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Free-air CO_2 enrichment effects on soil carbon and nitrogen

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Abstract

Since the onset of the industrial revolution, atmospheric CO_2 concentration has increased exponentially to the current 370 μmol mol^{-1} level, and continued increases are expected. Previous research has demonstrated that elevated atmospheric CO_2 results in larger plants returning greater amounts of C to the soil. However, the effects of elevated CO_2 on C and N cycling and long-term storage of C in soil have not been examined. Soil samples (in 0–50, 50–100, and 100–200 mm depth increments) were collected after 3 years of cotton (*Gossypium hirsutum* L.) production under free-air CO_2 enrichment (FACE, at 550 μmol CO_2 mol^{-1}), in combination with 2 years of different soil moisture regimes (wet, 100% of evapotranspiration replaced, or dry, 75% and 67% of evapotranspiration replaced in 1990 and 1991, respectively) on a Trix clay loam (fine, loamy, mixed (calcareous), hyperthermic Typic Torrifluvent) at Maricopa, Arizona. Ambient plots (370 μmol CO_2 mol^{-1} (control)), in combination with the wet and dry soil moisture regimes, were also included in the study. Soil organic C and N concentrations, potential C and N mineralization, and C turnover were measured. Increased input of cotton plant residues under FACE resulted in treatment differences and trends toward increased organic C in all three soil depths. During the first 30 days of laboratory incubation, available N apparently limited potential C mineralization and C turnover in all treatments. Between 30 and 60 days of incubation, soils from FACE plots had greater potential C mineralization with both water regimes, but C turnover increased in soils from the dry treatment and decreased in soils where cotton was not water stressed. These data indicate that in high-CO_2 environments without water stress, increased C storage in soil is likely, but it is less likely where water stress is a factor. More research is needed before the ability of soil to store additional C in a high-CO_2 world can be determined.

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1. Introduction

There is no doubt that the combined impact of population increases, industrial expansion and deforestation has resulted in an increased atmospheric CO_2 concentration (Holland, 1978; Smil, 1985; Warneck, 1988; Keeling et al., 1989). Furthermore, atmospheric CO_2 concentration is projected to double in the next century (Bolin, 1986). If trends in the use of fossil fuels and deforestation are not reversed, alterations in atmospheric CO_2 are likely to change the functioning of both natural and agro-ecosystems. In particular, C and nutrient accumulations and rates of turnover in terrestrial ecosystems will probably be altered in a CO_2-enriched world, and changes in C and nutrient cycling patterns with rising CO_2 will probably have important economic consequences.

A central problem in understanding global C cycling is the inability of researchers to account for C fluxes. Despite two decades of scientific bookkeeping, the C budget is as yet unbalanced. Whereas sources of atmospheric CO_2 are well documented, sinks for C are not (Houghton et al., 1990; Schlesinger, 1991). With emissions of 5 Pg C $year^{-1}$ from the use of fossil fuel and 1.8 Pg g C $year^{-1}$ from the destruction of vegetation, 3 Pg C $year^{-1}$ are accounted for by atmospheric increase and oceanic uptake, leaving an unknown sink of 2.2 Pg C $year^{-1}$ (Houghton et al., 1990; Schlesinger, 1991). One hypothesis that has been proposed is C storage in terrestrial ecosystems (Tans et al., 1990), as a result of higher plant productivity and fixation induced by elevated CO_2 (Kimball, 1983; Allen, 1990; Lekkerkerk et al., 1990). Carbon fixed within biomass ultimately enters the soil via plant residues, where it may reside for hundreds of years (Parton et al., 1986).

The long-term capacity of soil to store C from CO_2 fertilization has not been elucidated (Houghton et al., 1985). Schlesinger (1986, 1990) found little evidence for soil C storage. Lamborg et al. (1984) have argued that increased soil microbial activity caused by greater biomass C inputs in a high-CO_2 world would lead to increased soil organic matter decomposition (i.e. 'the priming effect') and, therefore, atmospheric CO_2 enrichment would not result in accumulation of soil organic C. Alternatively, Goudriaan and De Ruiter (1983) proposed that increased soluble, easily decomposed C inputs as a consequence of elevated atmospheric CO_2 could accentuate soil microbial substrate preference mechanisms. They further speculated that preference for easily decomposable substrates would retard the decomposition of plant debris and native soil organic matter. The end result of their scenario would be an accumulation of soil organic matter. To date, neither of these hypotheses has been rigorously tested. Nevertheless, the rate and extent of turnover of organic C may ultimately control C storage in terrestrial ecosystems (Van Veen et al., 1991).

Virtually no field research has addressed the effects of CO_2 enrichment on C cycling in terrestrial ecosystems. In a growth chamber study, Lekkerkerk et al. (1990) found that increased photosynthetic fixation with elevated CO_2 resulted in a proportional increase in distribution of C to plant and soil compartments; thus, elevated CO_2 resulted in increased C input into soil. Bazzaz (1990) reported predictions demonstrating that decomposition rates of plant residue would be slower in environments

with higher CO_2, although no experimental evidence for this hypothesis was given. However, Lekkerkerk et al. (1990) found an increased input of easily decomposable root-derived C compounds in soil under elevated CO_2. Their data suggest that soil microorganisms prefer easily decomposable root-derived material over more resistant native soil organic matter. They reported a net decrease in soil organic matter 49 days after wheat (*Triticum aestivum* L.) plants were exposed to 350 μmol CO_2 mol^{-1} and a net increase in soil organic matter when wheat plants were exposed to 700 μmol CO_2 mol^{-1}. However, the results reported were for short-term effects of CO_2 levels on soil organic matter, and extrapolation of their results to long-term accumulation could be erroneous (Lekkerkerk et al., 1990).

An important issue in the C storage question is N, as it is the element most limiting in biomass production systems and without it C cannot be fixed (Wong, 1979; Hardacre et al., 1986). Availability of N and other nutrients on a global scale could limit plant response to CO_2 enrichment (Strain and Cure, 1985). Carbon dioxide induced changes in soil N dynamics could reduce N availability by alterations of soil C:N ratios. For example, changes in the composition of plant residue in a CO_2-rich environment could reduce decomposition rates (Van Veen et al., 1991), thus limiting nutrient cycling (Trabalka, 1985).

Studies were initiated in 1989 at the Maricopa Agricultural Center for Resources and Extension of the University of Arizona, Maricopa, to determine the effect of elevated CO_2 on the plant–soil system under field conditions. The objective of this study was to determine the cumulative impact of 3 years of free-air CO_2 enrichment (FACE; 550 μmol CO_2 mol^{-1}) and moisture stress to cotton (*Gossypium hirsutum* L.) on soil organic C and N concentrations and microbial activity.

2. Materials and methods

2.1. Study site

The cumulative impact of 3 years of FACE at Maricopa, AZ (33.07°N, 111.98°W) on surface soil (Trix clay loam; fine, loamy, mixed (calcareous), hyperthermic Typic Torrifluvent) organic C and N concentrations and microbial activity was determined. Details of the design, rationale, operation and performance of the CO_2 exposure system used in this experiment can be found elsewhere (Lewin et al., 1994). Briefly, eight study plots were established in 1989, four plots at an elevated atmospheric CO_2 concentration (FACE; 550 μmol CO_2 mol^{-1}; surrounded by 23 m FACE arrays) and four plots under ambient conditions (control: 370 μmol CO_2 mol^{-1}; surrounded by 23 m 'dummy' FACE arrays). FACE was maintained in 1989 for 17 weeks, ending on 17 September, in 1990 for 19 weeks, ending on 16 September, and in 1991 for 20 weeks, ending on 15 September.

Cotton ('Deltapine 77') was grown at the study site during all 3 years of the experiment. The study site was managed as a conventionally tilled, irrigated production system, with the goal of optimum cotton lint yields. Recommended cultural practices (tillage, fertilization, pesticides, etc.) for the area were used. Row spacing

was 1 m, and within-row plant spacing was 0.1 m. Further details on management of the cotton crop can be found elsewhere (Mauney et al., 1994).

2.2. Experimental design and data analyses

The experimental design was a split plot, arranged as a randomized complete block with four replications. Main plot treatments were atmospheric CO_2 concentrations (FACE and control). Subplots were irrigation regimes, either wet (100% of evapotranspiration replaced) or dry (75% and 67% of evapotranspiration replaced in 1990 and 1991, respectively). Differential irrigation regimes were not imposed during 1989, when the plots were irrigated to replace 100% of evapotranspiration. Irrigation was supplied via subsurface drip tubes. Additional information on irrigation scheduling has been provided by Mauney et al. (1994).

Analyses of variance were performed using the Statistical Analysis Systems Institute Inc. (SAS Institute Inc.) package (SAS Institute Inc., 1982), testing for all main effects and their interactions. Unless noted otherwise, treatments and their interactions were considered statistically different at the $\alpha = 0.10$ level.

2.3. Sampling and chemical analyses

Soil samples were collected in mid-September 1991 from all combinations and replications of the atmospheric CO_2 and water regime treatments at Maricopa. Composite soil samples from 30 soil cores per plot were randomly collected at depth increments of 0–50, 50–100, and 100–200 mm, for measurement of soil organic C and N concentrations, potential N mineralization, microbial respiration, and C turnover. Soil samples were immediately cooled to approximately 5°C, and transported to Auburn University (Auburn, AL) within 1 day. On arrival, soil samples were maintained in their field-moist state at 5°C for 2 days until analysis and initiation of incubations.

Soil potential C and N mineralization were quantified using techniques described by Wood et al. (1990). After sieving to pass 2 mm, 25 g (dry weight basis) aliquots of each soil sample were weighed into plastic containers. Deionized water was added to bring the soils to a moisture content equivalent to −20 kPa at a bulk density of 1.3 Mg m^{-3}. Soils, in their plastic containers, were placed in 1 l jars containing 20 ml of water to maintain humidity and a vial containing 10 ml of 1 M NaOH to trap respired CO_2 (Anderson, 1982). The sealed jars were incubated in the dark at 25°C, and removed after 30 and 60 day periods.

Duplicate samples of preincubation soils from each plot–soil depth combination were dried (60°C) and analyzed for organic C by the Walkley–Black procedure (Nelson and Sommers, 1982). Duplicate samples were dried (60°C), ground to pass 0.15 mm and analyzed for organic N with a LECO CHN-600 analyzer (LECO Corp., St. Joseph, MI, USA). Soil NO_3-N plus NO_2-N and NH_4-N were extracted with 2 M KCl and measured (before and after incubation) by standard colorimetric procedures (Keeney and Nelson, 1982) on a Lachat autoanalyzer (Lachat QuickChem Systems, Mequon, WI, USA). Carbon dioxide in NaOH traps was determined by titrating

excess base with 1 M HCl in the presence of $BaCl_2$ (Anderson, 1982). Potential C mineralization was calculated as the difference between CO_2-C captured in individual base traps and the mean of CO_2-C captured in four blanks. Potential N mineralization was calculated as the difference between final and initial contents of inorganic N for each incubation. Carbon turnover was calculated as potential C mineralization divided by total organic C.

To estimate the amount of cotton residue C returned to the soil, cotton biomass samples at physiological maturity were collected from all treatments and replications during all 3 years of the field experiment. Methods used for collection and processing of these above-ground and below-ground cotton biomass samples have been given elsewhere (Rogers et al., 1992).

3. Results and discussion

FACE increased cotton above-ground and root biomass compared with the control in all 3 years of the field study (Table 1). Total cotton biomass was increased approximately 38% under FACE compared with the control. These data are consistent with results reported for cotton response to elevated CO_2 in growth chamber studies (Mauney et al., 1978; DeLucia et al., 1985), and suggest that greater amounts of C were being added to soil under FACE than under the control conditions. In addition, water regime had a significant effect on cotton biomass production in 1991; cotton biomass dry weight was 24% greater for the wet than for the dry regime.

Differences in cotton plant residue input to the soil apparently influenced soil organic C concentrations. In the 0–50 mm soil depth increment, a significant effect of moisture level and an interaction between moisture level and CO_2 level on soil organic C was observed (Table 2). In this soil depth increment, soil organic C concentration increased under FACE in combination with the wet treatment. For the 100–200 mm depth, FACE increased soil organic C, with a similar trend ($P = 0.180$) observed in the 50–100 mm increment. Below 50 mm, no significant effect of moisture regime on soil organic C concentration was observed.

Our observations of increased soil organic C under FACE are supported by isotopic fractionation studies conducted at the FACE site by Leavitt et al. (1994), who found that 6% of the organic C residing in the 0–300 mm soil depth after cotton harvest in 1991 in FACE plots was derived from FACE inputs. Although differences were not statistically significant, their data indicated that FACE plots contained more soil organic C than control plots. Because soil organic C is typically concentrated near the soil surface, lack of a significant difference between FACE and control soil organic C in the Leavitt et al. (1994) study, as opposed to the significant differences observed in our study, may have been caused by dilution of soil organic C in their 0–300 mm composite samples (our samples were collected from a shallower soil depth, 0–200 mm).

Except in the 100–200 mm depth, soil organic N concentration was not significantly affected by CO_2 or moisture regime (Table 2). A significant interaction between

Table 1
Cotton above-ground and below-ground biomass (in Mg ha^{-1}) at physiological maturity as affected by atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Year	Above-ground		Below-ground	
	Control	FACE	Control	FACE
1989	18.6 (1.1)	25.2 (1.4)	0.7 (0.1)	1.3 (0.1)
1990	15.9 (1.0)	22.7 (1.2)	0.9 (0.1)	1.2 (0.1)
1991	8.7 (0.4)	11.5 (0.5)	0.5 (0.1)	0.9 (0.1)
	Moisture regime			
	Dry	Wet	Dry	Wet
1990	19.1 (1.8)	19.6 (1.6)	1.1 (0.1)	1.1 (0.1)
1991	9.0 (0.4)	11.2 (0.5)	0.6 (0.1)	1.8 (0.1)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2 Level (C)	Moisture regime (M)	$C \times M$
1989			
Above-ground	0.146		
Below-ground	0.014		
1990			
Above-ground	0.051	0.707	0.512
Below-ground	0.040	0.588	0.793
1991			
Above-ground	0.023	0.001	0.456
Below-ground	0.003	0.010	0.977

[a] Values represent means of four replicates; standard error of the mean is given in parentheses. Because the CO_2 level by moisture regime interaction was not significant in any case, data for the effect of CO_2 level on biomass production are averaged across water regimes. Likewise, data for the effect of water regime on biomass production are averaged across CO_2 levels.
[b] Probability of a greater F.

CO_2 level and moisture regime occurred in the 100–200 mm depth, with FACE and the wet moisture regime resulting in the greatest organic N concentration.

Net N mineralization in laboratory incubations was erratic, especially during the 30–60 day incubation period (Table 3). During the 0–30 day incubation period, N mineralization decreased significantly for the wet treatment in the 0–50 and 50–100 mm soil depths. In the 100–200 mm depth, a significant interaction between CO_2 level and moisture regime was observed with FACE in combination with the wet treatment, resulting in increased net N mineralization. This interaction corresponds to the interaction observed with organic N concentration, with more organic N available for mineralization. No significant treatment differences were observed for N mineralization during the 30–60 day or total incubation period.

No significant difference in soil respiration during the 0–30 day incubation period

Table 2
Soil organic C and N (in g kg^{-1}) as affected in atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Soil depth (mm)	Organic C		Organic N	
	Control	FACE	Control	FACE
Dry moisture regime				
0–50	7.6 (0.6)	7.1 (0.3)	1.2 (0.1)	1.2 (0.1)
50–100	6.8 (0.1)	6.9 (0.1)	1.1 (0.1)	1.3 (0.1)
100–200	5.2 (0.2)	5.4 (0.1)	1.1 (0.2)	0.9 (0.1)
Wet moisture regime				
0–50	7.7 (0.7)	8.8 (0.6)	1.2 (0.1)	1.2 (0.1)
50–100	6.5 (0.3)	6.8 (0.2)	1.1 (0.1)	1.2 (0.1)
100–200	5.1 (0.3)	5.6 (0.1)	0.9 (0.1)	1.1 (0.2)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2	Moisture regime (M)	$C \times M$
Organic C			
0–50 mm	0.545	0.046	0.059
50–100 mm	0.180	0.420	0.442
100–200 mm	0.024	0.900	0.528
Organic N			
0–50 mm	0.783	0.556	0.932
50–100 mm	0.650	0.743	0.274
100–200 mm	0.339	0.889	0.059

[a] Values represent means of four replicates; standard error of the mean is given in parentheses.
[b] Probability of a greater F.

was observed at any soil depth, although a trend ($P = 0.201$) for FACE to increase respiration in the 0–50 mm depth existed (Table 4). During the 30–60 day and total incubation period, FACE significantly increased soil respiration in the 50–100 and 100–200 mm depth increments. In addition, a trend ($P = 0.113$ and $P = 0.123$ for 30–60 day and total incubation period, respectively) toward FACE increasing soil respiration in the 0–50 mm depth was observed. Moisture regime had no significant effect on soil respiration for any incubation period or soil depth increment, although a trend for the wet treatment to enhance respiration was observed for the 100–200 mm depth during the 0–30 day ($P = 0.168$) and total ($P = 0.234$) incubation periods.

The lack of a significant treatment response for soil respiration during the first 30 days of incubation could have been caused by reduced N availability. Research has indicated that N supply limits microbial utilization of C compounds (Merckx et al., 1987; Van Veen et al., 1991). Reduced N availability under FACE was evidenced by the significant reduction in N mineralization (Table 3) and a significant increase in the C/N mineralized ratio (Table 5). For C/N mineralized, significant effects for moisture level in the 0–50 mm depth and an interaction between CO_2 level and moisture regime in the 50–100 and 100–200 mm depths were observed (Table 5). The ratio of C/N

Table 3
Soil N mineralization (in mg kg^{-1}) in laboratory incubations as affected by atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Soil depth (mm)	Control			FACE		
	30 days	60 days	Total	30 days	60 days	Total
Dry						
0–50	15.5 (5.0)	7.0 (5.3)	22.5 (8.7)	13.3 (3.6)	14.5 (3.8)	27.8 (7.3)
50–100	8.8 (3.9)	8.3 (3.9)	17.0 (7.8)	6.5 (1.3)	10.3 (1.4)	16.8 (2.7)
100–200	5.5 (1.6)	7.3 (1.5)	12.8 (2.9)	4.3 (0.8)	7.0 (0.6)	11.3 (1.3)
Wet						
0–50	10.8 (5.3)	11.0 (2.3)	21.8 (6.7)	9.0 (1.8)	15.3 (3.7)	24.3 (5.4)
50–100	5.3 (2.3)	20.3 (14.3)	25.5 (16.3)	6.0 (0.6)	10.0 (0.9)	16.0 (1.5)
100–200	4.3 (1.3)	6.3 (1.2)	10.5 (2.4)	8.5 (1.5)	14.0 (6.0)	22.5 (7.0)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2 Level (C)	Moisture regime (M)	$C \times M$
30 days			
0–50 mm	0.473	0.005	0.821
50–100 mm	0.761	0.087	0.176
100–200 mm	0.360	0.259	0.062
60 days			
0–50 mm	0.208	0.342	0.507
50–100 mm	0.643	0.331	0.312
100–200 mm	0.249	0.383	0.256
Total			
0–50 mm	0.344	0.498	0.658
50–100 mm	0.663	0.463	0.385
100–200 mm	0.263	0.305	0.144

[a] Values represent means of four replicates; standard error of the mean is given in parentheses.
[b] Probability of a greater F.

mineralized is an index of labile substrate availability (Nadelhoffer et al., 1991), and large proportions of available C relative to N can result in net N immobilization (Wood and Edwards, 1992). The higher C/N mineralized under the wet treatment indicates that N availability may have limited soil respiration (Table 4). During the 30–60 day incubation period, no significant treatment effects were observed for the C/N mineralized (Table 5). Apparently, N was no longer limiting during this incubation period, which resulted in a trend ($P = 0.208$ and $P = 0.249$ for 0–50 mm and 100–200 mm depth, respectively) for increased N mineralization (Table 3) and allowed an increase in soil respiration (Table 4).

Lamborg et al. (1984) hypothesized that increased C input into the soil would result in increased decomposition and, thus, an increase in soil microbial respiration. Although increased soil respiration was observed under FACE during the 30–60 day incubation, no significant effect of FACE was observed during the 0–30 day

Table 4
Soil microbial respiration (in mg CO_2-C kg^{-1}) in laboratory incubations as affected by atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Soil depth (mm)	Control			FACE		
	30 days	60 days	Total	30 days	60 days	Total
Dry						
0–50	220 (24)	304 (27)	524 (50)	266 (21)	433 (64)	699 (82)
50–100	177 (9)	247 (24)	424 (29)	191 (17)	299 (20)	490 (36)
100–200	131 (8)	178 (10)	309 (7)	143 (7)	212 (10)	355 (15)
Wet						
0–50	238 (26)	320 (36)	558 (61)	282 (37)	464 (85)	746 (119)
50–100	188 (11)	284 (7)	472 (16)	179 (3)	308 (22)	487 (25)
100–200	145 (12)	192 (11)	336 (18)	169 (21)	241 (26)	410 (44)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2 Level (C)	Moisture regime (M)	$C \times M$
30 days			
0–50 mm	0.201	0.399	0.943
50–100 mm	0.847	0.952	0.366
100–200 mm	0.417	0.168	0.642
60 days			
0–50 mm	0.113	0.295	0.727
50–100 mm	0.004	0.355	0.576
100–200 mm	0.011	0.343	0.723
Total			
0–50 mm	0.123	0.287	0.867
50–100 mm	0.654	0.498	0.444
100–200 mm	0.067	0.234	0.671

[a] Values represent means of four replicates; standard error of the mean is given in parentheses.
[b] Probability of a greater F.

incubation (possibly owing to N limitation). The depression of C respiration observed during the 0–30 day incubation indicates that changes in nutrient cycling in a high-CO_2 world may restrict decomposition of organic matter, which may result in C accumulation as a response to increased C input.

Because organic C concentration was mainly affected by moisture regime in the 0–50 mm depth (Table 2), the soil respiration results (Table 4) do not correspond to the concentration of organic C found in the soil. These results indicate that factors other than total organic C concentration contributed to respiration rates. A possible explanation for these results is that an increase in easily decomposable C compounds (increased quality) resulted from FACE. Lekkerkerk et al. (1990) reported an increase in the easily decomposable C compounds with 700 μmol CO_2 mol^{-1} compared with 360 μmol CO_2 mol^{-1}. Their results are consistent with the results of this study; they reported a 74% increase in soil plus root respiration for their 700 μmol CO_2 mol^{-1} treatment.

Table 5
Soil C and N mineralization ratio (in g g^{-1}) in laboratory incubations as affected by atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Soil depth (mm)	Control			FACE		
	30 days	60 days	Total	30 days	60 days	Total
Dry						
0–50	14.2 (3.9)	28.9 (5.8)	18.1 (2.4)	23.9 (5.4)	33.3 (5.4)	28.4 (4.2)
50–100	17.7 (3.7)	27.6 (6.7)	22.8 (5.2)	31.6 (4.2)	30.7 (3.9)	31.0 (4.0)
100–200	27.9 (4.7)	32.1 (12.6)	29.4 (8.4)	36.6 (5.9)	30.6 (1.6)	32.5 (3.1)
Wet						
0–50	25.5 (12.0)	32.8 (7.7)	24.2 (8.3)	34.7 (6.4)	32.2 (2.9)	32.9 (3.9)
50–100	31.0 (8.1)	44.1 (19.5)	26.9 (10.3)	30.5 (2.5)	31.1 (1.6)	30.8 (1.6)
100–200	53.2 (23.3)	34.4 (6.8)	39.3 (10.9)	20.7 (1.9)	22.6 (4.2)	21.0 (3.1)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2 Level (C)	Moisture regime (M)	$C \times M$
30 days			
0–50 mm	0.490	0.032	0.941
50–100 mm	0.178	0.058	0.033
100–200 mm	0.393	0.673	0.101
60 days			
0–50 mm	0.848	0.668	0.839
50–100 mm	0.426	0.858	0.741
100–200 mm	0.488	0.472	0.217
Total			
0–50 mm	0.066	0.123	0.793
50–100 mm	0.524	0.512	0.475
100–200 mm	0.428	0.806	0.013

[a] Values represent means of four replicates; standard error of the mean is given in parentheses.
[b] Probability of a greater F.

The abstraction that C substrate quality was affected by FACE is supported by our C turnover results. Carbon turnover was significantly affected by the interaction of CO_2 level and water regime in the 0–50 mm depth during the 30–60 day and total incubation period (Table 6). Although no significant effect was observed as a result of N limitation of soil respiration, a similar trend ($P = 0.111$) for C turnover during the 0–30 day incubation period as affected by the interaction between CO_2 level and moisture regime was observed. At this depth, FACE resulted in increased C turnover under the dry treatment, but had no effect on it under the wet treatment (Table 6). Likewise, the wet treatment increased C turnover under control conditions, but decreased it under FACE compared with the dry treatment.

The most plausible explanation for these results is that increased quantity of C input under the wet treatment interacted with the increased quantity and quality of C input under FACE. The increased quality of C substrate under FACE resulted in

Table 6
Soil C turnover (in g (100 g)$^{-1}$) in laboratory incubations as affected by atmospheric CO_2 concentration and water regime at Maricopa, AZ[a]

Soil depth (mm)	Control			FACE		
	30 days	60 days	Total	30 days	60 days	Total
Dry						
0–50	2.9 (0.2)	4.0 (0.2)	6.9 (0.4)	3.7 (0.2)	6.0 (0.7)	9.8 (0.8)
50–100	2.6 (0.1)	3.7 (0.4)	6.3 (0.5)	2.8 (0.3)	4.4 (0.3)	7.2 (0.5)
100–200	2.5 (0.1)	3.5 (0.3)	6.0 (0.3)	2.6 (0.1)	3.9 (0.2)	6.6 (0.3)
Wet						
0–50	3.2 (0.5)	4.2 (0.4)	7.3 (0.9)	3.2 (0.3)	5.2 (0.7)	8.4 (0.9)
50–100	2.9 (0.1)	4.4 (0.1)	7.3 (0.2)	2.6 (0.1)	4.5 (0.3)	7.1 (0.3)
100–200	2.8 (0.3)	3.8 (0.2)	6.6 (0.4)	3.0 (0.3)	4.3 (0.4)	7.4 (0.7)

Parameter	Analysis of variance ($P > F$)[b]		
	CO_2 Level (C)	Moisture regime (M)	$C \times M$
30 days			
0–50 mm	0.428	0.551	0.111
50–100 mm	0.621	0.781	0.264
100–200 mm	0.688	0.139	0.885
60 days			
0–50 mm	0.167	0.274	0.092
50–100 mm	0.007	0.258	0.425
100–200 mm	0.028	0.413	0.895
Total			
0–50 mm	0.220	0.311	0.062
50–100 mm	0.048	0.348	0.374
100–200 mm	0.170	0.262	0.884

[a] Values represent means of four replicates; standard error of the mean is given in parentheses.
[b] Probability of a greater F.

increased microbial respiration and therefore higher C turnover under the dry treatment, whereas the increased C input under the wet treatment compared with the dry treatment did not significantly affect respiration or C turnover. Thus, even though soil respiration tended to be higher with FACE, the increased C under the wet treatment resulted in decreased C turnover when these treatments were combined (Table 6).

This conclusion is further validated by results from dehydrogenase activity studies conducted at Maricopa during June and August 1991 by Runion et al. (1994). In their study, elevated CO_2 significantly increased dehydrogenase activity at both sampling periods. Runion et al. observed no significant effect of water regime or an interaction with CO_2 level. Their results indicate that FACE stimulated soil microbial activity, most likely as a result of increased concentration of easily decomposable C compounds.

Below 50 mm, there was no significant difference in C turnover among treatments

during the 0–30 day incubation period (Table 6). During the 30–60 day incubation, FACE resulted in a significant increase in C turnover, in both the 50–100 and 100–200 mm depths. Carbon turnover during the total incubation period was significantly increased by FACE in the 50–100 mm depth, with a similar trend ($P = 0.170$) occurring at the 100–200 mm depth. These results are consistent with microbial restriction owing to N limitation during the 0–30 day incubation and with increased quantity and quality of C substrate as a result of increased root growth (Table 1) under FACE.

4. Summary

After 3 years of CO_2 exposure under field conditions, it appears that soil C and N cycling patterns may be altered by elevated atmospheric CO_2. However, potential changes in long-term C storage from these alterations remains unclear, as evidence to support contradictory hypotheses can be found in these data. For example, during the 0–30 day incubation period, decreased levels of N mineralization and increased ratios of C/N mineralized indicated that N may be limiting for decomposition under FACE. These data support the hypothesis that decomposition rates in soil under elevated CO_2 would be slower, resulting in increased C storage in soil (Bazzaz, 1990). These data also support the hypothesis of Strain and Cure (1985) that nutrient limitations on a global scale would limit plant response to CO_2 enrichment and thus limit long-term C storage in soil. Likewise, although N limitation did not appear to be a factor during the 30–60 day incubation period, interpretation of these data could lead to contradictory extrapolation to long-term C storage in soil. During this period, microbial respiration was increased whereas C turnover was decreased by FACE in combination with the wet treatment. These data support the hypothesis of Goudriaan and De Ruiter (1983) that microbial preference for easily decomposable C substrates under conditions of elevated CO_2 would result in reduced C turnover. However, on including field water stress, which would probably be present on a global basis, C turnover increased along with soil microbial respiration. These data support the hypothesis that increased microbial activity as a result of increased C input would limit the long-term storage of C in soil (Lamborg et al., 1984). More research is needed on C and N cycling patterns after long-term exposure to elevated CO_2 in various soil–plant systems before interpretation of data can be extrapolated to the long-term C storage question.

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References

Allen, Jr, L.H., 1990. Plant responses to rising carbon dioxide and potential interactions with air pollutants. J. Environ. Qual., 19: 15–34.

Anderson, J.P.E., 1982. Soil respiration. In: A.L. Page, (Editor), Methods of Soil Analysis, Part 2, 2nd edn. Am. Soc. Agron., Madison, WI, pp. 831–871.

Bazzaz, F.A., 1990. The response of natural ecosystems to the rising global CO_2 levels. Annu. Rev. Ecol. Syst., 21: 167–196.

Bolin, B., 1986. How much CO_2 will remain in the atmosphere? In: B. Bolin, B.R. Doos, J. Jager and R.A. Warrick (Editors), The Greenhouse Effect, Climatic Change, and Ecosystems. Wiley, New York, pp. 93–155.

DeLucia, E.H., Sasek, T.W. and Strain, B.R., 1985. Photosynthetic inhibition after long-term exposure to elevated levels of atmospheric carbon dioxide. Photosynth. Res., 7: 175–184.

Goudriaan, J. and de Ruiter, H.E., 1983. Plant growth in response to CO_2 enrichment, at two levels of nitrogen and phosphorus supply. 1. Dry matter, leaf area, and development. Neth. J. Agric. Sci., 31: 157–169.

Hardacre, A.K., Laing, W.A. and Christeller, J.T., 1986. The response of simulated swards of perennial ryegrass and white clover to enriched atmospheric CO_2: interaction with nitrogen and photosynthetic photon flux density. NZ J. Agric. Res., 29: 567–573.

Holland, H.D., 1978. The Chemistry of the Atmosphere and Oceans. Wiley, New York, 350 pp.

Houghton, J.T., Jenkins, G.J. and Ephraums J.J. (Editors), 1990. Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge, 364 pp.

Houghton, R.A., Schlesinger, W.H., Brown, S. and Richards, J.F., 1985. Carbon dioxide exchange between the atmosphere and terrestrial ecosystems. In: J.R. Trabalka (Editor), Atmospheric Carbon Dioxide and the Global Carbon Cycle. DOE/ER-0239, US Department of Energy, Washington, DC, pp. 114–140.

Ingham, E.R., Klein, D.A. and Trlica, M.J., 1985. Responses of microbial components of the rhizosphere to plant management strategies in a semiarid rangeland. Plant Soil, 85: 65–76.

Keeling, C.D., Bacastow, R.B., Carter, A.F., Piper, S.C., Whorf, T.P., Heimann, M., Mook, W.G. and Roeloffzen, H., 1989. A three dimensional model of atmospheric CO_2 transport based on observed winds: observational data and preliminary analysis. Geophys. Monogr. Am. Geophys. Union, 55: 165–235.

Keeney, D.R. and Nelson, D.W., 1982. Nitrogen—inorganic forms. In: A.L. Page (Editor), Methods of Soil Analysis, Part 2, 2nd edn. Am. Soc. Agron., Madison, WI, pp. 643–693.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: an assemblage and analysis of 430 prior observations. Agron. J., 75: 779–788.

Lamborg, M.R., Hardy, W.F. and Paul, E.A., 1984. Microbial effects. In: E.R. Lemon (Editor), CO_2 and Plants: The Response of Plants to Rising Levels of Atmospheric CO_2. Am. Assoc. Adv. Sci. Selected Symp., 2–6 April 1979, Annapolis, MD. Westview Press, Boulder, CO, pp. 131–176.

Leavitt, S.W., Paul, E.A., Kimball, B.A., Hendrey, G.R., Mauney, J.R., Rauschkolb, R., Rogers, H., Lewin, K.F., Nagy, J., Pinter, Jr, P.J. and Johnson, H.B., 1994. Carbon isotope dynamics of free-air CO_2-enriched cotton and soils. Agric. For. Meteorol., 70: 87–101.

Lekkerkerk, L.J.A., van de Geijn, S.C. and van Veen, J.A., 1990. Effects of elevated atmospheric CO_2 levels on the carbon economy of a soil planted with wheat. In: A.F. Bouwman (Editor), Soils and the Greenhouse Effect. Wiley, New York, pp. 423–429.

Lewin, K.F., Hendrey, G.R., Nagy, J. and LaMorte, R.L., 1994. Design and application of a free-air carbon dioxide enrichment facility. Agric For. Meteorol., 70: 15–29.

Mauney, J.R., Fry, K.E. and Guinn, G., 1978. Relationship of photosynthetic rate to growth and fruiting of cotton, soybean, and sunflower. Crop Sci., 18: 259–263.

Mauney, J.R., Kimball, B.A., Pinter, Jr, P.J., LaMorte, R.L., Lewin, K.F., Nagy, J. and Hendrey, G.R., 1994. Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. Agric. For. Meteorol., 70: 49–67.

Merckx, R., Dijkstra, A., den Hartog, A. and van Veen, J.A., 1987. Production of root-derived material and associated microbial growth in soil at different nutrient levels. Biol. Fert. Soils, 5: 126–132.

Nadelhoffer, K.J., Giblin, A.E., Shaver, G.R. and Laundre, J.A., 1991. Effects of temperature and substrate quality on element mineralization in six arctic soils. Ecology, 72: 242–253.

Nelson, D.W. and Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: A.L. Page (Editor), Methods of Soil Analysis, Part 2, 2nd edn. Am. Soc. Agron., Madison, WI, pp. 565–571.

Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1986. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am. J., 51: 1173–1179.

Rogers, H.H., Prior, S.A. and O'Neill, E.G., 1992. Cotton root and rhizosphere responses to free-air CO_2 enrichment. Crit. Rev. Plant Sci., 11: 251–263.

Runion, G.B., Curl, E.A., Rogers, H.H., Backman, P.A., Rodríguez-Kábana, R. and Helms, B.E., 1994. Effects of free-air CO_2 enrichment on microbial populations in the rhizosphere and phyllosphere of cotton. Agric. For. Meteorol., 70: 117–130.

Statistical Analysis Systems Institute Inc., 1982. SAS Users Guide: Statistics. SAS Institute Inc., Cary, NC, pp. 549–640.

Schlesinger, W.H., 1986. Changes in soil carbon storage and associated properties with disturbance and recovery. In: J.R. Trabalka and D.E. Reichle (Editors), The Changing Carbon Cycle: A Global Analysis. Springer, New York, pp. 194–220.

Schlesinger, W.H., 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. Nature, 348: 232–234.

Schlesinger, W.H., 1991. Biogeochemistry: An Analysis of Global Change. Academic Press, New York, 443 pp.

Smil, V., 1985. Carbon Nitrogen Sulfur: Human Interference in Grand Biospheric Cycles. Plenum, New York, 459 pp.

Strain, B.R. and Cure, J.D. (Editors), 1985. Direct effects of increasing carbon dioxide on vegetation. DOE/ER-0238. Office of Energy Research, US Department of Energy, Washington, DC, 286 pp.

Tans, P.P., Fung, I.Y. and Takahashi, T., 1990. Observational constraints on the global atmospheric CO_2 budget. Science, 247: 1431–1438.

Trabalka, J.R. (Editor), 1985. Atmospheric carbon dioxide and the global carbon cycle. DOE/ER-0239. Office of Energy Research, US Department of Energy, Washington, DC, 315 pp.

Van Veen, J.A., Liljeroth, E., Lekkerkerk, L.J.A. and van de Geijn, S.C., 1991. Carbon fluxes in plant–soil systems at elevated atmospheric CO_2 levels. Ecol. Appl., 1: 175–181.

Warneck, P., 1988. Chemistry of the Natural Atmosphere. Academic Press, London, 757 pp.

Wong, S.C., 1979. Elevated atmospheric partial pressure of CO_2 and plant growth. 1. Interactions of nitrogen nutrition and photosynthetic capacity in C_3 and C_4 plants. Oecologia, 44: 68–74.

Wood, C.W. and Edwards, J.H., 1992. Agroecosystem management effects on soil carbon and nitrogen. Agric. Ecosyst. Environ., 39: 123–138.

Wood, C.W., Westfall, D.G., Peterson, G.A. and Burke, I.C., 1990. Impacts of cropping intensity on carbon and nitrogen mineralization under no-till dryland agroecosystems. Agron. J., 82: 1115–1120.