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Long-term climate change mitigation potential with organic matter management on grasslands

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Abstract

Compost amendments to grasslands have been proposed as a strategy to mitigate climate change through carbon (C) sequestration, yet little research exists exploring the net mitigation potential or the long-term impacts of this strategy. We used field data and the DAYCENT biogeochemical model to investigate the climate change mitigation potential of compost amendments to grasslands in California, USA. The model was used to test ecosystem C and greenhouse gas responses to a range of compost qualities (carbon to nitrogen [C:N] ratios of 11.1, 20, or 30) and application rates (single addition of 14 Mg C/ha or 10 annual additions of 1.4 Mg $\mathrm{C{\cdot}ha^{-1}{\cdot}yr^{-1}}$). The model was parameterized using site-specific weather, vegetation, and edaphic characteristics and was validated by comparing simulated soil C, nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) fluxes, and net primary production (NPP) with three years of field data. All compost amendment scenarios led to net greenhouse gas sinks that persisted for several decades. Rates of climate change mitigation potential ranged from 130 ± 3 g to 158 ± 8 g $\mathrm{CO_2\text{-}eq{\cdot}m^{-2}{\cdot}yr^{-1}}$ (where “eq” stands for “equivalents”) when assessed over a 10-year time period and 63 ± 2 g to 84 ± 10 g $\mathrm{CO_2\text{-}eq{\cdot}m^{-2}{\cdot}yr^{-1}}$ over a 30-year time period. Both C storage and greenhouse gas emissions increased rapidly following amendments. Compost amendments with lower C:N led to higher C sequestration rates over time. However, these soils also experienced greater N_2O fluxes. Multiple smaller compost additions resulted in similar cumulative C sequestration rates, albeit with a time lag, and lower cumulative N_2O emissions. These results identify a trade-off between maximizing C sequestration and minimizing N_2O emissions following amendments, and suggest that compost additions to grassland soils can have a long-term impact on C and greenhouse gas dynamics that contributes to climate change mitigation.

Introduction

Grasslands are geographically expansive and store approximately one-third of the terrestrial soil organic carbon (C) pool (Lal 2004). However, soil degradation is widespread in grasslands and has resulted in significant soil C losses (Bai et al. 2008). Grassland restoration efforts targeted at reducing or preventing soil degradation have the additional benefit of climate change mitigation if soil C stocks increase (Lal 2004, Soussana et al. 2004, Sanderman and Baldock 2010). In general, management practices that increase plant production are associated with greater soil C stocks (Conant et al. 2001, Follett 2001). Soils amended with organic matter have been shown to increase plant production by enhancing nitrogen (N) and water availability (Derner and Schuman 2007, Albaladejo et al. 2008, Ryals and Silver 2013). Organic matter amendments add C directly to the soil, some of which may remain in stable pools (Lynch et al. 2005, Cabrera et al. 2009, Ryals et al. 2014). Moreover, organic matter amendments can contribute to greenhouse gas offsets such as avoided methane (CH_4) emissions from the diversion of organic wastes from landfills or slurry ponds (DeLonge et al. 2013).

Organic matter amendments may also increase greenhouse gas emissions from grassland soils (Dalal et al. 2003, Gregorich et al. 2005). These amendments typically increase soil N availability (Gagnon et al. 1998, Conant et al. 2005) and may stimulate nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching (Chang et al. 1998, Bouwman et al. 2002) or suppress CH_4 uptake (Bodelier and Laanbroek 2004). Enhanced emissions can decrease the net value of organic matter amendments as a climate change mitigation strategy.

Long-term studies (>20 years) of the effects of organic matter additions on soil C storage and greenhouse gas emissions are lacking in grasslands, but data from cropping systems suggests that C sequestration rates can persist for many years following amendments (Blair et al. 2006, Bhogal et al. 2009). The ultimate impact of organic matter amendments is likely to be strongly influenced by application rate and chemical quality of the material (Burke et al. 2013). Fresh, slurried, or dried livestock manures are common amendments, but these have been associated with high N_2O emissions (Davidson 2009). Composted organic material is becoming a more common amendment. Compost has already undergone partial decomposition, which tends to produce more recalcitrant organic matter with higher C:N ratios than an equal amount of fresh plant litter or animal manures (Powlson et al. 2012, Zhang et al. 2012).

In this study, we assessed the net climate change mitigation potential of compost additions to grasslands. We used the DAYCENT ecosystem model to simulate changes to soil greenhouse gas fluxes (N_2O, CH_4, and heterotrophic soil respiration) and ecosystem C stocks following a single application of composted green waste to grazed grasslands in California, USA (see *Materials and methods: DAYCENT model description*). Results from simulations were compared to data from a three-year field experiment exploring the effects of a single addition of compost to net ecosystem production (Ryals and Silver 2013) and soil C dynamics (Ryals et al. 2014). The model was then used to evaluate the net long-term climate change mitigation potential of a range of compost amendment scenarios that differed in application intensity, frequency, and chemical quality. The DAYCENT model has been applied widely for assessments of agricultural soil C sequestration, but contributions from grazed grassland systems are currently limited (Ogle et al. 2007).

Materials and Methods

DAYCENT model description

The DAYCENT model is the daily time step version of CENTURY, a model used to simulate ecosystem C, N, S, and P dynamics (Parton et al. 2001). CENTURY and DAYCENT are widely used biogeochemical models first developed for grasslands and since used for a variety of ecosystem types (Kelly et al. 2000, Del Grosso et al. 2002, Li et al. 2006, Parton et al. 2007). These models were developed to simulate changes to ecosystem C and nutrient dynamics and plant productivity in response to changes in land management and climate (Parton et al. 1994). The DAYCENT model simulates soil fluxes of CO_2, CH_4, and N_2O at daily timescales and is used to assess regional to global-scale greenhouse gas inventories (e.g., EPA 2012). The model contains interacting submodels of soil organic matter cycling, waterflow, denitrification, nitrification, and phosphorus dynamics. We used DAYCENT_UV, a version of the model derived from DAYCENT version 4.5, which explicitly simulates photosynthesis as well as photodegradation of surface litter (*available online*).[4]

Site descriptions

We parameterized the model using data collected from field experiments in valley and coastal grasslands, two dominant grassland types in California, USA. The valley grassland site was located in the Sierra Nevada foothills, with mean annual precipitation of 730 mm/yr (22-yr mean) and seasonal temperatures ranging from 2°C in January to 35°C in July. The coastal grassland site was located in the north-central coast of California, with mean annual precipitation of 950 mm/yr (38-yr mean), and seasonal temperatures ranging from 6°C in January to 20°C in July. Both grassland types are dominated by typical vegetation for the region, which consists primarily of non-native annual grasses, though native perennial bunchgrasses are also present at the coastal grassland.

Three replicate blocks were established at each grassland type with treatments consisting of a one-time compost application and non-amended control plots (25 × 60 m). Ecosystem data were collected for three years (September 2008–August 2011) following the single surface application of composted green waste in December 2008 (14 Mg C/ha; C:N = 11.1). Annual field data collection included aboveground net primary production (ANPP), belowground net primary production (BNPP) to 20-cm depth, plant C and N concentrations, and soil C and N content to a depth of 1 m. Soil trace gas fluxes (CO_2, CH_4, and N_2O) were measured weekly to monthly using an infrared gas analyzer (LI-8100, LICOR Biosciences, Lincoln, Nebraska, USA) for CO_2 and static flux chambers and gas chromatograph for N_2O and CH_4. Soil texture and bulk density were measured and not affected by the compost addition. All field data collection included replicate sampling within plots to capture spatial variation. Detailed site descriptions and data collection methodology are available in Ryals and Silver (2013).

For modeling purposes, we used three site characterizations defined by differences in climate and soil texture that expands the range of conditions present throughout the field study sites. The valley grassland was represented as one site characterization, as there were no significant differences in ecosystem characteristics and management responses between blocks at this site (Ryals and Silver 2013). These model simulations are referred to as “valley.” The coastal grassland study site, on the other hand, was represented by two site characterizations to capture a significant difference in soil texture of one of the replicate blocks (Ryals and Silver 2013). Simulations referred to as “coastal sandy loam” represent site conditions from the coastal grassland block with sandy loam soils. Simulations referred to as “coastal loam” represent average site conditions from the other two coastal blocks, which did not differ significantly in edaphic characteristics. Results from model simulations were reported as the mean and standard deviations of these three site characterizations and are intended to represent the range of ecosystem C and greenhouse gas responses to management of grazed annual grasslands, ecosystem types that are underrepresented in both empirical and modeling studies (Ogle et al. 2007).

Model parameterization and evaluation

There are more than 1000 interacting parameters in DAYCENT, but only a small subset is needed to calibrate the model to site-specific conditions (Parton et al. 1998, 2001). Required abiotic drivers for the DAYCENT model consist of daily precipitation and daily minimum and maximum air temperatures. Solar radiation, wind speed, and relative humidity were used as additional abiotic drivers at the valley grassland where data were available. For valley grassland simulations, weather data from 1990 to 2012 were acquired from a local station (Browns Valley, #84), which is part of the California Irrigation Management Information System (CIMIS) located <2 km northwest of the study site (data *available online*).[5] For coastal grassland simulations, local precipitation data from 1980–2012 were acquired <2 km from the site at the Nicasio Town Station from Marin Municipal Water District (J. Klein, *personal communication*). Daily maximum and minimum air temperature was estimated using Daymet from 1 × 1 km pixel using latitude and longitude of the study plots (Thornton et al. 2012; data *available online*).[6] Most soil input variables (texture, bulk density, and pH) were measured at each field site. Field capacity, wilting point, and saturated hydraulic conductivity were estimated using algorithms based on soil texture (Saxton et al. 1986). Plant characteristics were established for a C_3 perennial grass and a C_3 annual grass growing in a Mediterranean climate. Perennial grass parameters were used to initialize the model until 1750, at which point the plant type was switched to annual grass to reflect the vegetation shift observed in the region (Biswell 1956, D'Antonio 2007). Model equilibration consisted of a period with perennial grass and light grazing (between years 0 and 1750), a period with annual grass and moderate grazing representing the widespread shift in vegetation due to introduction of European grasses and cattle (between the years 1750 and 1900), and a period of modern cattle grazing with annual grasses (between the years 1900 and 2007).

Once sites were characterized, the model was evaluated using published values from similar ecosystems (e.g., Chou et al. 2008, Silver et al. 2010) and observed values from control plots from 2008–2012. Once the vegetation input parameter values (e.g., potential growth rate and root fraction) were optimized to represent annual grass physiology, they remained unchanged in later simulations. The same vegetation parameters were used for all three site characterizations. Simulated values were generally similar to measured values, and the magnitude and direction of soil C change with organic matter amendment was similar between measurements and simulations (Del Grosso et al. 2005).

Simulated management scenarios

Our model simulations tested compost application intensity and quality on ecosystem C storage, soil greenhouse gas emissions, and net climate change mitigation potential. Two types of compost application intensities were simulated: a one-time surface application of 14.27 Mg C/ha (equivalent to 70 Mg dry mass/ha, the amount and intensity applied in the field experiment) and annual applications of 1.427 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ for 10 consecutive years. This approach allowed for the total amount of amendment C and nutrient inputs over a decade to be held constant while exploring the difference between the lasting effects of acute vs. chronic C and nutrient additions. Compost application was initiated in the model using the organic matter addition function (OMAD), which includes information about the compost C content, C to nutrient ratios, and lignin content. This function also indicates which soil organic matter pools in the model the amendment is added to. In these simulations, composted material was added to the surface slow pool (i.e., som2c(1)) to mimic partially decomposed organic material. The OMAD function was modified to add the compost either with or without a simulated isotopic label. Labeling allowed us to trace the decomposition of compost through time by tracing the extinction of the added label from the som2c(1) pool. Further, labeling the compost input allowed us to distinguish between direct additions of C from the compost vs. increases in ecosystem C due to NPP and soil C storage.

To test a range of compost qualities, we adjusted the C:N ratio from 11.1 (S11, a single addition of compost consisting of a C:N of 11.1 as in the field experiment), to 20 (S20), and to 30 (S30). These conditions represent a range of suggested C:N ratios for finished compost depending on feedstock and level of maturity (CCQC 2001). Variations in application intensities and compost qualities were run in combination. All scenarios included medium-intensity spring and fall grazing typical of the region. A list and description of model scenarios is provided in Table 1.

Table 1. Descriptions of grassland organic matter amendment scenarios simulated with the DAYCENT model.

Scenario name	Desc
Control†	no organic matter am spring grazing
S11†	single large applicatio Mg C/ha) with C:N moderate spring gra
S20	single large applicatio Mg C/ha) with C:N spring grazing
S30	single large applicatio Mg C/ha) with C:N spring grazing
M11	multiple small applica (1.427 Mg C·ha^{-1}·y years) with C:N rat spring grazing

Model validation, scenario analyses, and statistical analyses

We used the unamended control and S11 scenarios from each site characterization to validate the model; these simulations corresponded to the treatments included in the field experiment. The model was validated using correlation analyses between measured vs. modeled values of soil C, total soil respiration, ANPP, and BNPP for all three site characterizations. Measured plot-level means of these variables prior to treatment, when available, and for three years following treatment were included in correlation analyses for all sites and for both control and amended plots.

Model output variables were plotted at a monthly or annual timescale from 2008 to 2108. Treatments were evaluated as the differences relative to the control scenario. Soil fluxes of N_2O, CH_4, and CO_2 were plotted on a daily timescale for three years following compost addition, as these variables are temporally dynamic and sensitive to short-term changes in microclimate. Annual climate change mitigation potential was assessed over a 10, 30, and 100-year time frame, and calculated as ecosystem C sequestration minus greenhouse gas emissions in units of g CO_2-eq·m^{-2}·yr^{-1} (where “eq” stands for “equivalents”) using 100-year global warming potentials of 1, 34, and 298 for CO_2, CH_4, and N_2O (Myhre et al. 2013), as follows:

$$\text{Climate change mitigation potential}(\text{g } \mathrm{CO_2\text{-}eq} \cdot \mathrm{m}^{-2} \cdot \mathrm{yr}^{-1}) = \frac{\Delta \mathrm{C_{seq}} - \Delta \mathrm{GHG_{soil}}}{t_f - t_i}$$

where t_f refers to the last year considered in the time frame of mitigation potential, and t_i refers to the year compost was applied. The term, ΔC_{seq}, refers to the difference in total system C between amended and control simulations. Total system C included aboveground biomass, belowground biomass, and soil C to 20-cm depth. Carbon losses via heterotrophic soil respiration were included as part of changes to the soil C pool. The term ΔGHG_{soil} refers to the difference in total N_2O and CH_4 (greenhouse gas) oxidation from year t_i (2008 in this study) to year t between amended and control simulations. Nitrous oxide emissions included direct N_2O emissions from the soil and indirect emissions from nitrate (NO_3^-) leaching. Losses from leaching were calculated using an emissions factor of 0.0075 g N_2O-N/g NO_3^- leached (Nevison 2000). The sign convention indicates a net source to the atmosphere with a negative value and a net sink to the ecosystem with a positive value, compared to control simulations.

To assess the effect of management, we used analysis of variance (ANOVA) on model output with treatment as a fixed effect and site as a blocking effect. When significant at $P < 0.05$, ANOVA tests were followed by Student's t test as a means separation test.

Response variables included ANPP, BNPP, NO_3^- leaching, N_2O flux, CH_4 flux, and heterotrophic respiration summed over 10, 30, or 100 years for each site characterization. Differences in total system C, soil C, and active, slow, and passive soil C pools at year 10, 30, and 100 were also evaluated. To assess changes over time, we used repeated measures ANOVA with annual measures of ANPP, BNPP, NO_3^- leaching, N_2O flux, CH_4 flux, heterotrophic respiration, total system C, soil C, and active, slow, and passive soil C pools as response variables. For repeated measures analyses, site, treatment, time, and treatment × time interactions were included as factors. Analyses were performed using 7.0.2 JMP software (SAS Institute, Cary, North Carolina, USA). Statistical significance was determined as $P < 0.05$ unless otherwise noted. Data are reported as site characterization mean ± SE to illustrate the range of ecosystem responses from these annual grasslands.

Results

Effects of historical soil conditions

During model equilibration, soil C remained stable until the year 1750 when the shift from perennial grasses to annual grasses was induced in the model (Fig. 1). The vegetation shift caused an exponential decline in soil C, which had still not stabilized by the year 2120. The average decline in soil C over the period of 1750–1900 was approximately −2.7, −2.9, and −4.3 g $C \cdot m^{-2} \cdot yr^{-1}$ at the coastal sandy loam, coastal loam, and valley grassland sites, respectively. Rates of soil C loss declined to −0.7 g $C \cdot m^{-2} \cdot yr^{-1}$ from the period of 1990 to 2000, and continued at a similar rate when projected for 100 years. Changes to soil C induced by management were considered in the context of the underlying decline observed with the baseline control model.

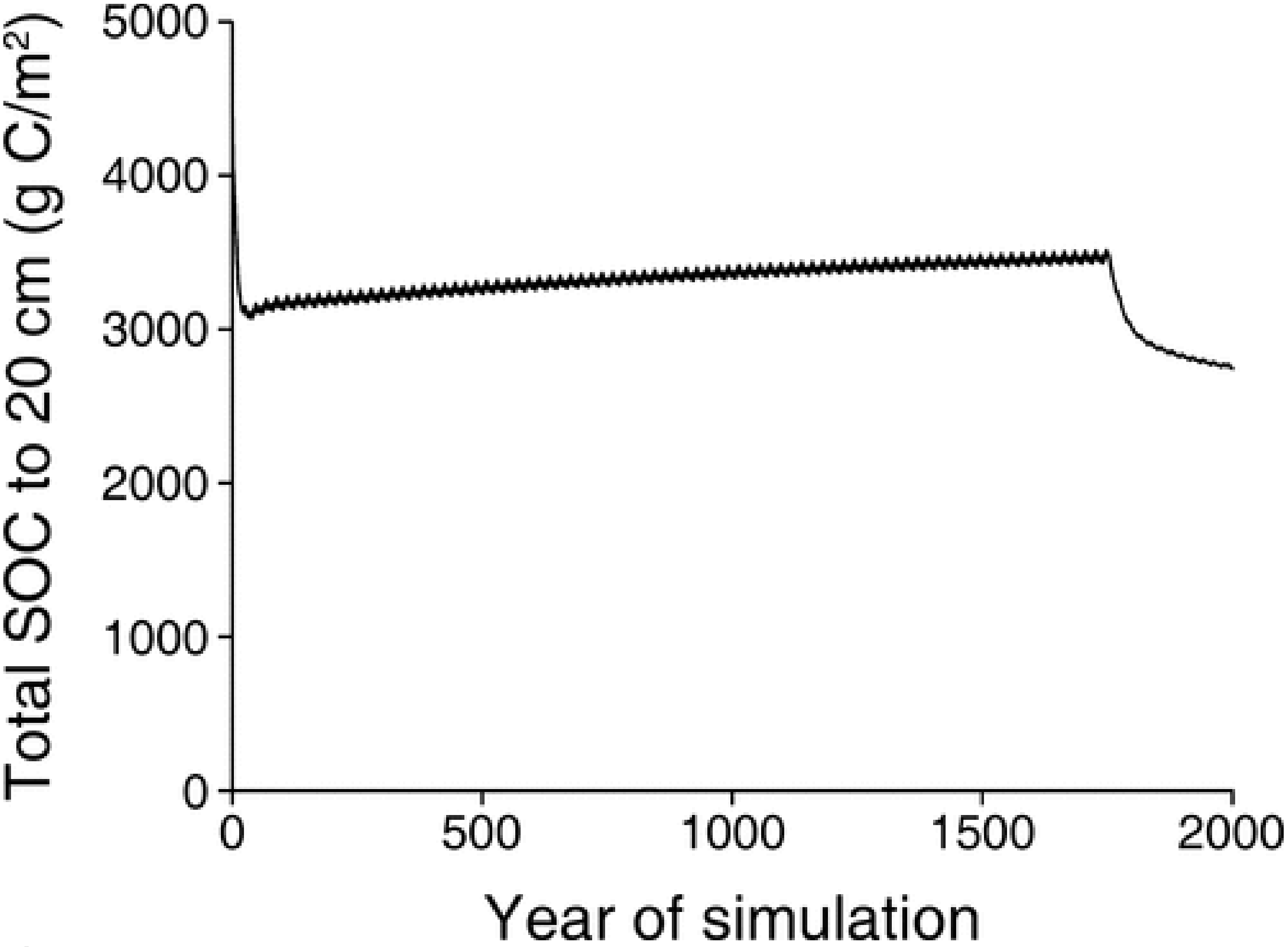

Figure 1

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Simulated monthly soil organic C (SOC; 0–20 cm) during model spin up (years 0–2007). DAYCENT was initiated with perennial grasses from years 0 to 1749, followed by a shift to annual grasses after 1750.

Model validation

The model tended to slightly overestimate ANPP and BNPP compared to measured values (Fig. 2a and b), and adequately captured the effective response of the treatment. The model was able to approximate background soil C pools at the coastal sandy loam and valley grassland sites, despite considerable interannual variability in soil C measurements of both control and amended plots, particularly at the valley grassland. The model also accurately simulated the relative response of soil C to compost amendments (Fig. 2c). Modeled daily N_2O and CH_4 fluxes were typically low, with short-lived N_2O pulses associated with rainfall events, and fluxes were within the range of values measured in a range of field conditions at these sites. Modeled annual total soil

CO_2 fluxes, including heterotrophic and autotrophic components, were also within the range of observed fluxes (Fig. 2d). Variance of modeled simulations of the three site characterizations was similar to variance of data collected at the field studies.

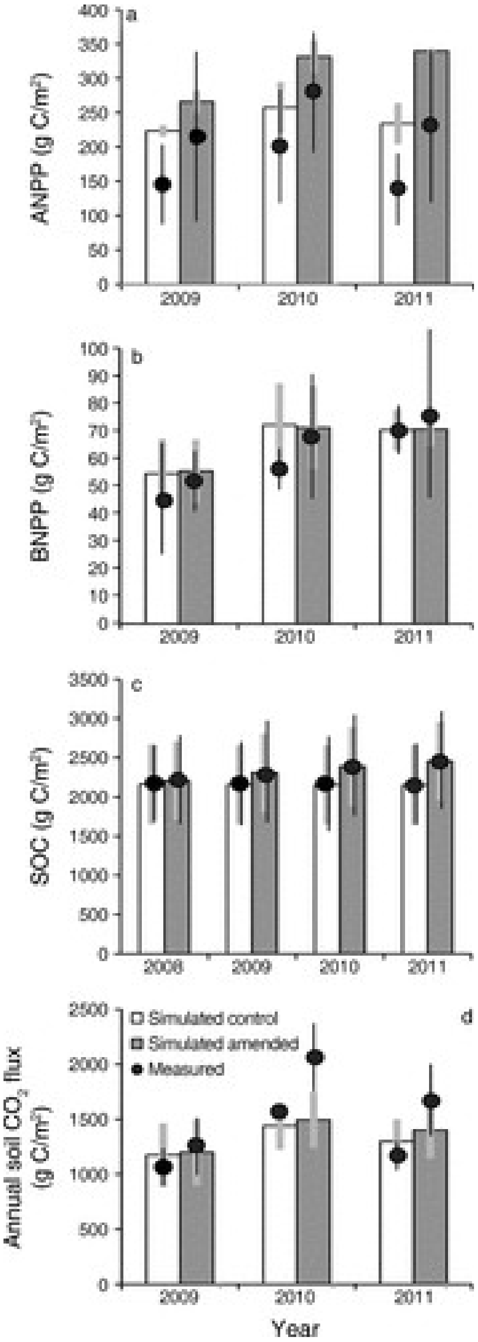

Figure 2

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Relationships between modeled and measured data of (a) aboveground net primary production (ANPP), (b) belowground net primary production (BNPP), (c) 0–20 cm soil organic C, and (d) annual soil respiration (heterotrophic + autotrophic components) from

2009 to 2011. Bars are model averages of the three site characterizations with light gray bars representing ±SD. Black circles are average measured values with black lines representing ±SD.

The loss of the labeled amendment material was traced through time in the simulations as an index of the decomposition of the amendment. The mass of amendment remaining through time followed a negative exponential decay curve ($R^2 = 0.99$) typical of litter decomposition (Fig. 3). Over 10-, 30-, and 100-year time frames, the decomposition *k* values predicted in the model were 0.040, 0.053, and 0.048 yr^{-1}, respectively. The proportion of compost-C remaining in the ecosystem after 10, 30, and 100 years was 67.6% ± 2.4%, 21.2% ± 3.5%, and 1.0% ± 0.2%, respectively.

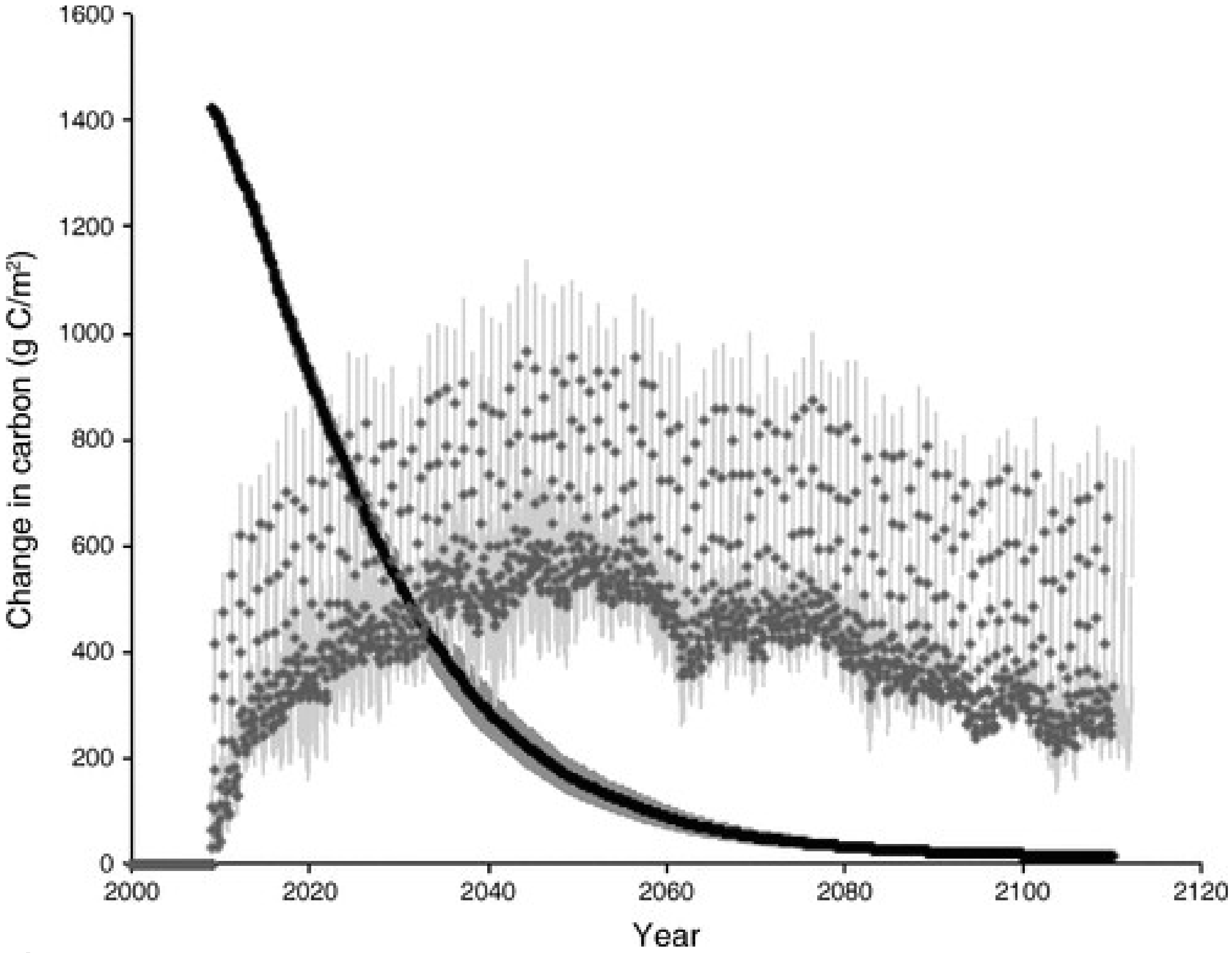

Figure 3

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The black line shows simulated decomposition of the composted organic matter amendment following application to grassland soils (site means ± SD; $y = 3 \times 10^{42} e^{-0.045x}$; $r^2 = 0.99$). Gray circles show the monthly change in total ecosystem carbon, not including compost carbon, in the S11 simulation. Values are averages across site characterizations, with standard error bars in light gray.

Effects of compost addition on long-term soil C

The DAYCENT model identifies three soil C pools that are operationally defined by their turnover times: active (1–5 years), slow (20–40 years), and passive (200–1500 years). Simulated changes to these three soil C pools were similar in trend and magnitude across all three sites (Fig. 4). In the control simulations, the active and slow pools remained relatively constant through time, with slight interannual variability. In contrast, the passive soil C decreased through time in the control model, reflecting ongoing losses of soil C observed during model equilibrium following the shift from perennial to annual vegetation.

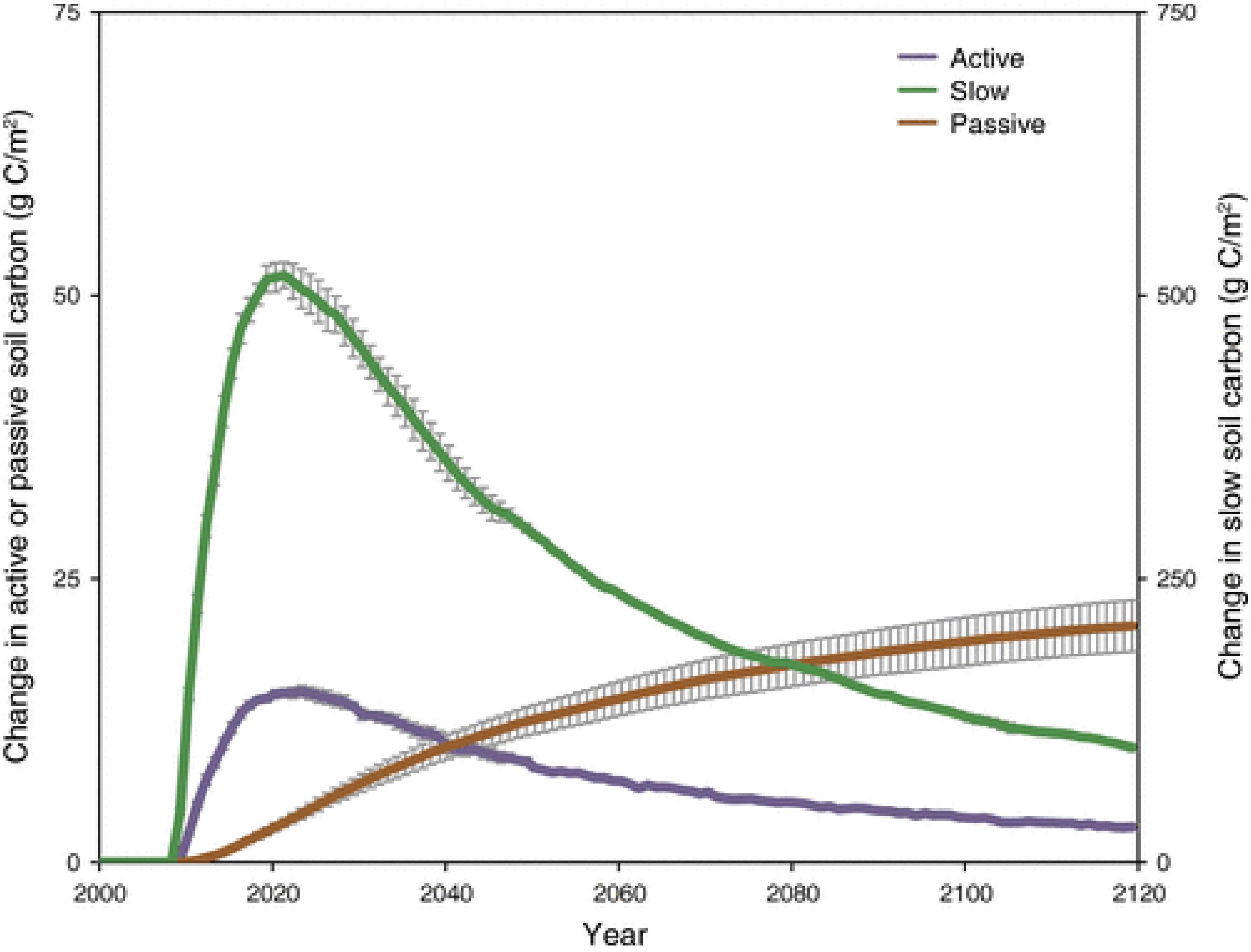

Figure 4

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Treatment differences (S11 amendment scenario minus control) of the active, slow, and passive soil C pools in the DAYCENT model. Lines are averages of the valley, coastal loam, and coastal sandy loam sites. Error bars show ±SE.

In the S11 amendment scenario, all three soil pools experienced gains in C that persisted through time (Fig. 4). The largest increase was observed in the slow soil C pool, and no pool experienced C losses after compost amendment relative to control soil C pools. The active and slow soil C pools responded quickly to amendment. Treatment differences in total soil C peaked at 14 years after the compost addition, showing a 26.4% ± 2.8% increase relative to controls. Although treatment differences declined through time, total soil C in amended simulations remained 6.3% ± 0.7% greater than control simulations after 100 years ($P < 0.0001$). Compost additions increased the active soil C pool by 14.3 ± 0.2 g, 11.4 ± 0.5 g, and 3.6 ± 0.3 g

$C \cdot m^{-2} \cdot yr^{-1}$ after 10, 30, and 100 years, respectively, when averaged across sites. For the slow C pool, increases were 501 ± 9.0 g, 371.5 ± 16.4 g, and 115.3 ± 2.8 g $C \cdot m^{-2} \cdot yr^{-1}$after 10, 30, and 100 years, respectively. The passive soil C pool declined through time following amendment, but loss rates were roughly half that of the control. As a result, the treatment differences in passive soil C continued to increase through time and appeared to stabilize by 100 years ($P < 0.0001$). The average increase in the passive soil C in the compost model relative to control across sites was 2.4 ± 0.3 g, 9.7 ± 1.1 g, and 20.1 ± 2.2 g $C \cdot m^{-2} \cdot yr^{-1}$after 10, 30, and 100 years. Thus, the response of total soil C was greatest within the first 30 years following a single addition of compost, but C continued to build up in the most stable, passive soil C pool even through 100 years (Fig. 4).

Application intensity and compost quality

The model was used to test the effects of differing compost application intensities (a single large addition vs. multiple small additions) and qualities (as determined by C:N ratio). Considerable interannual variability in ANPP was observed in both control and amendment model scenarios. However, ANPP was always greater in amendment scenarios, a result that lasted throughout the duration of the model projection (ANOVA, $P < 0.001$ for 10-year time frame, $P < 0.0001$ for 30 and 100-year time frames; Fig. 5a). Aboveground NPP responded rapidly following a single large compost addition (scenarios S11, S20, and S30). Similar net C gains in aboveground plant growth were observed with multiple smaller additions of compost, but the effects were more gradual for the first 20 years. Averaged across all three sites, scenario S11 had the strongest response and accumulated an additional 853, 2758, and 7230 g C/m^2 compared to control over 10, 30, and 100 years, respectively ($P < 0.05$ for all time frames). Scenario M30 had the weakest response and accumulated an additional 178, 1208, and 3737 g C/m^2 compared to control over 10, 30, and 100 years, respectively (not significant at 10 years; $P < 0.05$ for 30 and 100 years). The response of ANPP to amendments was almost two times greater at the coastal loam and coastal sandy loam sites than at the valley grassland. Aboveground NPP was greatly affected by compost quality. At the highest C:N ratio tested (C:N = 30), the increase in ANPP was reduced by about half compared to the low C:N ratio scenario.

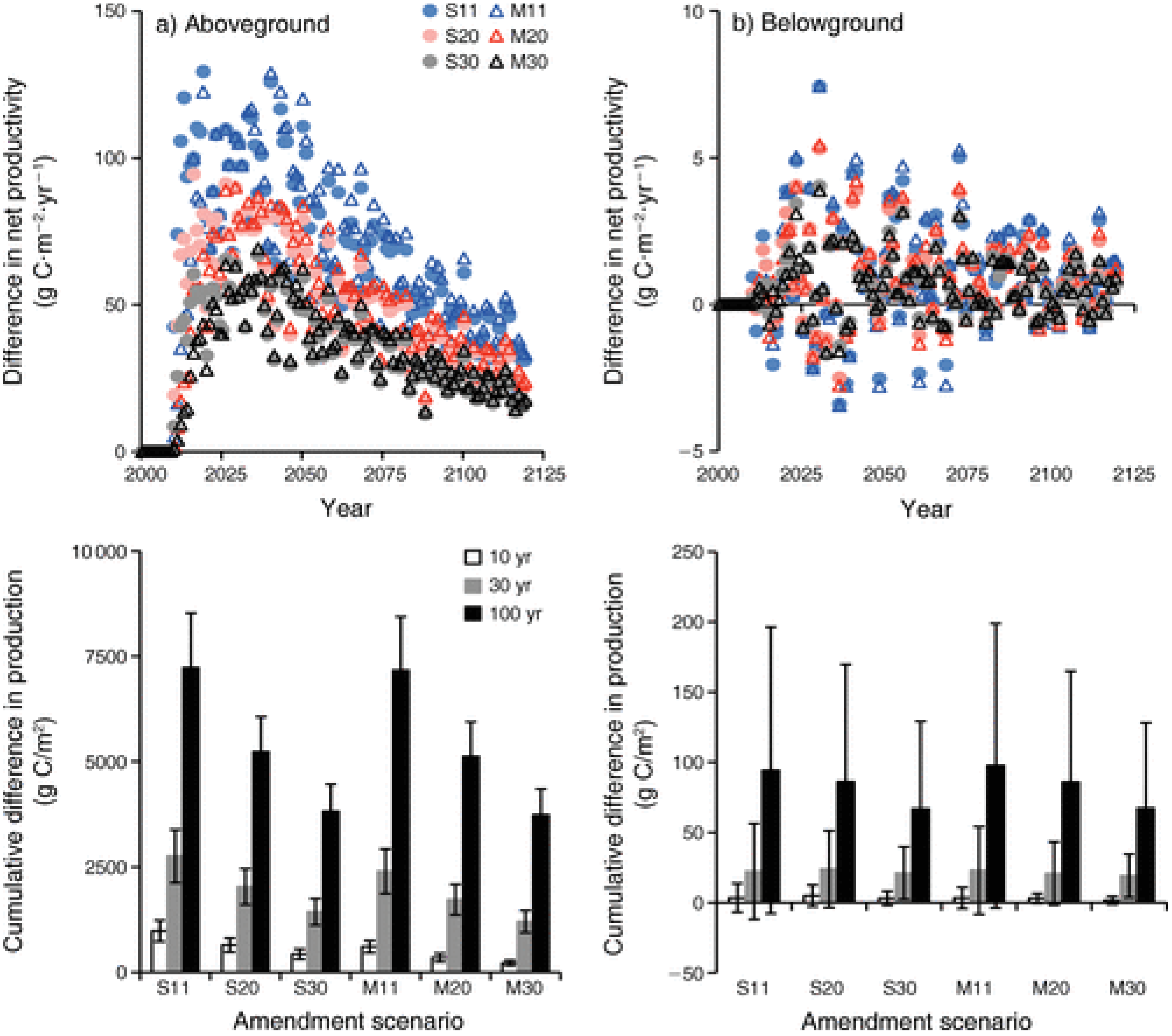

Figure 5

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Treatment differences averaged across site characterizations from control of (a) aboveground net primary production (ANPP) and (b) belowground net primary production (BNPP) for amendment scenarios are shown in the top row. In the bottom row, cumulative changes in ANPP and BNPP are shown over 10-, 30-, and 100-yr time periods. S indicates a single application of composted green waste (14.27 Mg C/ha). M indicates multiple annual applications of composted green waste (1.427 Mg $C \cdot ha^{-1} \cdot yr^{-1}$ for 10 consecutive years). The numbers next to S or M indicate C:N ratios, with 11 being a C:N ratio of 11.1, 20 indicating a C:N ratio of 20, and 30 indicating a C:N ratio of 30. Values above zero indicate greater aboveground C in amendment scenario vs. control.

The response of cumulative BNPP to amendments was five to seven times greater at the valley grassland than either of the coastal sites ($P < 0.0001$). Belowground NPP increased at the valley and coastal sandy loam sites under all amendment scenarios, but decreased slightly at the coastal loam site (Fig. 5b). The BNPP response at the coastal sites alternated between positive and negative, whereas the response was positive at the valley grassland site during most years. In the model, allocation to roots changes with N and water availability via the model parameters (FRTC in the crop file). Thus, BNPP was affected by interannual variability in rainfall as well as the contribution of available N and moisture from compost amendments. The positive response of BNPP to amendments was an order of magnitude less than the ANPP response, which corresponded to the changes observed in the three-year field experiment. The effects of application intensity or compost quality on BNPP were less clear than for ANPP responses due to differences between sites (ANOVA treatment effect $P = 0.50$, site effect $P < 0.0001$). Generally, the application intensity did not alter the cumulative response at 10, 30, or 100 years. However, the positive BNPP response was reduced with higher compost C:N ratios, an effect that was evident over longer time periods.

Total soil C (the sum of active, slow, and passive pools) increased under all amendment scenarios, with the greatest differences under scenarios M11 and S11 ($P < 0.05$ for all scenarios considered at 10-, 30-, or 100-year time frames; Fig. 6). Smaller, frequent applications of compost resulted in a more gradual buildup of soil C and in a shift of the peak of treatment response by about 10 years compared to a single large application. Thus, soil C increased more rapidly and declined earlier in the single-application scenarios. Over 100 years, there were no significant differences among the responses of soil C pools to the different application intensity scenarios. However, the effect of compost quality persisted through time. Model scenarios with lower C:N ratios showed significantly greater increases to the total soil C pools compared to higher C:N ratios (Fig. 6).

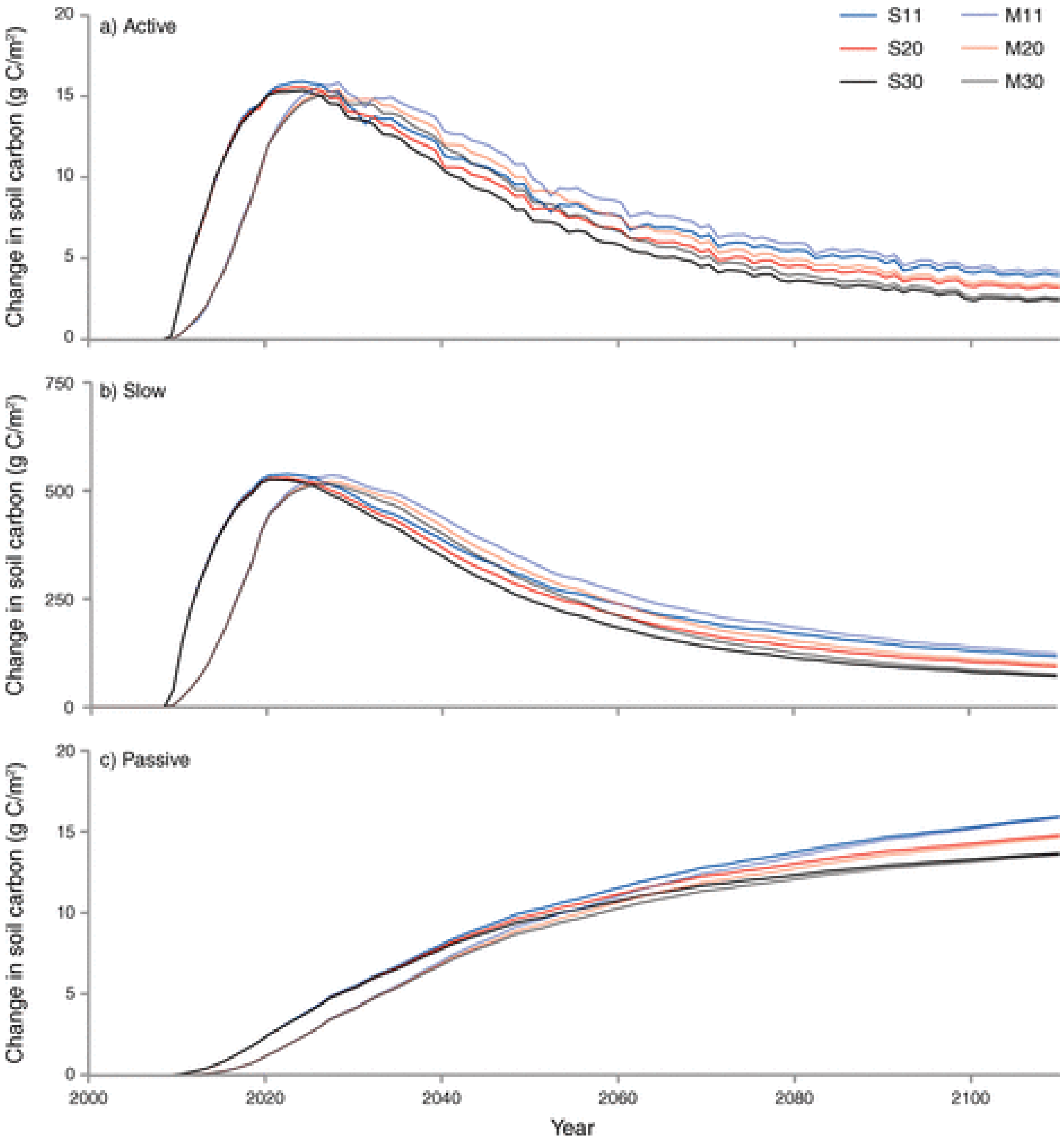

Figure 6

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Changes to soil C pools with a range of soil amendment scenarios from the valley grassland simulations. Soil C pools are defined in the DAYCENT model by their turnover times: 1–5 years for the active pool, 20–40 years for the slow pool, and 200–1500 years for the passive pool. Values above zero indicate greater soil C in amendment scenario vs. control. See Fig. 5 for an explanation of the scenarios in the key.

Treatment effects on soil N_2O and CO_2 fluxes were primarily restricted to the wet season (October–May), as low moisture conditions limited microbial activity during the dry season (June–September; Fig. 7). Amendments tended to increase soil N_2O and heterotrophic CO_2emissions when moisture was not limiting, and the largest responses corresponded to rain events followed by warm, dry conditions. Increases in daily soil N_2O fluxes were greatest for the single, large compost addition with low C:N ratios. Fluxes were considerably lower for scenarios with multiple, small additions or higher C:N ratios. Cumulative N_2O emissions were significantly greater compared to the control from scenarios S11, S20, and M11 over the 10- and 30-year time frames and from scenarios S11, M11, S20, and M20 over the 100-year time frame ($P < 0.05$). Cumulative differences ranged from 1.41 g to 2.57 g N_2O-N/m^2over a 100-year time frame.

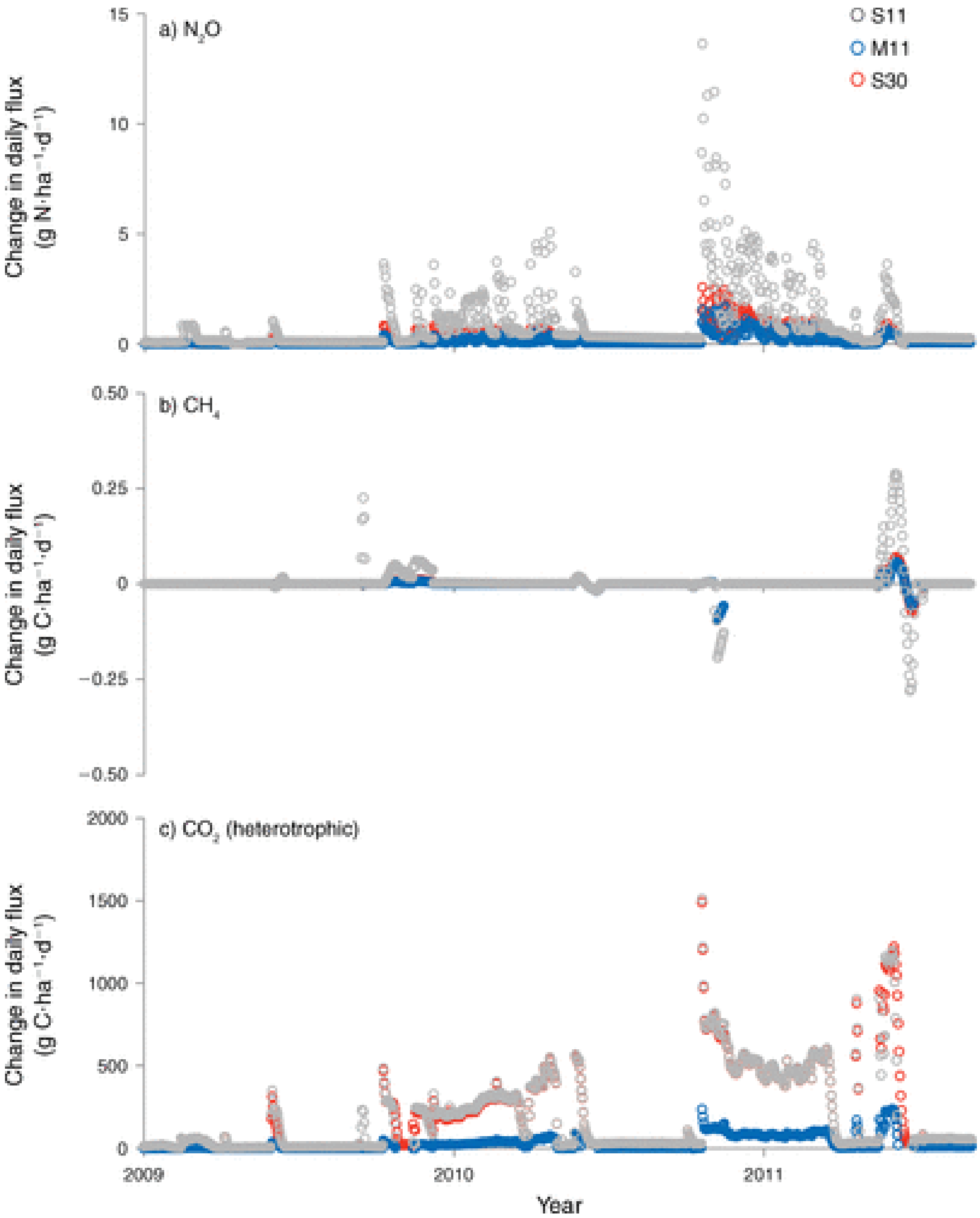

Figure 7

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Treatment differences averaged across site characterizations from control in daily soil (a) N_2O, (b) CH_4, and (c) heterotrophic respiration for three years. Positive values indicate greater gaseous loss to the atmosphere from amended soils compared to control soils. For illustrative purposes, only scenarios S11, M11, and S30 are shown here. See Fig. 5 for an explanation of the scenarios.

Nitrate leaching was also restricted to the wet season, and treatment differences diminished over time (Fig. 8). At the 10-year time frame, scenarios S11, S20, and M11 were significantly greater than the control scenario. Analyzed at the 100-year time frame, all amendment scenarios were significantly greater than the control scenario. Compost quality scenarios differed significantly, with the greatest treatment differences resulting from low C:N ratios ($P < 0.05$). Nitrous oxide emissions from NO_3^- leaching were an order of magnitude less than those from direct soil N_2O fluxes.

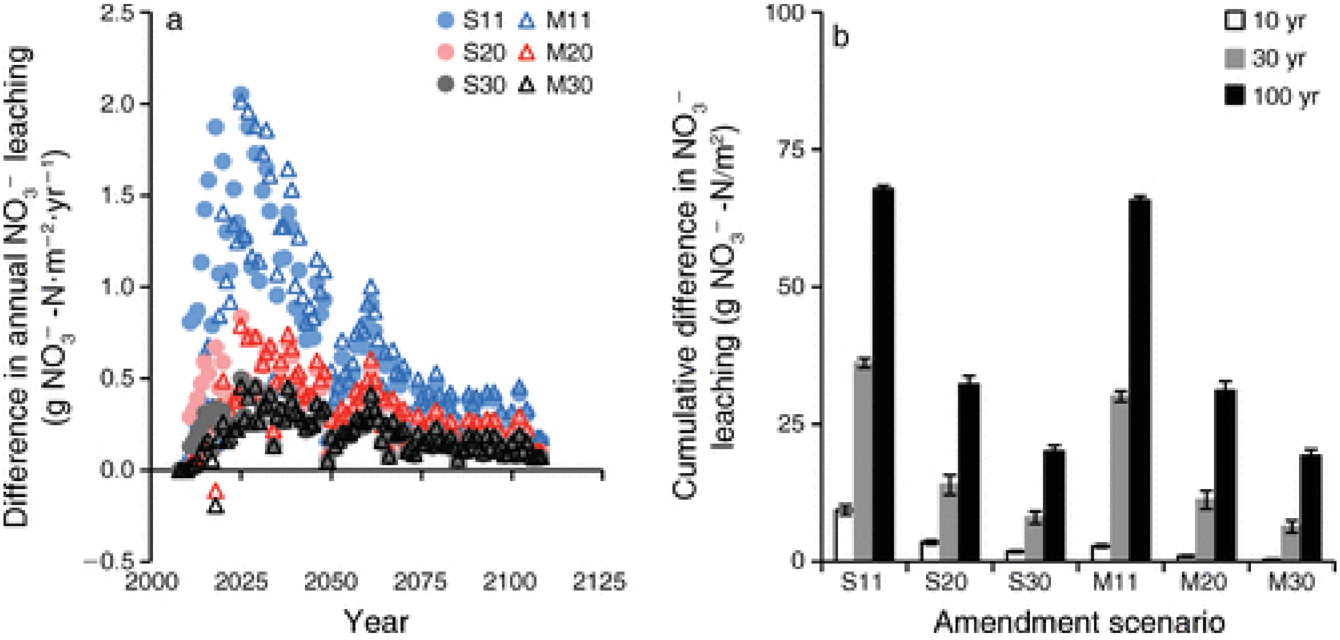

Figure 8

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Treatment differences averaged across site characterizations from control of (a) annual NO_3^- leaching and (b) cumulative change in NO_3^- leaching over 10, 30, and 100 years under a range of amendment scenarios (see Fig. 5 for an explanation of the scenarios). Positive values indicate greater loss of N via leaching from amended soils compared to control soils.

For heterotrophic soil respiration, treatment differences were greatest for scenarios with a single, large application of compost. The C:N ratio of compost had a smaller effect than application intensity, and responses for S11 and S30 were similar through time. Cumulative C losses through heterotrophic respiration were significantly greater from amended vs. control scenarios when analyzed over the 10- and 30-year time frames ($P < 0.05$). Cumulative differences ranged from 2832 g to 5405 g CO_2-C/m^2 over the 100-year time frame. These ecosystems are slight CH_4 sinks and CH_4 fluxes have been shown to be unresponsive to organic matter amendments (Ryals and Silver 2013). The model simulations did not produce differences in CH_4 fluxes with amendment.

Potential for climate change mitigation

The potential for climate change mitigation for each model scenario was evaluated by calculating the difference in net C sequestration and net soil greenhouse gas emissions between the control and amendment scenarios over 10-, 30-, and 100-year time frames (Fig. 9). Trends in net climate change mitigation potential were similar across scenarios and sites, but differed in magnitude depending on the site-specific responses to C and N dynamics described above. Total ecosystem C, not including the direct addition of compost C, increased for several decades after treatment (Fig. 3). Climate benefits of compost additions were offset partially by soil greenhouse gas emissions, particularly N_2O. While C sequestration rates were similar across sites (despite differences in the magnitude of ANPP and BNPP responses), net soil greenhouse gas emissions were greater at the valley grassland sites compared to either coastal grassland site. Therefore, estimated net mitigation potential was greater at the coastal grassland sites and highest at the coastal loam site in particular.

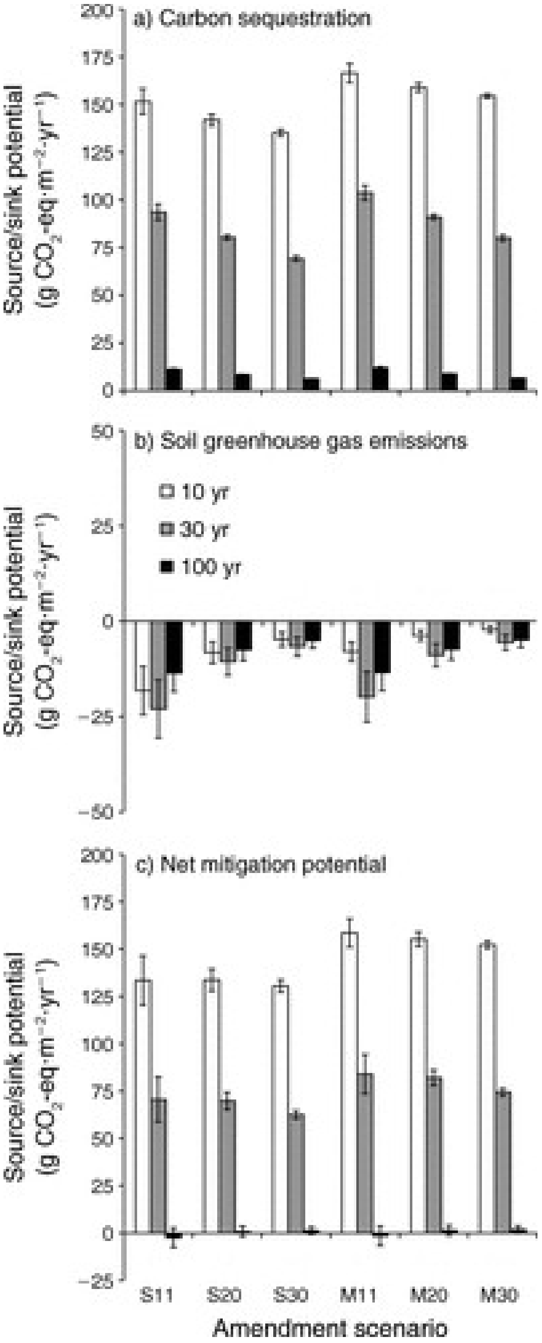

Figure 9

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Potential for climate change mitigation due to (a) C sequestration, (b) changes in soil greenhouse gas emissions, and (c) net climate change mitigation for a range of organic matter amendment scenarios based on DAYCENT simulations listed in Table 1. Negative values indicate a net source of CO_2-equivalents (eq) to the atmosphere. Positive values indicate that the ecosystem is a net sink of CO_2-eq. See Fig. 5 for an explanation of the scenarios.

As expected, compost quality and application intensity played a role in determining the net climate change mitigation potential. The C:N ratio of compost amendments was particularly important in regulating soil greenhouse gas losses. Greater N_2O emissions were projected with lower C:N ratios, leading to lower overall climate change mitigation potential in most cases. Application intensity played a smaller role. Typically, slightly greater mitigation potential was achieved using multiple smaller applications of the same compost quality.

The time frame considered for the management scenarios substantially changed its potential for climate change mitigation. Because the largest soil C and plant responses were observed within the first 10 to 30 years, the potential for these amended ecosystems to act as net sinks was greatest when evaluated over shorter timescales. Analyzed over a 10-year time period, significant net sinks ranging from +130 ± 3 g CO_2-eq·m^{-2}·yr^{-1} to +158 ± 8 g CO_2-eq·m^{-2}·yr^{-1} were observed across sites and amendment scenarios ($P < 0.0001$ for all scenarios). Sinks were greater relative to control in the following order: M11 > M20 > M30 > S20 > S11 > S30. Over a 30-year time period, all scenarios remained net sinks ($P < 0.0001$ for all scenarios), with values ranging from +63 ± 2 g CO_2-eq·m^{-2}·yr^{-1} to +84 ± 10 g CO_2-eq·m^{-2}·yr^{-1}. Sinks were significantly greater relative to control ordered as: M11 > M20 > M30 > S11 > S20 > S30. Extended further to a 100-year time frame, no amendment scenarios were significantly different from control.

Discussion

Historical carbon losses

We found that the model baseline for soil C pools was sensitive to the non-steady state conditions of most California grasslands resulting from a historic widespread shift from perennial- to annual-dominated grasslands (Biswell 1956, D'Antonio 2007, Koteen et al. 2011). Background soil C losses were 44 g C·m^{-2}·yr^{-1} and 228 g C·m^{-2}·yr^{-1} at the coastal and valley grassland sites over the three-year field study. Soil C losses have also been documented in a similar valley grassland at a rate of 150 g C·m^{-2}·yr^{-1} (Chou et al. 2008), suggesting that the model is accurately capturing the observed trend. The DAYCENT model operates with one vegetation type at a time; thus, vegetation changed abruptly in model simulations. In reality, there was likely a transition phase of several years to decades. However, over the timescale of the model initialization (>200 years) the model was likely able to capture the general long-term trends in baseline soil C losses.

Response of soil C and plant productivity to organic matter amendments

The modeled labeling experiment suggested that the compost decomposed very slowly ($k = 0.048 \pm 0.002$ yr^{-1} once applied to soil. This modeled decomposition rate is within the range of values generated from field observations of composted green waste, manure, and peat (k= 0.0048–0.21 yr^{-1}) and greater than soil humus (Gerzabek et al. 1997, Lynch et al. 2005). The DAYCENT model adds the composted plant waste first into the slow soil organic matter pool, reflecting the partially decomposed nature of the material. From there, the added C can be further humified and incorporated into more stable soil organic matter pools or decomposed, mineralized to CO_2, or leached through the soil profile. At these sites, total soil respiration of the amended soil was elevated relative to control soils for three years, of which 24% ± 6% of the treatment difference was attributed to the decomposition of compost (Ryals and Silver 2013). Physical fractionation and chemical spectroscopic analyses of soil indicated that a portion of the compost C was directly incorporated into stable C pools (Ryals et al. 2014).

The DAYCENT model partitions soil C into two surface microbial pools (active and slow) and three soil organic matter pools (active, slow, and passive) defined by turnover time. It was interesting that the rapid positive response of the active and slow C pools to simulated amendments generally agreed with laboratory fractionation, which detected increases in the free and occluded light fractions from these soils (Ryals et al. 2014). The peak increase in total soil C storage occurred 15–25 years after compost applications in amendment scenarios. This likely reflects both the contributions from compost C undergoing humification as well as contributions from increased plant C inputs. Surprisingly, as the short-term impacts of compost amendments to the active and slow soil C pools decreased over time, the passive soil C pool continued to increase over time. California's Mediterranean grassland ecosystems have experienced considerable loss in soil C due to a widespread shift from the dominance of perennial bunchgrass to annual grasses (Norton et al. 2007, Koteen et al. 2011). Our results suggest that organic matter amendments may help to offset soil C losses from legacy conditions.

Several shorter-term studies (ranging from 2 to 16 years, median 3 years) have measured increases in total soil C in rangelands amended with organic material, as well as several indicators that suggest increased C stabilization, such as improved soil aggregation, increases in microbial biomass, and shifts in chemical quality of soil C

(Pascual et al. 1999, Lynch et al. 2005, Sullivan et al. 2006, Fernandez et al. 2007, Albaladejo et al. 2008, Cabrera et al. 2009, Ippolito et al. 2010, Kowaljow et al. 2010). Grasslands are generally limited by water and N availability (Harpole et al. 2007). As a result, plant production typically responds positively to synthetic or organic N additions (Derner and Schuman 2007). Our results suggest that both single large and multiple small applications of compost have an immediate and surprisingly long-lasting impact on plant productivity. Plant production responses were sensitive to compost quality with lower compost C:N ratios resulting in greater plant production, likely due to greater mineral N availability (Amlinger et al. 2003, Antil et al. 2013).

Response of soil greenhouse gas emissions to organic matter amendments

Soil greenhouse gas emissions are sensitive to short-term changes in soil moisture and temperature conditions. In Mediterranean ecosystems, even small rain events following a dry period can result in large soil CO_2 and N_2O fluxes (Fierer and Schimel 2002). The dynamic nature of soil greenhouse gas emissions, and particularly N_2O emissions, make it difficult to assess annual fluxes or to adequately compare treatment effects using commonly available field methods (Bouwman et al. 2002, Desjardins et al. 2010). However, changes in heterotrophic respiration or N_2O emissions have the potential to offset gains by C sequestration (Dalal et al. 2003, Conant et al. 2005, Derner and Schuman 2007). Significant increases in total soil respiration during the wet season were detected for three years following a single application of compost to valley and coastal grasslands (Ryals and Silver 2013). Similar results were observed in the S11 scenario. The treatment responses of heterotrophic respiration were not affected by C:N ratio, but were considerably reduced when considering multiple small additions compared to a single large application of compost. While autotrophic and heterotrophic components of total soil CO_2 fluxes were not separated in the field experiment, the model includes outputs for each component. According to the model, heterotrophic respiration accounted for no more than 40% of the annual cumulative soil CO_2 flux, and the ratio of heterotrophic to total soil respiration did not differ significantly between control and amendment scenarios.

No changes to soil N_2O emissions were detected from the field experiment when measured once every two to four weeks. Laboratory-simulated rainfall (wet-up) events revealed small, short-lived but statistically significant increases in the N_2O flux from amended soils (Ryals and Silver 2013). Modeling results suggested that N_2O fluxes from all amendment scenarios were greater than those from control scenarios, and that smaller increases were generated from amendments with higher C:N ratios. This may be due to increased N immobilization or a reduction in N mineralization of the compost amendment. We detected interesting differences between modeled site characterizations in the response of soil N_2O fluxes to amendments. Valley grasslands had greater gaseous N_2O losses compared to coastal sites, which may result from differences in soil texture. Emissions of N_2O tend to be lowest in well-drained, sandy soils where denitrification rates are lower (Del Grosso et al. 2002, Del Grosso et al. 2006), and lower N_2O fluxes were observed in the coastal site with higher sand content. Conversely, NO_3^- leaching losses were larger from the coastal sandy loam site than the coastal loam site. Nitrate leaching is also influenced by soil texture and has been shown to increase with N fertilization (Ledgard et al. 1999) and urine patches from intensively grazed pastures (Di and Cameron 2000, 2005). As such, leaching losses were greater in the amended vs. control scenarios. Indirect N_2O emissions from NO_3^- leaching were, at most, half that of direct soil N_2O emissions.

Net climate change mitigation potential

Our simulations suggest that organic matter amendments, regardless of the quality or application intensity, consistently resulted in net C sequestration across grassland sites over timescales relevant to management and policy. Following a single application of composted organic material, three-year field measurements showed an increase in soil C content, ANPP, BNPP, and total ecosystem C storage (Ryals and Silver 2013). In another field experiment, Albaladejo et al. (2008) found sustained increases in soil C and aboveground biomass 16 years after a single addition of composted urban wastes. Our modeling results suggest that ecosystem C storage continues to build for several decades. While net sink conditions remained over decadal timescales, the amendment scenarios revealed trade-offs between C sequestration and soil greenhouse gas emissions through time. The amendment scenarios that resulted in the greatest rates of C gains through ANPP, BNPP, and soil C storage (scenarios S11 and M11) also resulted in the greatest rates of losses of N_2O via gaseous fluxes and NO_3^- leaching. Thus, maximizing NPP (i.e., forage) production with a low C:N ratio amendment may result in slightly lower climate change mitigation potential.

The assessment of sink–source potential of amendments relative to the control based on short (10-year), medium (30-year), and long-term (100-year) time frames revealed the impact of amendment management through time. Increases to ecosystem C storage occurred immediately and lasted several decades, highlighting the capacity of short-term management activities to have multi-decadal carryover effects on ecosystem processes. When climate change mitigation potential was assessed over a 10-year time frame, greenhouse gas emissions offset just 5% ± 1.5% of the benefits from C sequestration. This offset grew over time as the rate of C sequestration benefits declined, but remained positive on average. These results suggest that single or short-term management events can have significant and long-lasting impacts on ecosystem C storage and climate change mitigation.

Conclusions

Managing grasslands for C storage may play an important role in regulating global climate, yet these ecosystems are underrepresented in modeling efforts (Ogle et al. 2007). Our results couple field and modeling approaches to provide a range of estimates of the capacity of compost additions to grazed grassland to help mitigate climate change. Results from field and modeling experiments showed that ANPP, BNPP, and soil C pools in California grasslands responded rapidly and positively to a range of compost amendment scenarios. Changes to these pools persisted for several decades, reflecting the ability of compost to act as a slow release fertilizer. Scenarios of single vs. multiple applications of compost resulted in similar changes in C and N cycling, but responses were delayed in multiple application scenarios. Compost quality significantly influenced rates of C sequestration and greenhouse gas emissions. The response of ecosystem C tended to be downregulated by higher C:N ratios. As a result, increases to ANPP, BNPP, and soil C pools were greatest in the S11 and M11 amendment scenarios and lowest in the S30 and M30 scenarios. Soil greenhouse gas emissions, particularly direct soil N_2O fluxes and indirect losses through NO_3^- leaching, partially offset C sequestration benefits. The highest rates of soil greenhouse gas emissions were observed in the S11 scenario, where compost with a low C:N ratio was added as a single event. Relative to the S11 scenario, N_2O emissions were reduced if using compost with higher C:N ratio or if compost was applied in multiple, small applications. These results suggest there is a trade-off between maximizing production and minimizing soil N_2O emissions. All amendment scenarios indicate that compost amendments have considerable potential for mitigating climate change over many decades.

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