The Effects of Temperature and Precipitation on Carbon Dioxide Flux from California Grassland Soil

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Abstract Atmospheric carbon dioxide (CO_2) is a major green house gas contributing to global climate change. The terrestrial CO_2 sink has great potential for carbon sequestration because it is about three times larger than the atmospheric carbon pool. CO_2 is released from soil by root respiration, breakdown of organic matter by organisms, and microbial respiration, which are grouped as belowground respiration. Using mesocosms containing a common California grass species *Avena barbata*, the study was able to examine how higher temperature and increased precipitation influence belowground CO_2 emissions using a full factorial design. I hypothesized that with elevated temperature and higher precipitation there will be an increase in CO_2 emissions from soil. The data was analyzed using a repeated measures ANOVA statistical test and found no significance between treatment groups throughout the duration of the experiment. The results imply that in the event of global climate change, precipitation and temperature variation will not have a significant effect on belowground soil respiration rates from Mediterranean climates. Therefore, possible feedback cycles contributing to global climate change would not be a point of concern. However, because the findings of this study contradict many existing studies, the debate over which environmental variables control belowground soil respiration most is still an issue. Therefore, more studies are necessary to effectively create models to predict ecosystem response to climate change.

Introduction

Since the Industrial Revolution, anthropogenic sources and atmospheric concentrations of greenhouse gases have risen (Kaufmann *et al.* 2006, Muller 2007). Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor (Liebig *et al.* 2005). In the atmosphere, these gases promote climate change in the form of warming and cooling through various feedback cycles.

In particular, CO_2 is a major contributing factor to radiative forcing of the atmosphere whereby the capture of solar radiation is increased relative to its release from the troposphere (Bowden *et al.* 1998, Liebig *et al.* 2005). CO_2 acts as an insulation layer by absorbing infrared radiation in the atmosphere, blocking the release of radiation from the Earth and re-radiating some of the infrared radiation back toward the Earth, thereby increasing Earth's surface temperature (Harte 1998).

In addition to anthropogenic sources of atmospheric CO_2, such as fossil fuel combustion, there are numerous natural sources of CO_2 including cellular respiration by organisms, volcano emissions, hot springs, the process of fermentation, and the decomposition of organic material (Harte 1998, Kanerva 2007, Martin *et al*. 2007). Given the close link between global climate change and atmospheric carbon, it is important to understand the carbon cycle and the relationship between oceanic, atmospheric and terrestrial pools of carbon (Harte 1998, Litynsky *et al*. 2006, Falloon *et al*. 2007). Within the terrestrial pool, carbon is sequestered in soil and biomass. Soil is the largest global pool of terrestrial C, and the soil organic C pool (approximately 2400 Pg of C) is two to three times larger than the size of the atmospheric carbon pool (Batjes 1996). The natural process of photosynthesis allows for the temporary sequestration of carbon in the form of biomass. In the carbon cycle, organic matter in the form of biomass is broken down and CO_2 is released into the atmosphere by microbes and fungi. In soils, this release of carbon is due to belowground respiration, which is composed of both autotrophic respiration from plant roots and heterotrophic respiration from microbes and fungi (Martin *et al*. 2007).

Knowledge of carbon stocks and flows from soil is particularly important because stocks of carbon could be depleted through natural and anthropogenic actions (Jackson 2003, Liebig *et al.* 2005, Falloon *et al.* 2007, Insam and Wett 2008). According to Litynsky *et al.* (2006), the main anthropogenic contributors to the increase in atmospheric concentrations of CO_2 are "fossil fuel combustion, land use conversion, and soil cultivation". Land conversion and soil cultivation for agriculture deplete the terrestrial carbon pool and release atmospheric CO_2 because soil disturbances alter soil microbiology, metabolic processes, and gaseous fluxes (Jackson *et al.* 2003).

The processes by which greenhouse gases are produced and react in the atmosphere to promote increased global temperatures are well known (Bowden *et al.* 1998, Insam and Wett 2008, Litynsky *et al.* 2006, Liebig *et al.* 2005). Concomitant with temperature change, it is expected that precipitation levels will change becoming higher or lower depending on the location (California Climate Change Center 2006). According to Harte (1998), in areas that experience warming, precipitation will increase through a positive feedback cycle, whereby both temperature and moisture increase together. The warmer surface temperature caused by this global warming will increase the rate of evaporation of water from the Earth's surface. Since water vapor is also a greenhouse gas, this increased water vapor in the atmosphere will promote warming. If global climate change alters the amount of precipitation and timing that the ecosystem receives it, it could greatly alter the existing environment. An example of ecosystem changes due to global climate change is the idea that "higher minimum temperature likely leads to a longer growing season and higher biomass" (Tan 2006).

However, the effects of global climate change on belowground soil respiration are less understood (Kanerva 2007). Numerous studies have contradictory results regarding whether the main driving factor affecting belowground soil respiration is temperature, precipitation or temperature in combination with precipitation. Martin *et al.* (2007) identified low temperature as the limiting variable in rates of soil carbon loss in the form of CO_2. Asensio *et al.* (2007) showed soil moisture as the main factor driving carbon flux from soil, while temperature was constrained by soil moisture. Alternatively, Li *et al.* (2006) coupled soil temperature and moisture as the major abiotic factors determining soil respiration in most ecosystems. Further examining the relationship and interactions between temperature, precipitation and belowground soil respiration can simplify the debate over which variables most influence soil respiration.

In order to create better models to predict ecosystem response to the climate changes, we need a better understanding of the response of soils to different climate conditions such as increased temperature and higher levels of precipitation. Therefore my research focuses on the question of how elevated temperature and increased precipitation influence CO_2 flux from California grassland soil.

I hypothesize that with elevated temperatures and higher precipitation levels, there will be an increase in CO_2 emissions from soil based on previous studies conducted by Raich and Schlesinger (1992), Gaumont-Guay *et al.* (2006), Shinjo *et al.* (2006), and Martin *et al.* (2007). Additionally, I expect both precipitation and temperature treatments will show significant effects to the overall CO_2 emissions from soil, with temperature having a larger influence as compared to precipitation.

To test these hypotheses, a full factorial mesocosm experiment was designed which allowed for the manipulation of temperature and precipitation variables to simulate possible scenarios of climate change, and CO_2 flux measurements were recorded using an infrared gas analyzer over the experimental period.

The project focused on California grasslands within a Mediterranean climate, because of the fact that the dry and wet periods of the ecosystem regulate the growing season and microbial activity. Additionally, it is essential to understand how environmental variables affect CO_2 flux over grassland, "since grasslands comprise almost one-third of the earth's natural vegetation" (Xu and Baldocchi 2004). These data can be used to create models that predict ecosystem response to future environmental conditions. By looking at California grasslands, we can come up with models that are specific to this Mediterranean climate and used in other areas with similar ecosystems.

Methods

This project is a part of a larger project called "An Annual Grassland Mesocosm Exploration of Scaling from Genomes to Ecosystem Function" (Firestone, Ackerly, and Torn, UC Berkeley). My portion of the project examines the CO_2 gas flux in mesocosms that represent different ecosystems subject to possible climate change scenarios.

Study Site The study site was located at a large greenhouse at the Richmond Field Station in Richmond, California. To conduct the experiment, mesocosms filled with soil collected from the UC Hopland field station in California (39°N, 123°4'W) were used. The Firestone lab had already put great efforts into researching the composition of the soil and the microbial communities within it. Data from their efforts was used when necessary. The soil is from

Mediterranean-climate sandstone, derived with low organic matter and extensively studied by the Firestone Lab of UC Berkeley. To mimic field conditions of the UC Hopland field station, natural soils were planted with *Avena barbata*, which is a common annual grass in Calfornia's Mediterranean climate that is manageable in a mesocosm setting. Mesocosms, also known as enclosed outdoor experimental systems, are large pots planted with soil and/or vegetation that give researchers the ability to maintain realistic growth conditions while manipulating exposure conditions (Tingey 2008). This is advantageous because either "parts of or whole ecosystems can be experimentally studied and replicated in space" to examine this question (Tingey 2008). The mesocosms were constructed from 20" schedule 40 PVC pipe with a diameter of 50cm and height of 75cm. This created a soil surface area of $0.78m^2$. Seeds were sown in mesocosms using the protocols and field bulk densities with horizon depths from the field used by the Jasper Ridge MECCA experiment (Chiariello and Field 1996).

Treatments In order to determine whether elevated temperature and increased precipitation in concert influenced CO_2 flux from soil, the full factorial experiment (temperature(T) x precipitation(P)) used 16 vegetated mesocosms including four replicates of each combination. The four combinations of precipitation and temperature were defined using letters A (low P, ambient T), B (low P, high T), C (high P, ambient T) and D (high P, high T). The temperature treatments are defined as ambient and high temperature, where ambient is the current temperature of the Richmond Field Station greenhouse and high refers to ambient environmental conditions increased by 5°C.

The precipitation treatments called high and low were based on data collected by the Agriculture and Natural Resources Research and Extension centers in California of the past 30 years' low and high rainfall years in Central Coast California. The watering treatments were consistently administered at 9:30 am each day to avoid any inconvenience to other labs using the mesocosms and began on November 30, 2000 and ended on March 31, 2008. The amount administered at each watering treatment was $3828 cm^3$ in order to have realistically sized events (Torn 2007, pers. comm.). The difference between the high and low watering treatments was in the frequency with which each mesocosm is watered. The watering schedule was set up in 6 cycles, each 21 days. Within each cycle, there was one wet period and one dry period intended to simulate pulse rainfall events typical of Mediterranean climates. For high precipitation treatments, watering was done on days 1-4 and days 8-11. For low precipitation treatments, watering was done on days 1, 10 and 11. By the end of data collection (December 2007 through April 2008), the mesocosms treated with high precipitation had approximately 2.5 times more total precipitation than the low precipitation treatments to mimic precipitation frequency increase due to predicted climate change.

Soil Respiration Sampling Measurements of CO_2 flux were made with a Li-Cor 6400 infrared gas analyzer (LI-COR, Inc., Lincoln, NE, USA) at 10:00 am on days of data collection, as to not interfere with mesocosm watering. Collars made from thin-walled PVC piping with a diameter of 9.9 cm and a height of 4.4 cm were inserted into the soil of mesocosms at least one half hour before measurements were taken to limit disruption to the soil.

Measurements were taken on days 12 and 19 of each 21 day cycle in order to measure one wet and one dry day of each cycle. Each mesocosm CO_2 flux measurement taken by the infrared gas analyzer was an average of three cycles taken one after the other. Soil temperature was also recorded using a temperature probe inserted at 10 cm in soil depth.

Data Analysis CO_2 soil flux measurements from four treatments A-D were compared using repeated measures ANOVA with the Greenhouse-Geisser test correction to better fit the data and account for the assumption of sphericity. Additionally, the data was $\log_{10}$ transformed in order to fit assumptions for repeated measures ANOVA statistical analyses. Analyses were completed using JMP statistical program (SAS Institute, Cary, NC, USA).

Results

Overall, between subjects, treatments A-D did not have a significant effect on CO_2 flux from soil ($F=0.2626$, $df=1$, $p>0.6177$) (Fig. 1). Furthermore, temperature showed no treatment effect ($F=1.1925$, $df=1$, $p>0.2963$), nor did precipitation show a treatment effect ($F=0.0054$, $df=1$, $p>0.9428$).

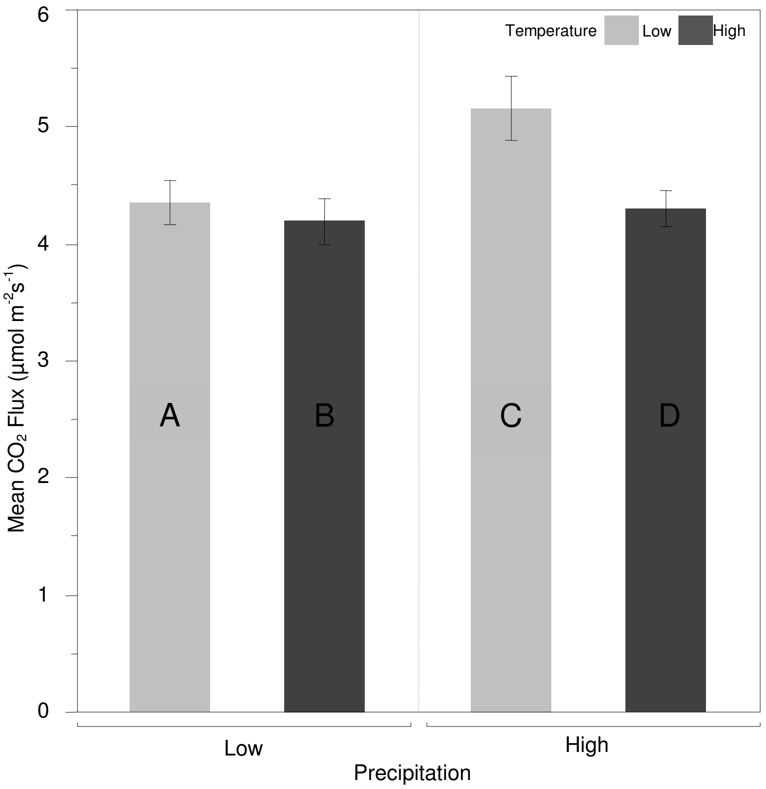

Figure 1. Mean CO_2 respiration (± 1 S.E.) in vegetated mesocosms under four different treatments over the course of data collection. A: low precipitation, ambient temperature; B: low precipitation, high temperature; C: high precipitation, ambient temperature; D: high precipitation, high temperature.

Within subjects, using the Greenhouse-Geisser test correction, time influenced belowground CO_2 flux (F=18.8990, df=14, p<0.0001) (Fig. 2). Additionally, time influenced the precipitation treatments (F=6.4132, df=2.9405, p>0.0015). However, time did not influence temperature treatments (F=1.4405, df=2.9405, p>0.2478), nor did it influence the interaction between precipitation and temperature treatments (F=0.3443, df=2.9405, p>0.7896).

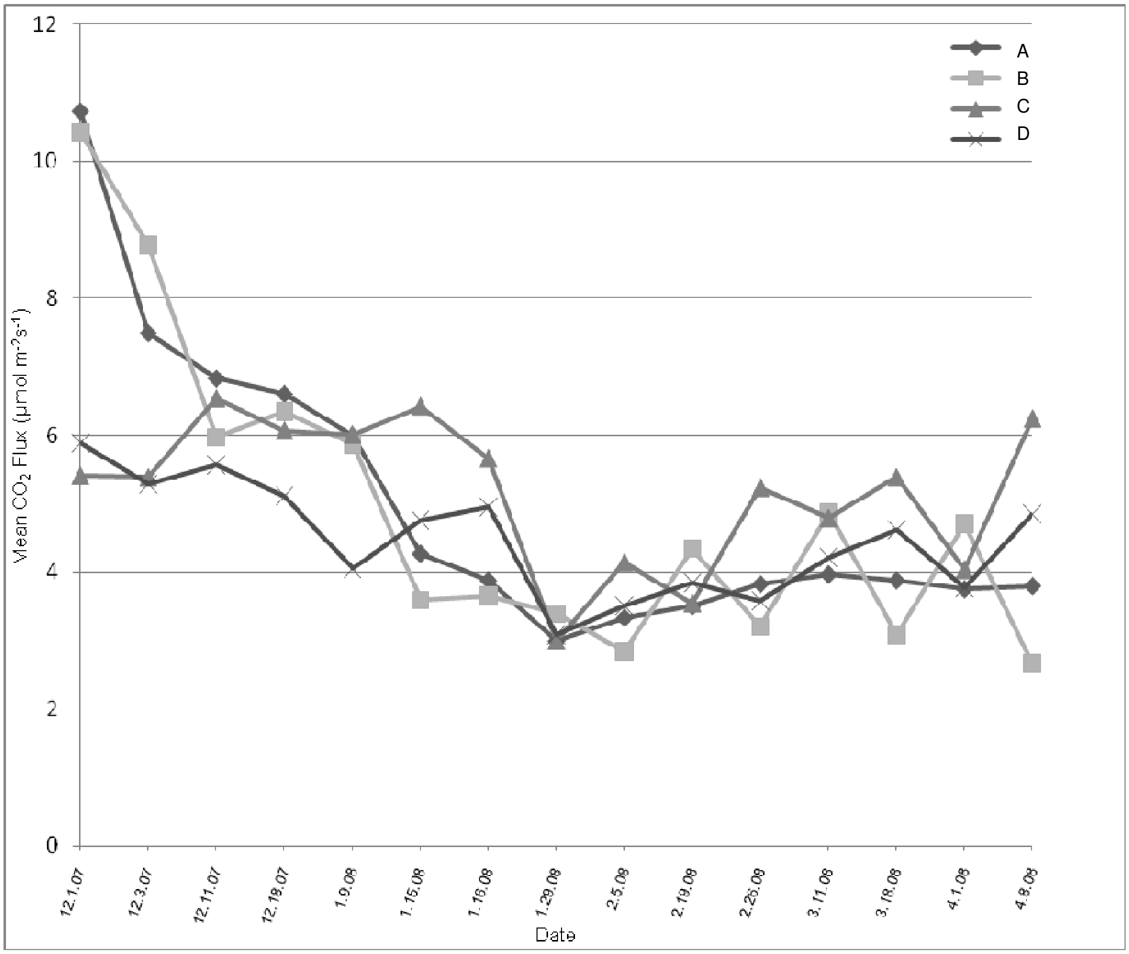

Figure 2. Mean CO_2 flux separated by treatments A-D over the course of the data collection period. A: low precipitation, ambient temperature; B: low precipitation, high temperature; C: high precipitation, ambient temperature; D: high precipitation, high temperature.

Discussion

In summary, the results showed none of the treatments A-D had significant differences between them based on CO_2 emissions, meaning that temperature and precipitation treatments in concert did not significantly affect belowground respiration from the mesocosms. Additionally, precipitation showed no treatment effect and temperature showed no treatment effect. When examining the influence of time on treatments, only precipitation was influenced by time.

The finding that all treatments A-D had no significant effects rejects the hypothesis that treatment D (high precipitation, high temperature) would result in the highest CO_2 flux. Other studies by Li *et al*. (2006) and Kanerva (2007) conclude that both temperature and moisture in combination are major abiotic factors determining soil respiration in most ecosystems. Specifically, Kanerva (2007) concludes that soil CO_2 flux is known to correspond to temperature and soil moisture, since extreme conditions usually reduce soil CO_2 emissions. Martin *et al.* (2007) found that when temperature sensitivity of belowground respiration was low, temperature was still found to be a more significant controlling factor than soil moisture. Additionally, studies have shown that extreme moisture conditions constrain microbial activity and can even reduce the response to other environmental variables, such as temperature (Kirshbaum 2000).

In this study, we did not find significant temperature effects on soil respiration in vegetated mesocosms, which rejects the hypothesis that temperature variation would have a greater role in the promotion of below ground soil respiration. This contradicts many studies that have found a correlation between elevated temperatures and increased CO_2 soil respiration (Shinjo *et al.* 2006, Gaumont-Guay *et al.* 2006, Bowden *et al.* 1998). Similarly, the data contradict findings by Wiant (1967) that conclude temperature as the primary factor in the rate of CO_2 emissions from soil. Furthermore, the data contradicts a study conducted by Martin *et al.* (2007), which identifies low temperature as the most limiting variable in rates of soil carbon loss in the form of CO_2. Confounding factors that may have influenced the results showing the insignificance of temperature influence on soil respiration rates are substrate availability and soil enzyme capacity. In a recent study by Atkin *et al.* (2005), at low temperatures root respiration was mediated by a limitation of enzymes and at moderate to high temperatures root respiration was limited by substrate availability. These are examples of other variables that effect soil microbe activity that are unaccounted for in my study.

Precipitation levels in vegetated mesocosms did not significantly influence soil respiration. This result is contrary to studies that have found precipitation and soil moisture are strong factors contributing to variability of soil respiration (Waldrop 2006). The result of this study that high precipitation did not increase CO_2 flux rates rejects my hypothesis. One explanation for this result is that the level of increased precipitation provided may have saturated the soils, restricting CO_2 transport out of the soil, thus inhibiting CO_2 production due to a lack of oxygen (Bunnell *et al.* 1977, Gaumont-Guay *et al.* 2006). Another possible explanation for the absence of a precipitation treatment effect is the death of much of the vegetation in two of the replicates, specifically the mesocosms treated with high precipitation and ambient temperature. Mildew and aphids contaminated the same two replicates more intensely, which resulted in the death of much of the vegetation. The lack of vegetation allowed for possible water saturation in soils because there was not enough transpiration and photosynthesis to use the water. This may have been the case in treatments C and D, where precipitation was high.

Time did have a significant influence on precipitation treatments. This is to be expected, due to the experimental design that mimics pulsing rain episodes characteristic of California Mediterranean grasslands (Xu *et al.* 2004, Jarvis *et al.* 2007). Furthermore, the relationship between time and precipitation is not surprising because CO_2 fluxes of Mediterranean ecosystems respond more dramatically to changes in water availability (Ma *et al.* 2007).

Implications My project offers evidence that there will be no change in how below ground soil respiration in California grasslands will react in light of predicted climate change. Therefore, there is not a positive relationship between CO_2 flux from California grassland soil and climate change, and a positive feedback cycle that would accelerate climate change does not exist. However, it is entirely possible that more extreme climate conditions could invoke this feedback cycle and further research needs to be conducted.

Future Research After completing this project, several recommendations for future research come to mind, especially in the experimental design. It would be beneficial to extend the data collection to a full year or more to see possible trends over a longer course of time, which may clear up any confusion between true seasonal differences versus differences over the experiment alone. In regards to the existing treatments, it would be valuable to test several additional degrees of climate change or more extreme climate conditions. For instance, temperature treatments could be defined as ambient, ambient increased by 5°C and ambient increased by 10°C, which may result in information about threshold effects that would be valuable to climate change predictions. It may also be beneficial to set up an experiment in the field because mesocosms are not "substitutes for the 'real world'" (Tingey *et al.* 2008). Furthermore, it would be valuable to design experiments that limit experimental errors such as pests and mildew. It is probable that these factors greatly compromised the results of the experiment due to their harmful effects on the vegetation.

Additionally, to further examine the relationship between time on precipitation, it would be helpful to conduct a similar repeated measures ANOVA introducing wet and dry days as a treatment. This could result in further information about California grassland ecosystem response to climate change and pulsing rain episodes. Furthermore, I recommend that initial precipitation episodes be compared to subsequent days further into the data collection period to investigate whether or not there are trends over time. For instance, extending the duration of the experiment and comparing specific periods of data collection could show significantly higher levels of CO_2 flux from soils at the first wet up, or could show that CO_2 flux plateaus over time.

Conclusion There was no significant difference in CO_2 flux between treatments A-D when examining the entire data collection period from December 2007 to April 2008. Also, this study did not identify either temperature or precipitation as having a powerful role in belowground respiration in Calfornia grasslands, which is contrary to a great deal of existing research on climate change. As this study suggests it could be that global climate change will not accelerate CO_2 emissions from California grassland soils. However, it would be valuable to conduct further research incorporating other global climate change predictions or the testing of more extreme conditions.

Acknowledgments

I would like to thank Professor Margaret Torn of Lawrence Berkeley Laboratory and the members of the Torn Lab, specifically, Christina Castanha and Rachel Porras. Members of the Firestone Lab offered assistance in gaining an understanding of the experimental design and methods and transportation to the study site, specifically, Don Herman, Sarah Placella, and Marissa Lafler. Researchers Erika Sudderth, Laurie Koteen and Kallista Bley aided in data collection and transportation to and from the study site. Thanks to ES196 instructors, specifically, Shelly Cole and Pete Oboyski and fellow ES students because of their support and advice throughout the course of the project.

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