Maize and Soybean Litter-Carbon Pool Dynamics in Three No-Till Systems

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After harvest, the litter-C pool contributes 20 to 23% of the total C present in maize (*Zea mays* L.)-based agricultural ecosystems. Therefore, understanding litter-C pool dynamics is important in determining the overall C dynamics of the system and its potential to sequester C. We examined litter-C production and in situ decomposition of maize and soybean [*Glycine max* (L.) Merr.] litter using four annual litter cohorts (2001–2004) in three no-till management regimes: irrigated continuous maize, irrigated maize–soybean rotation, and rainfed maize–soybean rotation. Litter inputs, i.e., litter-C production, was 20 to 30% higher in irrigated fields than the rainfed field, and maize produced approximately twice as much litter C as soybean. Litter losses, i.e., decomposition, were highly variable, but overall, after 3 yr of decomposition, only 20% litter C remained on average. We fit decomposition models to our data to predict litter-C accretion after 10 yr of management. While management and annual variation were important in fitting the model, tissue type increased model fit most, suggesting a strong role of litter physical structure in decomposition. The predicted 10-yr standing litter pool was 15 and 35% higher in the irrigated maize field than the irrigated or rainfed maize–soybean rotations, respectively. Our data clearly show that the litter-C pool is highly dynamic, with as much as a 60% increase within 1 yr. Thus, short-term C sequestration estimates in agricultural ecosystems largely reflect litter-C pool changes, which are primarily driven by litter inputs and not decomposition differences.

Abbreviations: IMZ, intensive management zone.

In agroecosystems, as in most terrestrial ecosystems, the C balance at the Earth's surface is the difference between productivity and decomposition (Austin, 2002), and C can be stored in transient pools, such as the litter pool, or in more stable long-term pools, such as the soil-C pool. Soil C represents the long-term C storage pool, with a residence time estimated between months and thousands of years (Campbell, 1967). The litter-C pool represents a short-term C pool, with a turnover time of months to several years, which will either be respired back to the atmosphere via decomposer organisms or incorporated into stable soil organic matter C (Hutchinson et al., 2007; Janzen et al., 1992). To attain long-term C storage in temperate maize-based agroecosystems, C must be physically and chemically protected as humified soil organic C. Therefore, understanding the decomposition patterns of plant litter and the fate of litter C is necessary to determine how long agricultural systems can retain C in increased litter pools and the amount of litter C that is eventually incorporated into stable soil organic matter. In addition, an increase in litter-C inputs through management practices that increase crop yield also may allow short-term C sequestration if these management practices do not also lead to increased C losses through decomposition of litter and

soil organic matter C. Verma et al. (2005) estimated that 65 to 75% of gross ecosystem primary production in intensively managed agricultural systems is emitted as ecosystem respiration, and others have found the field CO_2 fluxes are similar to litter-C inputs (Jacinthe et al., 2002; Paul et al., 1999). Thus, plant litter pool C dynamics may contribute substantially to estimates of short-term C sequestration and in the long-term play an important part in the overall C balance of agroecosystems.

In general, the importance of the litter pool as one of the major C pools in terrestrial systems is relatively unknown. We do know, however, that the size of the litter pool can be affected by increases and decreases in both productivity and decomposition and is therefore highly dynamic. Maize-based agricultural systems have seen an increase in crop productivity and, through no-till practices, a decrease in litter burial and soil disturbance. Thus, the propensity for substantial litter buildup in agroecosystems seems probable and yet the magnitude and temporal dynamics of litter-C accretion is generally unknown.

In large-scale, no-till production fields in Nebraska, seed is harvested at the end of the growing season, but the remainder of the plant, including the seedless cob, stalks, and leaves as well as all belowground portions of the plant, is left in the field to decompose without being incorporated into the soil matrix via tillage. Although crop productivity has been increased in these systems, the effect of different management regimes on the decomposition of crop residues is relatively unknown (Kochsiek et al., 2009). For example, irrigation increases crop productivity but it has also been shown to affect decomposition patterns (Aerts, 1997; Couteaux et al., 1995; Kochsiek et al., 2009; Leith, 1975; Meentemeyer, 1978). The availability of water could have a direct impact on decomposition by improving the abiotic environment for decomposers and indirect impacts by either enhancing or lowering plant tissue quality. Also, crop rotation rather than monocropping can have impacts on the standing litter pool through differences in both crop productivity and decomposition patterns.

We investigated the changes in litter-C production and decomposition for four annual litter cohorts, each of which decomposed in situ for 3 yr in three no-till management regimes that represent the major cropping systems in the western U.S. Corn Belt (Verma et al., 2005). Our first objective was to investigate how annual variability and different field management changes litter-C production. Second, we asked if there were significant annual variation and management impacts on litter decomposition rates. Third, we generated site-specific decomposition models using maximum likelihood analysis to characterize the decomposition processes. Fourth, we coupled decomposition and litter-C production to investigate the effects of management on the litter-C balance and litter-C accretion during 10 yr of management. In total, this allowed us to evaluate both how important the litter pool is in the overall C budget of these agroecosystems and how sensitive the litter pool is to management changes.

MATERIALS AND METHODS
Study Sites

This decomposition study was part of a larger C sequestration project to examine the potential to sequester C in agricultural systems (Verma et al., 2005). We used three production-scale agricultural fields at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Each field was no-till managed, where the grain was harvested at the end of the growing season but the remainder of the plant, including the seedless cob, stalks, and leaves as well as all of the belowground portions of the plant, was left in the field to decompose without being incorporated into the soil matrix via tillage. All fields contained the same four related soil series: Yutan (a fine-silty, mixed, superactive, mesic Mollic Hapludalf), Tomek (a fine, smectitic, mesic Pachic Argiudoll), Filbert (a fine, smectitic, mesic Vertic Argialboll), and Fillmore (a fine, smectitic, mesic Vertic Argialboll) (Verma et al., 2005). Before this study, Fields 1 and 2 were split in two and had 10 yr of a no-till alternating maize–soybean rotation, while Field 3 had a much more variable cropping history that included soybean, maize, oat (*Oryza sativa* L.), and wheat (*Triticum aestivum* L.) grown in 2- to 4-ha plots with tillage. At the initiation of the study, the soil in all three fields was disk tilled to incorporate accumulated surface residues from previous management and incorporate P and K fertilizers. All three fields were approximately 65 ha and were within 1.6 km of each other. Field 1 was continuous maize, irrigated with a center-pivot irrigation system. Field 2 was an annual maize–soybean rotation irrigated in the same way. Both of the irrigated fields received a pre-emergence fertilization application by coulter injection of 128 kg N/ha (28% urea–NH_4NO_3) and two subsequent fertilization events, termed *fertigation*, where fertilizer is added to the irrigation water and applied to the crops when there is maximum need for fertilizer during critical times in crop development (Table 1). Field 3 was a rainfed, annual maize–soybean rotation, relying solely on natural precipitation, and received one pre-emergence fertilization application at the same rate and by the same method as the irrigated fields. These three management practices represent the three main cropping systems in the midwestern part of the United States (Verma et al., 2005).

We conducted our decomposition study in six 20- by 20-m intensive measurement zones (IMZs) within each management regime. Crop growth, soil moisture, soil C, soil and plant gas exchange, and productivity were measured at regular intervals within each IMZ. Before the initiation of the study, IMZ locations were selected by using a fuzzy-*k* mean clustering technique, which classified each management regime into six categories based on elevation, soil type, electrical conductivity, soil organic matter content, near-infrared remotely sensed imagery, and digital aerial photographs (Dobermann and Ping, 2004; Minasny and McBratney, 2003). Once the management regime was separated into the six different fuzzy-class environmental categories, the exact location of the IMZ was placed randomly within each category area for a total of six IMZs for each management regime. The purpose of classifying each site into six IMZs was to

capture and maximize landscape-level spatial variability so that the measurements could be scaled up to the entire management site. This approach allowed us to quantify the natural variability within each management regime to gain an estimate of the maximum variability of our measured variables at a biologically or agriculturally relevant field scale (Minasny and McBratney, 2003). There was within-site variation in productivity, with an average coefficient of variation (CV) of 9% within each field and year. Soil C varied by approximately 26%, and litter C lost was, in general, the most variable measurement, with an average CV of 38% for each tissue type, field, and year; however, these factors were not highly correlated with one another. We used individual IMZ measurements as replicates for each management regime and applied statistics and made conclusions about treatment differences on this basis (Cottenie and De Meester, 2003; Hurlbert, 1984, 2004). Note that each management regime was not replicated. Replication of 65-ha fields was not possible, and using small replicated plots would not represent realistic estimates of entire agricultural production fields because the equipment and irrigation are designed for large agricultural production fields. Our approach, therefore, was to measure litter decomposition and remaining litter pools and to maximize the potential variability within each 65-ha management regime.

Field Methods

There were four annual litter cohorts from 2001 to 2004. The fertilization and irrigation regimen for each management regime in each litter production year (2001–2004) is shown in Table 1. Each year, at the end of the growing season (October), above- and belowground biomass was sampled next to each IMZ in each management regime. In 2001 and 2003, all three management regimes were planted with maize. In 2002 and 2004, the maize–soybean rotations were planted with soybean. In the years when the management regimes were planted with maize,

the aboveground portions of three plants and the belowground portion of six plants were harvested from each IMZ in each management regime. The aboveground portion of the plant was separated into cobs, leaves, and stalks and dried to a constant weight at 60°C. Belowground portions of the plants were washed, dried to a constant weight at 60°C, and separated into root stalks and coarse and fine roots. The root stalk was defined as the belowground portion of the stalk where the roots branch off. Coarse roots were defined as the large primary roots that branch directly off the root stalk, while fine roots were the portions of the root that branch off the coarse roots and have no direct contact with the root stalk. In soybean years, leaf litter traps were created to collect senesced leaves, and then the above- and belowground biomass was harvested from 12 plants adjacent to each IMZ. The aboveground portion of the plants was separated into pod walls, leaves, and stalks and dried to a constant weight at 60°C. Belowground portions of the plants were washed, dried to a constant weight at 60°C, and separated into coarse and fine roots. Soybean biomass does not have a definable root stalk and so this tissue type was not included in soybean litter cohorts. All other tissue types were defined in the same manner as in maize years.

For each annual litter cohort, 12 replicate litter bags per IMZ were prepared for leaves as well as stalks, for a total of 24 litter bags per IMZ. Six replicate litter bags per IMZ were prepared for root stalks as well as cobs for each IMZ, for a total of 12 litter bags per IMZ. There was a total of 144 bags for both leaves and stalks and 72 bags for root stalks and cobs in each management regime for each annual litter cohort. Each litter bag was 20 by 20 cm, with a mesh size of 1 mm, and 5 to 10 g of plant tissue was packed per litter bag (Burgess et al., 2002). Leaf, stalk, and cob litter bags were placed on the soil surface, while root stalk litter bags were buried at a 5-cm soil depth. From 0.15 to 0.25 g of coarse and fine roots was packed in minicontainers with a volume of 1.5 cm^3. Minicontainers are small polyethylene tubes with mesh closing either end (Eisenbeis et al., 1999). Once the minicon-

Table 1. Management at each site for the four annual litter cohorts. Different amounts of pre-emergence fertilizer were added in 2001 on the north (N) and south (S) sides of the irrigated continuous maize and irrigated maize–soybean management regimes.

Management	2001	2002	2003	2004
Irrigated continuous maize				
Crop	maize	maize	maize	maize
Pre-emergence fertilizer, kg/ha	127.86 (N), 85.12(S)	134.4	133.5	159.04
V-6 fertigation, kg/ha	33.04	44.80	45.47	33.6
V-12 fertigation, kg/ha	34.72	45.36	45.02	33.6
Annual irrigation, cm	33.60	28.68	37.84	22.81
Harvest, Mg/ha	13.51	12.97	12.12	12.12
Irrigated maize–soybean rotation				
Crop	maize	soybean	maize	soybean
Pre-emergence fertilizer, kg/ha	127.86 (N), 85.12(S)		111.89	
V-6 fertigation, kg/ha	33.6		28.89	
V-12 fertigation, kg/ha	34.27		27.55	
Annual irrigation, cm	32.97	20.96	34.80	15.88
Harvest, Mg/ha	13.41	3.99	14.00	3.36
Rainfed maize–soybean rotation				
Crop	maize	soybean	maize	soybean
Pre-emergence fertilizer, kg/ha	127.68	None	89.82	None
Harvest, Mg/ha	8.72	3.32	7.72	3.14

tainers were packed with root biomass, they were placed in polyvinyl chloride bars with minicontainer-sized holes drilled in them, hereafter referred to as *root bars*, and buried horizontally at approximately the 5-cm depth in each management regime (Paulus et al., 1999). Each root bar contained six minicontainers filled with coarse roots and six with fine roots for a total of 12 root samples per root bar. Three root bars were made for each IMZ in each management regime for a total of 216 minicontainers per management regime in each annual litter cohort: 108 fine-root samples and 108 coarse-root samples. Two mesh sizes, 20 and 2 μm, were used to make minicontainers. We detected no difference in decay rate between these mesh sizes, however, and so we report pooled results. It should be noted, however, that both of these mesh sizes will exclude soil macrofauna and therefore may underestimate root decomposition. In November of each year, the litterbags and root bars were placed in each management regime. For our statistical analyses, we treated each IMZ as a replicate for management regime (n = 6 per management regime) and averaged all sample replicates within each IMZ to determine the overall litter-C loss for each tissue type. Six harvests of litter bags were made after the initial placement in November of each year (Fig. 1). One-sixth of the litter bags from each litter type in each IMZ were harvested every 6 mo for 3 yr, cleaned of any soil contamination, and weighed to determine mass loss.

Above- and belowground crop biomass and grain yield were determined by destructive harvest. The aboveground biomass was collected at physiological maturity by harvesting 12 m of row in each IMZ. The belowground root biomass was determined at the R1 stage of growth in the following manner. Within each IMZ, three replicate transects of four cores each were taken perpendicular to the row at 13-cm increments to the center of the interrow space 38 cm from the crop row. Root cores were taken to a depth of 0.6 m and separated into 0.15-m increments and washed to remove soil and gross organic residue material. After washing, the roots were stained with Congo red to separate dead from live root material. Roots were then hand sorted, dried, and weighed. The root weight density of each core was integrated over distance to obtain an estimate of the root mass at each soil depth. These replicated estimates were then extrapolated to obtain the total root mass on a square-meter basis. All biomass samples were analyzed for C with a Costech 4010 elemental analyzer (Costech Analytical Technologies). Grain yield was determined on a whole-field basis by weighing the amount of grain removed through combine harvesting and measuring the grain moisture percentage in each load. Grain yield was then adjusted to a standard moisture content of 15% (Verma et al., 2005).

Tissue Quality Analysis

Initial tissue C and N contents of harvested plant organs for each tissue type, location (IMZ), and sampling time were determined by grinding a portion of the biomass from each sample in a Wiley minimill with a 2-mm (40-mesh) screen (Thomas Scientific). Total C and N were analyzed with a Costech ECS 4010 elemental analyzer. In addition, ash content was determined by burning a sample at 475°C in a muffle furnace and used to correct the mass loss data for ash content. We also estimated the initial C quality with

an Ankom 200/220 fiber analyzer (Ankom Technology), which is a common technique used to determine forage digestibility (Goering and Van Soest, 1970; Van Soest et al., 1991). This technique uses a sequential extraction to determine the amount of soluble, hemicellulose, cellulose, and lignin fractions within each sample. These classifications do not represent strictly identical chemical compounds but rather groups of similar compounds with similar resistance to decomposition. The data for tissue fraction analysis are presented as the four fractions (soluble, hemicellulose, cellulose, and lignin) totaling 100% of the plant tissue C quality. Therefore, any increase in one fraction leads to an equivalent decrease in the other fractions.

Statistical Analyses

The effect of year and management regime on the initial amount of litter produced for each tissue type for each litter cohort was determined using a two-way analysis of variance (ANOVA), with year and management regime as the main factors.

We determined differences in C loss for each tissue type individually and then for all tissue types pooled in each management regime for all four annual litter cohorts. For each tissue type, we determined the main effects of year and management regime with a two-way ANOVA. If either year or management regime proved significant, we determined differences between either year or management regime separately using one-way ANOVAs. All analyses included harvest time as a covariate.

Our litter bags were collected biannually in the spring and fall and thus captured both winter and summer decomposition periods. Because of the seasonal differences in climate, there were distinct differences in decomposition rates for each period. Fitting exponential decay functions to these data did not accurately capture the seasonal dynamics in decomposition, and thus we fit decomposition models to the data that were tailored to incorporate seasonality. We fit decomposition models using maximum likelihood analysis to determine the decomposition rates for each tissue type in each management regime for the four annual litter cohorts for each 6-mo decomposition period using Mathematica 7 (Wolfram Research). We created a model as a piecewise function with separate decomposition rates for each winter and summer decomposition period because decomposition tends to be rapid during the first year and then slow with time:

$$y(t) = \begin{cases} \exp(-w_1 t) \\ \quad 0 < t \leq 0.5 \\ \quad \text{0–6 mo (first winter)} \\ \exp[-w_1 0.5 - s_1(t-0.5)] \\ \quad 0.5 < t \leq 1.0 \\ \quad \text{6–12 mo (first summer)} \\ \exp[-w_1 0.5 - s_1 0.5 - w_2(t-1.0)] \\ \quad 1.0 < t \leq 1.5 \\ \quad \text{12–18 mo (second winter)} \\ \text{and so forth...} \\ \quad 1.5 < t \\ \quad \text{18–36 mo} \end{cases}$$
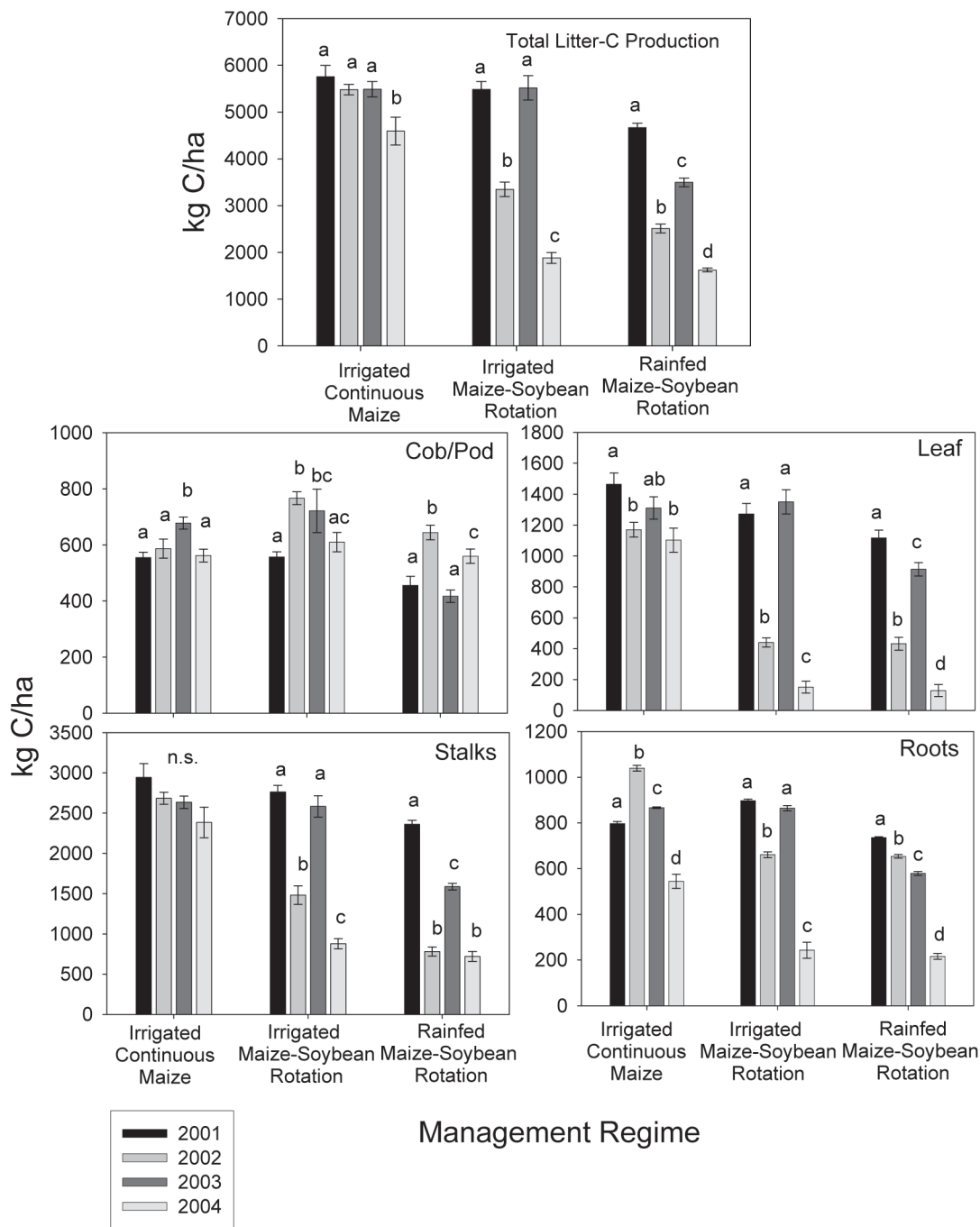
Fig. 1. Total litter-C production under each management regime and litter-C production for each tissue type from 2001 to 2004. Letters denote significant annual differences for each litter type in each management regime and were determined by one-way ANOVA at *P* < 0.05 in a LSD post-hoc comparison.

where w_1 is the first winter decomposition rate for Months 0 to 6, s_1 is the first summer rate for Months 6 to 12 of decomposition, w_2 is the second winter decomposition rate for Months 12 to 18, and so on for a total of three winter decomposition parameters and three summer decomposition parameters. We also examined two simplified models in which subsets of the six different decomposition periods were set equal. Because the litter structure for the first 6 mo of decomposition (the first winter) may be the most distinct from subsequent months, we fit a model with a specified decomposition rate for the first winter (w_1), a common winter decomposition rate for the later winter periods (w), and a

common decomposition rate for all summer periods (s). The third and simplest model had common decomposition rates for all the winter decomposition periods (w) and all summer decomposition periods (s). Each of these models still account for seasonal decomposition differences between summer and winter.

We then fit the decomposition models using maximum likelihood analysis (Bolker, 2008; Hilborn and Mangel, 1997). The C loss percentage was characterized best by a β distribution, where all values fall between 0 and 1 with a defined mean and shape parameter (Evans et al., 2000). The β distribution can have a bell-shaped appearance at intermediate values, but as the values

get closer to 0 or 1, the distribution becomes more skewed. The β distribution was found to be a better fit than a normal distribution in all our cases; thus, we only present results from the β distribution model. We added tissue type, field, and year by stepwise addition to each of the three models. The models were compared using the Akaike information criterion (AIC) (Burnham and Anderson, 2002; Sakamoto et al., 1986).

Using the decomposition parameters for the best-fit model, we predicted C loss with time. We used litter-C production and decomposition parameters to determine how much of a litter cohort remained at any period of time. For years after 2004, litter-C production was not monitored directly, but grain harvest was measured, so we calculated the relationship between litter-C production and grain production for each annual litter cohort (2001–2004) and then used this proportion to calculate litter-C production of each litter tissue type for years when only the grain harvest was measured. For 2009 and 2010, we used the mean litter-C production for each tissue type. We also used the mean C percentage remaining for each tissue type to predict decomposition in the years after 2004. By summing the remaining fraction of litter cohorts for any period of time, we could determine the amount of litter-C accretion in each management regime. We then tested the elasticity of productivity and decomposition by increasing both productivity and decomposition rates separately by 10% to see which process had a larger impact on litter-C accretion in each of the three management regimes. All statistics were performed with SPSS (version 20).

RESULTS

During the growing seasons (2001–2004), air and soil temperatures were similar for all years and management regimes (Supplemental Fig. S1). In each year, from July to September, the rainfed management regime had reduced soil moisture compared with the irrigated management regime (Supplemental Fig. S1c). Generally, the irrigated maize–soybean rotation had the highest soil moisture compared with the other management regimes throughout the growing season.

Productivity was highly variable among crop type, management regime, and year (Table 2; Fig. 1). In 2001 and 2003, when all three management regimes were cropped with maize, irrigation increased litter-C production by 20 and 57%, respectively (Fig. 1).

Irrigation also tended to decrease variability in maize production, as the irrigated continuous maize and the irrigated maize–soybean management regimes had CVs of 12 and 9%, respectively, while the rainfed site had a CV of 16%. Also, maize was always approximately twofold more productive than soybean. Irrigation increased litter-C production for soybean, but this effect was only significant in 2002 (Fig. 1). Irrigation also did not lead to reduced variability for soybean production as it did with maize. It should be noted, however, that we only had 2 yr of soybean production and in 2004 soybean was planted late due to rainy spring conditions, so a short-season hybrid was used, which produced less litter C. Therefore, there was increased variability in soybean production in both the irrigated (CV = 31.7) and rainfed (CV = 23.8) management regimes. Generally, there was a decrease in litter-C production during the 4 yr that were monitored.

Decomposition rates were also highly variable, with significant annual variation (CV = 40) and management impacts (CV = 41.4) (Table 3; Fig. 2). We investigated the impacts of tissue quality and environmental measures, such as volumetric water content and soil temperature at the 10-cm depth, on decomposition rates, and, while tissue quality varied among years and management regimes (Supplemental Fig. S1, S2, and S3), there was no significant correlation among any of these variables and decomposition rates (data not shown). Generally, the belowground tissue types were more responsive to irrigation than the aboveground tissue types because they tended to decompose more slowly under the rainfed management regimes than the irrigated management regimes, regardless of crop type (Supplemental Tables S1 and S2). Soybean tissue types also decomposed significantly faster than their maize counterparts for all tissue types ($P \leq 0.0001$), except for stalks ($F_{1,70} = 0.207$, $P = 0.650$). Regardless of crop type or management regime, there was, on average, 20% of the litter C remaining after 3 yr of in situ decomposition, which varied between 2 and 40% depending on tissue type.

For both maize and soybean, the model with the best fit included the three factors (year, tissue type, and field) with the six separate decomposition parameters that characterized decomposition in each 6-mo period (w_1, w_2, w_3, s_1, s_2, and s_3) (Table 4). While decomposition had significant management and annual variation effects (Tables 3 and 4), the model fit indicated the factors that explained the data better than others. For example, in-

Table 2. Changes in litter production for the four annual litter cohorts. Two-way ANOVAs were used to determine the main effects of year and management regime on litter production for each tissue type. Significant differences, determined with $P < 0.05$ in a LSD post-hoc comparison, are in bold type.

| Main effect	df	Cob or pods		Leaf		Stalk		Roots	
		F	P	F	P	F	P	F	P
Maize litter productivity									
Year	3, 40	3.21	**0.033**	6.11	**0.002**	9.47	**<0.0001**	229.04	**<0.0001**
Management	2, 40	19.06	**<0.0001**	18.05	**<0.0001**	29.52	**<0.0001**	149.73	**<0.0001**
Year × management	3, 40	4.44	**0.018**	2.65	0.083	3.71	**0.033**	34.90	**<0.0001**
Soybean litter productivity									
Year	1, 40	19.07	**<0.0001**	63.67	**<0.0001**	18.24	**<0.0001**	453.99	**<0.0001**
Management	1, 40	9.77	**0.005**	0.17	0.687	30.39	**<0.0001**	0.711	0.409
Year × management	1, 40	1.72	0.204	0.03	0.857	12.20	**0.002**	0.248	0.624
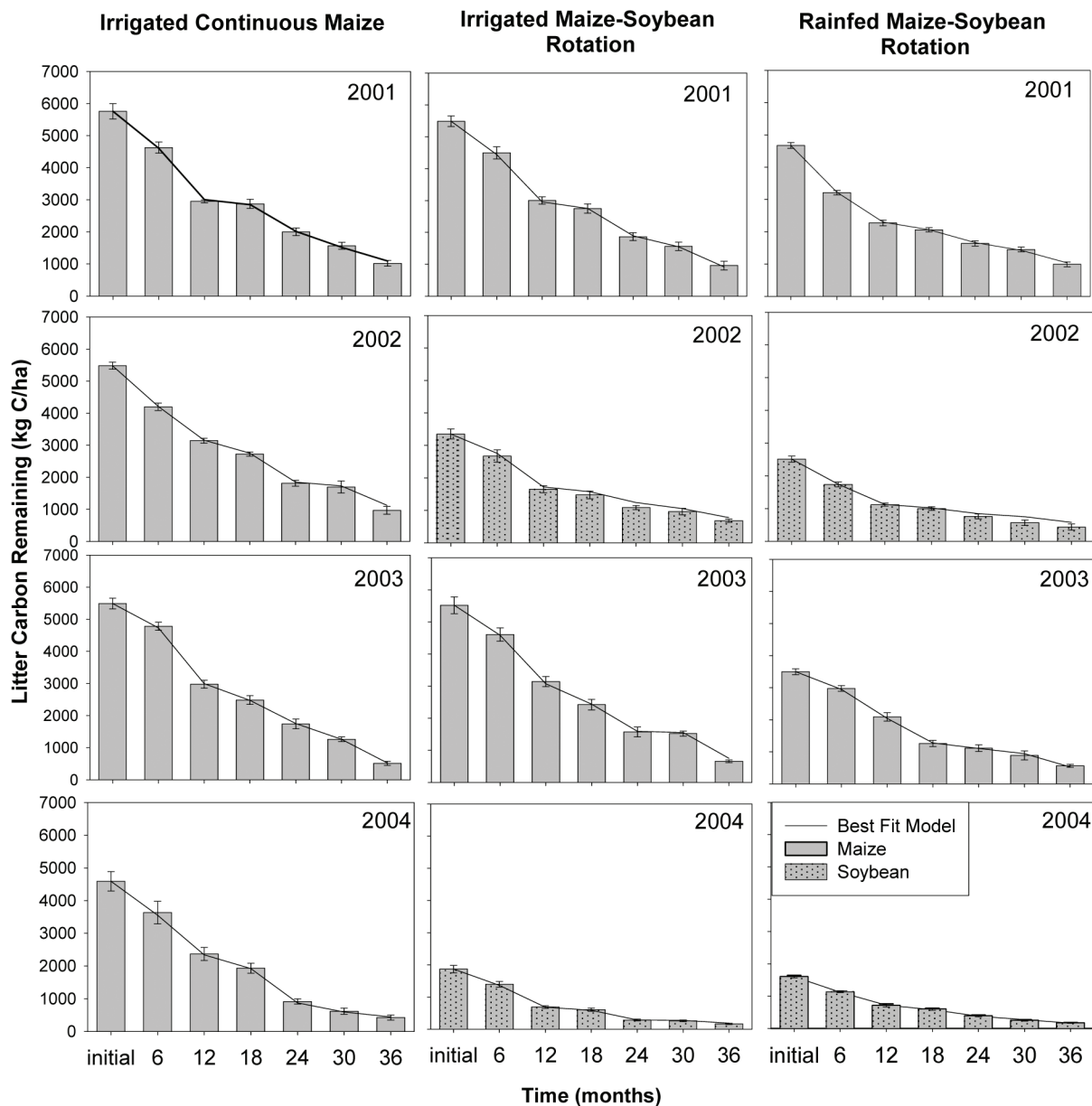
Fig. 2. Litter-C remaining in each management regime in each year. Shown are the means for litter C remaining ± 1 SE for each harvest. Lines denote the best-fit model for each management regime determined by maximum likelihood analysis.

Table 3. Changes in litter decomposition for the four annual litter cohorts. Two-way ANOVA were used to determine the main effects of year and management regime on litter decomposition for each tissue type. Significant differences were determined where $P < 0.05$ in a LSD post-hoc comparison.

Main effect	Cob or pods		Leaf		Stalk		Coarse roots		Fine roots	
	df	F	df	F	df	F	df	F	df	F
Maize										
Year	3, 276	9.30***	3, 558	21.47***	3, 565	45.17***	3, 845	79.57***	3, 830	38.91***
Management	2, 276	3.00*	2, 558	6.38**	2, 565	3.87*	2, 845	40.10***	2, 830	23.06***
Year × management	2, 276	1.97	2, 558	2.88	2, 565	2.84	2, 845	18.71***	2, 830	0.73
Soybean										
Year	1, 135	6.58**	1, 273	44.75***	1, 279	209.5***	1, 392	5.94**	1, 384	57.67***
Management	1, 135	0.01	1, 273	10.63**	1, 279	1.53	1, 392	43.99***	1, 384	16.91***
Year × management	1, 135	5.59**	1, 273	8.06**	1, 279	8.40**	1, 392	6.36**	1, 384	1.84

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

Table 4. Maize and soybean decomposition models. Shown is the fit for each model tested for both crop types. Each model tested is represented by the parameters included in the model. Also included are the log likelihood values, total number of parameters, Akaike information criterion (AIC) value, and the difference between the model tested and the model with the best fit (Δi). The model with the best fit has the lowest log likelihood and AIC values.

| Log likelihood	Total parameters	Factors†	Model‡	AIC	Δi
			Maize		
−3456	240	y, t, m	$w_1, s_1, w_2, s_2, w_3, s_3$	−6429	0
−3156	121	y, t, m	w_1, s, w	−6071	358
−3148	121	y, t	$w_1, s_1, w_2, s_2, w_3, s_3$	−6054	375
−2961	81	y, t, m	w, s	−5759	670
−2934	61	y, t	$w_1 s, w$	−5747	682
−2782	41	y, t	w, s	−5482	947
−2682	91	t, m	$w_1, s_1, w_2, s_2, w_3, s_3$	−5182	1248
−2567	46	t, m	$w_1 s, w$	−5041	1388
−2482	31	t	$w_1, s_1, w_2, s_2, w_3, s_3$	−4902	1527
−2471	31	t, m	w, s	−4879	1550
−2403	16	t	w_1, s, w	−4773	1656
−2318	11	t	w, s	−4614	1815
−2220	25	y, m	$w_1 s, w$	−4390	2039
−2206	25	y	$w_1, s_1, w_2, s_2, w_3, s_3$	−4363	2066
−2167	13	y	w_1, s, w	−4308	2121
−2156	17	y, m	w, s	−4278	2151
−2135	19	m	$w_1, s_1, w_2, s_2, w_3, s_3$	−4232	2198
−2120	10	m	w_1, s, w	−4221	2208
−2110	9	y	w, s	−4202	2227
−2079	7	m	w, s	−4143	2286
			Soybean		
−1640	97	y, t, m	$w_1, s_1, w_2, s_2, w_3, s_3$	−3087	0
−1563	49	y, t, m	w_1, s, w	−3028	59
−1523	49	y, t	w, s	−2948	139
−1506	33	y, t, m	w, s	−2947	140
−1473	25	y, t	w_1, s, w	−2896	191
−1426	17	y, t	w, s	−2819	268
−1353	61	t, m	$w_1, s_1, w_2, s_2, w_3, s_3$	−2584	503
−1296	25	t, m	w_1, s, w	−2543	544
−1295	31	t	$w_1, s_1, w_2, s_2, w_3, s_3$	−2528	559
−1256	13	t	w_1, s, w	−2486	601
−1255	17	t, m	w, s	−2477	610
−1219	9	t	w, s	−2419	668
−562	13	y, m	w_1, s, w	−1099	1988
−556	7	y	w_1, s, w	−1099	1988
−562	13	y	$w_1, s_1, w_2, s_2, w_3, s_3$	−1098	1989
−571	25	y, m	$w_1, s_1, w_2, s_2, w_3, s_3$	−1092	1995
−542	9	y, m	w, s	−1065	2022
−536	5	y	w, s	−1062	2025
−521	13	m	$w_1, s_1, w_2, s_2, w_3, s_3$	−1016	2071
−513	7	m	w_1, s, w	−1013	2074
−495	5	m	w, s	−979	2108

† Possible factors: y, year; t, tissue type; m, management regime.

‡ Decomposition rate parameters included in model: w, all winters combined (or the second and third winters combined if preceded by w_1); s, all summers combined; w_1, first winter (6 mo); s_1, first summer (6 mo); w_2, second winter (6 mo); s_2, second summer (6 mo); w_3, third winter (6 mo); s_3, third summer (6 mo). For example, the most complex model, denoted $w_1, s_1, w_2, s_2, w_3, s_3$, had separate decomposition parameters for each 6-mo period of decomposition.

cluding tissue type (t) with any of the three decomposition models had a lower log-likelihood and AIC value and thus fit the data better than including either management regime (m) or year (y) alone. Also, generally including more decomposition parameters increased the model fit, where the common winter (w) and summer (s) decomposition parameters were a poorer fit than including a separate decomposition parameter for the first winter period (w_1) and then common decomposition parameters for the remaining winter periods (w) and all summer periods (s) (Table 4).

By combining litter-C production and decomposition, we predicted the amount of litter C after 10 yr of management. The irrigated continuous maize regime had approximately 15 and 35% more litter C than the irrigated maize–soybean rotation and the rainfed maize–soybean rotation, respectively, after 10 yr of management (Fig. 3A). Increasing the decomposition rates by 10% had small impacts on litter-C accretion and only increased litter C by 5%, on average (Fig. 3B). Litter C decreased more in the maize–soybean rotations than the continuous maize system by 2.5 to 3.5%. Increasing litter-C production, however, was directly related to the amount of standing litter C because each management regime increased its standing litter-C pool by 10% (Fig. 3C). We also calculated litter-C accretion in the spring and fall (after harvest)
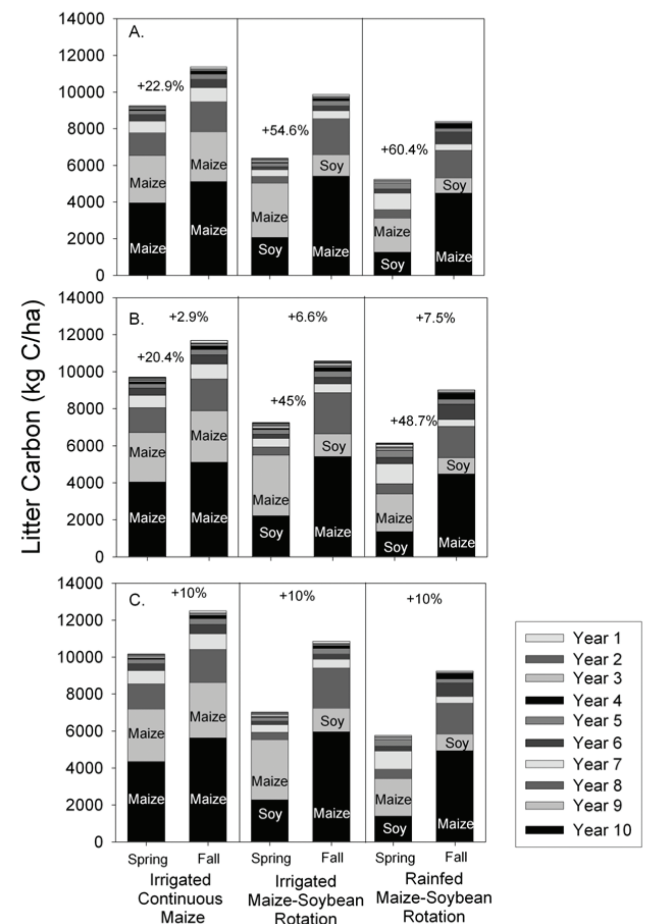
Fig. 3. Litter-C accretion in each management regime during 10 yr: (A) litter-C accretion with known productivity and decomposition parameters; (B) litter-C accretion with a 10% decrease in decomposition rates; and (C) litter-C accretion with a 10% increase in productivity.

after 10 yr of management (Fig. 3). From spring to post-harvest, there was a dramatic increase in the litter pool of each management regime, with the biggest increases of 55 to 60% seen in the maize–soybean rotations (Fig. 3). The large increases seen in the maize–soybean rotations were due to the differences in litter-C production, with the maize crop producing approximately twice as much litter C as soybean. When decomposition was decreased by 10%, the difference between the spring and post-harvest litter pools, while still dramatic, was lessened by only 2% in the irrigated continuous maize regime but by 10 to 12% in the maize–soybean rotations. Because decomposition rates decreased, this led to more litter C remaining in the spring and therefore less of a difference between the spring and the post-harvest standing litter pools.

DISCUSSION

Irrigation and fertigation allowed the administering of water and N to the crop at key times in crop development or when water became limiting for plant growth. Because precipitation varied among years, the rainfed field experienced reduced yields compared with the irrigated fields (Table 1). When the irrigated management regimes were cropped with maize, they tended to have less variation in litter-C production compared with the rainfed regimes because the crops always had sufficient water and fertilizer inputs. Due to environmental factors, 2004 was a particularly bad year for litter-C production at all of the sites. First, a late freeze damaged corn plants in the irrigated continuous maize management regime and in the irrigated and rainfed maize–soybean rotations, and second, soybean planting was delayed because of large spring rains, and thus a short-season hybrid was used.

While there were significant management effects and annual variation in litter-C decomposition, all tissue types decomposed rapidly, and after 3 yr of decomposition, 80% of the litter C was lost. Litter-C loss was highly variable among tissue types, management, and years, and it was not significantly correlated with environmental variation, such as soil temperature or moisture, or initial tissue quality (Kochsiek et al., 2009). This contrasts with studies in natural and managed systems where decomposition has been shown to be impacted by both the environment and plant tissue quality (Aerts, 1997; Aerts et al., 2003; Alberda, 1965; Beyaert and Voroney, 2011; Swift, 1979). Maize tissue generally has about 50% lower lignin concentration than natural C_4 grasses (Pastor et al., 1987; Wedin et al., 1995), and this may favor its rapid decomposition. Instead of tissue quality or environmental variation leading to decomposition differences, the observed differences in litter-C loss between tissue types seemed to be more related to plant tissue structure than tissue quality. For example, cob tissue is a large, dense structure that takes time for microbial colonization and is more resistant to fragmentation than other tissue types (Foley and Vander Hooven, 1981). Thus, cob tissue had the slowest decomposition rates. While we did not formally quantify litter structure, there is at least a qualitative relationship between litter-C loss and litter structure.

In the first 6 mo of decomposition, which was a winter period, between 20 and 30% of litter C was lost. Our winter C loss-

es for leaves and stalks (~21% lost) are in agreement with other studies of corn decomposition in southwestern Quebec (~ 20%; Burgess et al., 2002) and southeastern Ontario (Gregorich and Ellert, 1994) and were slightly lower than the 25% loss seen in Missouri (Ghidey and Alberts, 1993). The significant amount of litter-C loss during this time points to the potential importance of physical processes such as freeze–thaw dynamics, precipitation interception, and litter fragmentation in the decomposition process. Other studies also have shown that some portion of the decomposer community is active at cold temperatures (Stott et al., 1986). Thus, those studies that ignore winter decomposition patterns and only investigate decomposition during the summer months are potentially missing critical decomposition processes.

The C loss during the first summer period for maize surface litter (cobs, leaves, and stalks) was 27%. This is higher than the 21% C loss reported for summer decomposition rates in southwestern Quebec (Burgess et al., 2002), but lower than the 35% loss reported in Quebec (Rochette et al., 1999) and also lower than rates from Missouri (Broder and Wagner, 1988). After 2 yr of decomposition, for surface litter, we lost 73% of litter C, which is within 1 to 3% of what was reported for similar tissue types during the same decomposition interval in southwestern Quebec (Burgess et al., 2002) and surprisingly very close to rates for litter that was buried at the 10-cm soil depth in North Platte, NE (Tarkalson et al., 2008). Thus, it is clear that there is some consistency (±10%) in decomposition rates across large geographic areas. It should also be noted, however, that the litter bag mesh size used in this study excluded mesofaunal decomposers such as earthworms, resulting in conservative rates of decomposition.

Because our decomposition data were collected at 6-mo intervals, which were summer and winter seasons, there were distinct differences in decomposition rates for each period. Fitting exponential decay functions to these data did not accurately capture the seasonal dynamics in decomposition, and thus we fit decomposition models to the data that were tailored to incorporate seasonality. By doing this, we were able to make more precise estimates of the litter C remaining at each 6-mo interval for the entire 3 yr of decomposition for each annual litter cohort (Fig. 2). This also allowed us to make within-year estimates of the change in the size of the litter-C pool from spring to post-harvest (Fig. 3).

Litter-C accretion was higher in the irrigated continuous maize regime than in either of the maize–soybean rotations. Because maize produces much more litter C annually, the continuous maize regime had annual inputs around 5000 kg C/ha, whereas in a soybean year, productivity dropped to between 2000 and 3000 kg C/ha. Soybean also tended to decompose significantly faster than maize for all tissue types except for stalks. Thus, for the maize–soybean rotations, the combination of reduced litter-C production in soybean years plus the increased decomposition rates seen with soybean led to decreased litter-C accretion rates. When we increased decomposition and litter-C production in these management regimes, it became clear that litter-C inputs have more of an impact on litter-C accretion than does decomposition. Increasing decomposition rates by 10%

only led to an average of a 5% increase in litter-C accretion over 10 yr (Fig. 3). When looking at the contribution of each annual litter cohort to the entire amount of litter C accumulated over 10 yr, it is clearly driven by litter-C production and decomposition in the most recent three to four litter cohorts, and after about 4 yr of decomposition, very little remains in any litter cohort regardless of management regime. Thus, even with the large observed differences in decomposition rates with different management, as well as significant annual variation in litter C lost, litter decomposition is so rapid in these systems that this variation has little impact on litter-C accretion. Litter-C accretion is more driven by changes in litter-C production than by decomposition (Fig. 3). We clearly show that the litter-C pool in intensively managed systems, such as these, tends to be dynamic and ephemeral, with large inputs and rapid losses of C, and even within 1 yr, the litter-C pool can change by as much as 65%.

Our data demonstrate that after harvest, the litter pool comprises about 20 to 23% of the total field C pool (litter and soil in the 0–15-cm depth), and as much as 80% of this litter C can be lost in 3 yr of decomposition, which would suggest that the litter-C pool in systems such as these would be a major contributor to annual net ecosystem production (Jacinthe et al., 2002; Kucharik and Twine, 2007; Verma et al., 2005). The highly dynamic nature of this pool suggests that it could be key in understanding short-term ecosystem C dynamics. At these sites, there was no change in soil C within the first 4 yr of management (2001–2004), suggesting that most of the litter C is respired back to the atmosphere and not stored in stable soil organic matter (Verma et al., 2005). To determine the ability of these ecosystems to sequester C across longer time scales, it will be necessary to quantify the ultimate fate of the litter-C pool, whether it is respired back to the atmosphere or stored as stable soil organic matter.

CONCLUSIONS

This study shows that litter accretion is more sensitive to litter-C inputs, i.e., crop productivity, than litter-C losses, i.e., decomposition. The differences among the litter-C pools can be related to higher litter-C production associated with annual inputs of maize, which produced approximately twofold more litter C annually than soybean. Irrigation also reduced the variation in litter-C production for maize crops, allowing consistently large inputs of litter C. While decomposition was variable, it tended to be rapid, with between 2 and 40% of the litter C remaining after 3 yr of in situ decomposition, depending on tissue type. Thus, litter-C accretion is most sensitive to changes in management, with the irrigated continuous maize rotation having a significantly greater litter-C pool after 10 yr of management than either the irrigated or the rainfed maize–soybean rotations. The most important result from this study is the finding that the litter pool is a highly dynamic and ephemeral C pool that can change as much as 60% within 1 yr. Post-harvest litter is the second largest C pool in these systems after soil C. This study demonstrates precise litter-C balance of a system and that the litter can be a substantial short-term C pool in highly managed systems such as

these. Thus, understanding C cycling through this pool will help to determine entire ecosystem C gains and losses and how long a system will retain C in short-term pools such as the litter-C pool.

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