIC) from enhanced weathering and would lower N₂O emissions due to soil pH buffering. We also posited that compost additions to GR treatments would increase soil organic C stocks from greater plant productivity, and that the net CO₂e benefit would be offset by increases in N₂O emissions from added N. Finally, we hypothesized that combining GR with compost and biochar amendments would create additional synergistic effects, as biochar can buffer soil pH, preventing nutrient leaching and directly sequester C in soils. We predicted that combining all three amendments would lead to the highest rates of enhanced weathering and organic soil C sequestration, and the greatest reductions in net CO₂e emissions.

2. Methods

2.1. Site Description

The field site was located at the University of California Sierra Foothill Research and Extension Center (SFREC) in Browns Valley, California. Soils are derived from Mesozoic and Franciscan volcanic rock and classified as xeric Inceptisols and Alfisols in the Auburn-Sobrante complex (Soil Survey Staff, 2020). Soil depth is approximately 30 cm overlaying unconsolidated rock. The area is classified as oak woodland and annual grassland has been exclusively grazed by cattle since at least 1960. Recent stocking rates were approximately 8 acres per cow. The field sites were not otherwise seeded, irrigated, fertilized, or tilled. The study region has a Mediterranean climate with average annual precipitation of 700 mm with high interannual variability and a mean annual temperature of 16.6°C (California Irrigation Management Information System, 2023), but experienced an extended drought throughout the experiment (Liu et al., 2022). The growing season occurs during the cool, wet weather conditions, typically from October to May while summers are hot and dry. The site was dominated by naturalized stands of annual grasses (Ryals et al., 2016).

2.2. Experimental Design

A control treatment and five combinations of GR, compost (CP), and biochar (BC) soil amendments were applied in a randomized block design to account for background spatial variability of the site conditions. This included five 15 × 60 m plots randomly located in each of three blocks (15 total plots, $n = 3$ per treatment), with each block containing a control plot and plots amended with GR- or CP-only, GR plus compost (GR + CP); GR plus compost plus biochar (GR + CP + BC) was added in year 2 (Table 1). To measure continuous soil greenhouse gas

emissions, three additional 10 × 10 m replicate plots were established for each of control, GR-only, and CP-only treatments ($n = 9$ total plots).

Amendments were applied individually and onto the soil surface as these soils are not tilled. Ground rock for enhanced silicate weathering was finely ground metabasaltic rock sourced as waste material from a regional mining operation (Specialty Granules, Ione, CA). A summary of relevant soil amendment properties, chemistry, total C and N content, and mineralogy are provided in Tables S1-S3 in Supporting Information S1. Compost amendments were derived from a mixture of organic yard debris (garden trimmings and wood chips) and cow, chicken, and horse manures and were commercially produced at the West Marin Compost Facility (Nicasio, California) by maturing in watered piles with weekly aeration for approximately 3 months (Vergara & Silver, 2019). Biochar amendments were purchased commercially (Rogue Biochar, Oregon Biochar Solutions, White City, OR) and made with a feedstock of Douglas fir and pine woody biomass sourced from local logging and mill residues. Compost and biochar amendments were applied once during the study following typical rancher practice in the region, and GR was applied annually in 2019, 2020, and 2021 (Table 1). We note that there were no field-scale data available for GR amendments to rangelands, so we adopted suggested best practices for cropland applications (Andrews & Taylor, 2019; Larkin et al., 2022). All amendments were applied before the first rainfall in the fall prior to onset of the growing season.

2.3. Soil and Aboveground Biomass Analyses

Soil samples were collected prior to amendment application and annually at the end of each of three growing seasons. Soil was collected from five random locations within each plot using hand augers (6 cm diameter). Soil was collected from 0 to 10, 10–20, and 20–30 cm depths. Samples were air-dried, sieved to <2 mm, visible roots removed, and a subsample ground to a fine powder. Samples were then analyzed in duplicate for total C and N on an elemental analyzer (CE Elantech, Inc., Lakewood, New Jersey). To quantify changes in soil inorganic C, air-dried soil samples were analyzed on an *sol*iTOC cube (Elementar, Ronkonkoma, NY) using temperature ramping method DIN 19539 which can separately calculate total organic C, residual organic C, and total inorganic C (TIC).

Subsamples were analyzed for soil pH, gravimetric soil moisture, and extracted with potassium chloride (KCl) to quantify inorganic N pools within 24 hr of sample collection. Soil pH was determined by vortexing a 1:1 soil to water solution (5 g soil to 5 ml deionized water) for 1 min then measuring the solution pH after 10 min (McLean, 1982). Soil moisture was determined gravimetrically by weighing fresh soil, oven drying for 24 hr at 105°C, reweighing the dried soil, and calculating the difference as percent soil moisture.

Nitrate (NO_3^-) plus nitrite (NO_2^-) and ammonium (NH_4^+) were measured after extraction of 15 g of field-fresh soil in 75 ml of 2 M KCl solution. Soil KCl extracts were stored at -20°C until colorimetrically analyzed using a discrete analyzer (Model AQ300, Seal Instruments, Mequon, WI). Bulk density was sampled at 0–10, 10–20, and 20–30 cm in each plot prior to amendment application and after three growing seasons using a 6.35 cm diameter bulk density corer (Table S9 in Supporting Information S1). Subsamples were dried at 105°C to a constant weight. Bulk density was calculated as the rock-free dry volume of the total soil core.

Aboveground vegetation was sampled at peak standing crop for biomass production at the end of each growing season ($n = 9$ sample replicates per plot). In annual grasslands, peak standing crop is generally considered an index of aboveground net primary productivity (Chiariello, 1989). Live aboveground plant tissue was clipped from randomly located 20 cm diameter rings and collected into pre-dried and weighed paper bags. Samples were dried at 65°C and subsequently weighed for biomass. Aboveground biomass C content was assumed to be 50% of the oven dried mass.

2.4. Soil Pore Water Analyses

In Fall 2021, soil lysimeters (Soil Water Sampler, Soil Moisture Corp., Santa Barbara, CA) were installed at 30 cm depth to sample soil pore water following rain events. Lysimeter sampling was attempted approximately 24 hr after each rain event, but sample collection was not always possible due to low solute volumes. Sample collection occurred from November 2021 following the first rain event through January 2022 until collection was impossible due to decreases in soil moisture content. Following sample collection, dissolved organic carbon (DOC) and DIC were analyzed with a combustion oxidation nondispersive infrared absorption method on a total

dissolved C analyzer (varioTOC, Elementar, Hanau, Germany), with DIC calculated as the difference between acidified and non-acidified samples. Sample acidification to $\text{pH} < 2$ was performed by adding a small amount of pure hydrochloric acid (Tisserand et al., 2024). To quantify another metric of silicate weathering, soil lysimeter subsamples were also analyzed for calcium (Ca), magnesium (Mg), and sodium (Na) in triplicate via inductively coupled plasma optical emission spectroscopy (ICP-OES; Model Optima 5,300 DV, Perkin Elmer, Waltham, MA).

2.5. Automated Soil and Greenhouse Gas Flux Measurements

Surface fluxes of N_2O , CH_4 , and CO_2 were measured continuously during three complete growing seasons (October to June) from 2019 to 2022 using an automated chamber system. The system consisted of nine opaque, automated gas flux chambers (eosAC, Eosense, Nova Scotia, Canada) plumbed to a multiplexer (eosMX, Eosense, Nova Scotia, Canada). Each chamber was randomly deployed in a 10×10 m replicate plot, and plants were included in the soil collars and only trimmed to ensure complete chamber closure. The multiplexer allowed for dynamically signaled chamber deployment and routed gases to a cavity ring-down spectrometer (Model G2508, Picarro Inc., Santa Clara, CA, USA). Chambers were measured sequentially approximately every 2 hours, with a 10 min sampling period with a 1.5 min flushing period before and after each measurement. Chamber volumes were used to calculate the minimum detectable flux of $0.004 \text{ nmol N}_2\text{O m}^{-2} \text{ s}^{-1}$, $0.02 \text{ nmol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and $0.004 \text{ nmol CH}_4 \text{ m}^{-2} \text{ s}^{-1}$ (Nickerson, 2016).

Flux calculations and analyses were first performed using Eosense eosAnalyze-AC v. 3.7.7 software; data quality assessment and control were performed in R (RStudio, v.1.1.4633). Fluxes were removed from the final dataset if they were associated with erroneous spectrometer cavity temperature or pressure readings or if any gas concentrations were negative, corresponding to instrument malfunction. Fluxes were also removed if the chamber deployment period was less than 9 min or greater than 11 min, indicative of chamber malfunction. Calculated linear and exponential fluxes were compared using estimate uncertainty to estimate ratios, and in cases where both the linear and exponential models produced high uncertainty, the individual flux was eliminated from the dataset. Data filtering removed 8.7% of flux measurement periods, generating a final dataset of 47,762 simultaneous flux measurements of CO_2 , N_2O , and CH_4 . Daily mean flux values across years and treatments are presented in Figure S1 in Supporting Information S1. To convert flux measurements to CO_2e , we used the IPCC AR5 100 year GWP values of 28 CO_2e for CH_4 and 298 CO_2e for N_2O (Myhre et al., 2013).

2.6. Estimation of Weathering Rates and Net Ecosystem C Benefits

Bicarbonate production via enhanced weathering of basaltic minerals is largely dependent on Ca^{2+} and Mg^{2+} concentrations. As a conservative estimate to account for potential CO_2 production via carbonate (CaCO_3 , MgCO_3) precipitation, we assume 1 mol of CO_2 is converted to bicarbonate (HCO_3^-) per Ca^{2+} and Mg^{2+} produced via weathering (Beerling et al., 2018). The weathered metabasaltic material in this study was applied annually for 3 years at a rate of $37.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and contained 4.25%–6.46% Ca and 1.02%–4.14% Mg by mass (Table S2 in Supporting Information S1). During the study period, annual rainfall in this location varied from 266.7 to 548.2 mm yr^{-1} (1 mm is equivalent to $10,000 \text{ L ha}^{-1}$), with 266.7 mm yr^{-1} of rainfall during the lysimeter observation period (California Irrigation Management Information System, 2023). To calculate net rates of enhanced weathering, all rainfall was assumed to become soil water with similar DIC concentrations to our lysimeter observations. As this approach likely overestimates solute movement through the soil values should be treated with appropriate caution. We used the 2021–2022 value as an estimate for weathering rates during the other two growing seasons; since 2021–2022 was the lowest rainfall year of the study these should be considered conservative estimates.

We estimated the net ecosystem C benefit of each treatment after three growing seasons. This was done by combining annual changes in aboveground biomass, net changes in soil C stocks from the initial baseline, estimates of annual enhanced weathering rates, and measured or estimated changes in annual N_2O and CH_4 fluxes in CO_2e from the individual compost and GR treatment flux measurements. Changes in soil C stocks within blocks were calculated as the difference in soil C stocks at each depth (0–10, 10–20, and 20–30 cm) from prior to treatment application in Fall 2019 and the end of third growing season in Spring 2022 and converted to CO_2e values. As a first approximation of the changes in N_2O and CH_4 fluxes for combined treatments, we calculated the summed differences from both compost and/or GR only treatments relative to the control. It is important to

Table 2

Sum of the Mean Annual Changes in Aboveground Biomass Carbon (Mg C Ha⁻¹) by Treatment Relative to the Control During Each of the Three Growing Seasons, Net Change in Soil Carbon Stocks (Mg C Ha⁻¹) Relative to the Control at the End of the Third Growing Season, Sum of Total Carbon Dioxide (CO₂) Consumption by Enhanced Weathering (Mg CO₂ Ha⁻¹) After Three Growing Seasons, Greenhouse Gas (GHG) Reduction (Mg CO₂e ha⁻¹, Sum of Annual Changes in Methane (CH₄) and Nitrous Oxide Fluxes Relative to the Control), Change in CO₂e From Baseline (Mg CO₂e ha⁻¹, Sum of Changes per Treatment Since Prior to Amendment Additions), and Net Ecosystem Benefit Relative to the Control (Mg CO₂e ha⁻¹) by Treatment (CT: Control, CP: Compost, GR: Ground Rock, GR + CP: Compost and Ground Rock, GR + CP + BC: Compost, Ground Rock, and Biochar) After Three Growing Seasons

Treatment	Change in biomass C (Mg C ha ⁻¹)	Change in soil C (Mg C ha ⁻¹)	Weathering estimates (Mg CO ₂ ha ⁻¹)	Change in GHG emissions (Mg CO ₂ e ha ⁻¹)	Change in CO ₂ e from baseline (Mg CO ₂ e ha ⁻¹)	Net ecosystem benefit (Mg CO ₂ e ha ⁻¹)
CT	-	-8.3 ± 3.0	0.21 ± 0.01	-	+30.3 ± 11.0	-
CP	1.3 ± 0.4	2.0 ± 2.9	0.21 ± 0.01	0.20 ± 0.07	-8.1 ± 10.6	-38.4 ± 15.3
GR	-1.1 ± 0.2	-3.2 ± 2.6	1.02 ± 0.1	-0.06 ± 0.01	+13.9 ± 12.1	-16.3 ± 16.4
GR + CP	0.8 ± 0.4	6.0 ± 3.0	1.20 ± 0.07	<i>0.14 ± 0.01</i>	-20.2 ± 13.6	-50.5 ± 17.5
GR + CP + BC	0.7 ± 0.3	15.3 ± 4.8	2.01 ± 0.16	<i>0.14 ± 0.01</i>	-55.7 ± 22.4	-86.0 ± 24.7

Note. Numbers in italics represent estimated values based on the single amendment treatments.

recognize that these values may not capture the synergistic effects of combined amendments and are used here to capture likely order-of-magnitude scale impacts. Emissions associated with amendment production, transport, and application were not included, thus reported values should be considered net C benefit estimates from within ecosystem boundaries.

2.7. Calculations and Statistical Analyses

All statistical analyses, except for the linear mixed effects model, were performed using JMP Pro 15 (SAS Institute Inc., Cary, NC). Differences in treatment, year, total C, and inorganic soil C stocks, aboveground biomass, soil characteristics (soil moisture, soil pH, mineral N), lysimeter cation concentrations, and annual CO₂, CH₄, and N₂O fluxes were analyzed with two-way ANOVAs followed by post-hoc Tukey tests to account for variability across treatment blocks and identify differences across treatments within each treatment year. A linear mixed effects model was performed in *R* (Bates et al., 2015) to further explore effects of individual and combined treatments on total and organic soil C stocks across site years. Figures were created using ggplot2 in *R* (Wickham, 2009). Values reported in the text are means ± standard errors unless otherwise noted.

3. Results

3.1. Amendment Effects on Soil Organic C Stocks

The soil organic C in GR-only plots declined over 3-year study (-3.2 ± 2.6 Mg C ha⁻¹ yr⁻¹) but declines were less than observed in the control (Table 2). Soil organic C in the control plots also declined at a rate of -2.8 ± 3.0 Mg C ha⁻¹ yr⁻¹ for a total loss of -8.3 ± 3.0 Mg C ha⁻¹ after three growing seasons, significantly higher than the rate of C loss from the GR-only treatment (Figure 1, *p* < 0.01). All treatments with a compost addition (CP, GR + CP, GR + CP + BC) significantly increased total (0–30 cm) soil organic C stocks (2.0–15.3 Mg C ha⁻¹) relative to the control (Figures S1, S2 in Supporting Information S1, 0–10 cm: *p* < 0.001, 10–20 and 20–30 cm: *p* < 0.05). Only the GR + CP + BC treatment increased soil organic C stocks (15.3 Mg C ha⁻¹) greater than the total C added directly as organic amendments (compost: 9.2 Mg C ha⁻¹ and biochar: 3.3 Mg C ha⁻¹, total: 12.5 Mg C ha⁻¹). Soil C increased predominantly in the 0–10 cm depth except for the CP-only treatment where significant increases were largely at 10–20 cm (Figure S2 in Supporting Information S1, Table S4 in Supporting Information S1). The combined GR + CP + BC treatment had the highest observed increases in soil organic C stocks in the 30 cm profile (15.3 ± 4.8 Mg C ha⁻¹) relative to all other treatments by the end of the third growing season (Figure 1, bottom, Table S4 in Supporting Information S1, *p* < 0.01). Soil organic C stocks in the control and GR-only treatments decreased at 0–10 and 10–20 cm after three treatment years, with the GR-only treatment containing slightly higher soil C stocks at 20–30 cm (Figure S2 in Supporting Information S1, bottom left). Differences in soil organic C stocks across plots and over time were primarily driven by changes in soil C concentrations as bulk density did not vary significantly over time (Tables S4, S9 in Supporting Information S1).

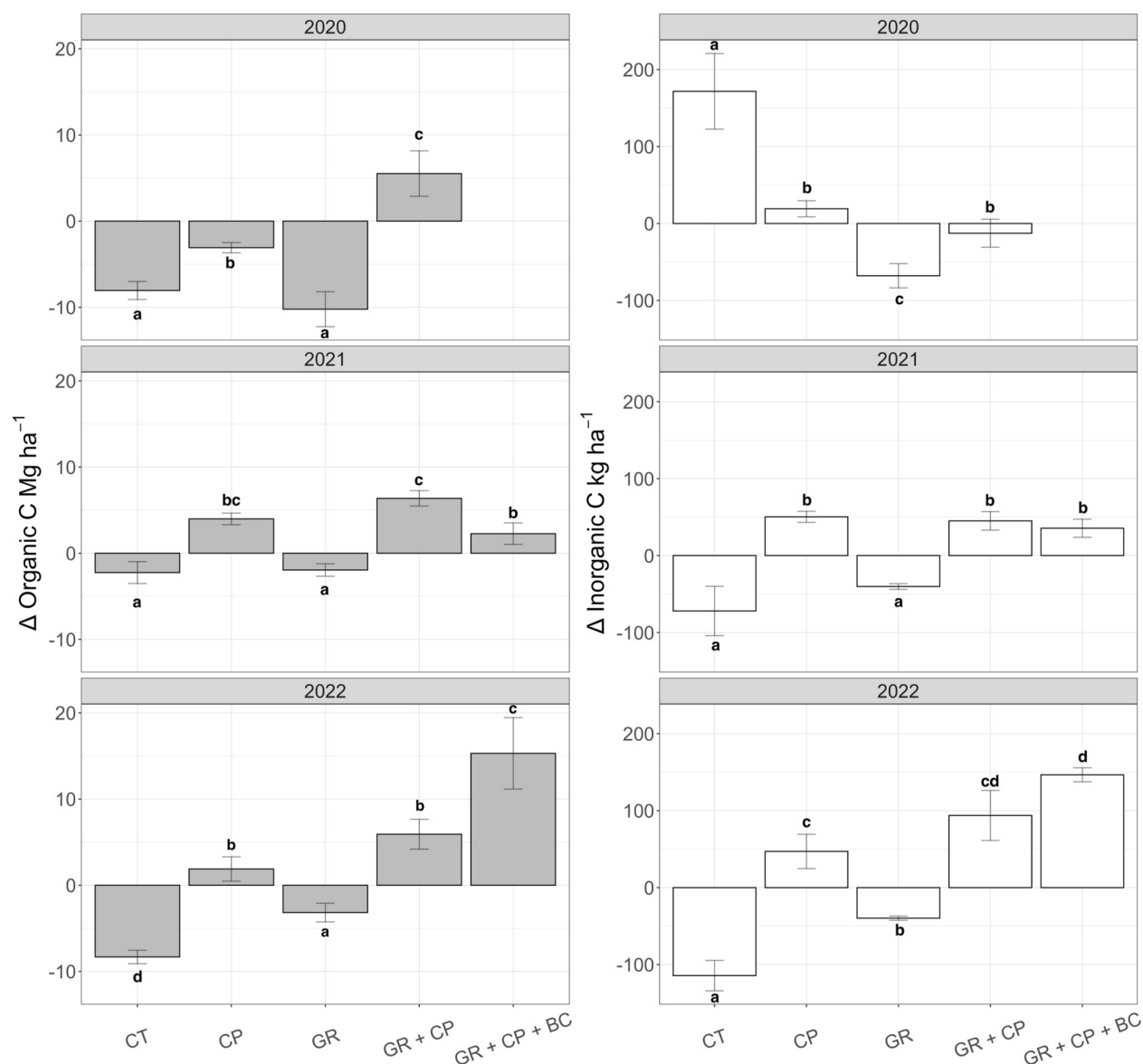


Figure 1. Change (Δ) \pm standard error in 0–30 cm annual total C (Mg C ha^{-1} , gray) and inorganic C stocks (kg C ha^{-1} , white) relative to initial 2019 baseline. Note the different units for total and inorganic C pools. Years (2020: top, 2021: middle, and 2022: bottom, represent the end of the growing season in each year. Treatment abbreviations include CP = compost, GR = ground rock, BC = biochar, and CT = control. Significant differences across treatments within years are denoted by letters (a, b, c, d).

The linear mixed-effects model incorporating treatment effects across all site-years suggested the CP-only treatment resulted in the largest increase in soil organic C, amounting to $3.0 \pm 0.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ more than the control ($p < 0.001$). The combined GR + CP + BC significantly increased soil organic C by a mean of $1.1 \pm 0.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ($p = 0.01$) over the 2-year observation period of this treatment. In contrast, the GR-only and GR + CP treatments did not significantly affect soil organic C, with values of $0.7 \pm 0.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ($p = 0.29$) and $0.5 \pm 0.7 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ($p = 0.50$), respectively. This high variability in soil C stocks in all treatments over time made it difficult to detect trends in these treatments.

3.2. Amendment Effects on Inorganic and Dissolved C Pools

Inorganic C stocks were low, amounting to 0.01%–0.04% of the soil organic C stocks (Table S5 in Supporting Information S1). After three years, the combined GR + CP + BC treatment exhibited greater increases in the inorganic C pool than all other treatments at 0–10 cm depth (Figure S2 in Supporting Information S1, bottom

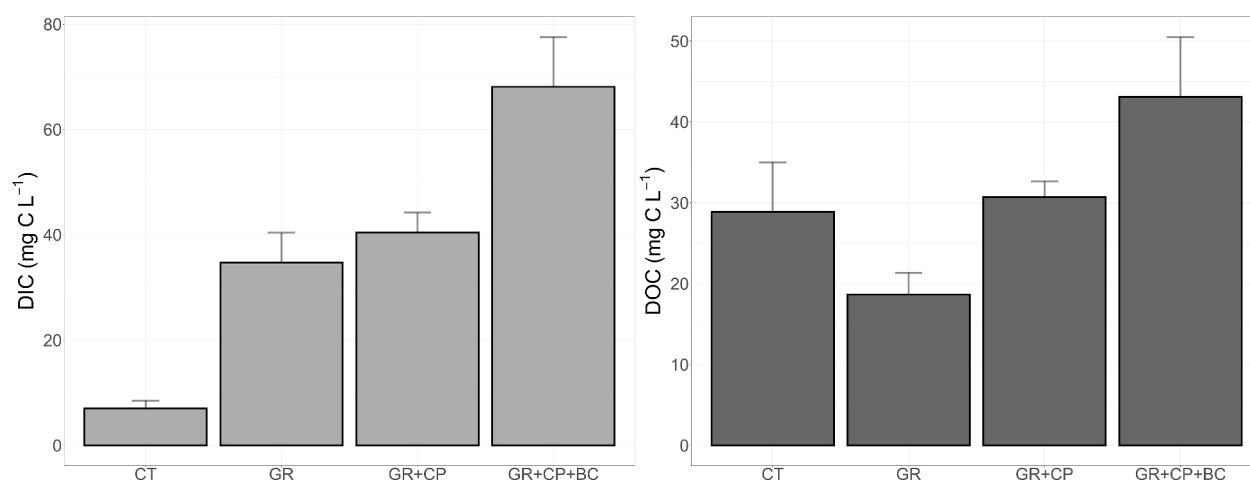


Figure 2. Mean (\pm standard error) of (left) dissolved inorganic (dissolved inorganic carbon) and (right) organic (dissolved organic carbon) in lysimeter samples for all sampled dates in the 2021–2022 growing season. Treatment abbreviations include CP = compost, GR = ground rock, BC = biochar, and CT = control.

right, $p < 0.001$). All treatments containing compost significantly increased soil inorganic C stocks at 10–20 cm after three growing seasons, and inorganic C stocks at 20–30 cm decreased in the GR + CP and the GR + CP + BC treatments (Figure S2 in Supporting Information S1, bottom right, $p < 0.01$). The control treatment had the largest increase in inorganic C stocks at 0–10 cm after one growing season ($p < 0.001$) but had significantly lower inorganic C stocks across all depths at the end of the third growing season ($p < 0.01$). The GR-only treatment consistently increased inorganic C stocks at 0–10 cm across all three growing seasons and had consistently lower inorganic C stocks at 20–30 cm across all years (Figure S2 in Supporting Information S1, right panels).

Ground rock treatments increased DIC in soil pore water. Lysimeter samples collected following rain events in the third year from all treatments containing GR (GR + CP, and GR + CP + BC) had significantly higher DIC concentrations than the controls (Figure 2, left, $p < 0.001$). The GR + CP + BC treatment exhibited significantly higher DIC concentrations relative to other GR treatments (GR-only, GR + CP, Figure 2, left, $p < 0.01$). The GR-only treatment exhibited significantly lower DOC concentrations relative to all other treatments, while the combined GR + CP + BC plots had significantly higher DOC concentrations relative to all other treatments (Figure 2, right, $p < 0.01$). When binned by sample date, the GR-only treatment significantly increased dissolved Mg relative to the control, and dissolved Na was higher in both GR-only and GR + CP treatments relative to the control (Table S10 in Supporting Information S1, $p < 0.03$).

3.3. Amendment Effects on Soil Greenhouse Gas Emissions

The GR-only treatment lowered annual N_2O emissions relative to the control across all three growing seasons by up to 0.01 ± 0.002 mg N_2O m⁻² d⁻¹ or 11 ± 1.1 kg CO_2e ha⁻¹ yr⁻¹ (mean 6.5 ± 1.6 kg CO_2e ha⁻¹ yr⁻¹ lower than control across three years, Figure 3, left, $p < 0.01$). The GR-only treatment also significantly increased CH_4 consumption in treatment years one and two by up to 0.18 ± 0.004 mg CH_4 m⁻² d⁻¹ or 18.5 ± 4.4 kg CO_2e ha⁻¹ yr⁻¹ (mean difference from control across years one and two: 13.3 ± 3.0 kg CO_2e ha⁻¹ yr⁻¹, Figure 3, middle, $p < 0.001$). In contrast, the CP treatment increased N_2O emissions by 0.02 ± 0.001 to 0.07 ± 0.003 mg N_2O m⁻² d⁻¹, or 25.0 ± 1.3 to 77.7 ± 4.3 kg CO_2e ha⁻¹ yr⁻¹ (mean difference from control: 60.0 ± 5.7 kg CO_2e ha⁻¹ yr⁻¹, Figure 3, left, $p < 0.001$) across all three growing seasons and significantly decreased the CH_4 sink in treatment years two and three (mean difference from control: 0.23 ± 0.004 mg CH_4 m⁻² d⁻¹ or 5.4 ± 0.3 kg CO_2e ha⁻¹ yr⁻¹, Figure 3, middle, $p < 0.001$). In the second and third growing seasons, soil CO_2 fluxes were significantly higher (1.88 ± 0.02 g CO_2 m⁻² d⁻¹ to 2.64 ± 0.02 g CO_2 m⁻² d⁻¹ or 20.0 ± 0.1 to 21.81 ± 0.1 Mg CO_2 ha⁻¹ yr⁻¹) in the CP treatment relative to both the control (13.2 ± 0.1 to 16.4 ± 0.1 Mg CO_2 ha⁻¹ yr⁻¹) and GR (14.5 ± 0.1 to 17.2 ± 0.1 Mg CO_2 ha⁻¹ yr⁻¹) treatments (Figure 3, right, $p < 0.001$). The GR treatment also had significantly greater soil CO_2 fluxes relative to the control (Figure 3, right, $p < 0.001$).

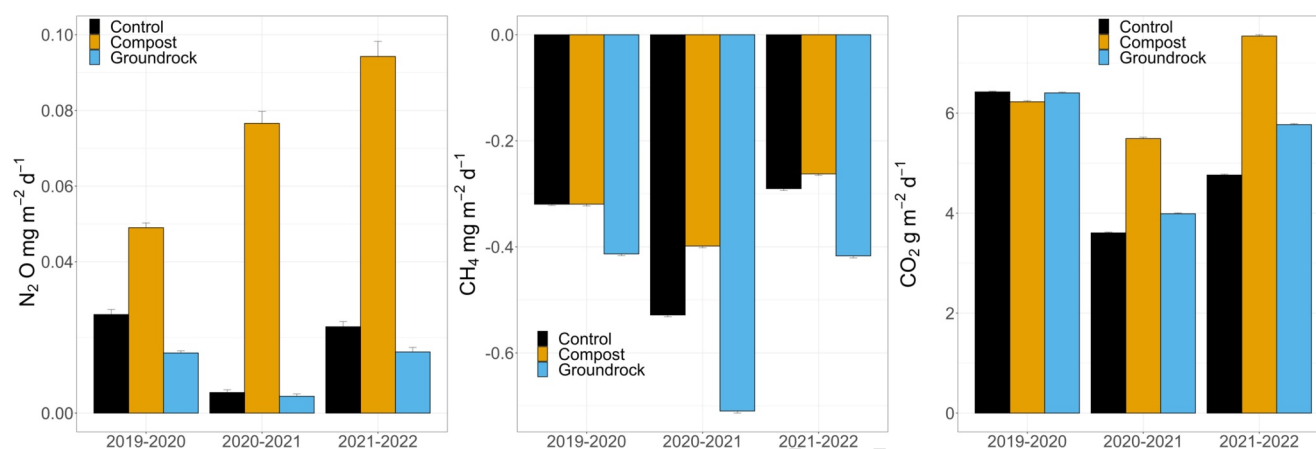


Figure 3. Annual mean (\pm standard error) nitrous oxide (N_2O $\text{mg m}^{-2} \text{d}^{-1}$, left), (b) methane (CH_4 $\text{mg m}^{-2} \text{d}^{-1}$, middle), and (c) carbon dioxide (CO_2 $\text{g m}^{-2} \text{d}^{-1}$, right) fluxes by treatment (compost = orange, control = black, and ground rock = blue) and across years (growing seasons: October - June).

3.4. Amendment Effects on Aboveground Biomass

All treatments containing compost amendments had significantly more aboveground biomass relative to control and GR-only treatments across years one and two (Table S6 in Supporting Information S1, $p < 0.05$). Aboveground biomass in all GR treatments were not significantly different than control treatments in years one and two, and all treatments with GR amendments were lower than control and CP-only treatments at the end of the third growing season (Table S5 in Supporting Information S1, $p < 0.05$). Treatments with combined GR and organic amendments had significantly higher aboveground biomass than the GR-only treatment in treatment years one (GR + CP) and two (GR + CP and GR + CP + BC) (Table S6 in Supporting Information S1, $p < 0.05$).

3.5. Amendment Effects on Soil pH and N Pools

Soil pH varied from 5.81 ± 0.06 in the control during the third treatment year to 7.09 ± 0.19 in GR + CP + BC at the end of the second treatment year (Table S6 in Supporting Information S1). The GR treatments significantly increased pH relative to the control and the CP only treatment in year 1 (Table S6 in Supporting Information S1, $p < 0.05$). After the second growing season, the combined GR + CP + BC treatment had a significantly higher pH than all other treatments, shifting the pH by more than 0.5 units from the control (Table S6 in Supporting Information S1, $p < 0.05$). In the final growing season, all treatments with amendments had significantly higher pH (0.14–0.22 units) than the control treatment at 0–10 cm (Table S7 in Supporting Information S1, $p < 0.01$). All treatments, except for the combined GR + CP + BC treatment, displayed significantly higher soil pH than the control treatment at 10–20 cm (Table S7 in Supporting Information S1, $p < 0.01$).

Overall, mineral N concentrations were low in surface soils (always $< 5.4 \mu\text{g N g}^{-1}$ soil) and averaged $2.59 \pm 0.44 \mu\text{g NO}_3^- \text{-N g}^{-1}$ soil and $2.26 \pm 0.25 \mu\text{g NH}_4^+ \text{-N g}^{-1}$ soil (Tables S6-S7 in Supporting Information S1). Amendments did not consistently alter mineral N availability over time relative to the controls in these soils, although there were some ephemeral differences. Soil NO_3^- concentrations at 0–10 cm were significantly higher in the CP only treatment relative to all other treatments at the end of the first growing season (Table S6 in Supporting Information S1, $p < 0.01$). In year two, soil NO_3^- concentrations were significantly higher across all treatments ($p < 0.05$) than other growing seasons but did not differ among treatments. During the third growing season NO_3^- concentrations were lower relative to other years (Table S6 in Supporting Information S1, $p < 0.05$). At the end of the third growing season NO_3^- concentrations at 0–10 cm were significantly lower in the GR-only treatment relative to the GR + CP + BC treatment (Table S7 in Supporting Information S1, $p < 0.05$). There were no statistically significant differences in NO_3^- concentrations between any treatment and the control at 10–20 or 20–30 cm at the end of the third growing season.

There were no differences in soil NH_4^+ concentrations at 0–10 cm depths at the end of the first growing season (Table S6 in Supporting Information S1). In year two, NH_4^+ concentrations were significantly higher in the CP only treatment relative to all other treatments except for the control (Table S6 in Supporting Information S1, $p < 0.05$). After three growing seasons, the combined GR + CP + BC had significantly greater NH_4^+

concentrations relative to the GR-only treatment ($p < 0.05$) but was not significantly different from any other treatments or the control (Table S7 in Supporting Information S1). Similar to NO_3^- , at the end of the third growing season NH_4^+ concentrations at 0–10 cm were significantly lower in the GR treatment relative to the GR + CP + BC treatment (Table S7 in Supporting Information S1, $p < 0.05$). After three growing seasons, the CP only treatment had significantly lower NH_4^+ concentrations relative to the control at 10–20 cm (Table S7 in Supporting Information S1, $p < 0.05$), with no differences across treatments at 20–30 cm depths (Table S7 in Supporting Information S1).

3.6. Estimation of Theoretical and Observed Dissolved Inorganic C Production

The weathered metabasaltic material in this study was applied annually for 3 years at a rate of $37.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and contained 4.25%–6.46% Ca and 1.02%–4.14% Mg by mass (Table S2 in Supporting Information S1). If completely weathered, this is equivalent to a CO_2 sequestration rate of $2.47 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ or a total of $7.42 \text{ Mg CO}_2 \text{ ha}^{-1}$ following three applications. Comparatively, this amounts to 13.2% of the largest increase in organic soil C stocks observed ($15.3 \text{ Mg C ha}^{-1} = 56.1 \text{ Mg CO}_2 \text{ ha}^{-1}$) in the combined GR + CP + BC treatment and roughly equivalent (101.1%) to relative changes in organic C stocks in the GR-only treatment ($2.0 \text{ Mg C ha}^{-1} = 7.34 \text{ Mg CO}_2 \text{ ha}^{-1}$).

The annual amount of CO_2 removal is likely less than this theoretical maximum. Annual rainfall was 266.7 mm yr^{-1} (California Irrigation Management Information System, 2023), and 1 mm of rainfall is equivalent to $10,000 \text{ L ha}^{-1}$ during the period of lysimeter measurement. Assuming all rainfall became soil water (a likely overestimate) with similar DIC concentrations to our lysimeter observations (Table S8 in Supporting Information S1), estimated rates of DIC production increased by 0.27 ± 0.06 , 0.33 ± 0.04 , and $0.60 \pm 0.09 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ for GR, GR + CP, and GR + CP + BC treatments, respectively (Table S8 in Supporting Information S1). This would amount to total CO_2 removal from DIC production over 3 years of by 0.81 ± 0.18 , 0.99 ± 0.12 , and $1.8 \pm 0.27 \text{ Mg CO}_2 \text{ ha}^{-1}$ for GR, GR + CP, and combined GR + CP + BC treatments, respectively. This amounts to 11%–24% of the maximum weathering potential estimate above.

3.7. Estimation of Net Ecosystem CO_2e Benefits of Single and Combined Amendments

The combined GR + CP + BC treatment had the largest potential net ecosystem CO_2e benefit after three growing seasons (Table 2, $p < 0.01$). The control and GR-only treatments lost an equivalent soil C of $30.3 \pm 11.0 \text{ Mg CO}_2\text{e ha}^{-1}$ ($-8.3 \pm 3.0 \text{ Mg C ha}^{-1}$) and $13.9 \pm 12.1 \text{ Mg CO}_2\text{e ha}^{-1}$ ($-3.2 \pm 2.6 \text{ Mg C ha}^{-1}$), respectively, after three growing seasons (Table 2). However, all soil amendment treatments exhibited significant positive net ecosystem C benefits (net reduction in CO_2e) relative to the control (Table 2, $p < 0.01$). The changes in N_2O and CH_4 emissions from the GR-only and CP-only treatments were used to provide a first approximation of greenhouse gas fluxes from the GR + CP and GR + CP + BC combined treatments. While we recognize that these greenhouse gas fluxes may not be additive, it is noteworthy that the *uncertainty* in the organic C pool alone was greater than the effect of greenhouse gas emissions on the net CO_2e in any of the treatments.

Combining organic and inorganic amendments increased the net ecosystem CO_2e benefit by 34.2 ± 17.0 for GR + CP and $69.7 \pm 20.1 \text{ Mg CO}_2\text{e ha}^{-1}$ for GR + CP + BC relative to the GR-only treatment (Table 2). Combined amendments also exhibited less variability than GR-only. While net ecosystem benefits from a one-time organic amendment are likely to decline over time, even a 50% reduction in the soil C sequestered ($17.1 \text{ Mg CO}_2\text{e ha}^{-1}$ for GR + CP and $16.7 \text{ Mg CO}_2\text{e ha}^{-1}$) from the compost treatment would still result in a greater net C gain than the maximum potential CO_2 sequestered ($7.4 \text{ Mg CO}_2 \text{ ha}^{-1}$) from complete weathering of three annual GR applications.

Emissions associated with amendment production, transport, and application were not included, although these processes typically involve fossil fuel use and energy consumption, which contribute to the overall carbon footprint of amendment application. However, it's important to note that there are ongoing efforts and potential strategies to minimize these life cycle emissions that are outside the scope of this study. Therefore, reported values should be considered net C benefit estimates from within ecosystem boundaries.

3.8. Regional Climate Mitigation Potential

We performed a simple upscaling exercise to quantify the climate mitigation potential of the rangeland area that could be amended with the materials available by 2050 within California (Di Vittorio et al., 2024). This amounted to an area of approximately 1.8 million ha, equivalent to 50% of privately held California rangelands and 8% of California's rangeland area overall (Forest and Rangeland Resources Assessment Program, 1988). Based on results from this study, three annual GR-only applications across 1.8 million ha of California rangelands would result in a net CO₂e benefit (reduction or reversal of soil C loss alongside inorganic C sequestration and N₂O and CH₄ reduction) of -9.8 ± 9.9 Mt CO₂e y⁻¹ with considerable uncertainty. The addition of a one-time organic compost (GR + CP) or a one-time organic compost and biochar (GR + CP + BC) application alongside the inorganic amendments would increase this to -30.4 ± 10.5 Mt CO₂e y⁻¹ and -51.7 ± 14.9 Mt CO₂e y⁻¹, respectively. Over 3 years the net benefit from combined amendments would be -91.2 ± 31.2 (GR + CP) to -155.1 ± 44.6 (GR + CP + BC) Mt CO₂e. Even assuming 50% of the benefits from a single organic amendment (CP or CP + BC) addition are lost over time, this still represents a net climate benefit of -45.5 Mt CO₂e and -77.6 Mt CO₂e from the addition of compost or compost plus biochar to the GR amendment, respectively.

4. Discussion

4.1. Ground Rock Effects on Ecosystem C Pools and Fluxes

The application of GR amendments to stimulate enhanced weathering is gaining momentum as a potential CO₂-removal technology in working lands (Almaraz et al., 2022; Calabrese et al., 2022; Kantola et al., 2017, 2023). However, few field studies on this technology exist and we know of no other field-scale studies conducted in grasslands. Grasslands represent an important potential option for enhanced weathering projects because of the large land area and ease of rock application due to the absence of row crops. In this study, we found that increases in DIC and the increases in soil inorganic C in GR-amended treatments confirmed the occurrence of enhanced mineral weathering. The combined GR + CP + BC treatment exhibited the highest concentrations of DIC, suggesting this treatment had the highest rates of weathering during the sample collection period. The decomposition of soil organic matter may have also contributed a significant proportion of soil water DIC (Sveinbjörnsdóttir et al., 2020) with Enhanced rock weathering (ERW) increasing conversion of dissolved CO₂ produced via soil respiration to bicarbonate and thus stable DIC. The combined GR + CP + BC treatment contained significantly higher DOC concentrations, suggesting increased organic matter availability and decomposition may be a significant contributor to the observed increases in DIC concentrations in compost- and biochar-amended treatments. Alternatively, a shift in pH can facilitate both carbonate formation and persistence within the soil environment (Haque et al., 2020), corresponding to the increases in TIC observed in the combined GR + CP + BC treatment. Both biochar and enhanced weathering can increase soil pH, and the largest increases in soil pH across all depths occurred in the combined treatment.

We calculated a conservative weathering rate to estimate annual bicarbonate production using measured soil and environmental conditions. Estimated enhanced weathering rates associated with GR amendments were net sinks of CO₂ at the ecosystem scale. The rangelands in this study have significant interannual variability in precipitation, therefore it is likely that the amount of CO₂ removal is less than this theoretical maximum in drier years. This was corroborated by our annual enhanced weathering estimates from our lysimeter measurements, which were only 4.6%–9% of the theoretical maximum. Weathering did not completely remove the applied material over one growing season or even after three growing seasons. Other field observations have measured enhanced weathering rates that are significantly lower than lab incubations (Dietzen et al., 2018) or modelling estimates (Calabrese et al., 2022). Here, unweathered GR material was observed at the end of the final growing season, further corroborating incomplete rock weathering. It is also worth noting that annual rainfall during the lysimeter monitoring period was the driest on record (California Irrigation Management Information System, 2023), thus our estimates of enhanced weathering rates from this growing season are likely conservative for this region.

Determining the ultimate fate of CO₂ sequestered as bicarbonate through enhanced mineral weathering is difficult. There are several alternative potential pathways for the fate of bicarbonate, some of which may not result in effective CO₂ sequestration. For example, bicarbonate stored in groundwater may be returned to the atmosphere if this groundwater is used for irrigation (Macpherson, 2009). Bicarbonate may also be lost from solution through shifts in speciation to CO₂ through decreases in soil and/or groundwater pH or decreases in solubility through increases in temperature. Potential plant uptake of either bicarbonate or associated cations (Ca²⁺, Mg²⁺)

may also affect the potential fate of bicarbonate (Bertagni & Porporato, 2022; Calabrese et al., 2022). Other alternative fates of bicarbonate-rich water should also be considered and quantified, including losses in stream connectivity and/or potential evaporation when determining net CO₂ sequestration from enhanced mineral weathering.

4.2. Total Soil C Pools and Ecosystem Productivity

Increases in net ecosystem C benefits across treatments were largely driven by changes in soil organic C stocks. The combined amendment of GR + CP + BC exhibited the largest increase in total soil C stocks of $15.3 \pm 4.8 \text{ Mg C ha}^{-1}$ in the top 0–30 cm over three years, confirming our hypothesis. Relative to the background losses from the control by the final year of the experiment, the soil C gain in the treatments with compost and biochar additions were the only treatments that exceeded the C added directly from the organic amendments ($12.5 \text{ Mg C ha}^{-1}$), likely through increases in plant productivity (Mayer & Silver, 2022; Ryals & Silver, 2013). The control treatment consistently lost soil C over the experiment, possibly associated with drought conditions the region experienced that spanned multiple growing seasons during this experiment (Liu et al., 2022), or the long-term decline in soil C following the invasion of annual grasses at the site (Chou et al., 2008). As background conditions were associated with soil C losses over time, the measured increase in soil C stocks of 2.0 ± 2.9 to $15.3 \pm 4.8 \text{ Mg C ha}^{-1}$ in the treatments with compost from 2019 is equivalent to a net change of 10.2 ± 3.1 to $23.6 \pm 6.2 \text{ Mg C ha}^{-1}$ relative to the control. Soil C increases in the CP-only treatments were somewhat lower than observed in a previous study at a nearby field site, although that study added twice the amount of compost than the current treatment (Ryals et al., 2014). The drought conditions during this experiment also likely limited soil moisture leading to lower net primary production than reported in previous research at the site (Ryals et al., 2016). Still, the one-time compost additions increased plant productivity; all treatments containing compost yielded greater aboveground biomass relative to the control in years one and two by 0.3 ± 0.1 to $1.1 \pm 0.3 \text{ Mg C ha}^{-1} \text{ y}^{-1}$, respectively. This increase in net primary productivity was likely driven by structural and chemical changes to the soil environment that resulted in N availability sustained even years following amendment application (Brinton, 1985; Kutos et al., 2023; Ryals et al., 2016; Ryals & Silver, 2013; Shiralipour et al., 1992). Both compost and biochar production divert materials from organic waste streams where a significant proportion of this photosynthetically derived C would otherwise be released back to the atmosphere as CO₂ or CH₄ (DeLonge et al., 2013; Pérez et al., 2023; Vergara & Silver, 2019). Therefore, any relative increase in the soil C stock in treatment plots represents a net C sink from the atmosphere. Soil CO₂ production resulting directly from compost or biochar decomposition was derived from recently fixed C and therefore is generally not considered as an additional emissions source.

After three treatment years, aboveground biomass was significantly lower than the control in all treatments containing GR amendments. This is in contrast to cropland systems that have observed increased aboveground biomass following GR applications (Kantola et al., 2023; Skov et al., 2024). Ground rock applications in this experiment were applied annually to the soil surface; as grasslands are rarely tilled, rock amendments were not incorporated into the soil as often occurs in other agricultural systems (Dietzen et al., 2018; Kelland et al., 2020). The presence of accumulated GR at the soil surface, or disturbance of litter cover following application may have decreased seedling density and annual grass emergence (Vanderburg et al., 2020). Biochar may have both positive and negative effects on seed germination rates (Duan et al., 2024). The lack of an aboveground biomass response from the treatment with biochar was unexpected as biochar is thought to enhance nutrient availability, although the lack of a growth response in grasslands has been observed elsewhere (Reed et al., 2017). Additive effects of nutrient and organic matter additions through compost and biochar amendments (Joseph et al., 2021; Kutos et al., 2023) improved weathering rates from combined compost and GR amendments (Di Vittorio et al., 2024), possible changes in belowground allocation, and/or pH buffering from GR and biochar (Shi et al., 2017) likely explain why the largest increases in aboveground biomass were observed in the combined GR + CP + BC treatment.

4.3. Amendment Effects on Soil Greenhouse Gas Emissions

One of the potential co-benefits of GR amendments is a decrease in N₂O emissions, although few, if any, studies have made continuous measurements of all three greenhouse gases in enhanced weathering experiments in the field (Kantola et al., 2023). Here, we measured both a decrease in N₂O emissions and an increase in atmospheric CH₄ oxidation. The measured decreases in CH₄ and N₂O fluxes in the GR treatment were equivalent to

$-20 \pm 7 \text{ kg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$. The GR-only treatment had 30% lower N_2O fluxes relative to the control. If a similar effect occurred in the combined GR + CP and GR + CP + BC treatments this could offset a significant portion of the increase in N_2O emissions associated with CP-only treatments, potentially helping to mitigate greenhouse gas emissions associated with compost amendments. This reduction in N_2O emissions was likely driven by shifts in soil pH toward more neutral conditions (Abalos et al., 2020; Kantola et al., 2017), or potentially increases in nutrient availability, such as copper which is important both for methanotrophic metabolism (Semrau et al., 2010) and for the activity of N_2O reductase that may facilitate more complete denitrification (Chang et al., 2022). Increases in soil pH also likely stimulated the observed increases in CH_4 consumption in the GR treatment in the first two growing seasons, as optimal CH_4 consumption is generally observed at near-neutral pH values (Reddy et al., 2020). Increases in soil pH from GR additions may have also stimulated microbial activity by reducing pH stresses (Fuentes et al., 2006). Additionally, the GR-only treatment had significantly higher ecosystem CO_2 fluxes relative to the control treatment in treatment years two and three, equivalent to 0.14 ± 0.01 to $0.37 \pm 0.01 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$. It is impossible to separate plant and microbial soil respiration with and abiotic sources of soil CO_2 fluxes measured in this study. However, aboveground biomass in the GR treatments was consistently similar to or significantly lower than the control, suggesting that the increase in CO_2 flux was not from respiration associated with increased plant biomass and may instead represent a stress-response of plant or microbial respiration (Crowther et al., 2015). Soil CO_2 uptake from initial weathering reactions may consume CO_2 relatively quickly, especially with finely ground minerals. However, carbonate precipitation may occur over longer timescales and is dependent on soil environmental conditions (Knapp & Tipper, 2022), thus potentially separating CO_2 uptake and potential CO_2 release associated with carbonate precipitation over time. Unweathered GR material was also observed at the end of the final growing season. This finely GR layer may have acted like a cap on the soil surface, similar to biocrusts that can retain soil moisture and increase the occurrence of conditions favorable to microbial respiration (Chamizo et al., 2013).

The combined decrease in CH_4 oxidation and slightly higher N_2O production from the CP treatment were equivalent to $0.20 \text{ Mg CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$. Changes in soil N_2O emissions following compost application were likely derived from organic N inputs and subsequent mineralization. The majority of N_2O emissions from all treatments were characterized by short-term hot moments of emissions (Anthony & Silver, 2021) following rain events during the wet season when soil moisture is typically high (Figure S1 in Supporting Information S1) suggesting denitrification as the main pathway of N_2O production in these systems. The CP treatments increased annual soil respiration by 22%, likely from a combination of increased autotrophic respiration from greater plant growth and direct decomposition of this organic material. Aboveground biomass increased by an average of 30% annually relative to controls in the CP plots. Biogenic emissions from compost decomposition are generally considered to have no net global warming effect as CO_2 emissions from biological systems are considered to cycle rapidly (Christensen et al., 2009; Rabl et al., 2007; Vergara & Silver, 2019). By using compost as a soil amendment, compost-associated C can be kept out of the atmosphere for longer periods of time than if non-composted organic matter were left to decompose naturally, slowing or limiting the return of this C to the atmosphere as CO_2 and CH_4 . Observed increases in soil respiration were similar to those observed previously in nearby compost-amended grasslands (Ryals & Silver, 2013). Methane consumption in CP plots was consistently lower than the control in the second and third growing seasons following compost application. Soil pH was generally lower, but not consistently, in CP plots, and higher NH_4^+ concentrations suggest that increased NH_4^+ concentrations may have inhibited CH_4 oxidation (Schnell & King, 1994).

4.4. Regional Climate Mitigation Potential

Rangelands globally have lost soil C due to management (Sanderman et al., 2017). In California, grasslands have been losing soil C on multidecadal timescales, likely driven by climate change and the invasion of non-native annual grasses in the 1800s that exhibit shallower, less extensive root systems (Chou et al., 2008; Koteen et al., 2011). Soil management practices that slow or reverse these losses in soil C provide a net climate benefit by reducing emissions and/or sequestering additional soil C. Recent modeling estimates of the potential for enhanced weathering-related inorganic C sequestration for the same 8% of California's rangeland area were on the order $6.6 \pm 4.8 \text{ Mt CO}_2\text{e y}^{-1}$ (Di Vittorio et al., 2024). This is approximately half of our net CO_2e upscaling estimates for GR-only application ($-16.3 \pm 16.4 \text{ Mt CO}_2\text{e y}^{-1}$). The addition of an organic C source (compost and/or biochar) with GR significantly increased the net climate benefit due to higher rates of soil organic C sequestration and greater estimated rates of ERW. Much of this benefit is from slowing decreases losses of organic soil C,

although there was significant variability in changes in organic C stocks in the GR-only treatment. If applied to 50% of privately held California rangelands, our estimates suggest a potential net CO₂e benefit of -30.4 ± 10.5 and -51.7 ± 14.9 Mt CO₂e y⁻¹ for the addition of compost (GR + CP) and compost and biochar (GR + CP + BC) together with GR amendments, respectively. When accounting for CO₂e associated with C added from compost and biochar amendments, GR + CP and GR + CP + BC still increase the net CO₂e benefit by -7.9 and -29.2 Mt CO₂e over the 3-year period, respectively. This highlights the significant additive climate mitigation potential of applying combinations of organic alongside inorganic amendments on California rangelands.

5. Conclusions

Together our findings suggest that adding GR with compost and biochar as a mixed amendment produced the largest increases in soil C stocks and potential C sequestration rates in grassland ecosystems. By conducting side by side, multi-year field experiments with separate and combined amendments we found that GR amendments alone do not necessarily result in high rates of inorganic C cycling over 3 years. Lower N₂O and CH₄ emissions in the GR treatments may potentially mediate increases in greenhouse gas emissions from compost in mixed amendments, although total CO₂e fluxes of N₂O and CH₄ were two to three orders of magnitude lower than associated changes in organic C stocks. In this study the enhanced weathering associated sink of inorganic C was estimated to only represent a maximum of 4% of the total ecosystem CO₂e benefit (emissions reductions plus organic C sequestration). Furthermore, it is important to note that lifecycle emissions from generating soil amendments, transporting them, and land applying, as well as emissions reduced by diverting high-emitting waste streams must be considered when estimating the full climate change impact of these practices. Future work on the molecular-scale dynamics of mixed organic and inorganic amendments, as well as effects on microbial communities will help determine specific interactions of these amendment in soils.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

[Dataset] All data (greenhouse gas fluxes, soil C stocks, and soil chemistry metrics) have unrestricted access in a Dryad database: <https://doi.org/10.5061/dryad.r2280gbnm> [Software] All associated R data processing and analysis scripts are found with unrestricted access in a Zenodo database: <https://doi.org/10.5281/zenodo.14172113>.

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