EFFECTS OF ELEVATED ATMOSPHERIC CO_2 ON SOIL CO_2 EFFLUX IN CONVENTIONAL AND CONSERVATION CROPPING SYSTEMS

G.B. Runion, S.A. Prior, H.H. Rogers, H.A. Torbert
USDA-ARS National Soil Dynamics Laboratory
411 S. Donahue Drive, Auburn, Alabama 36832

Author for correspondence
G. Brett Runion
USDA-ARS, National Soil Dynamics Laboratory
411 S. Donahue Drive
Auburn, Alabama 36832
tel: 334 844 4517
fax: 334 887 8597
email: gbrunion@ars.usda.gov

ABSTRACT

Elevated atmospheric carbon dioxide (CO_2) can affect both the quantity and quality of plant tissues produced, which will impact the cycling and storage of carbon (C) within plant/soil systems and thus the rate of CO_2 release back to the atmosphere. Research is needed to more accurately quantify the effects of elevated CO_2 and associated feedbacks on soil CO_2 efflux in order to predict the potential of terrestrial ecosystems to sequester C. Effects of elevated atmospheric CO_2 on soil CO_2 efflux were examined in a long-term study comparing row crops managed as either a conventional or a conservation tillage system. In the conventional system, grain sorghum and soybean were rotated each year using conventional tillage practices and winter fallow. The conservation system also uses a grain sorghum-soybean rotation, with three winter cover crops: wheat, crimson clover, and sunn hemp which were also rotated. All crops in the conservation system were grown using "no-till" practices. Plants were exposed to either 365 ppm (ambient) or 725 ppm (elevated) levels of atmospheric CO_2 using open top field chambers. Soil CO_2 efflux, over a full two-year cropping cycle, was increased by both elevated atmospheric CO_2 and by conservation management; these increases were due, primarily, to increased biomass inputs from these treatments. Implications of these data on soil carbon storage in these systems will be discussed.

INTRODUCTION

Carbon dioxide is the first molecular link from atmosphere to biosphere. It is essential for photosynthesis which sustains the entire food chain. No substance is more pivotal for ecosystems, either natural or managed. The increasing CO_2 content of the atmosphere may be the most significant change taking place on the earth today. Atmospheric CO_2 concentration has risen well over 30% in past two centuries since the onset of the Industrial Revolution in the late 18th century. The steady increase in CO_2 (along with increases in other greenhouse gases such as methane and nitrous oxide) has led to many predicted results and unknown outcomes with regard to changes in global climate, particularly warming. The general enhancement of crop growth brought about by increased levels of CO_2 suggests that CO_2 removed from the atmosphere by plants and stored in the soil could help to mitigate global climate change. The amount of CO_2 taken up from the air and its subsequent sequestration in the soil is important, but so is the amount lost through soil respiration. The management of the crop, its residue, and the soil will play a key role in rate of efflux of CO_2 from soil respiration.

As the ability of terrestrial ecosystems to store C in biomass and in soil is not based solely on net primary productivity (Cardon ,1996), elevated atmospheric CO_2 may also influence terrestrial ecosystem C storage through its effects on plant tissue quality, which will impact soil microbes, decomposition processes, and subsequent soil C storage. Plant tissue produced under high levels of CO_2 often has higher C:N ratios (Mellilo, 1983; Prior et al., 1997b) and may be structurally different, with alterations in leaf anatomy (Thomas and Harvey, 1983) and epicuticular waxes (Graham and Nobel, 1996; Prior et al., 1997a). Plants grown under elevated CO_2 also may exhibit altered tissue chemistry, including lower N concentrations (Norby et al., 1986; Runion et al., 1999), higher concentrations of carbohydrates (Yelle et al., 1989; Runion et al., 1999), and increased levels of defense compounds such as phenolics (Lindroth et al., 1993; Pritchard et al., 1997).

The fate of C within crop systems is affected by the full biological chain of events starting with transfer of C from air to leaf, transformation within the plant, translocation within the plant/soil system, return of plant residue to the soil, decomposition, and is impacted by the effects of other environmental factors (e.g., temperature, nutrients, and water) on these processes. Therefore, the ability of terrestrial ecosystems to sequester C will depend on the cycling of C among the various biomass and soil pools and on the residence time of the C in these pools (Hungate et al., 1997).

At many stages in the cycling of C within terrestrial ecosystems, CO_2 is transferred back to the atmosphere by both autotrophic and heterotrophic respiration. Soil respiration is a significant source of CO_2 efflux from terrestrial ecosystems to the atmosphere (Schlesinger and Andrews, 2000), with global estimates ranging from 68 Pg C yr^{-1} (Raich and Schlesinger, 1992) to 100 Pg C yr^{-1} (Musselman and Fox, 1991). Therefore, even small shifts in soil CO_2 efflux could have major implications for increasing or decreasing atmospheric CO_2 concentration and its potential impacts on global climate change (Rustad et al., 2000). Through its impact on the quantity and quality of C within the plant and soil system, elevated CO_2 can affect this feedback of C to the atmosphere. For example, an increase in root growth under elevated CO_2 could increase root respiration (Ball and Drake, 1998), while changes in root exudation and/or quality of high CO_2-grown plant material might enhance (Luo et al., 1996; Hungate et al., 1997) or suppress (Prior et al., 1997b; Ineson et al., 1998) microbial respiration. The combined effects on total soil CO_2 respired back to the atmosphere, and the potential for C sequestration, are difficult to predict.

A recent review of soil and microbial respiration demonstrates that elevated atmospheric CO_2 generally increases belowground respiration, with overall estimates ranging from 40-50 % for soil respiration and

20-35 % for microbial respiration (Zak et al., 2000); these estimates are in agreement with another review which reported an overall increase of 37 % for forest species (Janssens and Ceulemans, 2000). Other studies report stimulation of root or total soil respiration for plants growing under elevated CO_2 in the range of 15-50% (Gifford et al., 1985; Nakayama et al., 1994; Verburg, 1998), with even greater stimulation reported in some cases (Griffin et al., 1997; Vose et al., 1997). Enhanced root or soil respiration under high CO_2 is often related to increases in root biomass, i.e., autotrophic respiration (Nakayama et al., 1994; Vose et al., 1997; Griffin et al., 1997; Zak et al., 2000) and/or increases in the size or activity of the microbial community, i.e., heterotrophic respiration (Nakayama et al., 1994; Rice et al., 1994; Vose et al., 1997; Zak et al., 2000). However, elevated CO_2 has been shown to suppress soil respiration in some cases (Gifford et al., 1985; Ineson et al., 1998) or to have no effect in others (Oberbauer et al., 1986; Johnson et al., 2001). Soil CO_2 efflux can be highly variable on temporal and spatial scales within a single field experiment (Nakayama et al., 1994; Xu and Qi, 2001) and among experiments; therefore, even relatively large increases in soil efflux under elevated CO_2 may not be statistically significant (Zak et al., 2000). Some of the variation among individual studies may be due to differences in plant species, experimental conditions, or methods used for the determination of CO_2 efflux.

A major drawback of most methods for determining soil CO_2 efflux concerns the timescale of measurements (i.e., cumulative totals across hours to days with NaOH traps or discreet points in time with soil collars and gas exchange devises); efflux between measurement periods is then generally assumed to be linearly integrative across the intervening time periods (Nakayama et al., 1994; Vose et al., 1997). Given the variation in response of soil CO_2 efflux to elevated atmospheric CO_2 and the drawbacks of current measurement technology, more research is needed before we can confidently predict the impacts of elevated atmospheric CO_2 on the ability of terrestrial ecosystems to sequester C. The objective of this experiment was to assess the response of soil CO_2 efflux (root plus microbial respiration) to atmospheric CO_2 enrichment of two cropping systemsB conventional and conservationBusing a novel, continuous, CO_2 efflux monitoring system.

MATERIALS AND METHODS

The research on efflux of soil CO_2 is being conducted within open top chambers on soil bin facilities at the USDA-ARS National Soil Dynamics Laboratory (NSDL). A ten-year study comparing conventional and conservation tillage systems exposed to controlled levels of atmospheric CO_2 is underway. We are nearing completion of the fifth two-year cropping cycle. In the conventional system, grain sorghum (*Sorghum bicolor* L. Moench) and soybean (*Glycine max* L. Merr.) are being rotated each year using conventional tillage practices and winter fallow. The conservation system also uses a grain sorghum-soybean rotation, with three winter cover crops (wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), and sun hemp (*Crotalaria juncea* L.)) which are also rotated. All crops in the conservation system are grown using "no-till" practices. The wheat serves as cover as well as a grain crop. These five species offer contrasting characteristics with respect to photosynthetic pathways (C_3 and C_4), responses to CO_2, rooting patterns, N_2-fixation, decomposition rates, and their impact on soil C and N cycling; most are prominent the world over.

Two levels of atmospheric CO_2 (ambient = 365 ppm or elevated = 725 ppm) will be used for exposure of both cropping systems; exposures will run 24 hours per day throughout the entire growing season. Open top chambers (10 ft diameter), with state-of-the-art data acquisition and processing, are used for exposure. In addition, ambient plots (without chambers) have been included as a check on chamber effects. For the study, plots have been established along the length of an outdoor soil bin (20 ft X 250 ft X 6 ft deep) filled with a Decatur silt loam soil (clayey, kaolinitic, thermic Rhodic Paleudults).

The design is a split-plot with three blocks; one-half of each block is being managed as a conventional system and the other half as a conservation system. Split-plot treatments (CO_2 level) were randomly assigned within blocks. All statistical analyses will be performed using mixed model procedures (Proc Mixed) of the Statistical Analysis System (Littell et al., 1996).

Soil CO_2 efflux was measured using the Automated Carbon Efflux System (ACES) (U.S. patent # 6,692,970), developed at USDA Forest Service, Southern Research Station Laboratory in Research Triangle Park, NC; a description of the ACES has been previously reported (Butnor et al., 2003). Briefly, ACES is a chamber-based, multi-port respiration measurement system, which uses open system, dynamic soil respiration chambers measuring 9.8 in diameter (76 in^2) equipped with air and soil thermocouples (soil thermocouples were inserted to depth of 2 in). The soil chambers are designed with pressure equilibration ports to ensure that differences in chamber pressure do not compromise the quality of the respiration measurement (Fang and Moncrieff, 1996). Each ACES has 15 sample chambers and one null calibration chamber which are measured sequentially for 10 minutes each, allowing a complete run every 2 hours and 40 minutes or nine complete runs per day. When not being actively sampled, all chambers are refreshed with reference air to prevent buildup of CO_2. The ACES units constructed for our study were modified to allow use of reference air from two sources, owing to the differential atmospheric CO_2 concentrations employed; soil chambers in ambient CO_2 open top chambers were refreshed with ambient CO_2 air, while those in elevated open top chambers were refreshed with elevated CO_2 air. Ambient CO_2 reference air was obtained by placing an air compressor in an additional, empty, ambient open top chamber located on an adjacent soil bay and using the same CO_2 delivery system as the main study; elevated CO_2 reference air was similarly obtained by placing a second air compressor in an additional, empty, elevated open top chamber. The air compressors replace the ballast tanks commonly used with the ACES, which provide reference air for the ACES that is buffered against fluctuations in atmospheric CO_2 concentration (Butnor et al., 2003).

Constraints on distance between soil respiration chambers and the main ACES unit (housing the infra-red gas analyzer and data logger) necessitated use of two ACES units in this study; one was used for blocks 1-3, and a second for blocks 4-6. Two soil chambers were placed into each of the 12 open top chambers; the three additional soil chambers for each system were placed outside of open top chambers. Calibration chambers were placed into the ambient open top chamber nearest each main ACES unit. A soil moisture probe was placed adjacent to each calibration chamber and inserted to a depth of 8 in.

To minimize the effect of precipitation exclusion on the soil substrate within the soil chambers, soil chambers were moved every 3-4 days between two sample points (A and B) within each open top chamber. Litter on the soil surface was not removed from each sample point, but all points were kept free of live vegetation. The ACES units were installed on November 9, 2001, at the beginning of the second two-year cycle following planting of clover. The ACES units have run continuously (with the exception of brief periods for maintenance or due to system/power failures) since this date; however, data presented here include only the complete second cycle which ran through October 20, 2003 at which time soybean plants were harvested.

RESULTS AND DISCUSSION

Soil CO_2 efflux, over the full two-year cropping cycle, was increased by both elevated atmospheric CO_2 and by conservation management; in both cases soil CO_2 efflux was increased by approximately 50 % due to these treatments. This increase is consistent with other reports in the literature (Gifford et al., 1985; Nakayama et al., 1994; Verburg, 1998). While the combination of elevated CO_2 and conservation management did result in the greatest soil CO_2 efflux, the effects of these two treatments were not additive.

It is obvious that the conservation system would have higher CO_2 efflux during periods when cover crops were being grown, as the conventional plots were fallow (with the exception of weed invasion) during these periods. In fact, soil CO_2 efflux in the conservation system was sometimes 100+ % greater in the conservation than the conventional system during these periods. Autotrophic (cover crop vs. weed) respiration was likely primarily responsible for the differences in soil CO_2 efflux noted during these periods. However, heterotrophic (soil microbe) respiration might have added to the differences due to increased residue inputs in the conservation system. Soil CO_2 efflux was also greater in the conservation system during primary row crop (i.e., sorghum and soybean) production periods; these increases were most likely a result of differences in heterotrophic respiration due to the increased residue inputs occurring in the conservation system.

Elevated atmospheric CO_2 also increased soil CO_2 efflux in both the conservation and the conventional systems. Exposure to elevated CO_2 increased growth for all crops. These larger plants had larger root systems, which implies an increase in autotrophic respiration. However, increased plant growth led to greater plant residues returned to the soil (as well as a potential for increased root exudation) which implies larger amounts of substrate for microbial decomposition and, thus, an increase in heterotrophic respiration.

Increased efflux of CO_2 from soils to the atmosphere adds to the continually rising concentration of atmospheric CO_2. However, despite higher levels of soil CO_2 efflux, these systems may still increase soil C sequestration and contribute to mitigation of the rising atmospheric CO_2 concentration. Although this may appear contradictory, the total amount of C fixed by plants, either due to elevated atmospheric CO_2 and/or use of no-till management with cover crops (as in our conservation system) can far exceed that released back to the atmosphere as soil CO_2 efflux; we observed this same effect in a previous study with longleaf pine (Runion et al, 2007).

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