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CROP RESIDUE DECOMPOSITION AS AFFECTED BY GROWTH UNDER ELEVATED ATMOSPHERIC CO_2

H. A. Torbert[1], S. A. Prior[2], H. H. Rogers[2], and G. B. Runion[3]

Increasing atmospheric CO_2 level has led to concerns about process changes in the biosphere. Elevated atmospheric CO_2 concentration has been shown to increase plant biomass, resulting in greater amounts of residue returned to soil. However, the effects on long-term storage of C in soil are highly debated. Changes in both quantity and quality of plant residue, as well as residue management, may alter soil C and N dynamics that will, in turn, affect the ability of soil to store C. Plant residues were collected from an experiment using open top chambers to increase CO_2 levels under field conditions. A soil incubation study was conducted with a Blanton loamy sand (loamy siliceous, thermic, Grossarenic Paleudults) to examine the effect of residue additions to two crop species (soybean, *Glycine max* (L.) Merr. and grain sorghum, *Sorghum bicolor* (L.) Moench), grown at two CO_2 concentrations (ambient and twice ambient), and two incorporation treatments (incorporated or surface placement) on potential C and N mineralization. The difference in biomass inputs between plants grown in ambient and elevated atmospheric CO_2 was also considered. Simulated residue incorporation reduced inorganic N concentration but had no effect on C mineralization. Both inorganic N content and C mineralization were higher with soybean than with grain sorghum. Although changes to both plant residue quality and quantity caused by elevated CO_2 concentration affected C cycling in soil, residue quality may be more important for determining C storage. Nitrogen cycling in soil may be a controlling factor for C storage in terrestrial ecosystems. (Soil Science 1998;163:412–419)

Key words: Carbon dioxide, soil carbon and nitrogen dynamics, *Glycine Max, Sorghum bicolor,* residue decomposition.

THERE is little doubt that population increase, industrial expansion, and deforestation are significant contributions to increases in atmospheric CO_2 levels (Holland 1978; Smil 1985; Warneck 1988), which will likely result in further changes to the global environment. One potential and highly debated implication of global change is the alteration in the dynamics of soil C storage in terrestrial ecosystems. This potential change in soil C storage is important not only because of a possible mitigating effect on rising atmospheric CO_2 but also because of its influence on soil quality. Carbon fixed within the plant enters the soil via plant residues and may reside there for hundreds of years (Parton et al. 1986). Ultimately, the rate and extent of turnover of organic C produced in an elevated CO_2 environment will control C storage in terrestrial ecosystems (Van Veen et al. 1991).

The decomposition of plant residue added to soil is an important component in the turnover of organic C. This decomposition is dependent on several plant, soil, management (e.g., soil tillage), and climatic conditions (Potter et al. 1997). Plant factors controlling decomposition include age, size, chemical composition, and the C:N ratio of the plant residue (Ghidey and

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[1] USDA-ARS, Grassland, Soil and Water Research Laboratory, 808 East Blackland Rd., Temple, TX 76502. Dr. Torbert is corresponding author. E-mail: torbert@brc-sun0.tamu.edu

[2] USDA-ARS National Soil Dynamics Laboratory, Box 3439, Auburn, AL 36831–3439.

[3] School of Forestry, Auburn University, Auburn AL 36849.

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Alberts 1993). Many of these parameters can be affected by the atmospheric CO_2 level (Henning et al. 1996; Torbert et al. 1995).

The fate of residue derived from plants grown under elevated CO_2 has not been resolved. Elevated atmospheric CO_2 has been shown to increase biomass production, which could increase C storage in soil. However, this will depend on the level of C mineralization that occurs during residue decomposition. It has been theorized that the commonly observed increase in plant C:N ratio under elevated CO_2 could lead to slower plant decomposition (Bazzaz 1990), resulting in increased soil C storage. Others have suggested that increased biomass might enhance microbial activity, resulting in a "priming effect" and, thus, no increase in C storage (Lamborg et al. 1984). Alternatively, microbial preference for easily decomposable plant material produced during growth under CO_2-enriched conditions could reduce the turnover of more resistant organic material, thereby resulting in an increase in soil C storage (Goudriaan and de Ruiter 1983; Lekkerkerk et al. 1990).

Soil N dynamics may also be affected by CO_2-induced alterations of plant residue. For example, changes in the composition of litter in a CO_2-rich environment may reduce decomposition rate and limit nutrient cycling in soil (Cotrufo et al. 1994; Couteaux et al. 1991). Even if decomposition rates of plant components (produced under CO_2 enrichment) are not changed, the decomposition products of these plant components may have a considerable impact on soil N dynamics (Torbert et al. 1995).

Research considering the effect of elevated CO_2 on the decomposition of individual plant parts (Henning et al. 1996; Torbert et al. 1995) indicates that increased soil C storage could occur. However, these studies did not consider the impact of increased biomass input to the edaphic system or the potential priming effect. Differences observed between decomposition of different plant parts, such as leaves and stems (Henning et al. 1996), makes it difficult to predict the impact on soil of a mixture of parts normally found in plant residue. Changes in soil C and N cycling attributable to elevated atmospheric CO_2 under field conditions have also been reported previously (Prior et al. 1997b; Wood et al. 1994), but examination of the plant decomposition processes in soil was not possible in these studies. The objective of this study was to determine soil C and N mineralization during decomposition of plant residue grown under atmospheric CO_2 enrichment and, further, to separate changes caused by quality and quantity of biomass additions. Soybean and grain sorghum plant residue samples from plants exposed to two CO_2 levels (ambient and twice ambient) were compared. The effect of plant residue incorporation into soil was also evaluated.

MATERIALS AND METHODS

Plant material for this incubation study was collected from an ongoing elevated atmospheric CO_2 study conducted in an outdoor soil bin at the USDA-ARS National Soil Dynamics Laboratory in Auburn, Alabama. The bin was 2 m deep, 7 m wide, and 76 m long and was uniformly filled with surface soil of a Blanton loamy sand (loamy, siliceous, thermic Grossarenic Paleudult) that had been continuously fallow for more than 25 years (Batchelor 1984). Fertilizer and lime additions were used to maintain soil conditions within a normal range for crop production in these soils. A detailed description of the soil status before and during the study has been reported previously (Reeves et al. 1994).

The ongoing study had a split-plot design, with main plots of two plant species and CO_2 exposure regimes (two) as subplots replicated three times. Soybean and grain sorghum were chosen as test crops to provide legume and non-legume species, respectively, that are widely produced in agroecosystems. The CO_2 exposure regimes were open top field chambers at either ambient or twice ambient atmospheric CO_2 concentrations.

The open top field chambers, 3 m in diameter and 2.4 m in height, were described in detail by Rogers et al. (1983). Average CO_2 concentrations were 357.5 ± 0.1 (SE) and 369.9 ± 0.1 $\mu L L^{-1}$ for ambient chambers and 705.0 ± 0.3 and 731.7 ± 0.3 $\mu L L^{-1}$ for twice ambient in 1992 and 1993, respectively.

Soybean (Stonewall) and grain sorghum (Savannah 5) were planted in 76-cm rows oriented across the width of the soil bin on June 2, 1992, and May 5, 1993. Plants were thinned to a uniform density of 30 plants m^{-2} for soybean and 26 plants m^{-2} for grain sorghum.

To ensure adequate plant growth, fertilizer N was broadcast applied at a rate of 34 kg N ha^{-1} to both the grain sorghum and the soybean shortly after planting. An additional 67 kg N ha^{-1} was applied to grain sorghum 30 days after planting.

Harvest took place on October 1 for grain sorghum and October 5 for soybean in 1993, the second year of the study. Grain sorghum heads and soybean pods were removed from the plants and processed through a plot combine. To approximate a machine harvest, plant stalks were cut into 15-cm lengths using hedge clippers and were spread uniformly over the plots. Soybean pod hulls and grain sorghum chaff were added back to the plots. A sample of this residue material containing all of the component plant parts returned to the field was collected from each plot at the time of redistribution for analysis in the incubation procedures.

Plant residue samples were dried at 55°C (until weight loss was complete) and ground in a Wiley mill to pass a 0.44-mm screen. Total C and N contents of plant samples were determined using a Fison NA1500 CN Analyzer (Fison Instruments, Inc., Beverly, MA). Total dry weight, C, N, and C:N ratio of plant residues were described previously (Prior et al. 1997a), and total dry weights and C:N ratios are given in Table 1. In previous work from this site, Henning et al. (1996) reported plant quality measurements of C, N, C:N ratio, lignin, lignin:N ratio and cellulose of the individual plant components. They found increased lignin concentration for soybean leaf tissue and increased lignin:N ratio in soybean leaf and sorghum stem tissue in response to elevated CO_2.

Potential soil C and N cycling was determined using the methods of Wood et al. (1994). Sieved soil samples of Blanton loamy sand were weighed (25 g dry weight basis) and placed in plastic containers; deionized water was then added to adjust soil water content (soil water content equivalent to -20 kPa at a bulk density of 1.3 Mg m^{-3}). Ground residue of soybean and grain sorghum was either added at a rate of 0.07 g to the soil surface (not incorporated) or incorporated throughout the soil (incorporated). These treatments simulated the impact of having plant residue in intimate contact with soil or having surface contact only.

In addition, incubations were performed with plant material added in proportion to the biomass changes observed under CO_2 enrichment (elevated-PRO) (0.09 g for grain sorghum and 0.13 g for soybean, to 25 g of soil). Samples in the containers were placed in sealed glass jars with 20 mL of water (humidity control) and a 15-mL vial of 1 *M* NaOH (CO_2 trap) and then incubated in the dark at 25°C. Independent samples of each treatment were removed after 3, 7, 14, 30, and 60 days. Carbon dioxide in NaOH traps was determined by titrating excess base with 1 *M* HCl in the presence of $BaCl_2$. Potential C mineralization was the difference between CO_2-C captured in sample traps and in blanks (glass jars containing no soil). Soil inorganic N (NO_3-N and NH_4-N, on a dry wt. basis) was extracted with 2 *M* KCl from the moist soil samples and measured by standard colorimetric procedures using a Technicon Autoanalyzer (Technicon Industrial Systems 1973). Potential N mineralization was the difference between inorganic N contents of samples compared with blanks (soil with no plant residue added). As a result of technical problems during sampling, C mineralization at Day 7 was not considered.

Statistical analysis of data was performed using the ANOVA procedure, and means were separated using contrast statements and least significant differences (LSD) at an established *a priori* of $P \leq 0.10$ level (SAS Institute, Inc. 1982). Three different comparisons of C and N mineralization—including the impact of incorporation and plant species—were made: (i) comparison of differences due to atmospheric CO_2 treatment at the same biomass weight, (ii) comparison of differences due to atmospheric CO_2 treatment at biomass weights proportional to those observed for biomass production, and (iii) comparison of differences due to biomass weights proportional to those observed for production, but no difference in atmospheric CO_2 treatment.

RESULTS

Soil C Mineralization

Soil C mineralization proceeded very rapidly, with the largest portion of the total C mineralized within the first 14 days of the study (Table 2).

TABLE 1

Total dry weight and C:N ratio of crop residue grown under ambient (357 μLL^{-1}) or elevated (750 μLL^{-1}) atmosphere CO_2 concentrations†

Crop	Total dry weight			C:N		
	Ambient	Elevated	Contrast	Ambient	Elevated	Contrast
	Mg ha^{-1}					
Grain sorghum	515	666	<0.01	74.9	87.4	0.01
Soybean	290	517	<0.01	27.3	28.5	0.71

†Values represent means of three replicates.

TABLE 2

The effect of plant species on incubated soil cumulative carbon mineralization†

Crop	Time (days)			
	0–3	0–14	0–30	0–60
	mg CO_2–C kg^{-1} soil			
Soybean	188	531	632	723
Grain Sorghum	170	427	563	646
Blank	134	147	156	255
Contrast				
Sorghum vs. Soybean	0.132	0.001	0.092	0.102

†Values represent means of three replicates, plant additions proportional to production levels.

Because of the decomposing plant material, C mineralization was much greater with plant additions compared to the blank (soil only) throughout the incubation. In general, the level of C mineralization with soybean was higher than with grain sorghum plant residue additions to soil when the additions where made at rates proportional to plant production (Table 2).

Differences in C mineralization were also observed between plant residues grown under different CO_2 concentrations at both the same weight and the proportional weight treatments (Table 3). The ambient CO_2 plant residue additions had higher C mineralization rates compared with elevated CO_2 residue at the same weight on Days 14, 30, and 60 and compared with the elevated-PRO treatment on Day 30. At Days 3 and 14, a significant crop species by CO_2 concentration interaction was observed for soil C mineralization with the proportional weight treatments (Table 4).

At Day 3, no difference was observed in C mineralization of grain sorghum residue additions between CO_2 treatments, but C mineralization was increased for soybean residue additions at the elevated-PRO CO_2 treatment (Table 4). On Day 14, C mineralization with elevated CO_2 residue was lower compared with ambient CO_2 residue at the same weight for both grain sorghum and soybean, but with the soybean elevated-PRO CO_2 treatment, the C mineralization was higher compared with ambient CO_2 (Table 4).

The amount of CO_2-C evolved per gram of residue added to the soil at each sampling date is presented in Table 5. The amount of CO_2-C evolved per g of residue added was significantly higher for the ambient CO_2 residue compared with the elevated CO_2 residue treatment at sampling dates 14, 30, and 60 and significantly higher compared with the elevated-PRO residue treatment at all sampling dates (Table 5).

Carbon mineralization was not significantly affected by simulated soil incorporation. Also, no significant interaction was observed for either incorporation by crop species or incorporation by CO_2 treatment for soil C mineralization at any time during the incubation.

N Mineralization/Immobilization

The inorganic N concentration was generally lower for soils amended with plant residue

TABLE 3

The effect of atmospheric CO_2 concentration during plant growth on incubated soil cumulative carbon mineralization†

CO_2 treatment	Time (days)			
	0–3	0–14	0–30	0–60
	mg CO_2–C kg^{-1} soil			
Ambient	168	473	640	708
Elevated	167	393	505	568
Elevated-PRO	191	485	555	662
Blank	134	147	156	255
Contrast				
Amb. vs. Elv.	NS	0.052	0.007	0.006
Amb. vs. Elv.-PRO	0.071	NS	0.044	NS
Elv. vs. Elv.-PRO	0.0918	0.006	NS	NS

†Values represent means of three replicates.

TABLE 4

The effect of plant species and atmospheric CO_2 concentration during plant growth on cumulative soil carbon mineralization on days 3 and 14 of the incubation[†]

Time (days)	Grain sorghum			Soybean			Blank
	Ambient	Elevated	Elevated-PRO	Ambient	Elevated	Elevated-PRO	
	mg CO_2 Ckg^{-1} soil						
0–3	169	159	171	166	176	220	134
0–14	464	343	390	482	443	580	147

Contrast	*0–3 day*	*0–14 day*
Soybean vs. sorghum	0.132	0.013
Amb. vs. Elv. (sorghum)	NS	0.039
Amb. vs. Elv.-PRO (sorghum)	NS	0.175
Elv. vs. Elv.-PRO (sorghum)	NS	0.1421
Amb. vs. Elv. (soybean)	NS	NS
Amb. vs. Elv.-PRO (soybean)	0.028	0.080
Elv. vs. Elv.-PRO (soybean)	0.021	0.001

[†] Values represent means of three replicates.

compared with the blanks (except for Days 3 and 60 for soybean), indicating that the soils underwent a net N immobilization during incubation (Table 6). A significant crop species effect was observed for N concentration at all sampling times (3, 7, 14, 30, and 60 days). In all cases, inorganic N concentration of the soil amended with grain sorghum residue was lower than for soybean-amended soil.

A significant residue incorporation effect and a significant residue incorporation by crop species interaction was observed at all sampling dates except at Day 60 (Table 6). The simulated residue incorporation treatment reduced the soil inorganic N concentration compared to the not incorporated treatment at Day 3 and 7 for both sorghum and soybean amended soil, and at Day 14 and 30 with the soybean amended soil.

A significant crop species by CO_2 interaction was observed on Days 7 and 14 of the incubation for both the same weight and the proportional weight comparisons. On these two dates, the soil inorganic N content was not affected by the CO_2 treatment with grain sorghum, but it was reduced significantly under both the elevated and the elevated-PRO CO_2 soybean treatment compared with the ambient CO_2 soybean treatment (Table 7).

DISCUSSION

These data indicate that low soil N availability limited microbial decomposition in both grain sorghum and soybean, with net N immobilization conditions persisting throughout most of the 60 day incubation. Only the soybean-amended soils released sufficient N at the 60-day measurement to raise inorganic N concentration above that observed with the blank soil (Table 6). Net N-immobilization was promoted by residue incorporation. When plant residue was incorporated, the residue was in more intimate contact with soil solution N, resulting in even greater immobilization of the soil solution inorganic N (Table 6). The limitations on inorganic N meant that, in general, N availability was controlling residue decomposition processes in the soil. This can be observed with soybean that has higher C mineralization than grain sorghum (Table 2).

As a result of limited inorganic N, the impact of atmospheric CO_2 treatments on inorganic N concentration was significant only at Day 7 and Day 14 measurements. During this period, a significant interaction between plant species and atmospheric CO_2 concentration was observed. With grain sorghum, N immobilization was not

TABLE 5

The effect of atmospheric CO_2 concentration during plant growth on the cumulative mg of CO_2 evolved per g of residue added[†]

CO_2 treatment	Time (days)			
	0–3	0–14	0–30	0–60
	mg CO_2–C g^{-1} residue			
Ambient	138 a	389 a	526 a	581 a
Elevated	137 a	322 b	413 b	428 b
Elevated-PRO	105 b	257 c	300 c	355 b

[†] Values represent means of three replicates. Values within a column followed by the same letter do not differ significantly (0.10 level).

TABLE 6

The effect of plant species and incorporation on incubated soil inorganic nitrogen concentration†

Crop	Time (days)				
	3	7	14	30	60
	mg N kg^{-1} soil				
Sorghum Not Incorporated	3.9	2.0	0.9	0.3	1.6
Sorghum Incorporated	1.0	0.6	0.5	0.3	0.7
Soybean Not Incorporated	20.6	10.1	11.0	17.0	21.9
Soybean Incorporated	15.9	3.5	3.5	9.4	24.0
Blank	12.2	13.5	13.6	15.9	21.3
Contrast					
Not Incorp vs. Incorp	0.002	0.001	0.001	0.026	NS
Sorghum vs. Soybean	0.001	0.001	0.001	0.001	0.001
Not Incorp vs. Incorp (sorghum)	0.059	0.031	NS	NS	NS
Not Incorp vs. Incorp (soybean)	0.004	0.001	0.001	0.003	NS

†Values represent means of three replicates.

different between the CO_2 treatments (Table 7). It is believed that the extremely low soil inorganic N concentration with grain sorghum additions (caused by N immobilization) resulted in no significant difference for either the incorporation treatment effects or the CO_2 treatment effects. With soybeans, although the C mineralization was either not changed or increased significantly with the elevated CO_2 treatments, compared with ambient CO_2 during this period, the N content of the soil solution was reduced significantly with elevated CO_2 treatments (Table 7). This is consistent with results of Torbert et al. (1996), which suggested that nitrate movement below the rooting zone in the field was reduced under elevated CO_2 conditions, especially for soybean. Results reported here corroborate speculations by Torbert et al. (1996) that reductions in nitrate leaching observed in the field could have been caused by a reduction in N released from decomposing plant residue.

Although increased N immobilization was observed with plant residue incorporation, there was no significant effect of simulated incorporation on C mineralization. This does not agree with often observed increases in C efflux from tilled soil in the field (Prior et al. 1997a; Reicosky et al. 1997). Similar incubation methods have been used successfully to examine N dynamics (Smith and Sharpley 1990). However, incorporation treatment in this study was with finely ground plant residue and simulated the impact of having the plant residue either on the soil surface or in intimate contact with the soil, but it did not include most of the dynamics of soil tillage using tillage implements under field conditions. Re-

TABLE 7

The effect of plant species and atmospheric CO_2 concentration during plant growth on incubated soil nitrogen concentration†

Time (days)	Grain Sorghum			Soybean			Blank
	Ambient	Elevated	Elevated-PRO	Ambient	Elevated	Elevated-PRO	
	mg CO_2–Ckg^{-1} soil						
7	1.4	1.4	1.2	7.9	6.5	5.7	13.5
14	0.7	1.0	0.7	9.7	7.2	5.4	13.6

Contrast	*7 day*	*14 day*
Soybean vs. Sorghum	0.001	0.001
Amb. vs. Elv. (sorghum)	NS	NS
Amb. vs. Elv.-PRO (sorghum)	NS	NS
Elv. vs. Elv.-PRO (sorghum)	0.103	NS
Amb. vs. Elv. (soybean)	0.033	0.039
Amb. vs. Elv.-PRO (soybean)	0.003	0.001
Elv. vs. Elv.-PRO (soybean)	NS	0.016

†Values represent means of three replicates.

sults do indicate that N cycling may be more sensitive to residue placement than C mineralization, even under N limiting conditions.

During the first 14 days of the incubation, an interaction was observed between crop species and CO_2 treatment for C mineralization. With grain sorghum, C mineralization was either not changed (Day 3) or reduced (Day 14) with both of the elevated CO_2 and elevated-PRO CO_2 treatments compared with the ambient CO_2 treatment. In the case of the N rich soybean residue, only the elevated-PRO CO_2 treatment resulted in higher C mineralization compared with ambient CO_2 (Table 4). These results are consistent with Prior et al. (1997a) for measured short term CO_2 efflux from the field plots, with an increase in CO_2 efflux from elevated CO_2 soybean plots but a decrease in elevated CO_2 grain sorghum plots compared with ambient plots. In that study, CO_2 efflux measured over an 8-day period was 1.01 and 1.22 mol m^{-2} from soybean plots and 0.92 and 0.88 mol m^{-2} from grain sorghum plots for ambient and elevated atmospheric CO_2 concentrations, respectively (Prior et al. 1997a).

After 14 days, C mineralization with the ambient CO_2 treatment was higher than that of elevated CO_2 (same weight) in both plant species (Table 3). This indicates that decreases in residue quality (attributable to elevated CO_2) during plant growth may slow residue decomposition. This was true in soybean as well as grain sorghum, so that although it is not immediately evident in the short term (first 14 days) or when individual plant parts are examined (Henning et al. 1996), the effect of elevated CO_2 on residue quality may impact decomposition. However, the effect of residue quality (attributable to elevated CO_2) on C mineralization was reduced when the difference between biomass production was included in the comparison (Table 3). But even at the end of 60 days, under ideal conditions for microbial decomposition, there was no significant difference (with means being lower) in the level of C mineralization with the higher levels of biomass additions in the elevated CO_2 treatment.

The differences observed between the elevated CO_2 and the elevated-PRO CO_2 treatment indicate that a priming effect may occur in soil as a result of the increase in biomass additions, as predicted by Lamborg et al. (1984). However, since this increase was not as great as that observed between ambient and elevated CO_2 treatments (Table 3), the impact of residue quality (attributable to CO_2 treatment) may have an overriding impact on the level of residue decomposition. Further, residue decomposition with the elevated CO_2 treatment was the same or less than that observed with the ambient CO_2 after 60 days, regardless of the increased biomass input.

The impact of residue quality on C cycling in soil is also demonstrated from the analysis of CO_2-C evolved per g of residue added to the soil (Table 5). A significant reduction in CO_2-C mineralized per g of residue added was observed with the elevated CO_2 treatment compared with the ambient treatment at all but the first sampling period. When ambient residue was compared with the elevated CO_2 residue added at proportional levels, there was a significant reduction at all sampling dates. While there was an increase in the level of CO_2-C evolved when more residue was added, it was small compared with the increase in residue added.

Although the results from this study examine only the immediate impacts of the decomposition processes in soil on residue grown under elevated atmospheric CO_2, the data indicate that an increase in C storage is likely in soil under elevated atmospheric CO_2. These results agree with work on another soil type from a free-air CO_2 enrichment (FACE) study utilizing cotton (*Gossypium hirsutum* L.) (Wood et al. 1994) and wheat (*Triticum aestivum* L.) (Prior et al. 1997b), which provided evidence for increased soil C storage even though differences between the two species (cotton and wheat) were noted.

This study indicates that the impact of elevated atmospheric CO_2 concentration on plant residue quality may be more important than the impact on plant residue quantity in determining C cycling in soil. Therefore, the potential effect of elevated atmospheric CO_2 concentration on C storage in agroecosystems will be dependent on the crop species grown. Nitrogen cycling within the plant/soil system will likely be the controlling factor for C storage in these systems. The findings of this study demonstrate the importance of further research to develop mitigation strategies for global change based on wise management practices.

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