Scaling Soil Biogeochemical Processes in an Annual Grassland Ecosystem: The Interactive Effects of Management and Climate Change

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Introduction

Grassland ecosystems managed for livestock production represent the largest land-use footprint globally, covering more than one-quarter of the world's land surface (Asner et al. 2004). In California, rangelands cover an estimated 17 million hectares or approximately 40% of the land area (FRAP 2003). Rangeland soils hold considerable potential to store carbon (C) and offset greenhouse gas emissions (Lal 2004). The relative balance between C fixed in net primary productivity (NPP) and C lost via heterotrophic respiration (R_h) in large part determines rates of soil C sequestration in annual grasslands. Ecosystem dynamics in annual grasslands are tightly coupled with the timing and amount of precipitation (Duncan & Woodmansee 1975; George et al. 1989; Heady et al. 1992). Seasonality in rainfall and the strong summer drought decouples NPP and litter decomposition in time, resulting in *carry-over effects*: the biogeochemical, physical, and microenvironmental effects of residual necromass on ecosystem processes during the subsequent growing season. Decomposition of this residual material (i.e. residual dry matter, RDM) is initiated with the start of fall rains and is primarily responsible for early season soil respiration fluxes before plants fully establish. Carry-over effects in annual grasslands play an important role in C and nutrient budgets, linking biogeochemical cycling with climate within and across years. In these ecosystems, changes in rainfall quantity and distribution can alter source-sink relationships and result in significant feedbacks to global climate change at multiple temporal scales.

Management practices can have direct effects on C storage, such as those that alter soil chemical or physical characteristics, and indirect effects such as changes in plant morphology or life history, moisture, or microbial activity (Jones and Donnelly 2004; Steenwerth et al. 2002; Stromberg and Griffin 1996). These management-induced changes to C cycling at local scales can affect the global C cycle (Conant et al 2001; Schimel et al. 1990). Future legislation and C markets are likely to provide economic incentives for rangeland managers to change practices, yet research exploring C sequestration in rangelands is limited (Derner and Schuman 2007).

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Project Objectives

In this study, we conducted field and modeling experiments to explore the effects of management approaches on soil C and the interactive effects of management and precipitation change on soil C storage. Our research directly contributes to the current mission of the Kearney Foundation of Soil Science in the following ways:

- We quantified the separate and combined impacts of rangeland management and altered precipitation on soil biogeochemical cycling at multiple temporal scales, with a focus on carry over effects from one water year to the next. We captured soil C and N dynamics during a particularly dry water year and average water year. Using field experiments we explored patterns of and controls on biogeochemical cycling within and across seasons and years.
- Using the DayCent and Century soil organic matter models we are testing the effects of grazing intensity, drought intensity, and altered seasonality on soil C and nutrient dynamics over daily to decadal time scales. As part of this approach we are developing rangeland management scenarios based on current practices in the region. We will use these in our modeling activities to determine the potential interactions between grazing and other rangeland management alternatives and climate change. These activities will provide valuable information for sustainable land management as well as indications of significant feedbacks to climate change.

Approach and Procedures

Field experimental design

The field component of this research was conducted at the Sierra Foothills Research and Extension Center (SFREC) in Browns Valley, CA. The SFREC exists in a Mediterranean climate characterized by cool, wet winters and warm, dry summers. Annual precipitation averages 720 mm/y (>20 y mean); air temperatures range from 2^{o} C in January to 32^{o} C in July. Soils are classified as clay-rich, mixed, thermic Typic Haploxeralfs (Herbert and Begg 1969). The floristic composition of grassland at SFREC is dominated by non-native annual grass species such as *Avena barbata*, *Bromus hordeaceus*, *Lolium multiflorum*, and *Taeniatherum caput-medusae*, with additional presence of forbs (*Erodium* spp.) and legumes (*Trifolium* spp.). The growing season begins with the rains in September-November and ends in April-June. The site has been consistently grazed by cattle for at least 40 years (D. Flavell, pers. comm.).

The field manipulation, established in 2008, consisted of four treatments: control, compost amendments, plowed (vertical subsoiler), and compost + plow. Treatment plots were 25 m by 60 m buffered by a 5 m strip arranged in three randomized replicate blocks situated across the landscape. An organic-rich soil amendment was produced by adding one application of composted organic material with a C:N ratio of 11.1 (14 Mg C/ha equivalent to a 1.27 cm surface dressing) in December 2008. Subsoiled plots were plowed with a Yoeman Plow approximately 10 cm below rooting depth in December 2008. In combined management plots, soils were amended followed immediately by subsoiling. All plots experienced a cattle grazing regime typical of the region, where cattle grazed for 2-4 weeks in early spring and again in early fall to achieve a residual dry matter level of 1200 lbs/acre.

To test the interactive effects of management and climate, a drought experiment was conducted within control and amended plots. Within each plot, two 1 m by 1 m subplots were established to test the effects of late season rainfall events on soil respiration, moisture, temperature, and hydrolytic extracellular enzyme activities. One subplot received ambient late season rainfall, while the other received an experimental drought treatment using rainfall exclosure shelters built from transparent roofing material. Shelters were placed 1 m above soil surface during rain events. To minimize non-precipitation effects of shelters on soils and plants, the shelters were up for no longer than 24 hours before or after a rainfall event. Gravimetric soil moisture and temperature were measured weekly to a depth of 10 cm. Soil respiration was also measured weekly with a LI-8100 20 cm survey chamber (Li-Cor Biosciences, Lincoln, NE). Hydrolytic extracellular enzyme activities were measured near the end of the growing season at peak standing crop (May).

Net primary productivity

The vegetation community at the study site is dominated by annual grass species. These plants germinate at the onset of the fall rains and die at the end of the wet season. Aboveground biomass measurements were determined by harvesting nine replicate 16 cm diameter circles per plot at peak standing crop. Harvests were dried at 65^{o} C, weighed, and analyzed for C and N content on a Carlo Erba Elantech elemental analyzer (Lakewood, NJ). Since all plots were grazed, aboveground biomass was also harvest no more than 24 hours immediately before and after grazing. Aboveground net primary productivity was determined by adding the dry biomass removed by cows to the dry biomass collected at peak standing crop.

Belowground net primary productivity was collected at peak standing crop for year two only. Eight 0-10 cm and four 10-20 cm quantitative soil cores (5 cm diameter) were sampled per plot. Roots from each core were isolated according to Metcalfe et al. (2007) with the following modifications. Roots were picked by hand at 10-minute intervals for a total of 120 minutes. Roots were then rinsed in deionized water and dried at 65^{o} C for 48 hours. During our method tests, we extracted roots from 16 cores (8 control and 8 amended soils) for 160 minutes through a series of sieving (2 mm and 0.53 mm). We then compared actual root biomass data to predicted root biomass from a model fitted to the first 4, 6, 8, 10, 12, and 14 10-minute intervals, using a saturation, exponential, power, and logarithmic curve formulas. As in Metcalfe et al. (2007), a logarithmic curve resulted in the strongest fit (r^2 values ranged from 0.93 to 0.99 for the sixteen individual cores). Predicted root biomass for a 100-minute extraction period resulted in a -3.0 ± 0.7 % difference from actual data (Figure 1). Logarithmic models were determined for each root core, and models were extrapolated to the time at which a single

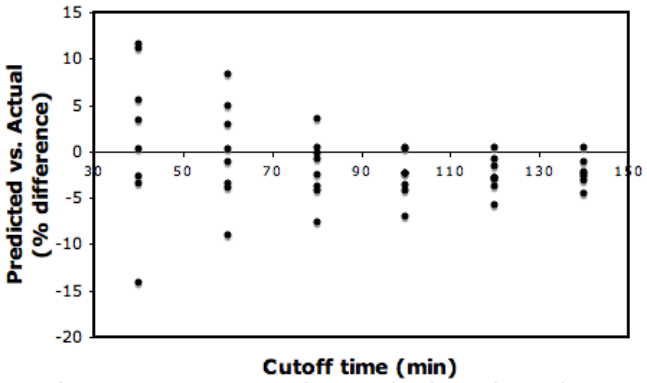

Figure 1. Root extraction method test based on timed extrapolation of 10-minute intervals of root picking. Predicted data extrapolated from logarithmic curves fit to the first 40, 60, 80, 100, 120, and 140 minutes, compared to actual data.

10-minute time interval was less than 0.5% of the cumulative total root biomass already collected.

Greenhouse gas emissions

Soil CO_2 fluxes were measured weekly using a LI-8100 infrared gas analyzer (Li-Cor Biosciences, Lincoln, NE) fitted with a 20 cm diameter soil efflux chamber. The chamber was used in a survey mode with polyvinyl chloride collars (five per plot, along a upper to lower slope transect). Fluxes were measured at least thirty minutes after driving collars firmly into the soil approximately 3 cm deep. Fluxes were sampled weekly for six weeks prior to organic amendment application.

Methane and N_2O fluxes were calculated using static flux chambers (Keller & Reiners 1994). Gas samples were collected at 0, 5, 15, 25, and 40-minute time points (Chou et al. 2008). Four chambers per plot were randomly placed along a slope transect. Methane concentrations were analyzed on a gas chromatograph using a flame ionization detector, and an electron capture detector was used to analyze N_2O concentrations. Fluxes were then calculated using a linear model. Methane and nitrous oxide fluxes were measured bi-weekly for the first six months and monthly thereafter.

Soil carbon content, nitrogen content, and bulk density

Soil bulk density was measured to a 10 cm depth using 5 cm diameter volumetric soil cores (n = 8 per plot). We measured bulk density to 100 cm depth in 10 cm depth increments using 1 bulk density pit per plot. We carefully excavated 10 cm diameter cores approximately 5 cm back from an undisturbed face of the pit. Soils at SFREC contain a large proportion of rocks, thus bulk density measurements were corrected for rock volume. Upon extraction from cores, rock volume and masses were measured and subtracted from initial bulk density calculations.

Soil organic C and N concentrations were measured prior to the application of management treatments (Nov. 2008) and at the ends of each growing season (Aug. 2009 and April 2010). Soils were collected using a 5 cm diameter corer to 10 cm depth in year one and at four depth increments (0-10, 10-30, 30-50, and 50-100 cm) in year two. Soils were air-dried and ground finely after removing large root fragments. Carbon and N concentrations were measured using a Carlo Erba Elantech elemental analyzer (Lakewood, NJ). Carbon and N concentrations were converted to content using bulk density values for each plot.

Soil moisture, soil temperature, and climate data

In May 2009, automated TDR-based probes were installed at 0-30 cm depth to measure volumetric water content (Campbell Scientific CS616, n = 3 per plot), and automated soil temperature probes were installed at 0-5 cm depth (Campbell Scientific 108L, n = 1 per plot). Soil moisture and temperature data output was averaged on hourly and daily timescales.

Daily rainfall and air temperature data were obtained from the Browns Valley climate station. Data are publicly available and maintained by the California Irrigation Management Information System (http://wwwcimis.water.ca.gov/cimis/data.jsp).

Soil extracellular enzyme activities

Fresh field soil samples were collected throughout the wet and dry seasons to analyze soil

extracellular enzyme activities. Three transects were established in each plot, extending from the upper to lower slope. Three 4 cm diameter x 10 cm deep core samples were composited along each transect. Samples were transported immediately to UC Berkeley and stored at ambient temperature overnight. We measured the activities of hydrolytic enzymes involved in labile C, N and P degradation (β-glucosidase, β–xylosidase, NAGase and α-glucosidase) and oxidative enzymes involved in the degradation of lignin and other recalcitrant C compounds (phenol oxidase and peroxidase) by a standard approach using synthetic substrates (Saiya-Cork et al 2002, Caldwell 2005). Briefly, two grams of soil were brought into solution with 125 mL of 200 mM sodium acetate buffer with an emersion blender for one minute. Next, 200 µL of soil slurry was pipetted into sixteen wells of a 96-count microplate, and 50 µL MUB-linked synthetic substrate was then added to the wells. A MUB standard curve was also included within each microplate. Fluorescence was measured on each plate using a plate reader. Fluorescence units were converted to concentration using individual plate standard curves.

Temporal scaling of soil biogeochemical cycles

Modeling provides a valuable tool for scaling biogeochemical cycling in space and time, and for linking microscale patterns to ecosystem processes. The Century soil organic model was designed to simulate soil C and nutrient dynamics in grasslands over long time periods (decades to centuries) (Parton et al. 1988). DayCent, the daily timestep of Century, provides a valuable tool for asking questions about mechanistic controls on biogeochemical cycling on short temporal scales. The daily outputs in DayCent include soil moisture, temperature, and trace gas fluxes of NO, NOx, and CH_4. Heterotrophic respiration is provided by the model on the weekly time step. DayCent was parameterized to SFREC using site-specific climatic, edaphic, and environmental inputs. Daily climate data were acquired from a 20 year record from the Browns Valley climate station publicly available from the CIMIS (Station #84). Information about the site's soil physical and chemical properties was acquired from a combination of field measurements and SSURGO soils databases. Rates of wet and dry N deposition were obtained from the 4 km resolution CMAQ model provided by the Center for Conservation Biology at the University of California Riverside (Tonneson et al. 2007). To test hypotheses about climate change impacts on rangeland soil biogeochemical cycling, we modified the model climate scalar values to simulate predicted changes in precipitation and temperature predicted for this region. We tested hypotheses about management impacts by modifying the schedule of management activities. Modeling results will include patterns in soil carbon storage or loss in active and passive pools, changes in above- and belowground NPP, and trace gas fluxes through time.

Results

Net primary productivity

In the first water year, ANPP responded significantly to organic amendments with 60% greater ANPP in amended relative to control plots (369 vs 230 g C/m^2; Figure 2) resulting in a gain of approximately 139 g C/m^2. Aboveground NPP in subsoiled plots responded negatively, decreasing in ANPP by about 31% relative to control. Although management treatments were not reapplied at the beginning of the second water year, the effects on ANPP carried over to the next growing season (Figure 2). Aboveground NPP was approximately 56% greater in amended versus control plots. The effects of subsoiling, however, were not significant during the second year. Belowground NPP was analyzed at peak standing crop of the second water year. Data are currently being processed.

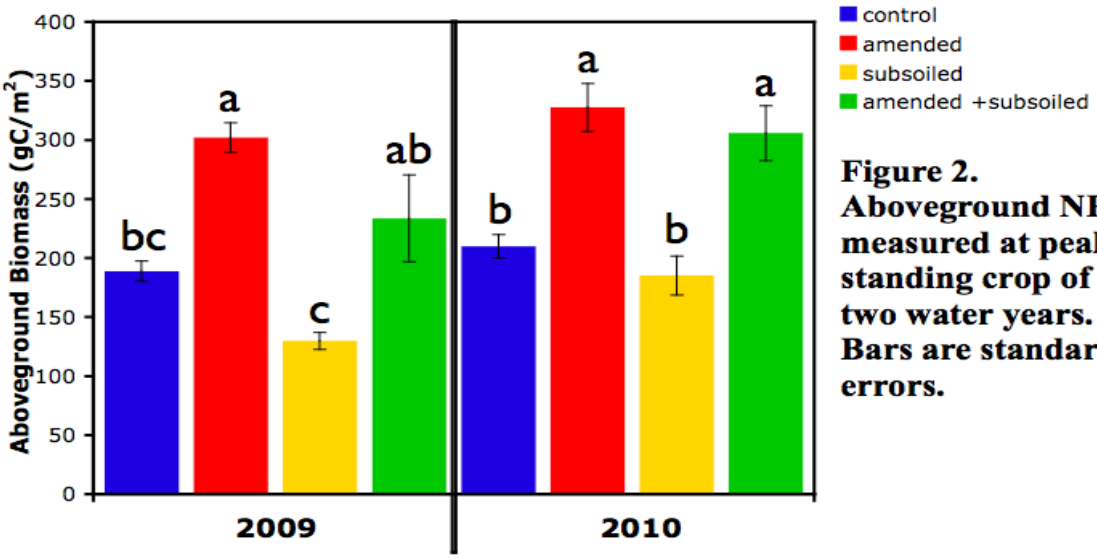

Figure 2. Aboveground NPP measured at peak standing crop of two water years. Bars are standard errors.

Greenhouse gas emissions

Soil CO_2 flux was strongly influenced by patterns of precipitation, which varied significantly between years (Figure 3a). The first wet season was characterized by dry conditions interspersed with short-duration medium-sized rain events with much of the rain falling during the months of February and March. The second wet season was characterized by consistent small to large rain events from mid-October through mid-June. Total rainfall in the second wet season was 75% greater than that of the first wet season.

During the first wet season, total soil respiration rates (root and heterotrophic) were consistently higher from the amended soils relative to control (Fig. 3b), resulting in a 26% greater cumulative C loss via soil respiration. However, this additional soil C loss accounted for just 9% (126 g C/m^2 as root plus heterotrophic respiration) of the C added to the surface soil. The C added during the first year led to sufficient stimulation in plant growth to more than compensate for the relatively small amount of additional C loss via heterotrophic respiration. This analysis does not account for root respiration (which will decrease the C loss term) or root biomass production (which will increase the C input term). If we assume that the heterotrophic component made up half

of total soil respiration and assume a 3:1 shoot to root ratio (Chou et al. 2008), the net C gain due to compost addition after the first water year (Oct through Aug) was 1480 g C/m^2 (14.8 Mg C/ha).

Although soils were amended with organic material only once, the effects carried over to the next water year (Fig 3b). Soil respiration from subsoiled plots was slightly less than control plots, whereas respiration from amended + subsoiled plots was not significantly different than amended plots (data not shown).

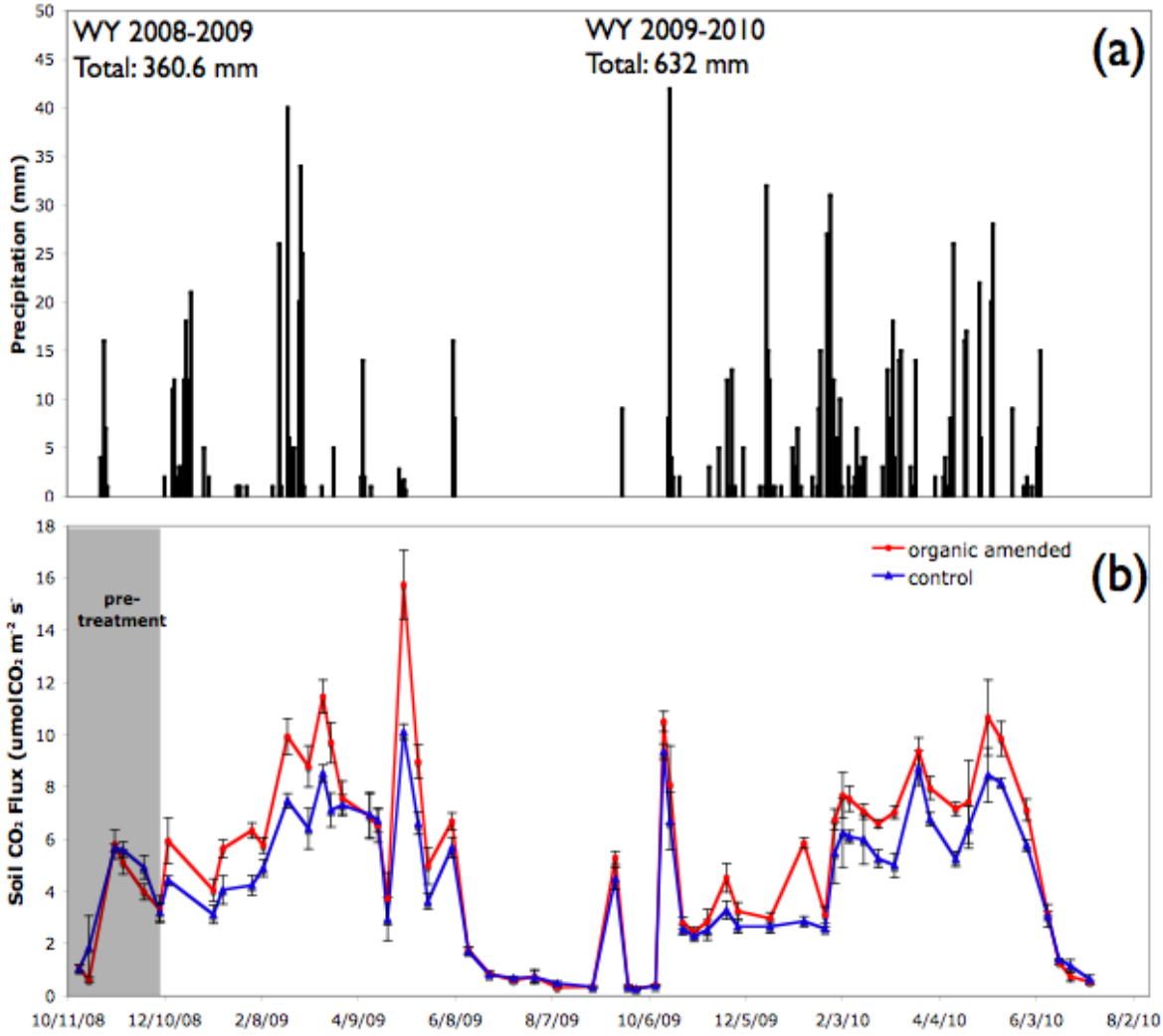

Figure 3. (a) Precipitation at Sierra Foothill Research and Extension Center (SFREC) from water years 2008-2009 and 2009-2010. (b) Soil respiration from compost and control plots at the Sierra Foothills Research and Extension Center. Respiration from compost plots was elevated significantly relative to control plots throughout the wet season, but differences were not significantly different during the warm, summer drought.

Soil respiration decreased by a similar magnitude in the control and amended soils with rainfall exclusion experiment (Figure 4). However, organic-rich amended soils still exhibited higher CO_2 fluxes than controls reflecting greater substrate availability and/or that higher levels of organic matter may have buffered the effects of drought on plant and microbial processes in these soils.

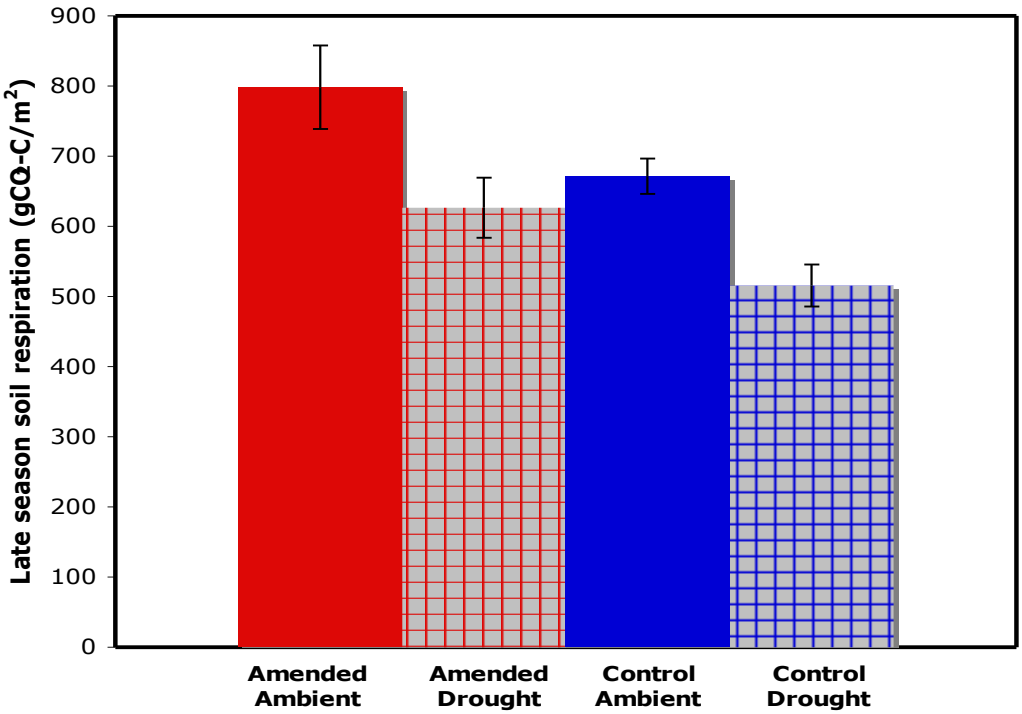

Figure 4. Cumulative late season soil respiration from control and amended soils, under drought and ambient rainfall conditions.

Methane and N_2O fluxes were measured biweekly during the first seven months of the field experiment and monthly thereafter (n=4 per plot), and there were no significant treatment differences, nor did we detect significant differences at any individual sampling time point. The number of occurrences of positive, negative, and zero CH_4 fluxes differed between compost and control soils, and were 4.7%, 29.2%, and 66.1% from amended soils and 2.9%, 40.9%, and 56.2% from control soils, respectively. Median negative CH_4 fluxes were -2.2 ng CH_4-C cm^{-2} hr^{-1} from both control and amended soils. The direction of CH_4 fluxes was not correlated with time. Approximately three-quarters of all N_2O fluxes from both treatments were not different from zero.

Soil carbon content, nitrogen content, and bulk density

Soil C and N concentrations were measured prior to treatment, eight months after the application of management treatments at a depth of 0-10 cm, and again after sixteen months from the depths 0-10, 10-30, 30-50, and 50-100 cm. Soils at SFREC are gravelly, and bulk density values are presently undergoing rock-correction. Thus, data here are presented in concentration, rather than content.

There were no significant differences in soil C or N concentration prior to management treatment. Results shown here only include the eight month time point as we are still processing the sixteen month samples (Figure 5). After eight months, subsoiled soils showed a significant decline in soil C and N concentrations (mean C= 2.67 ± 0.13%, mean N = 0.20 ± 0.01%; p-value < 0.0005). While not statistically significant, organic amended soils indicated a positive trend in soil C and N concentrations (mean C= 3.92 ± 0.29%, mean N = 0.32 ± 0.02%) relative to control soils (mean C= 3.52 ± 0.20%, mean N = 0.27 ± 0.07%). So far, the sixteen month samples show stronger trends (data not shown).

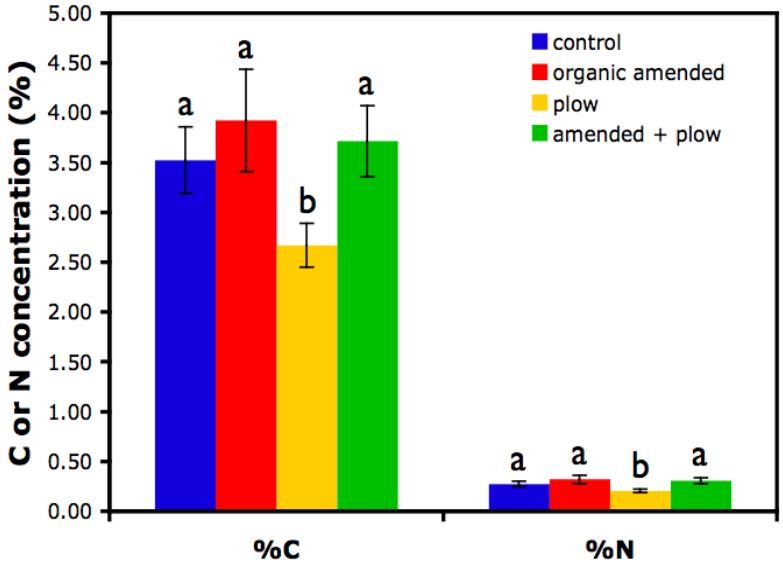

Figure 5. Changes in soil C and N concentrations eight months after management treatment application. Subsoiled soils lost C and N, while amended and amended + subsoiled soils showed an increasing trend in soil C and N relative to control soils. Error bars are ± standard errors.

Soil moisture and temperature

Soils with organic amendments maintained higher average soil moisture levels throughout the year and a smaller range in daily maximum and minimum soil temperature relative to control soils. Differences were greater under warm, dry conditions common at the end of the wet season (Figure 6a and 6b). Controls soils responded to late season rain with a significantly larger increase in moisture followed by a faster dry-up (Fig 6b).

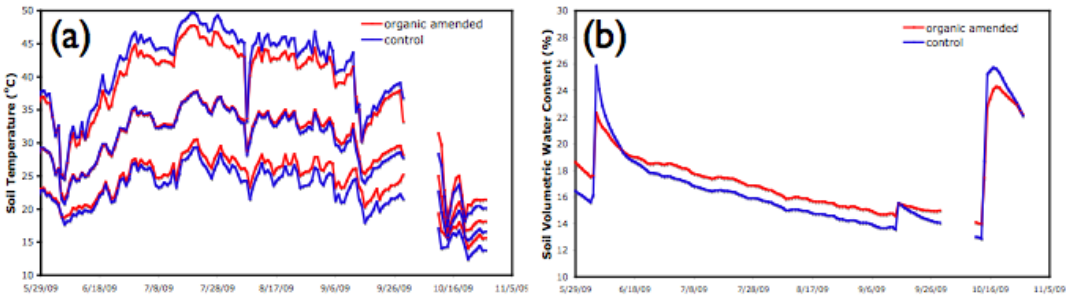

Figure 6. Soil (a) temperature to 10cm depth and (b) moisture to 30cm depth from the end of the first water year to the beginning of the second water year.

Tem pora

l scaling and management implications

The long-term response of the bulk soil C pool to changes in climate or management practices may not be detectable on seasonal to annual time scales. Modeling provides a valuable tool for scaling biogeochemical cycling in space and time. The Century soil organic model was designed to simulate soil C and nutrient dynamics in grasslands over long time periods (decades to centuries) (Parton et al. 1988). Century has been used extensively to evaluate the long-term effects of changes in management and climate on ecosystems (e.g. Farage et al. 2007, Wang et al. 2007). The DayCent model, the daily time-step version of Century, was developed to better represent patterns in trace gas fluxes in response to changes in soil water and temperature (Parton et al. 1998). Daycent provides a valuable tool for asking questions about mechanistic controls on biogeochemical cycling on short temporal scales, while long-term patterns can be explored using the decadal version of Century.

We are working in collaboration with William Parton, author of the Century and DayCent soil biogeochemical models. In July 2010, graduate student Rebecca Ryals completed an intensive training workshop at William Parton's lab at Colorado State University's National Resource Ecology Laboratory. We are currently in the process of parameterizing the models to SFREC using data on edaphic conditions, climatic history, and vegetative properties data collected from the field site. The models are also designed to test the effects of management, but the programs for testing effects of a variety of organic amendments are not well tested. Our work will help improved that aspect of DayCent. Once parameterized, we will validate the model with field data collected since 2008. We will then test the separate and combine effects of management and climate change.

References

Asner, G.P., A.J. Elmore, L.P. Olander, R.E. Martin, and A.T. Harris. 2004. Grazing systems, ecosystem responses, and global change. *Annual Review of Environment and Resources***. 29**:261-299.

Caldwell, B.A. 2005. Enzyme activities as a component of soil biodiversity: a review. *Pedobiologia.* **49:**637-644.

Chou, W.W., W.L. Silver, R.D. Jackson, A.W. Thompson, and B. Allen-Diaz. 2008. The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall. *Global Change Biology*. **14:**1382-1394.

Conant, R.T., K. Paustian, E.T. Elliot. 2001. Grassland management and conversion into grassland: effects in soil carbon. *Ecological Applications*. **11**:343-355.

Derner, J.D. and G.E. Schuman. 2007. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation.* **62**:77-85

Duncan, D. A., and R. G. Woodmansee. 1975. Forecasting forage yield from precipitation in California's annual rangeland. Journal of Range Management **28**:327-329.

Farage, P.K. J. Ardo, L. Olsson, E.A. Rienzi, A.S. Ball, J.N. Pretty. 2007. The potential for soil carbon sequestration in three tropical dryland farming systems of Africa and Latin America: A modeling approach. Soil & Tillage Research **94**(2):457-472.

FRAP. 2003. The Changing California: Forest and Range 2003 Assessment. California Department of Fire. Available online at www.frap.cdf.ca.gov/assessment2003.

George, M., J. Clawson, J. Menke, and J. Bartolome. 1985. Annual grassland forage productivity. *Rangelands.* **7**:17-19.

Heady, H., J. Bartolome, M. Pitt, G. Savelle, M. Stroud. 1991. California prairie. Pages 313-335 in Coupland, R. T., editor. Natural grasslands. Ecosystems of the World. Volume 8A. Elsevier Scientific, Amsterdam, The Netherlands.

Herbert, F.W. and E.L. Begg. 1969. Soils of the Yuba Area, California. County of YUBA, CA, University of California, Davis.

Jones, M.B., and A. Donnelly. 2004. Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO2. *New Phytologist.* **164**:423-439

Keller, M. and W.A. Reiners. 1994. Soil atmosphere exchange of nitrous-oxide, nitric-oxide, and methane under secondary succession of pasture to forest in the Atlantic lowlands of Costa-Rica. *Global Change Biology.* **8:**399-409.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma.* **123**:1-22.

Metcalfe, D.B., M. Williams, L.E.O. Aragao, A.C.L. da Costa, S.S. de Almeida, A.P. Braga, P.H.L. Goncalves, J. de Athaydes Silva Junior, Y. Malhi, and P. Meir. 2007. A method for extracting plant roots from soil which facilitates rapid sample processing without compromising measurement accuracy. *New Phytologist.* **174:** 697-703.

Parton, W.J. J.W.B Stewart, and C.V. Cole. 1988. Dynamics of C, N, P, and S in grassland soils – a model. *Biogeochemistry*. **5**:109-131.

Parton, W.J., M. Hartman, D. Ojima, and D. Schimel. 1998. DAYCENT and its land surface submodel: description and testing. *Global and Planetary Change*. **19**:35-48.

Saiya-Cork, K.R., R.L. Sinsabaugh, and D.R. Zak. 2002. The effects of long-term nitrogen deposition on extracellular enzyme activity in an *Acer saccharum* forest soil. *Soil Biology and Biogeochemistry*. **34:**549-563.

Schimel, D.S., W.J. Parton, T.G.F. Kittel, D.S. Ojima, and C.V. Cole. 1990. Grassland biogeochemistry - Links to atmospheric processes. *Climatic Change*. **17**:13-25.

Steenwerth, K.L., L.E. Jackson, F.J. Calderon, M.R. Stromberg, and K.M. Scow. 2002. Soil microbial community composition and land use history in and grassland ecosystems of coastal California. *Soil Biology and Biogeochemistry*. **34**:1599-1611.

Stromberg, M.R. and J.R. Griffin. 1996. Long-term patterns in coastal California grasslands in relation to cultivation, gophers, and grazing. *Ecological Applications*. **6:**1189-1211.

Tonnesen, G., Z.M.O. Wang, and C. Chien. 2007. Assessment of nitrogen deposition: Modeling and habitat assessment. In. California Energy Commission PIER Energy-Related Environmental Research CEC-500-2005-032.

Wang, Y.H., G.S. Zhou, and Y.H. Wang. 2007. Modeling responses of the meadow steppe dominated by *Leymus chinesis* to climate change. *Climatic Change.* **82**:437-452.

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