

Does Chemical Composition and Plant Part Affect Decomposition Rate?

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Abstract:

Understanding decomposition of plant residue is vital to understanding C and N cycling, both in terms of plant nutrient needs and global climatic change. Roots typically constitute less than half the total plant biomass but literature suggests they contribute 1.4 to 1.8 times as much C to the soil as above ground plant biomass. This study addresses the related issues of plant composition, residue decomposition, and C and N cycling. The first objective was to compare the biochemical composition of roots, both among species and with leaves and stems. The second objective was to evaluate the decomposition rates of roots, leaves and stems among species and relates to biochemical composition and to C and N mineralization rates. Plant materials from C-3 (alfalfa, cuphea and soybean) and C-4 species (corn and switchgrass) were collected at physiological maturity. Structural and nonstructural components from roots, stems and leaves were measured. Decomposition of plant material in soil was monitored as evolved CO₂ at 25° C and 60% water-filled pore space. Chemical composition and decomposition varied among species and plant organs. The results of these incubation studies indicate that it may be easier to predict decomposition of the active C fraction based on the composition but not the decomposition of the passive C fraction.

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Introduction:

The concentration of CO₂ and other greenhouse gases in the earth's atmosphere has increased significantly since the advent of the industrial age (IPCC, 1996). Greenhouse gases are those that reduce the Earth's ability to lose energy to space. Gases that contribute to the greenhouse effect include water vapor, carbon dioxide, ozone, methane and nitrous oxide. Carbon dioxide, CH₄, and N₂O are the major contributors to positive increases in radiative forces (IPCC, 1996). A positive radiative force indicates an increase in the level of energy remaining on the Earth (IPCC, 1996).

There are two general approaches to reducing atmospheric CO₂ concentrations, or to limiting its increase. One is to reduce the rate of C emissions and the second is to recapture atmospheric C and store it in the soil. Agricultural practices have the potential to sequester more C in the soil than farming emits through land use and fossil fuel combustion (Lal et al., 1998). There are three methods that can be utilized by agriculture to mitigate CO₂ emissions; 1) reduce agriculturally related emissions; 2) increase sequestration of C in soils; and 3) production of biofuels to reduce use of fossil fuels (Cole et al., 1997). This research focuses on mitigating CO₂ emissions by increasing C sequestration in soils.

The input of plant organic matter into the soil must exceed the rate of decomposition if there is to be net increase in soil organic matter (SOM). Photosynthetic plants are the primary source of SOM (Hedges and Mann, 1979) and the rate of C input will depend on land use management (cropping system, tillage practice). The rate of decomposition is

dependent on residue, microfaunal and soil factors (Parr and Papendick, 1978). Residue factors include chemical composition, C: N ratio, lignin content and composition, and size of residue particles. Residue C:N can be correlated inversely with the rate of breakdown (Green et al., 1995) but other reports indicate no relationship between residue C:N and rate of decomposition (Franck et al., 1997; Gorissen and Cotrufo, 2000). Important attributes of the soil environment include water potential, temperature, pH, oxygen supply and nutrient availability. The soil environment affects the population dynamics (diversity and mass) of microbes.

The mechanism of increasing C storage or SOM in the soil may be species and tissue dependent, as C:N, lignin, tannin, phenolic and polysaccharide concentration differ among species and tissues. Lignin contents and compositions vary among plant species (Campbell and Sederoff, 1996; Galletti et al., 1997; Ralph and Hatfield, 1991; Sewalt et al., 1997; Van Soest et al., 1991); crops with high phenolic or lignin content may provide a stable source of soil C. The interaction of various plant tissue components and their susceptibility to microbial degradation needs to be understood before crop rotations and cover crops can be used effectively to increase soil C (Stahl and Klug, 1996).

Only a small portion of the plant residue added to soil contributes to stable soil organic matter. The majority is returned to the atmosphere as CO₂ within about 2 years (Buyanovsky and Wagner, 1997). The contribution of root-derived C to soil organic matter was 1.5 times that of stalks and leaves of corn, even though roots represented less than 0.5 of the total biomass (Balesdent and Balabane, 1996). Therefore, it is important to include root material and the chemical composition in studies of soil organic matter formation.

The readily decomposable fraction is composed of simple sugars, soluble proteins, hemicellulose and cellulose and resistant fraction contains lignin (Buyanovsky and Wagner, 1997). The labile pool had a half-life of only one to two weeks (Buyanovsky and Wagner, 1997). The resistant fraction of organic carbon (cellulose and lignin) had a half-life of 69 days from soybean (*Glycine max* (L.) merr.), 301 days from corn (*Zea mays* L.) and 433 days from wheat (*Triticum aestivum* L.; Buyanovsky and Wagner, 1997). Soybean had nearly twice as much soluble components compared to corn and wheat, but less hemicellulose. Wheat had 141 g kg⁻¹ dry wt, soybean 119 k kg⁻¹ and corn only 56 g kg⁻¹ of lignin. In this study, ground leaves, stems and roots of field-grown alfalfa, corn, cuphea, soybean and switchgrass were incubated in Barnes soil and CO₂ evolution was measured over 218 days. The plant tissue was also analyzed for biochemical constituents. It was hypothesized that the rate of decomposition would vary by plant species and by tissue type dependent upon such factors as C:N ratio, lignin concentration and/or the concentration of other biochemical constituents. The goal of this research is to enhance our understanding of the relationships among biochemical constituents and the subsequent decomposition.

Material and Methods:

Five species were selected for this experiment-alfalfa (*Medicago sativa* L.), corn, cuphea (*Cuphea viscosissima* X *Cuphea lanceolata*), soybean and switchgrass (*Panicum virgatum* L.). Cuphea is a possible alternative crop for the northern Corn Belt that produces seeds high in medium chain fatty acids (Graham, 1989). Switchgrass and corn

use the C-4 photosynthetic pathway, while alfalfa, cuphea and soybean use the C-3 pathway.

At maturity, plant material was sampled from four replicated of field. Alfalfa and switchgrass were collected during their second growing season. Aboveground material was separated into leaves and stems. The roots were collected from the surface 15-cm, and hand-washed from the soil. Both aboveground and belowground materials were dried at 45° C, stored at -80° C, and ground to pass through a 2mm sieve.

Composition analysis:

The composition of plant material was determined using a sequential extraction of 0.5 g plant material for soluble sugars, starch, hemicellulose, cellulose and acid-soluble and acid-insoluble lignin (Martens and Loeffelmann, 2002; NREL, 1995; NREL, 1996a; NREL, 1996b; Tarpley et al., 1993). Soluble sugars, starch, hemicellulose and cellulose were determined by HPLC. Standards were included and concentrations adjusted to reflect recovery rates. Acid-soluble lignin concentration was determined spectrophotometrically (NREL, 1996b) and acid-insoluble lignin was determined by proximate method (NREL, 1995). The total C and N of the plant material were determined with a LECO CN-2000 (LECO Corporation, St. Joseph, MI).

Decomposition conditions:

Barnes soil was used for all incubations. The soil was collected from the surface 15 cm, air-dried and passed through a 2 mm sieve. About 0.2 g dried and ground plant material was mixed thoroughly with 50-g soil in a 230-mL bottle. Unamended soil was

used as a negative control. The experiment was initiated with the addition of water to achieve about 60% water-filled pore space (WFPS). Soil and residue mixtures were incubated in the dark for 218 days at constant temperature (25° C) with 49% humidity. Water was added as necessary to maintain the desired moisture content.

Decomposition was monitored by measuring CO₂ evolution. Four replicates were initiated on consecutive days to allow daily sampling for 21 days after initiation. Subsequently, gas samples were taken on days 24, 31, 43, 64, 92, 120, 148, 183, and 218. During the initial week of sampling, the jars were capped between 3 and 6 hours prior to taking a gas sample. The CO₂ accumulation time was increased to about 48 hours by 64 days after initiation as the flux rate had decreased. The accumulation time was recorded and used to calculate CO₂ flux. After the prescribed accumulation time, a 2.5 mL gas sample was removed from the jar using a gas-tight syringe and 2 mL of the gas was injected into an evacuated 1.8 mL amber sample vial. Duplicate 50- μ L gas samples were injected within 8 hours of sample collection into Varian gas chromatograph equipped with a thermal conductivity detector.

Data was analyzed using analysis of variance, step-wise regression analysis and non-linear regression.

Results and Discussion:

The biochemical composition among species and organs is summarized in Tables 1 and 2. There was a species by organ interaction for all components included in this study. As would be expected for a perennial root crop harvested in the fall, alfalfa had a large amount of starch in the roots, compared to its leaves and stems. This was not seen

in other plant species, even though switchgrass is also a perennial species. Corn stems had a large amount of soluble sugars in their stems compared to other species. For several species, roots had more total lignin (sum of acid-insoluble and acid-soluble) compared to aboveground organs, while alfalfa and corn stem had a larger concentration of lignin compared to roots. The concentration of lignin in alfalfa roots would be expected to increase as the plant ages; these plants were collected during their second growing season. Large acid-insoluble ash values are indicative of soil contamination and were seen in corn roots, corn leaves and cuphea leaves. Cuphea has numerous glandular hairs and corn leaves are also hirsute making it easy for soil particles to cling to their leaves.

The net C evolved (equation 1) assumes that the C evolved from unamended soil or control is representative of the C evolving from the soil after the addition of residue. This assumption neglects any potential priming effects (Kuzyakov et al., 2000).

$$netC_{evolved} = (C_{amended} - C_{control}) \quad \text{Equation 1}$$

The percent C remaining (equation 2) was calculated based on the net C evolved from the amended soil treatment.

$$\%C_{remaining} = (C_{initial} - C_{evolved}) / C_{initial} \times 100 \quad \text{Equation 2.}$$

Decomposition can be described biologically and mathematically using an exponential function (Wieder and Lang, 1982). We used a two-component model assuming a rapidly decomposing or active fraction (C_a) and a slowly decomposing fraction ($C_p = (100 - C_a)$) equation 3 (Figure 1).

$$C_t = C_a \times e^{(-k_a \times t)} + (100 - C_a) \times e^{(-k_p \times t)} \quad \text{Equation 3.}$$

The percent C remaining at time (t) is C_t , C_a is the percent C in the active fraction, k_a is the decomposition rate for the active component, $(100 - C_a)$ is the percent C in the passive

fraction and k_p is the decomposition rate of the passive component. The half-life for each fraction is calculated with equation 4. The half-lives varied among species and organs.

$$\text{Half life} = t_{1/2} = \frac{0.693}{k_i} \quad \text{Equation 4.}$$

The half-lives of the active components ranges from a little less than four days to over 20 days (Table 3). Half-lives of sugars, hemicellulose, cellulose and lignin are 0.6, 6.7, 14.0 and 364.5 days, respectively (Hagin and Amberger, 1974), cited in (Kumar and Goh, 2000). Slower rates of decomposition for hemicellulose of 21 to 26 days and for cellulose of about 100 to 150 days were reported by (Eiland et al., 2001). The half-life of heterogeneous mixtures should reflect the decomposition of the components. The observed half-lives are intermediate among sugars and more recalcitrant components (e.g. hemicellulose, cellulose). This is consistent with Buyanovsky and Wagner (1997) who found the half-life of the active fraction to be on the order of one to two weeks.

The half-life of the passive fraction (Table 3) was greater than those reported for corn, soybean and wheat by Buyanovsky and Wagner (1997). The roots did not necessarily have longer passive half-lives compared to aboveground organs. For cuphea and switchgrass, there was little difference in half-lives for the passive component among their respective organ. For soybean, stems had longer half-lives compare to roots or leaves. The half-life of alfalfa and corn, root half-lives were nearly twice those of their corresponding leaves or stems.

The calculated half-life of the active fraction remained constant over the duration of the incubation regardless if it was calculated after 120, 148, 183 or 218 days of incubation. However, the half-life of the passive component increased with increased incubation time. For example, half-lives for the first 120 days ranged from 350 to 1000

days (not shown), which is similar to the range reported by Buyanovsky (1997). However, by 218 days, the half-lives ranges from 560 to > 2200 days (Table 3). Crop residue is a complex, heterogeneous system, and the changing passive fraction half-life may suggest that a two-component model is insufficient to describe long-term mineralization studies. Another possibility would be residue-soil interaction, which are slowing decomposition.

The amount of C in the active pool (C_a) was correlated positively to the measured starch concentration and C:N ratio and negatively correlated to acid-insoluble lignin (Table 4). The half-life of k_a was correlated negatively with starch, but correlated positively with cellulose, hemicellulose, acid-insoluble lignin, total lignin, C:N and lignin:N. The half-life of the passive fractions was not correlated at $p < 0.05$ with any of the components, but was positively correlated with lignin:N at $p = 0.06$. The results of these incubation studies indicate that it may be easier to predict decomposition of the active C fraction based on the composition but not the decomposition of the passive fraction. Of the parameters measured, lignin:N may have some value but there must be components that have not yet been identified, which are the controlling factor determining k_p . Alternatively, it may be that using a two-component model may be too crude and better predictions could be obtained by a model with more components or perhaps we still need to identify the controlling components.

The approach used in this experiment allows comparison of how biochemical composition impacts subsequent decomposition. Uniformly grinding the soil eliminated the confounding issue of particle size, which would be found *in situ*.

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Table 1. Mean concentration of nonstructural components, n=4.

Species	Organ	Sucrose	Glucose	Fructose	Starch
		-----mg g ⁻¹ plant material-----			
Alfalfa	Leaves	12.8	5.60	4.69	48.7
	Stems	24.4	14.7	9.62	6.50
	Roots	45.2	0.66	0.14	114
Soybean	Leaves	6.69	7.28	8.44	9.73
	Stems	6.00	15.6	14.5	3.71
	Roots	2.65	4.45	6.02	1.01
Cuphea	Leaves	2.40	14.0	11.4	18.7
	Stems	3.13	8.13	6.29	1.63
	Roots	0.97	10.3	4.09	2.18
Corn	Leaves	19.0	6.21	6.64	2.11
	Stems	83.8	22.5	24.0	1.48
	Roots	7.52	6.52	6.02	0.53
Switch-grass	Leaves	28.7	2.51	0.58	4.08
	Stems	28.6	14.3	7.45	8.77
	Roots	13.6	7.60	8.76	4.08
LSD _(0.05)		10.0	4.33	4.38	17.9
Crop (C)		****	**	****	****
Organ (O)		****	****	****	****
C x O		****	****	****	****

*, **, ***, **** Significant at 0.05, 0.01, 0.001 and 0.0001 probability levels, respectively.

Table 2. Mean concentration C, N and structural components, n=4.

Species	Organ	C	N	Hemicellulose	Cellulose	A.I. [†] Lignin	A.S. [‡] Lignin	A.I. Ash
		-----mg g ⁻¹ plant material-----						
Alfalfa	Leaves	454	44.0	177	133	55.3	9.54	0.63
	Stems	448	21.2	200	415	117	6.41	2.75
	Roots	433	24.0	239	421	89.9	4.89	10.2
Soybean	Leaves	439	15.8	245	207	107	6.68	2.13
	Stems	468	4.36	289	526	168	4.78	1.44
	Roots	467	7.48	308	586	207	4.97	6.82
Cuphea	Leaves	384	26.3	141	55	108	16.8	93.4
	Stems	435	9.30	230	519	157	6.91	26.2
	Roots	432	13.6	261	309	179	10.4	12.3
Corn	Leaves	416	13.6	461	340	91.4	6.31	76.8
	Stems	458	5.86	375	457	108	5.69	5.97
	Roots	343	9.09	281	342	102	6.55	158
Switch-grass	Leaves	445	12.6	498	418	89.1	6.55	29.2
	Stems	452	4.05	646	517	123	4.36	12.3
	Roots	465	7.09	549	334	161	4.46	11.0
LSD _(0.05)		15.6	2.64	71	90	22	2.79	8.07
Crop (C)		****	****	****	****	****	****	****
Organ (O)		****	****	*	****	****	****	****
C x O		****	****	*	****	**	***	****

*, **, ***, **** Significant at 0.05, 0.01, 0.001 and 0.0001 probability levels, respectively.

[†] A.I., acid insoluble;; [‡] A.S. Acid soluble

Table 3. Coefficients of decomposition from a double exponential function and estimated half-lives for the active and passive-C components

$$C_t = C_a \times e^{(-k_a \times t)} + (100 - C_a) \times e^{(-k_p \times t)}$$

t = time (days)
 C_t = % total residue-C remaining at time t
 C_a = % rapidly (active) mineralizing-C
 k_a = decomposition rate of actively mineralizing-C
 k_p = decomposition rate of slowly mineralizing (passive)-C
 $t_{1/2a} = 0.693/k_a$, half-life of active pool in days
 $t_{1/2p} = 0.693/k_p$, half-life of passive pool in days

Species	Organ	Active fraction			Passive fraction	
		C_a %	k_a %C d ⁻¹ x10 ⁻²	Half-life d	k_p %C d ⁻¹ x10 ⁻⁴	Half-life d
Alfalfa	Leaves	33.4	21.2	3.3	10.4	665
	Stems	25.4	14.4	4.9	12.3	563
	Roots	26.3	16.4	4.2	6.8	1020
Soybean	Leaves	20.7	11.4	6.1	7.5	924
	Stems	30.1	3.4	20.4	4.3	1620
	Roots	24.5	3.5	19.6	4.9	1410
Cuphea	Leaves	21.9	11.5	6.0	6.1	1130
	Stems	26.7	5.3	13.2	6.2	1120
	Roots	20.6	6.4	10.9	6.5	1070
Corn	Leaves	24.2	10.4	6.7	6.4	1080
	Stems	29.1	6.4	10.8	5.3	1310
	Roots	18.6	4.4	15.8	3.1	2270
Switchgrass	Leaves	28.9	8.1	8.5	7.5	921
	Stems	29.7	6.3	11.1	6.4	1090
	Roots	23.6	3.6	19.4	7.2	962

Table 4. Pearson correlation coefficients.

Independent variable	C _a		Half-life active		Half-life passive	
	Coef	p	Coef	p	Coef	p
Soluble sugars	0.05	NS	0.28	NS	-0.08	NS
Starch	0.57	**	-0.70	***	-0.34	0.14
Hemicellulose	0.16	NS	0.55	*	-0.09	NS
Cellulose	0.12	NS	0.51	*	-0.09	NS
AI lignin	-0.54	**	0.53	*	0.14	NS
AS lignin	-0.17	NS	-0.10	NS	0.19	NS
Total lignin	-0.13	NS	0.64	****	0.15	NS
C:N	0.31	*	0.61	****	0.19	NS
Lignin:N	0.23	0.09	0.76	****	0.25	0.06
Ash	-0.34	0.14	0.28	NS	0.32	NS

*, **, ***, **** Significant at 0.05, 0.01, 0.001 and 0.0001 probability levels, respectively.

Figure 1. The net C remaining from decomposing roots, leaves or stems. The coefficients for decomposition for the predicted lines are summarized in Table 3.

% C remaining = (Initial C added – net C evolved)/initial C added x 100

Net C evolved = C evolved from amended soil - C evolved from control

$$C_t = C_a \times e^{(-k_a \times t)} + (100 - C_a) \times e^{(-k_p \times t)}$$

