Carbon Dioxide Fluxes on Walnut Gulch Experimental Watershed

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Abstract

Carbon dioxide is increasing in the atmosphere, presumably from human activities. Many soils on Walnut Gulch Experimental Watershed (WGEW) in southeastern Arizona contain carbonates that have accumulated over long periods of time. The hypothesis is that these soils are maintaining this carbon pool under present climatic conditions and are a sink for some of the increasing atmospheric carbon. Bowen ratio systems were used to measure CO_2 fluxes from a brush and a grass community with different soil types on WGEW. Contradictory to the hypothesis, the two sites were found to be losing carbon annually. The brush site with higher inorganic carbon in the soil, had an average annual loss of 144 g C m^{-2} and the grass site 127 g C m^{-2}. Based on measured aboveground biomass data and estimates of belowground biomass, the brush site took up 80 g C m^{-2} and the grass site 135 g C m^{-2} of organic carbon during the growing season. Inorganic soil carbon analysis showed a significant seasonal difference with more in the fall season. The average fall season soil inorganic carbon was 2.24% and the spring season was 1.96% to a depth of 30 cm. This significant seasonal difference indicated some of the measured CO_2 fluxes were into and out of the inorganic carbon pool. The source of carbon for the measured annual losses from these sites was concluded to be from the large inorganic carbon pool with carbon cycling through both the organic and inorganic pools at the sites.

Keywords: carbon dioxide, inorganic carbon, organic carbon, rangeland

Introduction

Arid and semiarid soils contain large amounts of inorganic carbon (750 to 950 Pg C) that has accumulated through long periods of time in the form of carbonates (Schlesinger 1985, Eswaran et al. 2000). Only the oceanic (38,000 Pg C) and soil organic (1,550 Pg C) carbon pools are larger (Schlesinger 1997). The uptake of carbon through the formation of carbonates requires an arid environment for the precipitation of the carbonate and a source of Ca/Mg from a non-carbonate source. The increasing atmospheric concentration of CO_2 may aid in the formation of carbonates and serve as a sink for some of the carbon being released from human activities.

Arid and semiarid zone soil accumulations and losses of carbonates are controlled by the carbonate-bicarbonate equilibria:

$$CO_2 + H_2O \rightleftharpoons HCO_{3^-} + H^+ \qquad (1)$$

$$CaCO_3 + H^+ \rightleftharpoons Ca^{+2} + HCO_{3^-} \qquad (2)$$

Equation 1 and 2 equilibriums are constantly shifting to the right and left controlling uptake and loss of inorganic carbon to the soil. Under the present climatic conditions, uptake and loss of carbon for the large inorganic carbon pool are mostly unquantified.

Intertwined with the inorganic carbon fluxes are the organic carbon fluxes from plant uptake and decomposition. Separation of inorganic and organic carbon fluxes is problematic, at best. In a tallgrass prairie, it has been estimated that several years of flux data are needed to begin an accurate quantification of grasslands as a sink/source for carbon (Suyker and Verma 2001).

The study hypothesis is that semiarid rangeland soils on Walnut Gulch Experimental Watershed (WGEW) typical of millions of hectare containing a large inorganic carbon pool are maintaining and /or taking

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up carbon on an annual basis under present climatic conditions. The objectives of this study were to: (1) characterize carbon fluxes in two different semiarid plant and soil communities on WGEW for four years to determine the magnitude of a carbon sink/source; and (2) use seasonal changes in soil carbon and aboveground biomass to relate the measured CO_2 flux to its possible organic and inorganic pool.

Methods

Experimental site descriptions

The two sites for this study are located on the Walnut Gulch Experimental Watershed in southeastern Arizona. Mean annual precipitation is 356 mm and mean annual temperature is 17°C. A brush community site was selected in 1996 in an area known as Lucky Hills (-110° 3' 5" W. 31° 44' 37" N.; elevation; 1372 meters). The dominant shrubs at this site are whitethorn Acacia (*Acacia constricta*), tarbush (*Flourensia Cernua*), creosotebush (*Larrea divaricata*), and desert zinnia (*Zinnia pumila*). The soil at this site is Luckyhills series (Coarse-loamy, mixed, thermic Ustochreptic Calciorthids) with 3 to 8 % slopes. The eluvial parent material for this soil contains many rock fragments of limestone. Surface A horizon (0-6 cm) contained 650 g kg^{-1} sand, 290 g kg^{-1} silt, and 60 g kg^{-1} clay with 290 g kg^{-1} coarse fragments >2mm, 8 g kg^{-1} organic carbon, and 21 g kg^{-1} inorganic carbon.

A grass site was selected in1996 in an area identified as Kendall (-109° 56' 28" W. 31° 44' 10" N. elevation; 1526 meters). Vegetation at the site is predominantly sideoats grama (*Bouteloua curtipendula*), black grama (*Bouteloua eriopoda*), harry grama (*Bouteloua hirsuta*), and lehmann lovegrass (*Eragrostis lehmanniana*), with a few existing shrubs of fairy duster (*Calliandra eriophylla*), and burroweed (*Haplopappus tenuisectus*). The soils at the site are a complex of Stronghold (Coarse-loamy, mixed, thermic Ustollic Calciorthids), Elgin (Fine, mixed, thermic, Ustollic Paleargids), and McAllister (Fine-loamy, mixed, thermic, Ustollic Haplargids) soils, with Stronghold the dominant soil. The eluvial parent material for these soils contains some limestone rock fragments. Slopes range from 4 to 9 %. The Stronghold surface A horizon (0-3 cm) contains 670 g kg^{-1} sand, 160 g kg^{-1} silt, and 170 g kg^{-1} clay with 790 g kg^{-1} coarse fragments >2mm, 11 g kg^{-1} organic carbon, and 7 g kg^{-1} inorganic carbon.

Micrometeorological measurements

Continuous, 20-minute average carbon and water vapor flux measurements were made at both sites using a Bowen ratio energy balance system (BREB) (Model 023/CO_2 Campbell Scientific Inc., Logan, UT, USA). The theory and procedures used to calculate the fluxes has been presented in detail by Dugas (1993) and Dugas et al. (1999). Briefly, atmospheric gradients of air temperature, moisture, and CO_2 were measured every 2 seconds and averaged every 20 minutes. The 20-minute averages were stored in a datalogger (model 21X, Campbell Scientific Inc.). Carbon dioxide, water vapor, and energy fluxes were calculated from the 20-minute average data. Temperature and water vapor gradients were used to calculate Bowen ratios. Bowen ratio, net radiation, soil heat flux, and soil temperature were used to calculate sensible heat flux. Eddy diffusivity was calculated from sensible heat fluxes and temperature gradients and assumed to be equal for heat, water vapor, and CO_2. Fluxes were calculated as the product of the eddy diffusivity and CO_2 and moisture gradients.

Biomass and soil measurements

Centered at each BREB system, radial transects were laid out at a compass direction of every 30° with sample locations at 80, 90, 100, and 110 m. Biomass and soil samples were taken at one sample location on each radial in the spring and fall. Biomass was clipped at the soil surface from 2 m by 2 m plots at the Lucky Hills site and 1 m by 1 m plots at the Kendall site and the material separated into shrub, grass, forb, and litter. The biomass was dried at 65° C, weighed, and amounts were calculated on a kg ha^{-1} basis. Subsamples of each biomass type were ground and analyzed for total carbon by total combustion (CN-2000 Leco Corp. St. Joseph, MI, USA). Total aboveground carbon was calculated from the amount of biomass and carbon concentration data.

Soil samples were collected with a hand spade on the 12 radials adjacent to the biomass plots at depths of 0-15 and 15-30 cm. The samples were air dried, ground to a powder, and analyzed for total carbon by total combustion (CN-2000). Subsamples were analyzed for carbonate-carbon by the pressure-calcimeter method (Nelson, 1982). Organic carbon was calculated as the difference between total and carbonate carbon. A SAS procedure for mixed models analysis of variance (Littell et al. 1996) was used to analyze the soils data for site, year, season, and depth effects and mean separation was determined by the student-t test ($P < 0.05$).

Results and Discussion

Precipitation effects on CO_2 flux

Precipitation was a major influence on CO_2 fluxes at both sites (Figures 1 and 2). Data obtained during precipitation showed numerous events associated with a sudden loss of CO_2, down to the 20-minute time step of the data collection. These releases of CO_2 were due, at least in part, to the dissolution of $CaCO_3$ by low pH (i.e. as low as 3.5 to 7.5) rainfall events known to occur in the area (author's unpublished data) (Equations 1 and 2).

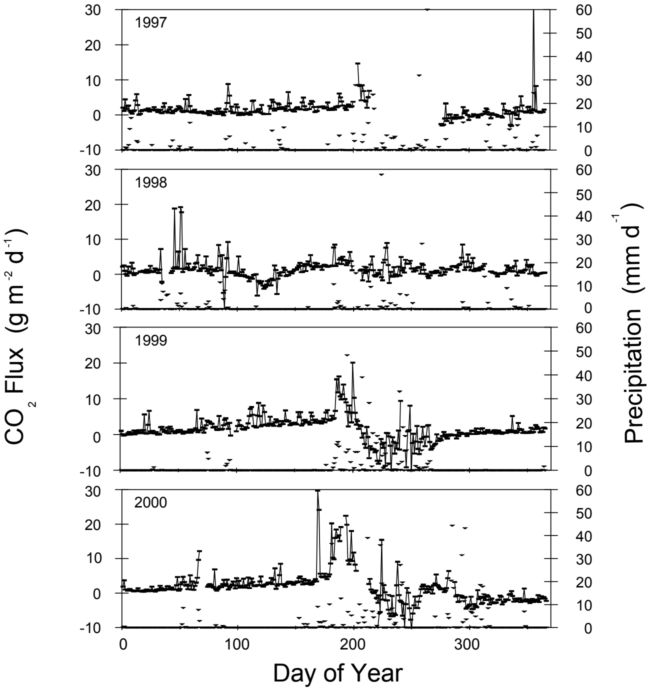

Figure 1. Lucky Hills yearly carbon dioxide flux and precipitation (negative values, indicate carbon uptake).

Acid precipitation would drive the equilibrium for Equation (2) to the right and Equation (1) to the left, thus releasing CO_2 to the atmosphere. Around day 200 for most years at the start of the summer precipitation and growing season, precipitation events large enough to wet the soil profile caused increased CO_2 losses starting 6-24 hours after the rainfall (see Lucky Hills 1999 day 185+ Figures 1 and 3). These types of CO_2 losses have been attributed to increases in microbial activity (Kessavalou et al. 1998). The losses of CO_2 continued until the vegetation started its summer growth period, reversing the CO_2 loss with uptake of carbon into plant biomass. Once the summer growing season started, the carbon uptake rates were generally greater for the Kendall grassland site than for the Lucky Hills brush site (Figures 1 and 2).

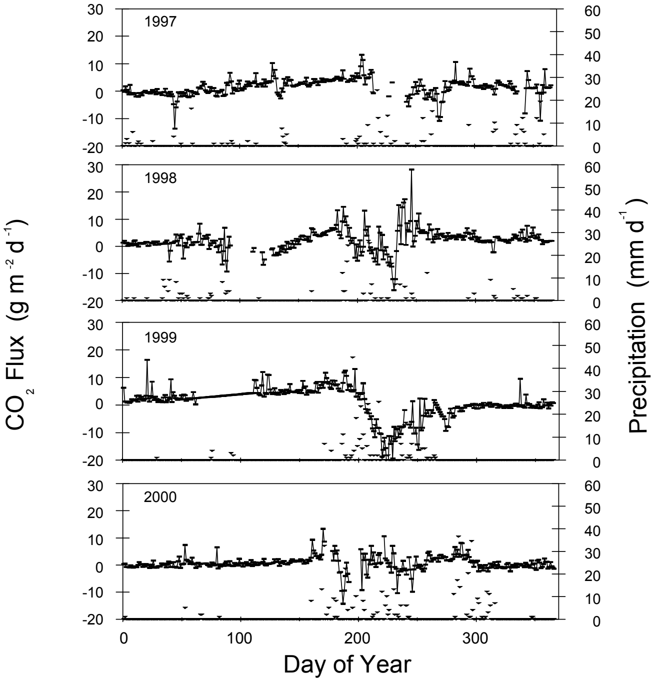

Figure 2. Kendall yearly carbon dioxide flux and precipitation (negative values, indicate carbon uptake; values estimated 1999 day 62-115 and 226-271).

The absence of precipitation throughout the year was another large influence on CO_2 flux. In 1999 and 2000, winter and spring at both sites were unusually dry (Figures 1 and 2). As the soil profile dried and became warmer, the CO_2 loss rate gradually increased until the summer rainy season started. Equilibrium for Equation (1) was shifting to the left by the removal of water from the soil solution causing the release of CO_2, and the equilibrium for Equation (2) was shifting to the left with the precipitation of $CaCO_3$. Soil moisture was exceedingly low at less than 0.02 kg kg^{-1}, hence soil microbiological activity as a large source of the CO_2 during this time was unlikely. With out microbial activity as the source of CO_2, the loss was concluded to be from the large inorganic soil carbon pool.

Precipitation pattern was more typical at the sites in fall 1997 and winter/spring 1998 as contrasted with the dry winter/spring in 1999 (Figures 1 and 2). The soil profiles in 1998 then contained moisture that could be utilized by the vegetation as the temperatures warmed up for plant growth. The vegetation utilized this soil moisture as evidenced by the uptake of carbon starting around day 100 and continuing until soil moisture was depleted. At the Kendall site, sporadic equipment failure prevented continuous measurement of carbon fluxes, but it is clear from the data collected that carbon was taken into plant biomass during this time (Figure 2).

Potential CO_2 flux sources

Carbon dioxide fluxes in and out of the two sites were from the organic and inorganic pools. Separation of the carbon fluxes from the two pools is difficult without the use of carbon isotopes, but the data did provide important insights into the origin of the measured fluxes. The dry winter and spring in 1999 and 2000 provided an opportunity to look further at CO_2 fluxes that likely would originate from the inorganic source as the CO_2 from microbial activity and plant growth would be moisture limited. The 1999 daily fluxes were separated into day and nighttime fluxes (Figures 3 and 4).

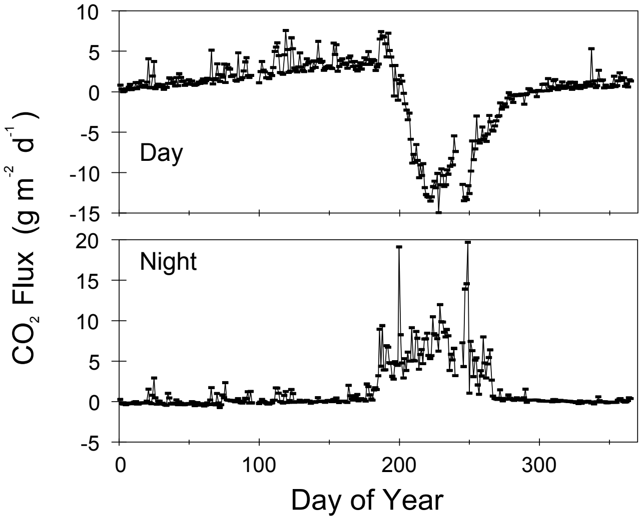

Figure 3. Lucky Hills, 1999 year, day and night carbon dioxide fluxes (negative values carbon uptake).

Nighttime fluxes are respiration fluxes and they remained relatively constant and small until the advent of summer rains, when night fluxes greatly increased. The constant nighttime fluxes during the dormant period were a further indication that there was no detectable increase in soil microbial activity as the soil and air temperatures increased. The increase in nighttime fluxes corresponding to the beginning of the summer rains represented soil microbial activity and plant respiration, hence an organic origin of the CO_2 fluxes (Linn and Doran 1984). The increasing daytime fluxes from winter to spring (i.e. dormant period) would then be from the inorganic carbon pool, controlled by evaporation shifting equilibrium for Equations 1 and 2 to release CO_2.

The growth and decomposition of the plant biomass at the two sites would be sources of organic carbon fluxes. Measured spring and fall aboveground biomass showed there was more carbon in the fall (Table 1). Averaged over 4 years, the annual increase in aboveground biomass carbon in the fall was 28 g C m^{-2} at the Lucky Hills site and 19 g C m^{-2} at Kendall. This represents a part of the organic carbon taken up during the summer growing season (Figures 1 and 2). The total organic carbon taken up was likely greater because some would have gone into below ground biomass. Cox et al. (1986) measured biomass distributions in these same plant communities and determined 65% of the biomass was below ground at the Lucky Hills site and 86% at Kendall. If these same percentages hold for carbon taken up into the aboveground and below ground biomass, the average annual total organic carbon taken up for the Lucky Hills site would be 80 g C m^{-2} and 135 g C m^{-2} for Kendall.

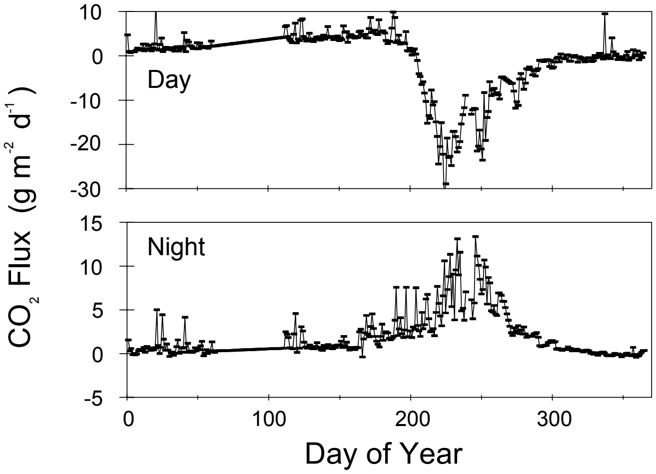

Figure 4. Kendall site 1999 year, day and night carbon dioxide fluxes (negative values, indicate carbon uptake, values estimated day 62-115 and 266-271).

The results of the soil analysis gave additional information on the potential sources of the CO_2 fluxes at the sites. SAS (Littell et al. 1996) analysis of variance results indicated there were significant site, depth and seasonal differences in the soil

Table 1. Yearly spring and fall aboveground biomass for Lucky Hills and Kendall sites.

Year	Spring	Fall
	------------ g C m^{-2} ------------	
	Lucky Hills	
1997	190	170
1998	150	240
1999	210	230
2000	210	230
	Kendall	
1997	90	120
1998	60	80
1999	100	150
2000	90	60

Table 2. Total annual and annual day and night time carbon fluxes at Lucky Hills and Kendall sites for years 1997 through 2000 (positive = source, negative = sink).

Year	Total	Day	Night
	-------------------- g C m^{-2} ----------------		
	Lucky Hills		
1997	130	70	60
1998	140	10	130
1999	155	5	150
2000	150	10	140
	Kendall		
1997	130	-30	160
1998	210	-140	350
1999	110	-80	190
2000	60	-100	160

inorganic carbon at the two sites. The significant seasonal effect had a mean 22.5 g kg^{-1} inorganic carbon in the top 30 cm of soil in the fall season and 19.4 g kg^{-1} in the spring season averaged over both sites. The seasonal differences imply that some of the measured carbon loss from fall through spring at the sites was from the inorganic pool and that some of the carbon taken up during the summer growing season went into the inorganic carbon pool (Figures 1 and 2).

Annual CO_2 fluxes

Annual CO_2 flux totals showed both sites were losing carbon (Table 2). The four-year average annual loss was 144 g C m^{-2} for the Lucky Hills site and 127 g C m^{-2} for Kendall. The Kendall site during the daytime took up three times the carbon lost from the Lucky Hills brush site on an annual basis. This was due to the higher carbon uptake at Kendall compared to Lucky Hills (Figures 1 and 2). The higher fluxes agree with the estimated higher total biomass accumulations during the growing season at the Kendall site. The average annual nighttime CO_2 flux losses at Kendall were twice those of Lucky Hills. The higher estimated biomass accumulation and higher nighttime CO_2 fluxes suggest there was more carbon cycling through Kendall than through Lucky Hills annually.

The 127 -144 g C m^{-2} average annual loss of carbon from these sites indicates they are a source of carbon to the atmosphere under the present climatic conditions (Table 2). For each of the four years, there was a carbon loss, even for 2000, a year with 30% above annual precipitation. The additional precipitation did not indicate the potential for organic carbon uptake annually. Recent studies indicate that some prairie sites are near equilibrium for organic carbon annually (Frank and Dugas 2001, Suyker and Verma 2001). If the Arizona sites are near annual equilibrium for organic carbon, much of the carbon loss could be from the inorganic carbon pool, which is substantial due to the limestone parent material. An estimation of the inorganic carbon in the soil profile was not made, but soil pits at the sites indicate increasing carbonate with depth (SCS, 1974). This large inorganic carbon pool could easily supply the observed annual carbon flux losses.

Conclusions

The hypothesis was that Walnut Gulch Experimental Watershed semiarid rangeland soils already containing carbonates are still taking up carbon into the inorganic and/or organic pools on an annual basis under the present climatic conditions. Actually, the two rangeland sites with different vegetation and soil types were found to be a source of CO_2 to the atmosphere annually. The carbon source appears to be from the large inorganic carbon pool in these soils. The Lucky Hills brush site with more inorganic carbon in the soil had an average annual loss of 144 g C m^{-2}, while the Kendall grass site, with less inorganic carbon in the soil, had an average annual carbon loss of 127 g C m^{-2}. The significantly greater inorganic soil carbon in the surface 30 cm on the soil in the fall than in the spring, implied that some of the observed CO_2 fluxes during the winter dormant and summer growing seasons cycled through the inorganic carbon pool. Carbon dioxide flux losses during very dry periods suggest that the source was primarily from the inorganic carbon pool. The next area of research is to determine the amount of carbon being lost from the inorganic pool through isotope analysis of the CO_2 fluxes.

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References

Cox, J.R., G.W. Frasier, and K.G. Renard. 1986. Biomass distributions at grassland and shrubland sites. Rangelands 8:67-69.

Dugas, W.A. 1993. Micrometeorological and chamber measurements of CO_2 flux from bare soil. Agricultural and Forest Meteorology 67:115-128.

Dugas, W.A., M.L. Heuer, and Mayeux, H.S. 1999. Carbon dioxide fluxes over bermudagrass, native prairie, and sorghum. Agricultural and Forest Meteorology 93:121-139.

Eswaran, H., P.F. Reich, J.M. Kimble, F.H. Beinroth, E. Padmanabhan, and P. Moncharoen P. 2000. Global Carbon Sinks. In R. Lal, J.M. Kimble, H. Eswaran, and B.A. Stewart, eds., Global Climate Change and Pedogenic Carbonates, pp. 15-26. CRC Press, Boca Raton, FL.

Frank, A.B., and W.A. Dugas. 2001. Carbon dioxide fluxes over a northern, semiarid mixed-grass prairie. Agricultural and Forest Meteorology 108:317-326.

Kessavalou, A., J.W. Doran, A.R. Mosier, R.A. Drijber. 1998. Greenhouse gas fluxes following tillage and wetting in a wheat-fallow cropping system. Jrnl of Environment. Quality 27:1105-1116.

Linn, D.M., and J.W. Doran. 1984. Effects of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Science Society of America Journal 48:1267-1272.

Littell, R.C., G.A. Stroup, W.W. Stroup, and R.D. Wolfinger. 1996. SAS® System for Mixed Models, pp. 633. SAS Institute Inc., Cary, NC.

Nelson, R.E. 1982. Carbonate and Gypsum. In A.L. Page, ed., Methods of Soil Analysis, Part 2. 2nd edition, Agronomy Monographs 9, pp. 181-197. ASA, Madison, WI.

Schlesinger, W.H. 1982. Carbon storage in the caliche of arid soils: A case study from Arizona. Soil Science 133:247-255.

Schlesinger, W.H. 1985. The formation of caliche in soils of the Mojave Desert, California. Geochimica et Comochimica Acta 49:57-66.

Schlesinger, W.H. 1997. Biochemistry: An Analysis of Global Change. 2nd edition. Academic Press, New York.

Soil Conservation Service (SCS) USDA. 1974 . Soil Survey Laboratory Data and Descriptions for Some Soils of....Arizona. Soil Survey Investigations Report 28.

Suyker, A.E., Verma, S.B. 2001. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. Global Change Biology 7:279-289.