Dynamics of Carbon Dioxide Evolution From Decomposing Wheat Straw

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ABSTRACT

Increasing concentration of CO, in the atmosphere is a concern because of the potential for global warming. Carbon exchange between soil and the atmosphere has an important role in the global C cycle, but partitioning soil CO, emissions by source (soil organic matter mineralization, crop residue decomposition, root respiration) is difficult. Our objective was to determine the contribution of decomposing wheat straw to CO, emissions from a Swinton silt loan under controlled conditions (constant 20°C). Two types of straw (i.e., fresh straw collected shortly after harvest and standing stubble that had ‘weathered’ in the field for a year) were either incorporated or placed on the surface of soil (contained in polythene-lined, wooden boxes 10 cm deep with area of 1363 cm^2) at a rate equivalent to 2,800 kg ha-‘. One set of soils was watered every two or three days to 90% of field capacity and a second set was allowed to dry (from 90% field capacity) to permanent wilting point before watering. Emissions of CO, were measured every two or three days using a vented chamber connected to a portable CO, analyzer. Within 2 d, incorporation of straw increased CO, flux from 0.3 to about 1.5 μmol CO, $m^{-2} s^{-1}$. Surface straw significantly ($P < 0.05$) increased fluxes, but the effect was small compared with incorporated straw. Straw type had little effect on emissions. Total CO,-C emitted from continuously moist soil in 77 d was 3.3 g box-’ (no straw added), 5.5 g box-’ when straw was placed on soil surface and 9.6 g box-’ when straw was incorporated. In all, 37% of incorporated straw C and 13% of surface straw C was emitted as CO,. Moisture limitation in soil subjected to moist/dry cycles reduced emissions to 34-59% of those observed under continuously moist conditions. Fluxes from soil with incorporated straw were least sensitive to moisture availability. In the absence of straw, CO,-C emitted during the experiment was about equal to the amount by which light fraction C decreased, suggesting that this labile fraction of organic matter was the main source of respired C.

INTRODUCTION

Carbon dioxide concentration in the atmosphere is increasing at a rate of about 0.5% annually. Increases in atmospheric CO, may be responsible for half of the so-called greenhouse effect. Fluxes of CO, between soil and the atmosphere are an important component of the global C cycle. It has been shown that soil, which contains about three times as much C as the atmosphere, has the potential to store additional C (Campbell and Zentner, 1993; Dumanski et al., 1996).

Dumanski et al. (1996) estimate that, if properly managed, agricultural lands could sequester 50-75% of CO, emissions from agriculture in Canada over the next 30 years. To store C in soil, inputs of C in crop residues must exceed fluxes of CO,-C from the soil. Management practices that increase C inputs are well known (e.g., adequate fertilization, reduction of summer fallow) and their adoption is being encouraged (Campbell and Zentner, 1993). Strategies to reduce fluxes from soil have not been well defined, partly because sources of CO, are difficult to quantify. Carbon dioxide is produced through a variety of processes such as biological oxidation of soil organic matter, decomposition of crop residues, and metabolism of plant roots. Information on the relative contributions of these processes is needed to interpret soil CO, flux measurements (Fortin et al., 1996). The objective of this study was to determine the contribution of decomposing wheat straw to CO, emissions from soil under controlled conditions.

MATERIALS AND METHODS

Soil and Straw Collection

A bulk sample of a Swinton silt loam (Brown Chemozem) was taken in November, 1994 from the top 15 cm of a field had been summer fallowed in the preceding growing season. The soil was sieved (< 4 mm) while still field moist (145 g H_2O kg-‘). Visible plant residues were removed by hand.

Two types of wheat straw were used, i.e., ‘fresh’ straw from the 1994 crop and ‘weathered’ straw from the 1993 crop. The weathered straw consisted of standing stubble on plots that had been chemically fallowed in 1994. Both straw types, which were from the same variety (cv. Lancer), were collected in November, 1994 from plots at the Semiarid Prairie Agricultural Research Centre, Swift Current, SK., by cutting stubble 4-5 cm above the soil surface. The straw was air-dried in the laboratory and cut into 2.5 cm lengths using a scissors.

Treatments and Measurement of CO, Fluxes

Subsamples (15 kg) of field-moist soil were placed in wooden boxes (39.5 x 34.5 x 10 cm) lined with black polythene sheets and packed to a bulk density of 1 .O Mg m^{-3}. The boxes were placed in a greenhouse for three weeks to allow the effects of soil disturbance on CO_2 emissions to subside. Distilled water was added (as a fine mist) every 2-3 days to return the soil to field moisture content.

Straw was applied at a rate of 38.2 g per box, equivalent to 2,800 kg straw ha“, which is about the average straw yield in semiarid areas of Saskatchewan (Campbell and Zentner, 1997). Straw treatments consisted of a no-straw check and two straw types, distributed evenly on the surface or mixed uniformly into the soil. For all treatments, soil was removed from the boxes, mixed (either with or without straw), and repacked to the original bulk density. After application of straw, the boxes were transferred to a growth chamber (maintained at 20°C and 60% relative humidity throughout the experiment). The next day, distilled water was applied to all treatments to increase soil moisture content to 220 g H_2O kg-’ (90% of field capacity).

One set of soils was watered every 2-3 days to compensate for evaporative losses (referred to as the continuously moist treatment) and a second set was allowed to dry to about permanent wilting point before addition of water (moist-dry treatment). To minimize damage to soil aggregates due to droplet impact, watering was always done by misting with distilled water from a hand-operated spray can. An aluminum collar (15 cm internal diameter) was inserted to a depth of 4 cm in each soil box to facilitate measurement of CO, emissions by the chamber method (For-tin et al., 1996). The collar remained in place throughout the experiment. Except during watering and measuring, the growth chamber was in darkness. The experimental design was a randomized complete block with three replicates.

Emissions of CO, were measured using a portable infrared analyzer (LiCor Model LI-6000, LICOR Inc., Lincoln, Nebraska) to determine accumulation of CO_2 in a vented chamber. The chamber, which was attached to the collar using quick-fit clamps (a rubber gasket was placed between the collar and the chamber to provide an air-tight seal), enclosed an area of 177 cm^2 and had a volume of 2 L. Fluxes of CO, [expressed as µmol CO, m^{-2} s^{-1} (1 µmol CO_2 m^{-2} s^{-1} ~ 10 kg C ha^{-1} day-‘) were calculated from the rate of increase in CO, concentration in the chamber during a 200 S deployment period. Accumulation of CO, in the chamber was linear over 200 s. Measurements of CO, emission were usually made every two or three days. Total CO, production during the experiment was calculated by linear interpolation of the mean fluxes and integration over time.

Analysis of Soil and Straw

At the end of the experiment, straw was separated from the soil by sieving (< 4mm). The recovered straw was gently rinsed in distilled to remove adhering soil, dried at 60°C and weighed. Original and recovered straw were analyzed to determine cellulose, hemicellulose and lignin. Total N and C were measured using an automated elemental analyzer (Carlo Erba™, Milan, Italy). Samples of air dry soil were analyzed for light fraction (LF) organic matter as described by Janzen et al. (1992). The LF was separated by floatation on a dense liquid (NaI solution with specific gravity of 1.7) and analyzed for C using a Carlo Erba elemental analyzer.

RESULTS AND DISCUSSION

Fluxes of CO,

Carbon dioxide emissions from soil responded rapidly to straw incorporation (Fig. 1). The first measurements (on day 2) showed emissions from straw-incorporated soil to be three to four times those found in the absence of straw. Surface-applied straw significantly ($P < 0.05$) increased CO_2 fluxes, but its effect was small compared with that of incorporated straw. Straw type had little effect on CO, emissions, presumably because the fresh and weathered straw had similar C:N ratio (127 and 132) and lignin content (78 and 83 g kg-‘). Those are the major composition factors determining the rate of crop residue decomposition (Harper and Lynch, 198 1; Virgil et al., 199 1; Douglas and Rickman, 1992).

When moisture was not limiting (continuously moist soil), fluxes of CO, from straw-incorporated soil were highest (1.5-2 µmol CO, m^{-2} s^{-1}) in the first few days of the experiment (Fig. 1). Emissions decreased with time to a minimum of about 0.5 µmol m^{-2} s^{-1} (- day 50). The highest fluxes from the straw-incorporated treatments are comparable to those reported for fallow plots under favorable moisture and temperature at Lethbridge, Alberta (Ellert et al., 1994). Under continuously moist conditions, fluxes from soil with surface-applied straw and from the check treatment remained relatively constant over time (Fig. 1).

As the soil dried (moist-dry treatment), fluxes decreased to <0.25 µmol CO, m^{-2} s^{-1} at moisture content of about 100 g kg^{-1} (permanent wilting point of Swinton silt loam). Re-wetting the soil caused a flush of second flush of CO, production. Within 10 min of watering, the flux from straw-covered soil had increased to about 2 µmol CO, m^{-2} s^{-1}, confirming that soil organisms can survive drought conditions and become active within minutes of soil wetting.

Total CO,-C evolved in 77 d ranged from 1.3 to 10.2 g box^{-1}, depending on whether straw was applied, placement method and moisture availability (Table 1). It appears that decomposing straw may be more important than soil organic matter as a source of CO, emissions from crop land.

Table 1. Total amount of CO_2-C evolved in 77 days as influenced by straw addition, placement method and moisture regime.

Moisture regime	No straw	Incorporated straw		Surface straw	
		Fresh	Weathered	Fresh	Weathered
		g CO_2-C box^{-1}			
Continuously Moist	3.3	9.0	10.2	5.3	5.6
Moist/Dry	1.3	5.3	5.6	2.0	1.9

The proportion of straw-C evolved as CO, in 77 d (estimated by subtracting C evolved from no straw treatment from that produced by straw-treated soil) was 37% (average of two straw types) under conditions best suited to decomposition (straw incorporated into continuously moist soil). Even though moisture was a limiting factor, 24% of incorporated straw C was emitted as CO, in the moist/dry treatment. Comparison of amounts of C evolved from incorporated straw with those produced in the absence of straw (Table 1) suggests that decomposition of straw was less sensitive to moisture than was soil organic matter mineralization. A total of 13% and 4% of surface-applied straw was evolved as CO, in continuously moist and moist-dry soil, respectively. Emissions from continuously moist soil with surface straw may have been underestimated because measurements were made one day after watering. Monitoring showed that emissions from that treatment peaked within 1 h of watering, and then declined as the straw dried. The contribution of surface straw to CO, output from the soil system may be especially important where there are frequent rains. Inserting measuring chambers into straw-covered soil can be difficult, but removal of straw before chamber deployment is not recommended as it could result in underestimation of CO, fluxes.

Our data were reasonably consistent with the Douglas-Rickman model for straw decomposition (Douglas and Rickman, 1992). That model estimates decomposition of straw based on air temperature (degree days), soil moisture, and initial N content of the straw from the equation:

$$\text{In}(Rs/Is) = k\, fN\, fW\ \text{CDD} \qquad [1]$$

where In(Rs/Is) is the natural logarithm of the ratio of straw remaining to the initial amount of straw, ***k*** is a general decomposition coefficient, *f*N is a coefftcient that is dependent on the N content of the straw, CDD is cumulative degree days (calculated by summing daily degree days from the date straw was placed in contact with the soil), and *f*W is a coefftcient that ranges from 0.2 to 1, depending on soil moisture availability. For straw buried in soil with optimum moisture for decomposition, *f*W is assigned a value of 1 (Douglas and Rickman, 1992). In the case of straw incorporated into continuously moist soil (*f*W = 1), Eq. [1] slightly underestimated the amount of straw C remaining in the soil during the first 45 d of the experiment, and slightly overestimated it thereafter (Fig. 2). With *f*W equal to 0.3 for straw placed on surface of moist soil (Douglas and Rickman, 1992), Eq.

[I] again approximated the amount straw C remaining as a function of time (Fig. 2). These preliminary results suggest that simple straw decomposition models could be useful in estimating annual or seasonal emissions of CO, from decomposing straw.

Changes in Straw During Decomposition

Carbon in straw recovered from the soil following the experiment was inversely related to amounts evolved as CO,. Cellulose and hemicellulose were the main straw components used by decomposing microorganisms (Table 2). Only about 10% of incorporated straw cellulose and hemicellulose was recovered from continuously moist soil. Recovery of cellulose and hemicellulose was similar, indicating that these constituents were equally utilized by soil microorganisms. This is consistent with Harper and Lynch (198 1) who reported that the decomposition rate constants of cellulose and hemicellulose differ little. Even though dryness limited microbial activity in the moist/dry treatment, only about one third of straw cellulose and hemicellulose was recovered, suggesting that those components are decomposed at relatively low moisture contents. Recovery of lignin, the straw component that is most resistant to decomposition (Harper and Lynch, 198 1), was close to **100%** except when straw was incorporated into continuously moist soil, when only 52-54% was recovered (Table 2).

Table 2. Percentage of original components of straw remaining after 77 day decomposition period as influenced by straw placement method, moisture regime, and straw type.

Placement and moisture	Cellulose	Hemicellulose	Lignin	N
	----------	---------- %	----------	----------
	Fresh straw			
Surface/Continuously Moist	70.6	67.8	88.1	121
Incorporated/Continuously Moist	11.6	8.7	52.3	112
Surface/Dry-Moist	88.4	87.7	83.8	111
Incorporated/Dry-Moist	32.7	33.9	88.9	124
	Weathered straw			
Surface/Continuously Moist	72.6	68.4	94.3	130
Incorporated/Continuously Moist	10.4	11.0	54.3	134
Surface/Dry-Moist	90.0	81.2	110.0	134
Incorporated/Dry-Moist	33.4	36.3	94.3	150

Changes in straw during decomposition included increases in N (Table 2) and decreases in the C:N ratio. When straw C:N ratio was plotted against the percentage of straw recovered from the soil, a curvilinear relationship was apparent (Fig. 3). An exponential function described the relationship between straw recovery and the C:N ratio (Fig. 3). Extrapolating this relationship to zero straw recovery suggested that C:N of decomposing straw could decrease to about 15. The relationship shown in Fig. 3 implies that, when its C:N ratio approaches 15, straw is degraded to the extent that recovery by sieving is minimal. At that point, the decomposing material would meet the operational definition of LF organic matter (i.e., organic material that passes through a sieve and is isolated by density separation).

Light Fraction Organic Matter as a Source of CO,

Soil to which straw was applied tended to be higher in LF-C than untreated soil (Table 3), but the difference was not significant ($P < 0.05$). Light fraction C was higher (significant at $P = 0.02$) in soil subjected to moist/dry cycles than in continuously moist soil, presumably because of greater utilization of LF by microorganism under favourable moisture. Our results suggest that, in the absence of applied straw, LF may have been the major source of CO,-C. A comparison of LF-C in soil before and after the experiment, shows that it decreased from 1.47 to 1.20 g kg^{-1} (0.27 g kg-‘) in continuously moist soil and by 0.17 g kg-’ under moist/dry conditions. These decreases, which amount to 3.5 and 2.2 g C box“ under continuously moist and moist/dry conditions, respectively, compare well with CO,-C evolution in the absence of straw (i.e., 3.3 and 1.3 g box^{-1}; Table 1).

Table 3. Light fraction C in soil at the end of experiment as influenced by straw addition, placement method, and moisture regime.

Moisture regime	No straw	Incorporated straw		Surface straw	
		Fresh	Weathered	Fresh	Weathered
	---------------------------------- $g\ kg^{-1}$ ----------------------------------				
Continuously moist	1.20	1.21	1.36	1.31	1.22
Moist-Dry	1.30	1.57	1.31	1.36	1.42

Light fraction C in the soil at commencement of the experiment was 1.47 g kg-‘.

While LF may be a good predictor of CO, production (C mineralization) under laboratory conditions where crop residues are removed by sieving the soil prior to incubation (Janzen et al., 1992; Biederbeck et al., 1994), in the field, the contribution of LF to CO, emissions may be relatively small compared with that of decomposing residues.

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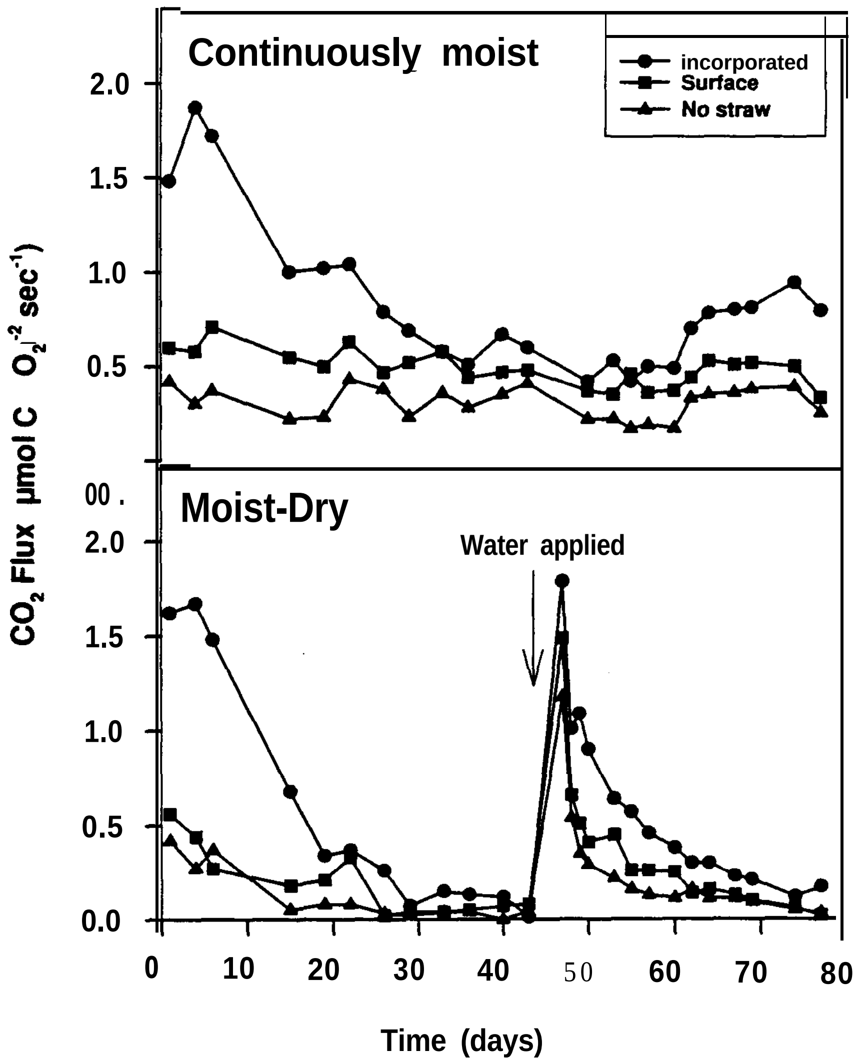

Fig. 1. Fluxes of CO, from soil as influenced by straw addition, placement method, and moisture regime.

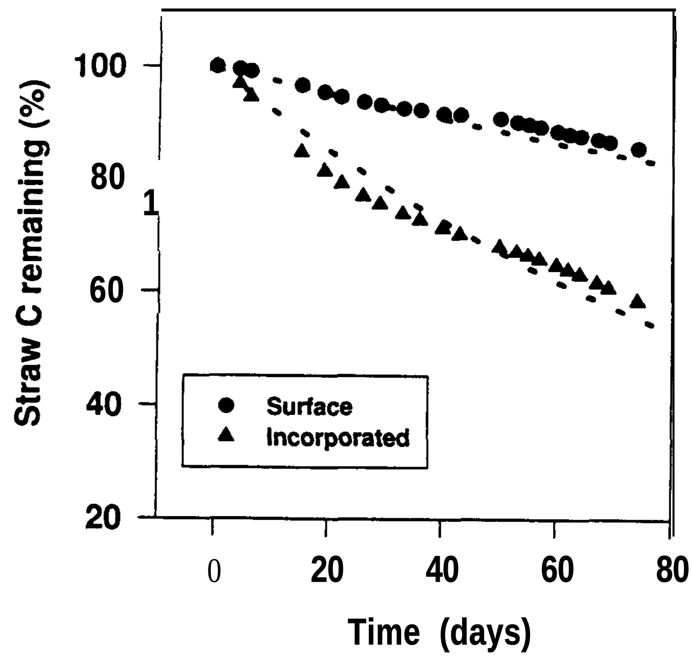

Fig. 2. Straw C remaining in continuously moist soil as a function of time. The broken lines represent predictions of the Douglas-Rickman model.

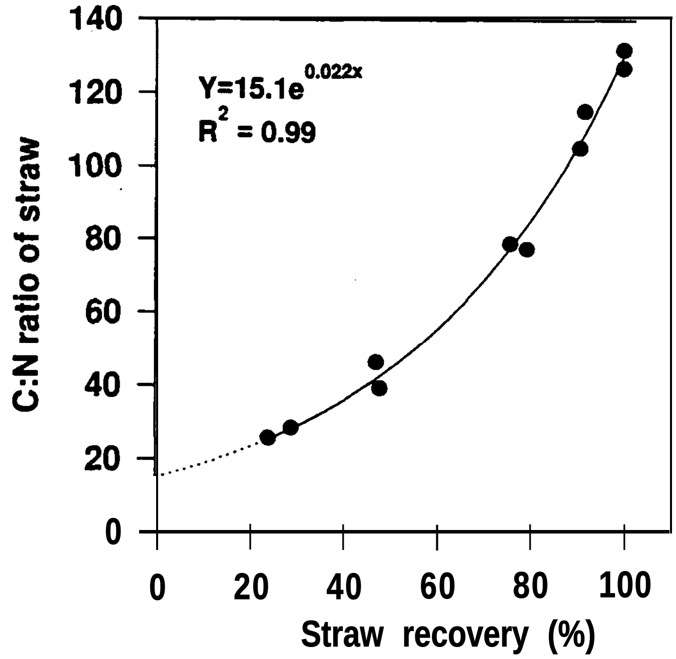

Fig. 3. C:N ratio of decomposing straw as a function of the percentage of applied straw recovered from the soil at termination of the experiment.