ECOSYSTEMS

A Lifecycle Model to Evaluate Carbon Sequestration Potential and Greenhouse Gas Dynamics of Managed Grasslands

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ABSTRACT

Soil amendments can increase net primary productivity (NPP) and soil carbon (C) sequestration in grasslands, but the net greenhouse gas fluxes of amendments such as manure, compost, and inorganic fertilizers remain unclear. To evaluate opportunities for climate change mitigation through soil amendment applications, we designed a field-scale model that quantifies greenhouse gas emissions (CO_2, CH_4, and N_2O) from the production, application, and ecosystem response of soil amendments. Using this model, we developed a set of case studies for grazed annual grasslands in California. Sensitivity tests were performed to explore the impacts of model variables and management options. We conducted Monte Carlo simulations to provide estimates of the potential error associated with variables where literature data were sparse or spanned wide ranges. In the base case scenario, application of manure slurries led to net emissions of 14 Mg CO_2e ha^{-1} over a 3-year period. Inorganic N fertilizer resulted in lower greenhouse gas emissions than the manure (3 Mg CO_2e ha^{-1}), assuming equal rates of N addition and NPP response. In contrast, composted manure and plant waste led to large offsets that exceeded emissions, saving 23 Mg CO_2e ha^{-1} over 3 years. The diversion of both feedstock materials from traditional high-emission waste management practices was the largest source of the offsets; secondary benefits were also achieved, including increased plant productivity, soil C sequestration, and reduced need for commercial feeds. The greenhouse gas saving rates suggest that compost amendments could result in significant offsets to greenhouse gas emissions, amounting to over 28 MMg CO_2e when scaled to 5% of California rangelands. We found that the model was highly sensitive to manure and landfill management factors and less dependent on C sequestration, NPP, and soil greenhouse gas effluxes. The Monte Carlo analyses indicated that compost application to grasslands is likely to lead to net greenhouse gas offsets across a broad range of potential environmental and management conditions. We conclude that applications of composted organic matter to grasslands can contribute to climate change mitigation while sustaining productive lands and reducing waste loads.

Key words: annual grasslands; compost; greenhouse gas emission factors; fertilizer; global warming potential; rangelands.

INTRODUCTION

Grasslands cover 25% of the Earth's land surface and are the dominant land-use globally (Asner and others 2004). These ecosystems occur in a biome characterized by periodic drought and high belowground allocation of plant tissues, leading to significant soil carbon (C) sequestration potential (Conant and others 2001, 2011). Despite the environmental and economic importance of these lands, soil degradation is widespread (nearly 2,000 Mha; Bridges and Oldman 1999; Bai and others 2008; FAO 2011) and many regions are losing soil C (Sanderman and Baldock 2010).

The application of soil amendments has been proposed as a means to increase net primary productivity (NPP) and soil C storage in grasslands (Paustian and others 1997; Conant and others 2001; Lal 2004a, b; Smith and others 2008; Cabrera and others 2009; Conant 2011; Ryals and Silver 2013). Many grasslands are limited by low nitrogen (N) availability, thus both inorganic and organic amendments rich in N are likely to increase NPP (Harpole and others 2007a, b). Commercial fertilizers applied to pasturelands and rangelands represent almost 10% of the total fertilizer land application in the US (>10.1 million ha in the US, USDA NASS 2009). Organic fertilizers include manure, compost, biosolids, and other green wastes and are widely used on rangelands to enhance forage production (Diacono and Montemurro 2010). Organic fertilizers have co-benefits that include increased soil fertility, soil water holding capacity, and drought resistance (Hudson 1994).

Manure is a form of organic fertilizer commonly added to pasture and cropland globally (81–128 Tg N y^{-1}, Potter and others 2010) and this practice is widespread in the U.S. (Cabrera and others 2009; Meyer and others 2011). Manure was used to treat 8.9 million ha of rangeland and pastureland nationwide in 2007 (USDA NASS 2009). Land application of manure disposes of waste while increasing soil nutrients, but has been implicated as a major contributor to greenhouse gas emissions from the livestock sector (Davidson 2009). Composts produced from manures and plant residues are an alternative to manure applications. Most composting systems maintain more aerobic conditions and lower greenhouse gas emissions compared to the moist and static conditions of many manure management facilities and landfills (Brown and others 2008), where high CH_4 emissions can result from low redox potential. For example, in the U. S., landfills are the second largest source of anthropogenic CH_4 (108 Tg CO_2e, EPA 2012a). The

opportunity to reduce wastes makes compost an attractive management strategy, but the overall benefits from compost depend on the emissions from composting, land application, and subsequent soil emissions. Under the best management practices, composting emissions are often considered negligible (EPA 2006; IPCC 2007). In practice, emissions from composting are variable (Anderson and others 2010; Larney and Hao 2007; Hao and others 2004), but guidelines are becoming established to minimize these emissions (Brown and others 2008; Fukumoto and others 2006). For example, using feedstocks with higher C to N ratios and lower moisture contents can reduce emissions (Brown and others 2008).

The potential for soil amendments to enhance soil organic matter content, increase NPP, sequester C, and reduce atmospheric greenhouse gas concentrations makes them appealing for both climate change mitigation and land-use sustainability. Yet, the net greenhouse gas impacts from soil amendments remain poorly understood. The purpose of this study was to quantify the soil C sequestration potential and greenhouse gas emissions throughout the full life cycles of different soil amendments (compost, manures, and inorganic N fertilizer). We developed a model to calculate greenhouse gas emissions and offsets resulting from amendment production and the effects of soil amendment application on NPP, soil C storage, and factors associated with ruminant grazers. We included offsets from the diversion of materials from alternative fates, namely landfills and manure management facilities. We developed a set of case studies for the model based on grazed California grasslands and used these to test the sensitivity of the model output to key variables. We also performed Monte Carlo analyses to propagate uncertainty through the model and to evaluate the model response to a broader range of conditions. The model is unique in that it explicitly focuses on ecosystem impacts while including a range of inputs and outputs relevant to soil amendments.

MATERIALS AND METHODS

Model Boundaries

The model explores the net impacts of manure, compost, and inorganic fertilizer application to grasslands on ecosystem C and greenhouse gas dynamics (Figure 1). Model components for this study included amendment production and transportation, ecosystem response to amendments (NPP, soil C storage, soil greenhouse gas effluxes),

impacts on grazers (feed availability, enteric fermentation), and offsets due to waste diversion. The model did not include emissions from milk or meat processing or details of animal management (dietary additives, emissions from confinement phase), which are treated elsewhere (for example, Rotz and others 2010; Pitesky and others 2009). The production costs of equipment were considered negligible. Emissions from landfill establishment (direct emissions or land-use change) and the production of landfill technologies were also not considered.

The model quantified the impacts of the three amendments types on the net greenhouse gas fluxes (GHG_{net}) as

$$GHG_{net} = GHG_{emissions} - GHG_{sinks} - GHG_{offsets}, \quad (1)$$

where GHG_{net} represents all emissions, sinks (direct removals of greenhouse gases from the atmosphere), and offsets (avoided emissions). The emissions component excluded biogenic CO_2, which was considered atmospherically neutral (EPA 2006). Results are reported as net greenhouse gas fluxes in CO_2-equivalents (CO_2e) (IPCC 2007). The units CO_2e represent the global warming potential (GWP), or relative radiative forcings, of greenhouse gases for different time periods, where CO_2 has a GWP of 1. We based the initial model runs on 100-year GWPs ($CH_4 = 25$ CO_2e, $N_2O = 298$ CO_2e) (IPCC 2007).

Case Studies

Study Area

In the case studies, we estimated the net greenhouse gas impact of a single application of amendments to Mediterranean annual grasslands. This initial case study (base case scenario) was developed using data from a field experiment that took place during 2008–2011 at a mesic coast range grassland (Marin County, California, 38.06°N, 122.71°W) and a drier valley grassland (Yuba County, California, 39.24°N, 121.30°W) (Table 1). During the field experiment, treatment (compost application) and control (unamended) plots were sampled for several ecosystem variables (NPP, biomass C content, soil N_2O, and CH_4 effluxes) (Ryals and Silver 2013; Table 1). We developed a single case study representing California grasslands; the implications of site differences were explored within the sensitivity analyses. The field experiment only included compost amendments, therefore, we used literature values and theory to include and compare the impacts of manure and inorganic N amendments.

Amendment Application Rates and Properties

Amendment application rates were defined by the total N added. To minimize confounding effects from differential N fertilization as well as uncertainties from differing N mineralization rates, amendments were applied one-time only (Ryals and Silver 2013) at an equal rate of total N (250 kg N ha^{-1}, Bouwman and others 2002) in the first case study; the impacts of different rates of total N addition were explored in alternative scenarios (described below). Physical and chemical properties (C:N, N concentration, bulk density, moisture content; Rynk 1992, Appendix A in Supplementary Material) were used to calculate the quantities required, as well as transportation costs. Compost for the initial case study was derived from manure and plant waste (75% manure by mass). Plant waste consisted of 50% grasses and 50% yard waste leaves (Eleazer and others 1997). We assumed that plant and manure wastes lost 40% of their mass during composting (Larney and others 2000).

Ecosystem Response to Soil Amendments

Soil amendments impact N and C trace gas emissions (Chen and others 2011; Stehfest and Bouw-
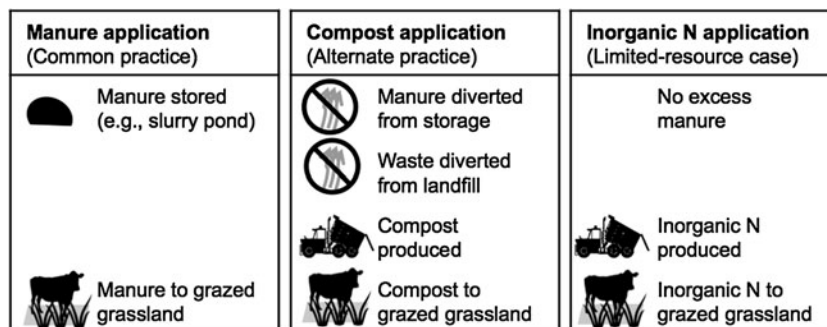

Figure 1. Key components (emissions and offsets) included in the quantification of net greenhouse gas flux associated with three different soil amendments: manure, compost, and inorganic fertilizer.

Table 1. (a) Ecosystem Properties of Two Grasslands Used as the Basis for Initial Case Study and (b) Effect of a One-time Compost Addition to These Grasslands for 3 Years

(a) Ecosystem properties	Valley	Coast range
Mean annual rainfall (mm y^{-1})	730	950
Rainfall during exp. (mm y^{-1})	380, 641, 843	771, 1,050, 1,163
Daily mean temperatures (°C)	2 (Jan.)	6 (Jan.)
	35 (Aug.)	20 (Aug.)
Soil N$_2$O (g N$_2$O ha^{-1} d^{-1})	0.13 ± 0.13	1.0 ± 0.4
Soil CH$_4$ (g CH$_4$ ha^{-1} d^{-1})	−2.5 ± 0.6	−1.4 ± 0.7
Aboveground NPP (g C m^{-2} 3y^{-1})	592 ± 31	470 ± 61
Belowground NPP (0–20 cm) (g C m^{-2} 3y^{-1})	161 ± 8	177 ± 13
Mean daily soil moisture (%): wet, dry seasons	29.1 ± 1.7 (wet)	28.3 ± 0.8 (wet)
	22.2 ± 1.3 (dry)	23.5 ± 0.8 (dry)
Mean daily soil temp (°C): wet, dry seasons	10.4 ± 0.1 (wet)	12.2 ± 1.0 (wet)
	26.0 ± 0.4 (dry)	21.1 ± 1.4 (dry)
(b) Treatment effect	**Valley**	**Coastal**
Soil N$_2$O (g N$_2$O ha^{-1} d^{-1})	0	0
Soil CH$_4$ (g CH$_4$ ha^{-1} d^{-1})	0	0
Aboveground NPP (g C m^{-2} y^{-1})	+145 ± 17	+54 ± 3
Belowground NPP (g C m^{-2} y^{-1})	+11.1 ± 2.0	+13.9 ± 3.0
Mean daily soil moisture (%): wet, dry seasons	+1.0 ± 0.9 (wet)	+0.3 ± 0.4 (wet)
	+0.6 ± 0.6 (dry)	−0.3 ± 0.5 (dry)
Mean daily soil temp (°C): wet, dry seasons	+0.40 ± 0.24 (wet)	−0.04 ± 0.18 (wet)
	+0.06 ± 0.45 (dry)	0.00 ± 0.69 (dry)

man 2006; Davidson 2009), as well as C uptake via NPP (Diacono and Montemurro 2010; Stavast and others 2005). Soil N$_2$O emissions occur both directly (through nitrification and denitrification) and indirectly (via volatilization and redeposition, or leaching and runoff) (De Klein and others 2006). Recently, a regression model was applied globally to estimate that 2.5% of synthetic-N and 2.0% of manure-N is ultimately converted to N$_2$O (Davidson 2009). These findings agreed well with recommended methodologies for calculating N$_2$O emissions from fertilizers (De Klein and others 2006), which we adopt here to account for direct and indirect sources separately. We assumed that 1.0% of added inorganic or manure-N and 0.25% of compost-N was converted directly to N$_2$O (Ryals and Silver 2013; Dalai and others 2009a, b; Paul and others 1993). Leaching losses from inorganic fertilizer were estimated as 0.0075 kg N$_2$O-N kg^{-1} leachate-N, where leachate contained 0.3 kg N kg^{-1} amendment-N (Mosier and others 1998); leaching rates were lower (by 75%) for manure-N (Kramer and others 2006) and there were no significant leaching losses from compost-amended lands due the slower N release rate of composted materials. Indirect N$_2$O from volatilization occurred at rates of 0.01 kg N$_2$O-N kg^{-1} volatilized-N, where the fraction of amendment-N volatilized was 0.1, 0.2, and

0.05 for inorganic fertilizer, manure, and compost, respectively (De Klein and others 2006). Nitrous oxide emissions depend on the quantity and quality of the N inputs as well as environmental factors (Stehfest and Bouwman 2006; Lesschen and others 2011), thus site-specific emissions estimates of N$_2$O should be adopted whenever possible (Kendall and Chang 2009).

Grasslands are typically a net sink for CH$_4$ (Le Mer and Roger 2001), with levels of annual uptake averaging approximately 1.5 kg C ha^{-1} y^{-1} for temperate, fine texture soils, but up to 3.5 kg C ha^{-1} y^{-1} in coarser grassland soils (Del Grosso and others 2000). Fertilization of grasslands has been shown to reduce levels of CH$_4$ uptake (Mosier and others 1991), with oxidation rates suppressed to 25–100% of unfertilized grasslands (Del Grosso and others 2000). During wet periods, unfertilized grasslands can become a source of CH$_4$ (1.6 kg C ha^{-1} y^{-1}, Tenuta and others 2010), with fertilized areas emitting relatively more CH$_4$ (by 69–118%, Tenuta and others 2010). The mechanisms for CH$_4$ uptake and emissions are not entirely understood, and in rare cases N fertilization can increase CH$_4$ emissions (Bodelier and Laanbroek 2004). Fertilization does not always change CH$_4$ fluxes relative to unamended grasslands; for example, this has been the case following compost

amendments (Ryals and Silver 2013; Chen and others 2011) and manure slurries (Glatzel and Stahr 2001). For the initial case study, we assumed a 25% reduction in CH_4 consumption following inorganic fertilizer and manure additions, and no impact to CH_4 effluxes following compost addition. Soil CO_2 emissions are likely to increase as C-based amendments decompose; we assumed that these emissions would have occurred regardless of the amendment's fate (that is, no priming effect), and thus they are not included here.

Based on field data, we estimated that compost amendments enhanced aboveground biomass by 56% (0.099 kg C m^{-2}) and belowground biomass by 21% (0.012 kg C m^{-2}) where biomass had a C concentration of 41% (Ryals and Silver 2013). In the model, N is the limiting nutrient and equal N inputs had equivalent impacts on NPP (Kramer and others 2006). Organic N mineralizes at slower rates than inorganic N, thus equal total N additions do not necessarily translate to equal plant-available N additions. In the base case scenario, we applied equal total N and assumed equivalent responses when considered over the 3-year period. Annual grasslands are commonly grazed to a fixed amount of residual biomass; therefore, we assumed that extra aboveground biomass was mostly consumed (90%).

The amount of C added from enhanced belowground biomass that is stored in long-term pools, termed the C sink efficiency, can be estimated based on a humification factor. Roots can have humification factors ranging from 0.16 to 0.30 (Plénet and others 1993) or up to 0.35 (Katterer and others 2011). As a first approximation, we assumed that 20% of added belowground biomass C from all amendments contributed to long-term pools (remaining in the system for 20 years). As C in the soil amendments was pre-existing, these direct additions were not considered a sink in this study. While direct additions of C can significantly enhance soil C pools (Ryals and others, in review-b; Cavigelli and others 2009) and have been considered a sink in other studies (Tian and others 2009; Brown and others 2011), we chose instead to account for this relative C gain primarily by defining avoided C losses as an offset. To avoid double counting, we conservatively omitted the direct C additions from our model.

Grazer Impacts

An average stocking rate (grazers ha^{-1}) was used to approximate the impact of a change in NPP on the demand for commercial feed, grazer emissions, and manure production. Although grazing intensity depends on numerous factors and remains poorly defined (Holecheck and others 1999), stocking rates for dairies are often between 0.2 and 4 cows ha^{-1} (Allard and others 2007; McDowell and others 2008; Powell and others 2002; Stout and others 2000). We assumed a low stocking rate of 0.5 cow ha^{-1} across all treatments.

Greenhouse gas offsets from avoiding commercial feeds (due to enhanced forage production) depend on feed variety. We assumed that forage production replaced an equal mass of dry matter intake otherwise obtained from hay and corn silage (50% of each). Reduced demand for these crops represented an offset that included the net greenhouse gas flux from inorganic fertilizer production (4.01 kg CO_2e kg^{-1} N, Davis and Haglund 1999), the production of other additives (17.2 kg CO_2e kg^{-1} herbicide, 18.0 kg CO_2e kg^{-1} insecticide, West and Marland 2002; Lal 2004c), direct and indirect soil N_2O emissions from fertilizer-amended cropland (at rates described above), and transportation. Emissions from farm operations were included and were based on estimates of the C costs of plowing, planting, amendment application, harvesting, and baling (31.8 kg C ha^{-1}, Adler and others 2007). Dry matter from feeds and additive rates were estimated using national averages (Benbrook and others 2010; USDA NASS 2011).

The impact of the dietary change from commercial feed to local pasture on grazer emissions was also estimated. We assumed that pasture consumption replaced a portion of dry matter intake (19.7 kg d^{-1}, Ellis and others 2010) previously consumed through commercial feed. The increase in CH_4 emissions from enteric fermentation (dCH_{4EF}, kg d^{-1}) due to replacement of more readily digestible grains with pasture was predicted based on Ellis and others (2007)

$$CH_{4EnF} = [(Frg \times 0.14) + 8.56]/55.65, \quad (2)$$

where Frg is the percent dry matter intake from pasture; the difference between CH_{4EnF} with the original diet (68% pasture, Ellis and others 2007) and the new diet was obtained to determine dCH_{4EF}. In the case study, we assumed that these dietary impacts lasted for the same duration as the enhanced NPP effect (3 years).

Transportation

Distances between the farm and other locations (materials, feed, fields) were assigned to approximate transportation emissions. We assumed that plant waste, feed, and fertilizers were available at a standard distance (20 km) from the farm (EPA 2006) and that manure was available locally

(5 km). Once on site, amendments were transported equal distances (5 km) for application. We used the gas mileage (5.9 mpg, EPA 2008), volume (40 yd), and weight capacity (36 Mg, CDOT 2012) of a standard heavy-duty diesel truck. Emissions from both fuel production (Beer and others 2002) and consumption (EPA 2008) were included.

Manure Management

A manure management emission factor (EF) was used to calculate CH_4 emissions from manure handling. This EF provides the fraction of total potential CH_4 emitted from the storage system (EPA 2012b). Storage systems lead to different amounts of CH_4 production depending on several factors, including oxygen availability, moisture, and temperature (Brown and others 2008; Dong and others 2006). Solid storage has a low EF (0.04), whereas slurry pits and lagoons are higher (0.35 and 0.74 on average, respectively). Substantial variability in EFs has been reported within and across systems, with EFs for slurry pits and anaerobic lagoons ranging nationally between 0.15 and 0.62 and 0.5 and 0.8, respectively (EPA 2012b). We assumed an EF of 0.35 for the initial case study, representative of a slurry pit, a common practice in California (Meyer and others 2011). Total emissions from manure management practices also depend on the duration of storage. In the case study, we reduced the predicted emissions from manure management by 15% to account for a shortened storage period prior to land application; this reduction in CH_4 emissions was applied to both the manure (emission) and compost (offset) treatments.

Emissions from Amendment Production

Emissions from production were calculated for each amendment. For manure, the production process included transportation and storage emissions (slurry pond; EPA 2006; IPCC 2007). Emissions from compost production included material transportation, construction, and composting emissions. To estimate construction emissions, we approximated the hours of machine use per truckload. Equipment fuel was used at a fixed rate (0.048 gallons diesel h^{-1}, Downs and Hansen 1998), and the net greenhouse gas flux was calculated at the same rates used for transportation. Greenhouse gas emissions from compost were calculated from piles shaped as windrows (1.8-m tall × 1.2-m wide). We used relatively low, but non-zero, rates of CH_4 (0.5 kg m^{-2}) and N_2O (0.01 kg m^{-2}) emissions for the initial case study;

these emission rates approach the negligible emissions expected from optimal conditions (EPA 2006). Emissions from the production of inorganic N fertilizer depend on the N form and the production process (Wood and Cowie 2004; ammonium nitrate: 2.99–7.11 kg CO_2e kg^{-1} N; urea: 0.913–4.02 kg CO_2e kg^{-1} N). We used a midrange value of 4.01 kg CO_2e kg^{-1} N (Davis and Haglund 1999; Wood and Cowie 2004).

Offsets from Amendment Production

Offsets from compost production, which was used to represent a non-traditional waste management practice, included the diversion of plant waste from a landfill and the diversion of manure from a specific manure management system. In contrast, the manure amendment scenario in this model was used to represent a practice where manure was stored in a traditional management system (that is, a slurry) prior to land application. Thus, for manure amendments, there were no offsets attributed to waste diversion. However, changing the manure management system or decreasing the length of manure storage time prior to land application would reduce the predicted emissions associated with manure application, as mentioned above. No waste offsets were included in the inorganic fertilizer production.

Composted plant waste was diverted from landfills and represented greenhouse gas offsets. The potential CH_4 loss from landfilling depends on waste composition. Based on the composition described above, 11% of the plant C would have been lost as CH_4 in a landfill (Eleazer and others 1997). Some landfills capture CH_4 and use the gas for utilities, reducing net landfill emissions. To account for these technologies, we applied a capture rate of 50% and a utilities credit of 0.14 kg CO_2e kg^{-1} CO_2e-CH_4 captured (EPA 2006). We excluded biogenic CO_2 losses, but included CO_2 from fuel production and consumption. Landfilled materials can require less maintenance than compost piles; we estimated that landfilling required 50% of the fuel needed for composting (EPA 2006).

Alternative Model Scenarios and Uncertainty Analyses

We developed additional model case studies to explore the impacts of amendments under a wide range of ecosystem and management conditions (Table 2). For example, we considered the potential for long-term impacts on ecosystem NPP to enhance soil C sequestration. Although our initial case study was based on a field experiment that

Table 2.   Alternative Scenarios Relative to Initial Case Study

Scenario description	Variable modified	Note*	Value
Global warming potential over shorter (20-year) timeframe	GWP (CO_2e)	N_2O	289
		CH_4	72
Longer NPP effect from single application of all amendments	NPP effect (years)		20
Longer NPP effect, but no change in enteric fermentation due to diet change	Enteric fermentation (CO_2e ha^{-1})		0
N addition rates unequal for different amendments	N addition rate (kg N ha^{-1})	C	1,250
		M	250
		INF	125
Manure stockpile (vs. slurry)	Manure management emission factor (–)		0.05
Production emissions non-negligible	Compost emissions (kg m^{-2})	CH_4	5.0
		N_2O	0.1
Optimal capture technology	Landfill CH_4 capture (%)	C	100
No utilities credit from landfill CH_4 (vs. avg.)	Landfill utilities credit (kg CO_2e kg CO_2e-CH_4)	C	0
Compost largely plant waste	Compost (% manure)	C	25
Compost hauled further	Hauling distance (km)	C	500

Changes apply only to the case for compost (C), manure (M), or inorganic fertilizer (INF) where indicated

showed 3 years of enhanced NPP due to an amendment application (Ryals and Silver 2013), model results suggest that the effect could be sustained for up to 20 years following a one-time-only application (Ryals and others, in review-a). Thus, we explored a 20-year impact on NPP, as well as a 20-year impact on soil trace gas emissions. We also considered the 20-year scenario with no increase in enteric fermentation due to the dietary change (Boadi and others 2004).

Among management scenarios, we evaluated the case where amendments were added at different rates: compost was added at 1,250 kg N ha^{-1} (1.27 cm, Ryals and Silver 2013), but manure and inorganic fertilizer were added at 250 and 125 kg N ha^{-1}, respectively. Nitrogen is generally highly labile in manure and inorganic fertilizers and thus these amendments are generally applied at rates below 250 kg N ha^{-1} (Bouwman and others 2002). In contrast, composted materials contain N that is more complexed leading to slower mineralization rates (Eghball 2000; Sikora and Szmidt 2001; Ryals and Silver 2013), which can require higher application rates.

Differences in management technologies and scales could also impact the effects of the practice. Some manure management practices produce fewer emissions than slurry systems; thus, we considered the case where the default system was a stockpile (EF = 0.05). Similarly, because some landfills can capture more CH_4, we evaluated the effect of a 100% capture rate. Emissions from composting are not negligible in all cases, so we included a scenario where CH_4 and N_2O emissions were significantly greater (10 times larger). Widespread adoption of compost amendments could encourage large-scale production. We therefore estimated the impact of transporting compost over large distances (500 km). Finally, to consider how the GWP values influenced our results, we used the 20-year GWPs (CH_4 = 72 CO_2e, N_2O = 289 CO_2e).

We performed sensitivity tests to identify the factors that had the largest impact on the model output. The effect of deviations of initial case study values from −90 to 500% of initial values was calculated (Appendix B in Supplementary Material). For most of these analyses, one variable was adjusted at a time while other values were held constant. However, some factors were covaried to reveal a wider range of potential impacts. For example, to investigate the sensitivity of results to a range of ecosystem characteristics, we covaried the annual expected change to NPP with both the duration of the NPP effect and the C sink efficiency. To evaluate a broader range of impacts related to management, we covaried the percentage of manure used in the compost with both the manure management factor and the landfill CH_4 capture rate.

To evaluate the uncertainty associated with variables used in the model, we performed Monte Carlo simulations based on the initial case study. Values of several model variables were assigned probability distribution functions based on values

from the literature (Table 3; Appendix A in Supplementary Material). Values for each variable were randomly assigned based on these distribution functions and 10,000 independent simulations were run. This set of Monte Carlo simulations was then used to further explore the uncertainties of the model and likely outcomes from the model scenarios. Results of the Monte Carlo simulations are presented as mean $\pm$ 1 standard error.

RESULTS

Initial Case Study for Annual Grasslands

Compost applications in the initial case study yielded a net greenhouse gas flux of -22.6 Mg CO_2e ha^{-1} over 3 years (Figure 2). This net reduction was largely due to offsets from avoided emissions from a manure slurry system and a landfill. The C sink resulting from increased NPP contributed a savings of 0.3 Mg CO_2e ha^{-1}. The emissions attributed to compost production and application in the initial case study were approximately 3.7 Mg CO_2e ha^{-1},
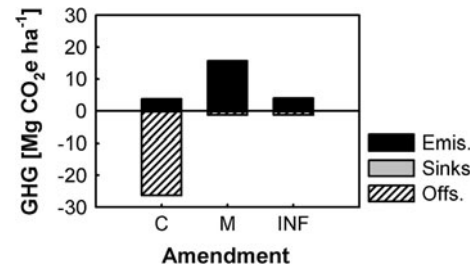

Figure 2. Net greenhouse gas flux (GHG_{net}) from the production and land application of compost (C), slurry manure (M), and inorganic N fertilizer (INF) to grazed annual grasslands. GHG_{net} per hectare is partitioned into emissions, sinks, and offsets. Negative values represent sinks and offsets.

which was due in large part to the assumed dietary changes of livestock.

Manure application was a large net source of 14.4 Mg CO_2e ha^{-1} (Figure 2), primarily due to high emissions from a slurry storage system prior to land application (15.0 Mg CO_2e ha^{-1}). The emissions from transportation and application were

Table 3. Model Parameterization for Grassland Case Study and Uncertainty Analysis

Variable	Note*	Case study		Uncertainty analysis descriptors		
		Value	References	Distrib.	μ, min	σ, max
Global warming potential (GWP) (CO_2e)	N_2O	298	a	Normal	298	64
	CH_4	25		Normal	25	5
Soil N_2O increase (direct) (kg N kg^{-1} added-N)	C	0.003	b	Lognormal	-6.1	0.5
	M	0.01	c	Lognormal	-4.7	0.6
	INF	0.01	c	Lognormal	-4.7	0.6
Increased aboveground (AG), belowground (BG) (NPP) (%)	AG	55	b	Normal	55	11
	BG	23		Normal	23	4
Soil trace gas (TG) effect (years)		1	b	Exponential	1.4	n/a
NPP effect (years)		3	b	Exponential	4	n/a
Enteric ferm. factor (fraction of dCH_{4EF} from Eq. 2)		1	d	Normal	0	0.20
C sink efficiency (kg C kg^{-1} added BG C)		0.2	e	Lognormal	-1.70	0.35
N addition rate (kg N ha^{-1})		250	f	Lognormal	5.40	0.45
Manure management emission factor (–)	M, C	0.35	g	Lognormal	-1.00	0.25
Manure management time factor (–)	M, C	0.85		Exponential	0.1	n/a
Inorganic N production (kg CO_2e kg^{-1} N)		4.01	h	Normal	4.01	1.00
Compost emissions (kg m^{-2})	CH_4	0.50	i	Lognormal	-0.2	0.8
	N_2O	0.01		Lognormal	-4.0	0.75
Landfill waste CH_4-C loss (% initial C)	C	11	j	Lognormal	2.25	0.5
Landfill CH_4 capture (%)	C	50	i	Normal	50	12
Landfill utilities credit (kg CO_2e kg^{-1} CO_2e-CH_4)	C	0.14	i	Normal	0.14	0.03
Compost (% manure)	C	75		Uniform	0	100
Hauling distance (km)	C	5		Exponential	5	n/a
Farm operations (kg C ha^{-1})		31.8	k	Normal	31.8	6.4

(a) IPCC (2007), (b) Ryals and Silver (2013), (c) De Klein and others (2006), (d) Ellis and others (2007), (e) Plénet and others (1993), (f) Bouwman and others (2002), (g) EPA (2012b), (h) Davis and Haglund (1999), (i) EPA (2006), (j) Eleazer and others (1997), (k) Adler and others (2007).
* Values apply only to the case for compost (C), manure (M), or inorganic fertilizer (INF) where indicated

0.6 Mg CO_2e ha^{-1}, which were lower than those from compost because we assumed that manure was available on site and that plant waste required longer transport distances. We assumed that all amendments impacted NPP equally, thus the C sink was the same as for compost (0.3 Mg CO_2e ha^{-1}). Offsets for manure application in this scenario (1.0 Mg CO_2e ha^{-1}) came from reduced demand for commercial feed.

Application of inorganic N fertilizer also resulted in greenhouse gases emissions (Figure 2, 4.0 Mg CO_2e ha^{-1}). However, net emissions from the inorganic fertilizer were smaller than from the manure slurry. Like the other amendments, the inorganic fertilizer enhanced NPP resulting in both a C sink (0.3 Mg CO_2e ha^{-1}) and offsets from reduced commercial feed production (1.0 Mg CO_2e ha^{-1}).

Case Studies with Alternative Ecosystem or Management Conditions

Variables were modified to represent alternative scenarios, with notable impacts on the estimated net greenhouse gas flux from soil amendment applications (Figure 3). For example, increasing the N application rate of compost relative to the other amendments (5× manure and 10× fertilizer rates) enabled a larger offset from waste diversion, leading to a net greenhouse gas flux of 110 Mg CO_2e ha^{-1} for compost over 3 years. Assuming that the NPP effect was sustained for 20 years increased the C sink from all amendments to 1.9 Mg CO_2e ha^{-1} over

20 years; this C accumulated over time through a fraction of the enhanced belowground biomass. The resulting net impact over 20 years was 24 Mg CO_2e ha^{-1}. If no increase in enteric fermentation occurred, then the net result was an even larger overall offset from compost (30.9 Mg CO_2e ha^{-1} over 20 years). Changing the manure management system from a slurry to a low-emission stockpile (EF = 0.05) decreased the net offset from compost to 6.0 Mg CO_2e ha^{-1} over 3 years, whereas net emissions from manure applications decreased correspondingly. However, the manure amendment remained a larger source than the inorganic fertilizer (by 0.7 Mg CO_2e ha^{-1}). Using the 20- versus 100-year GWP values for greenhouse gases roughly tripled the expected offset impact from compost (to 68.4 Mg CO_2e ha^{-1}) and emissions impact from slurry storage and application (to 40.3 Mg CO_2e ha^{-1}) over 3 years.

The results were sensitive to several of the model variables (Figure 4). Deviations from the initial case study values of 50% resulted in a change to the net greenhouse gas flux usually under 15 Mg CO_2e ha^{-1}. One of the largest observed impacts in the sensitivity tests occurred when the compost-N concentration was reduced by 50%, which corresponded to a need for more compost, a doubling of diverted waste, and an increase to offsets of over 20 Mg CO_2e ha^{-1}. The model was also quite sensitive to the manure management EF, compost composition, and N addition rate, all of which led to a change of over 5 Mg CO_2e ha^{-1}
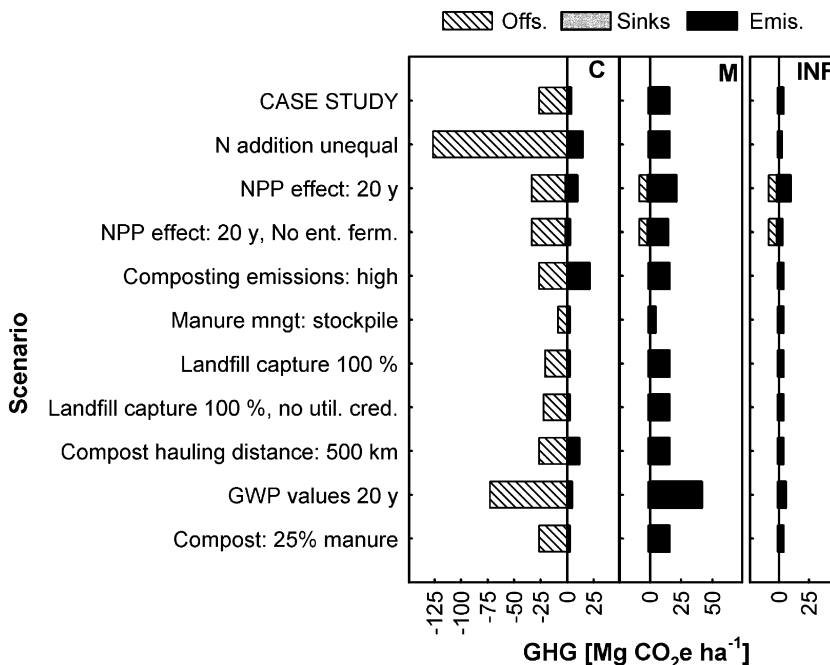

Figure 3. Net greenhouse gas flux (GHG$_{net}$) associated with soil amendments [compost (C), manure (M), and inorganic N fertilizer (INF)] applied to grazed grasslands under several alternative scenarios (Table 2) as compared to the initial case study.
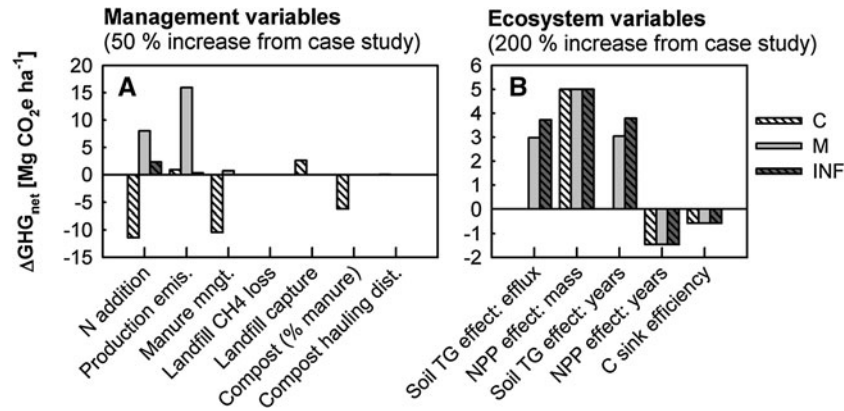
Figure 4. Change in net greenhouse gas flux (ΔGHG_{net}) associated with soil amendment applications [compost (C), manure (M), and inorganic N fertilizer (INF)] following **A** a 50% increase to management variables or **B** a 200% increase to ecosystem variables (as compared to initial case study values). Additional results from the sensitivity analyses are shown in Appendix B (Supplementary Material).

following a 50% change. Results were less sensitive (< 5 Mg CO_2e ha^{-1} response to a 50% change) to landfill emissions and CH_4 capture rate. Results were not strongly dependent on hauling distances. Changes to most ecosystem variables (soil trace gas effluxes, NPP, C sink efficiency) had a small effect over the sensitivity test ranges.

When two ecosystem or management variables covaried, a broader range of potential impacts was observed (Figure 5). In cases where the manure content of compost was high ($> 50\%$), results were particularly sensitive to the manure management EF (Figure 5A). When the full ranges of compost composition and manure management facilities were considered, compost amendment results reached a maximum net offset of 78.5 Mg CO_2e ha^{-1}. Compost materials largely derived from plant materials and high rates of landfill CH_4 capture significantly decreased the greenhouse gas savings from composting (Figure 5B). As long as manure composed at least 25% of the compost, compost application led to net greenhouse gas emissions reduction at all landfill capture efficiency rates (up to 100%). At 100% plant waste, capture efficiency rates below 80% were required to lead to a net greenhouse gas offset from compost application. On the other hand, at 100% plant waste but with no (0%) landfill capture rate, composting led to net savings of 30 Mg CO_2e ha^{-1}. A capture rate of 100% with a utilities credit resulted in net emissions from compost relative to landfill (by 12 Mg CO_2e ha^{-1}); removing the utilities credit reduced the relative advantage of landfilling to 7 Mg CO_2e ha^{-1}.

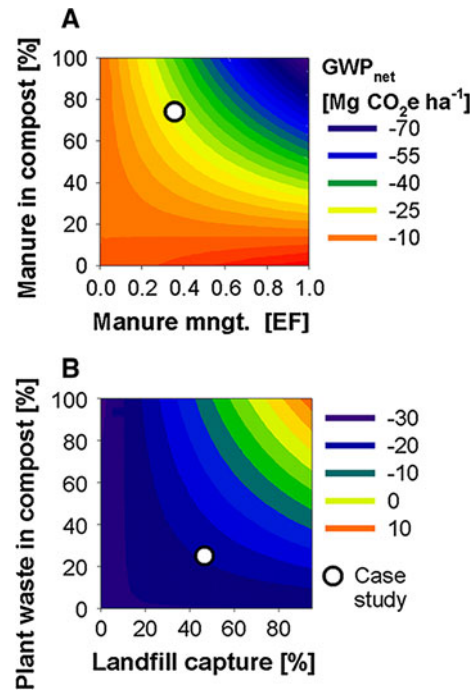Changes to two ecosystem variables had a smaller impact. In the initial case study, we assumed

Figure 5. Range of possible net greenhouse gas flux (GHG_{net}) resulting from the production and land application of compost amendments with different compositions and management conditions: **A** manure management emission factor (EF) and manure content, **B** landfill CH_4 capture rate and plant waste content.

that NPP increased by 0.11 kg C m^{-2} y^{-1} for 3 years. After increasing the magnitude and duration of the NPP effect, the net offset from composting reached over 100 Mg CO_2e ha^{-1}. We also initially assumed that 20% of the added belowground biomass C was stored in long-term soil C

pools. In the case that 0% of added C was stored in these stable pools, the C sink attributed to NPP was lost. However, if 40% or more of this C is stored, then the cumulative effect could become significant, leading to additional savings of up to 10 Mg CO_2e ha^{-1} over 20 years.

Uncertainty Analysis

We performed a Monte Carlo analysis including 10,000 independent simulations based on the distributions of the variables with the greatest uncertainty (Table 3). This analysis suggested that application of compost to grazed grasslands is highly likely to lead to net greenhouse gas offsets, even when considering a much broader range of possible conditions (Figure 6). The average predicted net offset from compost was 4.3 ± 0.8 Mg CO_2e ha^{-1}. The findings for the manure and inorganic fertilizer treatments also generally agreed with the base case scenario. Manure and inorganic fertilizer applications were most likely to lead to net greenhouse gas emissions (17.2 ± 0.7 and 3.1 ± 1.4 Mg CO_2e ha^{-1}). Although the uncertainty analysis agreed with the key findings from the initial case study, it also revealed that compost applications in some scenarios

Figure 6. A Monte Carlo simulations (n = 10,000) showing the impact of uncertain and widely ranging variables on projected net greenhouse gas fluxes resulting from the application of compost (C), manure (M), or inorganic fertilizer (INF) to grasslands. **B** Mean and standard error of net greenhouse gas fluxes from 10,000 independent simulations of three soil amendment treatments.

could lead to net emissions or that manure and inorganic fertilizer applications could potentially provide net offsets. For example, compost applications led to net emissions in cases where associated emissions were high (that is, due to poor management) but offsets were low (that is, materials were obtained from low-emission sources, ecosystem benefits were lower than expected). Alternatively, manure applications led to net offsets, but only if manure was handled in low-emission systems prior to land application and if measures were taken to minimize N losses after application. Although the model suggested that inorganic fertilizers could also potentially lead to net offsets, this was less likely due to the more ephemeral nature of these N inputs. Rapid N utilization and high loss rates led to a shorter period of beneficial ecosystem impacts that did not outweigh fertilizer production emissions over the long term.

Upscaling

We scaled up results to determine potential regional impacts of soil amendment-based management strategies (Table 4; Figure 7). Over a county-level region (65,000 ha), compost applications as described in the initial case study led to a reduction in the net greenhouse gas flux of 1.5 MMg CO_2e over 3 years. This is nearly equivalent to an offset of 10% of the annual emissions from the California commercial sector, which is the economic sector that includes categories such as food services, health care, education, and retail (CARB 2011). Extended to 5% of California rangelands (1,275,000 ha), this strategy would offset nearly 1 year of emissions from the California agriculture and forestry sectors (over 28 MMg CO_2e, CARB 2011); although this estimate is based on 3 years of enhanced NPP, the majority of the benefit was obtained in the first year.

The availability of organic materials suitable for land application was assessed regionally and statewide (Table 4; Figure 7). Composted plant waste (including food) diverted from California landfills could be used to treat over 150,000 ha annually. Based on estimates of manure production, over 400,000 ha could also be treated annually with composted manure.
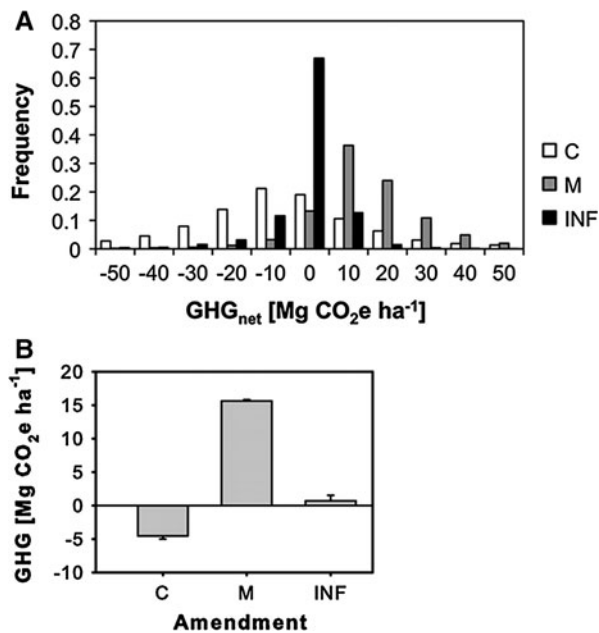
DISCUSSION

Effects of Soil Amendments on Grassland C and Greenhouse Gases

The initial case study revealed that applying composted wastes to rangelands could significantly reduce greenhouse gas emissions attributed to the

agricultural sector. At the field-scale, the net greenhouse gas offsets from compost per hectare of treated land were approximately equal to the greenhouse gas emissions of four trips of a diesel truck from San Francisco to Washington, DC (Graham and others 2008) or the annual CH_4 emissions from eight grass-fed cows (Laubach and Kelliher 2004). In contrast, the application of manure from slurry ponds, a common practice (EPA 2011; Meyer and others 2011), led to large greenhouse gas emissions.

The largest potential for greenhouse gas savings from compost amendments was due to diverting waste materials (both plant and manure wastes) from traditional high-emission waste management practices. The manure management factor used in the case study represented a slurry system where manure is liquefied. C-rich manure slurries facilitate the development of anaerobic conditions that stimulate CH_4 production. The high C cost of CH_4 emissions from the slurry system generally outweighed C gained via NPP and soil sequestration. It should be noted that other waste management strategies for manure such as anaerobic digestion with gas capture could help to reduce CH_4 emissions relative to common liquid management systems. Similar to manure slurry systems, landfills typically experience anaerobic conditions that promote methanogenesis; rates depend on the physical and chemical properties of the waste and landfill environment, which is likely to vary over time and space. At landfills equipped with technologies to capture CH_4 emissions, the benefits of organic waste diversion would be smaller relative to the default practice.

Diverting manure, yard and food wastes to composting systems can lead to significant greenhouse gas offsets. Unlike manure slurry systems and landfills, composting is specifically managed to promote aerobic decomposition by maintaining moisture content below saturation, providing
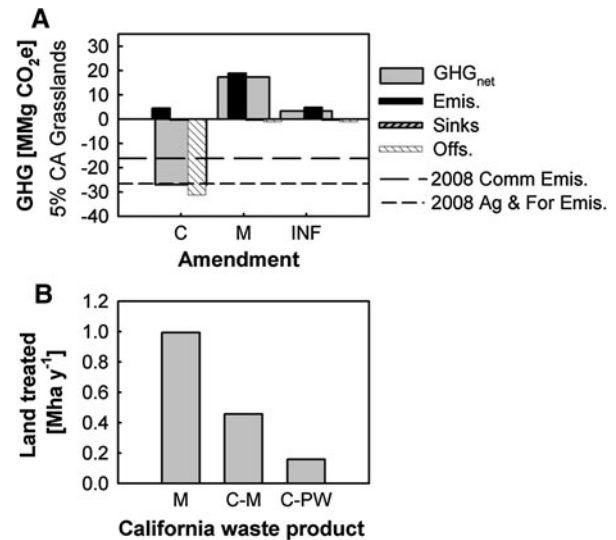

Figure 7. **A** Potential impacts of soil amendments on net greenhouse gas fluxes when applied over an area equal to 5% of California grasslands. Emissions from the California Agriculture and Forestry and Commercial Sectors (CARB 2011) are shown for comparison. **B** Area of land statewide that could potentially be treated annually using cattle manure (M), composted manure (C-M), or composted plant waste (C-PW) assuming application rates used in the initial case study (Table 3) and material availability (Table 4).

Table 4. Resource Availability for Soil Amendment Production and Application

	Grassland (Mha)	Cattle (mill. head)	Cattle manure[a] (MMg y^{-1})	Compostable waste at collection facilities[b,c] (MMg y^{-1})		
				Yard waste	Food	Paper
Marin	0.065[d]	0.032[g]	0.067	0.025[i]	0.054[i]	0.077[i]
CA	24.0[e]	5.2[g]	10.8	2.8[j]	6.2[j]	6.9[j]
US	238.0[f]	90.8[h]	189.0	33.4[k]	34.8[k]	71.3[k]

[a] Assuming a rate of 2.08 Mg dry manure $cow^{-1} y^{-1}$ (USDA NRCS 2008).
[b] California and the US currently process greater than 9.3 MMg (http://www.calrecycle.ca.gov/climate/Organics/default.htm) and greater than 20 MMg (EPA 2011), waste, respectively, into compost annually.
[c] Biosolids are also composted and could be included to increase compost production (Brown and Leonard 2004); approximately 6.5 MMg of dry biosolids are produced annually in the US (Lu and others 2012).
[d] Silver and others (2010).
[e] Brown and others (2004).
[f] Includes grassland pasture and range (Lubowski and others 2006); Avg US farm is 170 ha (USDA NASS 2012c).
[g] USDA NASS (2012a) (Milk cows: Marin—10,000, California—1,750,000).
[h] USDA NASS (2012b) (Milk cows: US—9,194,000).
[i] CalRecycle, Solid Waste Characterization Database: 1999 Data, available at: http://www.calrecycle.ca.gov/WasteChar/.
[j] CAIWMB (2009).
[k] EPA (2011).

aeration, stimulating high temperatures, and decreasing labile C through high C:N ratios. In theory, these conditions lead to low CH_4 and N_2O emissions, and, although results vary (Anderson and others 2010; Larney and Hao 2007; Hao and others 2004), emissions are generally lower than other waste management approaches. When we assumed significantly higher composting emissions, compost amendments still resulted in an overall greenhouse gas offset, although the magnitude was considerably lower. In the model, additional C benefits came from enhanced C sequestration through biomass, particularly when impacts on NPP lasted multiple years. A smaller offset came from a reduced need for purchased feed and the associated reduction in fertilizer, herbicide, and pesticide use. Although this was only a minor greenhouse gas savings, it can be crucial from an economic perspective, adding to the feasibility of these management approaches.

The predicted greenhouse gas impacts from compost, manure, and inorganic N fertilizers were influenced by emissions throughout the amendment life cycles. The manure management system was the primary cause for the high emissions from the manure amendment, whereas the landfill CH_4 emissions and capture rates affected the outcome for compost amendments. These findings emphasize the importance of a thorough understanding of current practices (for manure management) and community resources (for landfill capabilities) when assessing the potential benefits of soil amendments. The greatest benefits from compost application are likely to be achieved in regions where either (1) high-emission manure management systems (slurry systems, lagoons) are widespread, or (2) large amounts of organic wastes are produced (for example, near urban and agricultural environments). Based on our parameterization of landfills and manure management, increasing the ratio of manure to plant waste in the compost increased the predicted greenhouse gas offset. This balance would shift depending upon local availability of materials, land, and infrastructure. The model can be used to explore the impact of these management practices on net greenhouse gas fluxes in regions with different resource availabilities.

Soil Amendment Impacts in Alternative Scenarios

Alternative scenarios were used to evaluate the outcomes from soil amendment applications under a wide range of environmental and management conditions. Results were most sensitive to the N application rate and amendment-N concentration. Together these variables determined the mass of materials used and, therefore, the magnitude of the offsets (compost) or emissions (manure, inorganic fertilizer). Although the initial case study assumed equal N additions, these amendments would likely be applied at different rates; composts, with slower rates of N mineralization, may be applied more heavily ($>1,000$ kg ha^{-1}) than inorganic fertilizers, which are often used more sparingly (<250 kg ha^{-1}, Bouwman and others 2002). Changing these rates accordingly enables greater waste diversion for compost, increasing the associated greenhouse gas offset, even when accounting for processing and transportation. It is likely that there would be different impacts on NPP if N application rates were unequal among the amendments, leading to additional relative benefits for the compost, particularly if the NPP effect is sustained over a decade or more. For example, the initial case study assumed that equal N additions led to equal benefits (magnitude and duration of enhanced NPP) from all amendments. However, compost differs from manure and inorganic fertilizer in that it is partially decomposed and has a high proportion of complexed or recalcitrant materials (Eghball 2000). These materials break down more slowly than fresh residues, acting as a slow release fertilizer (Eghball 2000; Sikora and Szmidt 2001). This mechanism is likely to sustain NPP for longer time periods than, for instance, a short pulse of inorganic fertilizer (Sullivan and others 1998).

Manure amendments were associated with larger greenhouse gas emissions than inorganic fertilizers, despite the additional energy cost required for synthetic fertilizer production. Although the energy costs of producing inorganic fertilizer were not negligible, emissions from production were lower than other emissions attributed to fertilizer use, such as soil N_2O emissions (Adler and others 2007). Additionally, a smaller mass of inorganic fertilizer was required to achieve the same N application rates.

The inorganic fertilizer did not use any waste materials, unlike compost and manure. For manure, we estimated emissions from storage prior to application and included these estimates in the total greenhouse gas emissions. In contrast, for the compost, we considered a diversion of manure to be an offset as compared to the uncomposted manure application (considered the current default practice). For inorganic N, we considered the case where manure was a limited resource and unavailable. These boundaries were designed to weigh the production costs of inorganic fertilizer

against the potential ecosystem benefits. If inorganic N fertilizer was used in a location where manure was available, emissions from manure storage and management would also need to be considered; in this scenario, net emissions from inorganic fertilizer would likely exceed the emissions from manure application.

The impacts of soil amendments on several ecosystem properties were also areas of uncertainty in the model. Nitrogen losses from ecosystems, either directly as N_2O or indirectly through leachate and volatilization, depend on the quantity, chemical quality, and application method of amendments, as well as ecosystem conditions (for example, soil moisture, drainage, temperature, pH; Lesschen and others 2011; Stehfest and Bouwman 2006). We applied widely used EFs for manure and inorganic N fertilizers, but these values should ideally be determined specifically for each site (De Klein and others 2006; Kendall and Chang 2009). Minimizing N_2O losses for quick-release fertilizers and manure can require multiple, rather than one-time applications, increasing emissions associated with transportation. Therefore, the case studies may have underestimated net greenhouse gas fluxes associated with manure and inorganic fertilizer applications. On the other hand, enhanced efficiency inorganic fertilizers (that is, with nitrification inhibitors and polymer-coated fertilizers) have the potential to decrease greenhouse gas emissions relative to conventional inorganic fertilizers (Akiyama and others 2010). In addition to impacts on soil N_2O emissions, recent research suggests that compost additions could lower soil CH_4 emissions (Chen and others 2011) or minimize CH_4 uptake inhibition (Mosier and others 1991). If compost can provide ecosystem benefits without decreasing CH_4 oxidation, this could improve the strength of the compost greenhouse gas emissions offset relative to other amendments.

Considerations for Widespread Adoption

The greenhouse gas benefits of soil amendments can be significant when materials are diverted from waste streams and applied to the land. We focused on specific regions in California, although our model can be applied on larger national or even global scales. The large-scale applicability of these ideas is due to the ubiquity of grasslands, grazing, and waste management concerns.

The relatively small impact of transportation on the amendment net greenhouse gas flux indicates that these practices could be adopted over larger regions. Low relative C costs of transportation have been found in other analyses (Weber and

Matthews 2008). Local projects would be the most logical and least expensive; however, our results suggest that small additional C costs to move waste materials to suitable land would not strongly impact the offset potential from composting.

These results are dependent on the GWP values, which represent the long-term atmospheric impacts of key greenhouse gases. The difference between the results for manure and compost using 20-year rather than 100-year GWP values was striking. When focusing on a shorter timescale, the impact of offsets from diverting waste for compost more than doubled (to nearly 100 Mg CO_2e ha^{-1}). The 100-year values for GWP are the most commonly used. These values are somewhat arbitrary from an ecosystem perspective and our analyses illustrate the significant effect that these assumptions could have on management and policy decisions.

Overall, this study has demonstrated that producing compost and applying it to rangelands has the potential to significantly offset GHG emissions. As the largest offsets were obtained from the diversion of materials from high-emission waste streams, this study also generally highlights the opportunity to mitigate greenhouse gas emissions by improving waste management. In the case of compost, using existing waste materials and land area could lead to significant offsets annually, with numerous co-benefits also achieved. Climate mitigation benefits from this practice are likely to be greatest when it is applied near rural or urban centers where high-emission manure management systems are common or where large amounts of organic materials could be diverted from landfills. Increased forage production and soil quality, though not the primary drivers of the mitigation potential, provide important co-benefits and incentives to land managers. The model can be applied broadly to identify the potential for grassland management to mitigate climate change in regions with different resources and ecosystem characteristics.

this study. We also thank the Marin Agricultural Land Trust, and N. Scolari, B. Berner, P. Hickey, D. Lewis, S. Larson, S. Carlsen, T. Estrada, C. Epifano, and Marin Organic for their partnership in the Marin Carbon Project. J. Neff and two anonymous reviewers provided insightful feedback that improved the manuscript.

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