

Decomposition and Nitrogen Dynamics of Crop Residues: Residue Quality and Water Effects

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ABSTRACT

Understanding environmental and residue influences on decomposition and nutrient dynamics under diverse conditions is critical for efficient resource management. Our objective was to evaluate the influence of water on decomposition and N dynamics for surface and buried residues. Decomposition of alfalfa (*Medicago sativa* L.), grain sorghum (*Sorghum bicolor* [L.] Moench), and winter wheat (*Triticum aestivum* L. emend. Thell.) residues in fiberglass bags on the surface or buried at 120 mm in Pullman soil (fine, mixed, thermic Torrertic Paleustoll) at Bushland, TX, was measured from May 1990 to May 1991. A line-source sprinkler provided five water regimes (336, 287, 166, 60, and 5 mm) while precipitation provided 305 mm water. Decomposition coefficients (k) were greater for alfalfa than for wheat or grain sorghum and were greater for buried than for surface residues. Rate coefficients increased linearly with water applied. The increase was greater for alfalfa than for sorghum and wheat. Net N mineralization occurred from alfalfa residues throughout the study. Net N immobilization was longer than 1 yr for surface wheat and sorghum and about 0.33 yr for buried residues. Both N_{\max} (grams N immobilized per kilogram of original biomass) and N_{eqv} (grams N immobilized per kilogram of biomass loss) were influenced by crop and placement but not water regime. The N_{\max} value was similar for surface wheat and sorghum residues but was 50% lower for buried wheat than for sorghum. The N_{eqv} indicated the N requirement of microorganisms was less for buried than for surface residues. Water and residue quality interactions affecting decomposition and N dynamics should be considered in residue management strategies for soil protection and nutrient cycling.

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EMPHASIS on improved residue management to meet soil conservation goals has increased the need for understanding crop residue decomposition under different field environments. Compared with clean tillage, minimum tillage cropping systems leave more residue on the soil surface, resulting in reduced soil erosion, less on-farm energy use, and greater water conservation (Unger and McCalla, 1980). Surface residues persist longer than incorporated residues because greater fluctuations in water and temperature regimes and reduced availability of soil nutrients adversely affect the microbes colonizing surface residue, thus slowing decomposition (Brown and Dickey, 1970; Douglas et al., 1980).

During decomposition, there is a rapid loss of soluble material followed by the relatively rapid disappearance of cellulose from the litter. Rates of mass loss have been correlated with initial litter quality (Meentemeyer, 1978; Parr and Papendick, 1978; Aber and Melillo, 1982; Reinertsen et al., 1984) and environmental variables (Stott et al., 1986; Roper, 1985). Indices of litter quality often include concentrations of elements or various classes of structural and nonstructural compounds, i.e., cellulose and lignin. Initial litter quality also influences residue N dynamics. Materials rich in N and low in lignin generally decay rapidly, with much of the N being mineralized. Decomposition of residues with low N and high lignin contents require additional N that will be immobilized from the soil. Few studies of agricultural residues have focused on the patterns of N accumulation and release and interactions with environmental factors

(Holland and Coleman, 1987; Pastor et al., 1987; Andren et al., 1993).

Resource quality and environmental influences on N immobilization-mineralization of decaying litter are complex but can be evaluated through the relationship between mass loss and N concentration (Aber and Melillo, 1982; Melillo et al., 1984; Aber et al., 1990; Pastor et al., 1987). This relationship exhibits an inverse linear function, which has been shown to exist for several litter types and environments (Aber and Melillo, 1982; Holland and Coleman, 1987; McClaugherty and Berg, 1987; Berg and McClaugherty, 1989; Pastor et al., 1987) during the exponential phase of mass loss (Aber et al., 1990). With the slope and intercept of this relationship, the amount of N immobilized and the length of the immobilization period can be estimated. Using this approach, Holland and Coleman (1987) showed that surface wheat straw residues immobilized more N than did incorporated residues and that microbial N cycling efficiency was greater where residues were allowed to remain on the surface.

Microbial activity in decomposing residues is controlled by substrate availability, temperature, and water potential (Stott et al., 1986). Laboratory studies indicate that water and temperature have a greater effect during early stages of decomposition when soluble C and N compounds are readily available (Stott et al., 1986; Roper, 1985); but C and N availability become major limiting factors during later stages (Knapp et al., 1983). These and other studies have been used to develop relationships that simulate temperature and water influences on residue decomposition (Stroo et al., 1989).

Water and temperature relationships determined under laboratory conditions must be evaluated under a range of field environmental conditions to determine their applicability to long-term prediction. Published data from different environments can be difficult to use for this purpose because of variation in collection techniques, residue quality, and management practices (Christensen, 1986; Stott et al., 1990; Stroo et al., 1989; Douglas and Rickman, 1992). Multilocation studies specifically designed to sample a range of environments increase the time required for plot establishment, maintenance, and data collection and require duplication of climate monitoring equipment.

The line-source sprinkler system (hereafter designated *line-source*) was originally developed to study interactions of water stress with secondary factors such as fertility or genotype on crop growth (Hanks et al., 1976). The system provides continuously variable water levels dependent on plot proximity to the sprinkler line. The numerous environments thus created should be useful

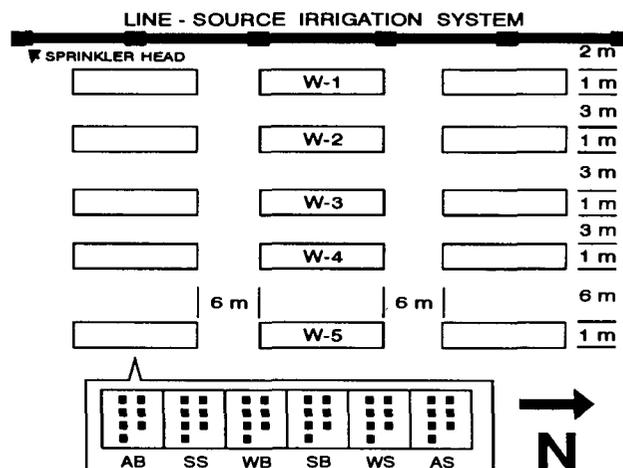


Fig. 1. Crop residue decomposition study (not to scale) indicating location of water regimes W-1 through W-5 in relation to the line-source irrigation system. Lower diagram indicates the arrangement of residue bags within one water regime and replication. Crop-placement treatments indicated are as follows: AB, alfalfa buried; AS, alfalfa surface; SB, sorghum buried; SS, sorghum surface; WB, wheat buried; WS, wheat surface.

for evaluating at one location the influence of water on microbial activity in agricultural systems. We adopted the line-source to acquire data describing the influence of water on residue decomposition, which we needed for developing a crop residue decomposition model. The specific experimental objective was to determine the influence of water on decomposition and N dynamics of buried or surface-placed alfalfa, grain sorghum, and wheat residues during a 12-mo period.

MATERIALS AND METHODS

Field and Laboratory Methods

A line-source sprinkler system was used to create a range of water regimes for decomposition of alfalfa, grain sorghum, and winter wheat residues placed on the soil surface or buried at 120 mm in Pullman clay loam at Bushland, TX (Fig. 1). Grain sorghum and wheat residue consisted of stems and leaf sheaths cut to 210-mm lengths from material collected immediately following grain harvest in 1989. Alfalfa residues consisted of leaves and stems from baled hay harvested at the full bloom stage during spring 1988 and could be considered green manure but is referred to as *residue*. Residues were dried in a forced draft oven at 50°C for 48 h before 15 g of residue were weighed into 250 by 250 mm fiberglass mesh bags with 1-mm openings. Initial chemical properties of the residues, determined by the methods of Robertson and Van Soest (1981), are presented in Table 1 along with initial N content determined as described below.

The line-source consisted of 12 sections of irrigation pipe that were 6.1 m long by 0.1 m in diameter. Each pipe section

Table 1. Initial residue quality and N concentration of crop residues.

Crop	Solubles†	Hemicellulose	fraction			Ash	N g kg ⁻¹
			Cellulose	Lignin	Ash		
Alfalfa	0.47	0.19	0.19	0.05	0.12	40.1	
Grain sorghum	0.19	0.31	0.36	0.07	0.08	2.9	
Wheat	0.15	0.32	0.38	0.07	0.07	4.8	

† Material soluble in neutral detergent.

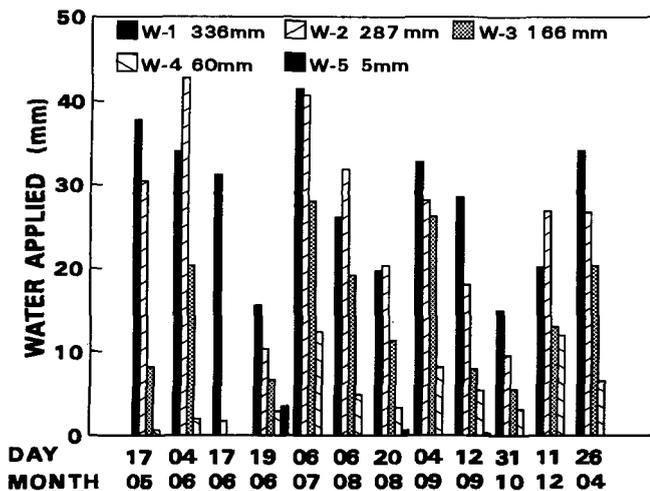


Fig. 2. Irrigation dates and quantity of water applied during the study. Total irrigation amounts for each water regime are given in the key. Rainfall was 305 mm.

had one impact sprinkler with an effective radius of 15 m at 414 kPa of pressure. We found in previous studies that water distribution on the two sides of the line-source is unequal because of wind at Bushland. We oriented the line-source north to south and placed the crop residues only on the east side of the line-source because prevailing winds are from the west and southwest. Plots were established at five distances from the line-source to provide five water regimes (Fig. 1). Irrigation was applied at frequent intervals primarily through the summer and fall and provided 336, 287, 166, 60, and 5 mm of water during the study (Fig. 2). Precipitation added 305 mm to all water regimes.

The area used for the experiment contained grain sorghum stalks from the previous growing season (May–October 1989). Prior to the experiment, the stalks were shredded to eliminate interference with water distribution and left on the soil surface to reduce wind erosion. Bagged residues were placed in three blocks (Fig. 1) on 10 May 1990 and removed on 12 June, 12 July, 10 Aug., 10 Oct., and 10 Dec. 1990 and 10 Mar. and 13 May 1991 (32, 62, 92, 153, 214, 304, and 369 d following placement in the field). Residues were placed on a 1-mm sieve to remove loose soil, rinsed briefly under a light stream of water to remove soil from the residue surface, dried at 60°C for 72 h, and weighed. After grinding to pass a 0.425-mm screen, 0.5- to 1.0-g subsamples were ashed at 450°C to determine ash content. Total N content of the residues was determined by Kjeldahl digestion (Nelson and Sommers, 1973) with colorimetric analysis to determine NH_4^+ (Technicon Industrial Systems, 1977). Ash content was used to adjust dry weight and N content to an ash-free basis because of the variable quantity of soil accumulated within the residues. Nitrogen content, which was also adjusted for total N content of soil accumulated within the residues (Christensen, 1986), is expressed as grams N per kilogram ash-free dry weight of initial residue (grams N in the recovered residue divided by kilograms of initial sample).

Statistical Analysis

In a line-source sprinkler experiment, irrigation levels are systematically arranged without randomization, and valid univariate tests of irrigation effects are available only when certain conditions as discussed below are met (Fernandez, 1991). Our data were analyzed as a repeated-measures experiment because

randomization of water regimes across plots was not possible. A repeated-measures analysis is used to evaluate treatment effects where the data are collected from the same sample units at several points in time or space (Littell, 1989). Measurements taken close together in space or time may be more highly correlated than measurements taken far apart, and certain conditions must be met by the correlations between these measurements for standard univariate F tests to be valid (Littell, 1989). The Huynh and Feldt (1970) (H-F) condition that must be met permits unequal variances and covariances between measurements but requires that any set of orthogonal contrasts among the repeated measures have equal variances and covariances (Littell, 1989). If the H-F condition is met, univariate F tests and probabilities are valid. When the H-F condition is rejected at significance $0.001 \leq P < 0.05$, then Greenhouse and Geisser (1959) adjustments to the denominator and numerator degrees of freedom for the repeated measure are made before evaluating the significance of the univariate F test (Littell, 1989). If the H-F condition is rejected at $P < 0.001$, multivariate analysis, which makes no assumption about the correlation between measurements but also is less rigorous than the univariate analysis, is used for the repeated measure (Littell, 1989). The H-F condition was evaluated as a sphericity test using the REPEATED option in the GLM procedure of the Statistical Analysis System (SAS Institute, 1989). The sphericity test for the H-F condition is not relevant to the validity of univariate tests on other treatments (crop and placement).

Littell (1989) pointed out that repeated-measures analysis can be simplified when response curves can be developed to describe treatment effects across the repeated measures. Parameters estimated from the response curves can then be analyzed as data to evaluate the other treatment effects. We determined first order decomposition rate coefficients, k , to integrate the time effect on weight loss. The first-order decomposition equation, $M_t = M_0 \exp(-kt)$, where M_t is the mass (g) remaining at time t (d), M_0 is the initial mass (g), and k is the decomposition rate coefficient (d^{-1}), was solved for each plot (water \times crop \times placement \times replication) using the MODEL procedure of ETS/SAS (SAS Institute, 1988). The k values were used as data in the repeated-measures analysis to evaluate water regime, crop, and placement effects on decomposition as described above. Linear regressions (GLM) of water level on k were determined for significant treatment effects as indicated by the repeated-measures analysis.

Analysis of the N data was complicated by the absence of a clear relationship (linear, quadratic, or exponential) between N content or N concentration and time. Therefore, time was used as a second repeated measure within the analysis (Freund et al., 1986). Having two variables treated as repeated measures resulted in insufficient degrees of freedom for performing the sphericity test for time \times water and higher order interactions and precluded using multivariate analysis of variance. The adjusted univariate probability values for these interactions were considered along with first- and second-degree polynomial contrasts for time \times water and higher interactions because no assumptions regarding the covariance matrix are required to validate significance of the contrast F tests (Littell, 1989).

A method evaluating resource quality and environmental influences on N dynamics of decaying litter using the interactions between mass loss and N dynamics of decaying litter was presented by Aber and Melillo (1982), Melillo et al. (1984), and Aber et al. (1990). The relationship between percentage of mass remaining vs. the grams of N per kilogram of the mass remaining is evaluated by solving for the intercept (b) and slope (m) of the resulting inverse linear relationship. Using the slope and intercept of this relationship, Aber and

Table 2. Equations developed by Aber and Melillo (1982) and Melillo et al. (1984) to evaluate biomass and N dynamics of decomposing litter at maximum N immobilization. Calculations are made using the slope (m) and intercept (b) of the inverse linear relationship between mass remaining and N concentration of the remaining residue, i.e., mass remaining (%) = $b + m \times$ N concentration (g kg^{-1}).[†]

Parameter	Equation [‡]
Biomass remaining, g	Biomass = $b0.5$
N concentration, g kg^{-1}	$N_i = [b/(-2m)]$
Maximum N immobilized, g kg^{-1} §	$N_{\text{max}} = [(b^2/4m) - 100N_0]0.01$
N equivalent, g kg^{-1} ¶	$N_{\text{eqv}} = N_{\text{max}}/(1 - b \times 0.5 \times 0.01)$
Time to N max, d	$t = \ln[(b0.5)0.01]/-k$

[†] The conversion factor used to calculate N_{max} and N_{eqv} was modified to allow use of N concentration expressed as grams per kilogram instead of a percentage as in the original equations.

[‡] N_0 = initial N concentration (g kg^{-1}); k = decomposition coefficient (d^{-1}); t = time (d); 0.01 = conversion factor.

[§] grams N per kilogram original biomass.

[¶] grams N per kilogram biomass loss.

Melillo (1982) presented a set of quantitative relationships for determining the point of maximum N immobilization, total amount of N immobilized, and the rate at which immobilization occurs (Table 2). The N immobilization parameters estimated through this approach for each crop \times placement \times water regime \times replication were subjected to repeated-measures analysis in the same manner as the decomposition rate coefficients. Initial N concentration and biomass were not used for fitting slopes and intercepts because of the apparent leaching loss following initial exposure of the residues to the decomposing environment (Aber and Melillo, 1982; Pastor et al., 1987). Also, only data for which mass remaining was $>20\%$ were used in the fitting of slopes and intercepts (Aber et al., 1990).

RESULTS

Despite minor problems caused by windy conditions, the line-source was effective in providing a range of water regimes for residue decomposition. The average monthly temperature and total monthly precipitation for the study period are presented in Fig. 3. The amount and distribution of water applied varied with each irrigation, even though irrigation events were limited to periods when wind speed was below 3.6 m s^{-1} (Fig. 2). Wind

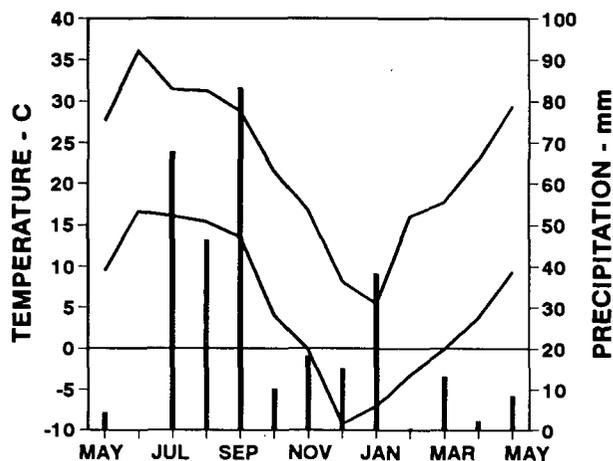


Fig. 3. Monthly precipitation (bars) and average high and low temperatures (lines) for Bushland, TX, from 10 May 1990 to 13 May 1991.

speed and direction were different for each irrigation and even changed during events, greatly influencing water distribution. For example, on 17 June, water was applied only to the first two water regimes because the wind intensity and direction changed following initiation of irrigation. Soil water content was measured periodically during the study to obtain a qualitative measure of water availability to the residues (Fig. 4). Measurements were usually taken 1 to 5 d following an irrigation event. Differences in water availability are more apparent for the 125- to 150-cm soil depth. Although drying of the soil surface occurs rapidly under conditions at Bushland, some differences in water availability between water regimes are apparent.

Residue decomposition rate was influenced by crop, placement, and water regime (Table 3). The effect of water and interactions between water and other main effects were evaluated with the multivariate analysis from the repeated-measures procedure because the sphericity test indicated that the univariate analysis was inappropriate (Littell, 1989; Fernandez, 1991). The k values increased with increased water application; however, the degree of increase was highly dependent on crop and placement (Tables 3 and 4).

The response to water application can be seen for the buried alfalfa residue on the first sampling date when

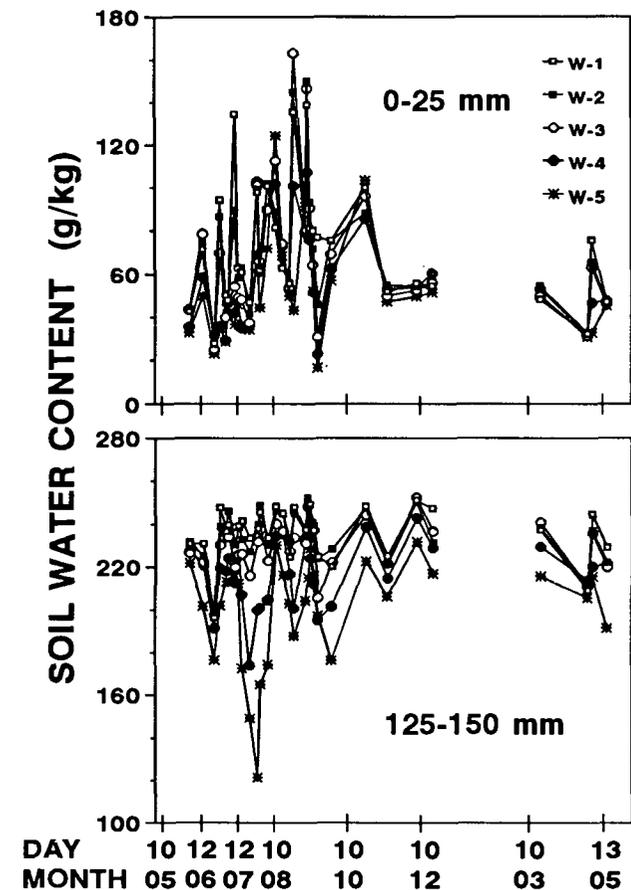


Fig. 4. Soil water content for the 0- to 25-mm and 125- to 150-mm soil depths. See Fig. 1 for location of water regimes W-1 through W-5 in relation to the line-source sprinkler system.

Table 3. Repeated measures analysis of variance $P > F$ values for crop (C), placement (P), water regime (W), and time (T) effects on changes in decomposition rate (k) \ddagger , N concentration, total N, and parameters associated with the point of maximum N immobilization.

Treatment	k \ddagger	N concentration \S	Total N content \P	Maximum N immobilization				
				Biomass remaining	Time	N concentration	N_{max} $\#$	N_{eq} $\ddagger\ddagger$
				$P > F$				
C	0.0001	0.0004	0.0002	0.0923	0.0004	0.0005	0.0496	0.2550
P	0.0001	0.0001	0.0019	0.0001	0.0001	0.7003	0.0001	0.0001
C \times P	0.0001	0.5028	0.0038	0.7313	0.0169	0.0138	0.0015	0.0016
W	0.0001	0.0001	0.1322	0.0624	0.0001	0.0251	0.0605	0.1215
W \times C	0.0001	0.2129	0.0082	0.6030	0.0023	0.2320	0.2431	0.1868
W \times P	0.0001	0.0059	0.4893	0.0356	0.0001	0.1534	0.4450	0.6262
W \times C \times P	0.0001	0.0702	0.0004	0.1796	0.0023	0.1303	0.1163	0.0818
T	—	0.0001	0.0001	—	—	—	—	—
T \times C	—	0.6490	0.3021	—	—	—	—	—
T \times P	—	0.0001	0.0001	—	—	—	—	—
T \times C \times P	—	0.3788	0.0004	—	—	—	—	—
T \times W	—	0.0373	0.4651	—	—	—	—	—
T \times W \times C	—	0.4148	0.4176	—	—	—	—	—
T \times W \times P	—	0.5818	0.0440	—	—	—	—	—
T \times P \times C \times W	—	0.6091	0.4713	—	—	—	—	—

\ddagger Analysis of decomposition rate includes alfalfa; all other analyses are for wheat and grain sorghum only.

\ddagger F for W and interactions with C and P are from multivariate analysis.

\S F for T and interactions with C, P, and W are Greenhouse-Geisser adjusted.

\P F for T \times W and interactions with C and P are Greenhouse-Geisser adjusted.

$\#$ N_{max} = maximum N immobilized (g) per kilogram original biomass.

$\ddagger\ddagger$ N_{eq} = N immobilized (g) per kilogram biomass loss.

there was a 16% difference in dry weight remaining between the wettest and driest water regime (Fig. 5). Similar differences between water regimes were observed for the buried wheat and grain sorghum residues at the second sampling date. The greatest differences in residue decomposition occurred between crops, with alfalfa residues decomposing much faster than wheat or grain sorghum. After 32 d, 63 to 77% of buried alfalfa had decomposed, whereas buried grain sorghum and wheat required 153 d for comparable decomposition. Surface residues decomposed much more slowly with 78 to 90% of alfalfa, 27 to 50% of grain sorghum, and 32 to 47% of wheat decomposing after 369 d. Water regime influences were more apparent at the final sampling date for grain sorghum and wheat than for alfalfa, primarily because of the rapid decomposition of alfalfa.

Some of the variability in the dry-weight data for surface residues is attributable to soil accumulation on and in the residues even though ash content was used to adjust data to an ash-free basis. Residues on the soil surface were subjected to blowing soil that packed into

openings in the residue, particularly in the stems of grain sorghum and wheat. Despite the cleaning procedure and correction of dry weights to an ash-free basis, the added variability probably influenced the fitting of k values and diminished the statistical significance of the water regime effects (residues from the wetter regimes tended to retain more soil).

The repeated-measures analysis indicated that water regime interactions with crop and placement were linear. Intercept values presented in Table 4 indicate minimal residue decomposition rates with no water application. The Y intercept values should be zero if no water was available; however, because our lowest water application was 310 mm (including precipitation), the relationship between k and water for lower water applications could not be determined. The slope values (Table 4) indicate that water increased k more for alfalfa than for grain sorghum and wheat, but the amount of increase depended on placement. The rate of change in k was two times greater for alfalfa than for sorghum and wheat on the surface and nearly five times greater when the residues were buried. The effect of placement on k had a dramatic effect within each crop. For alfalfa, the change in k for each added millimeter of water was nine times greater for buried than for surface placement. In contrast, the increases in k for buried grain sorghum and wheat residues were only 4.5 and 4.9 times, respectively, those for the same residue placed on the surface.

The N concentration and N content of decomposing residues changed with time depending on water regime, crop, and placement (Table 3, Fig. 6 and 7). Nitrogen movement into or out of the residues was believed to be associated with changes in N content of the microbial biomass and microbial products associated with the residues or with leaching losses, but this hypothesis was not tested. Total N analysis of alfalfa was limited by sample size after the third sampling for buried residues and after

Table 4. Linear relationship between millimeters of water (w) and decomposition rate coefficient (k) for buried and surface crop residues where $k = b + m \times w$.

Treatment	b	m	SE b \ddagger	SE m \ddagger	R^2
<u>Buried</u>					
Alfalfa	0.0056	50.5×10^{-6}	0.0031	6.2×10^{-6}	0.83
Sorghum	0.0017	11.3×10^{-6}	0.0010	2.1×10^{-6}	0.69
Wheat	0.0031	10.2×10^{-6}	0.0011	2.2×10^{-6}	0.62
<u>Surface</u>					
Alfalfa	0.00370	5.6×10^{-6}	0.00047	1.0×10^{-6}	0.73
Sorghum	0.00019	2.5×10^{-6}	0.00033	0.7×10^{-6}	0.51
Wheat	0.00049	2.1×10^{-6}	0.00021	0.4×10^{-6}	0.66

\ddagger Standard error of b . All intercepts significant at $P < 0.05$ except sorghum, buried and surface.

\ddagger Standard error of m . All slopes and regressions significant at $P < 0.05$.

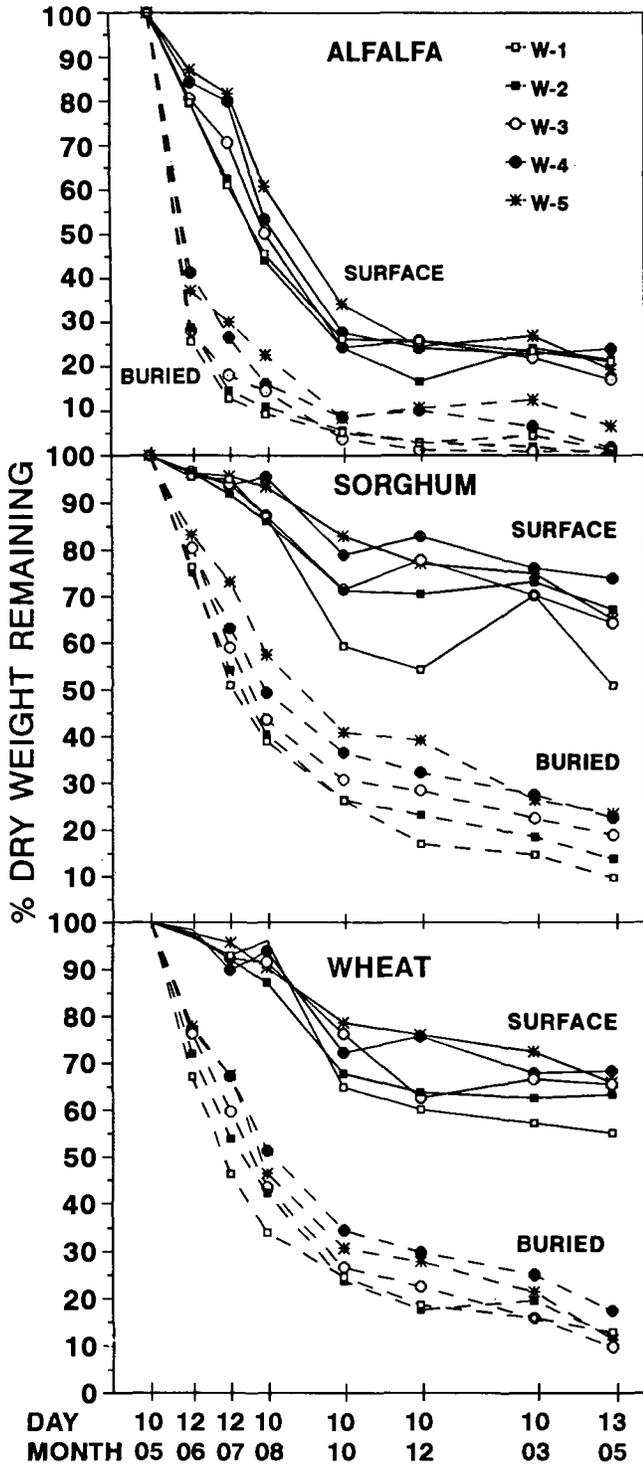


Fig. 5. Percentage of initial residue remaining for alfalfa, grain sorghum, and wheat decomposed under a line-source. See Fig. 1 for location of water regimes W-1 through W-5 in relation to the line-source sprinkler system.

the fourth sampling for surface residues. Nitrogen data for surface alfalfa residues were obtained by combining material from the three replications for each of the last three sample dates. Therefore, N results presented in Table 3 are for grain sorghum and wheat only. The

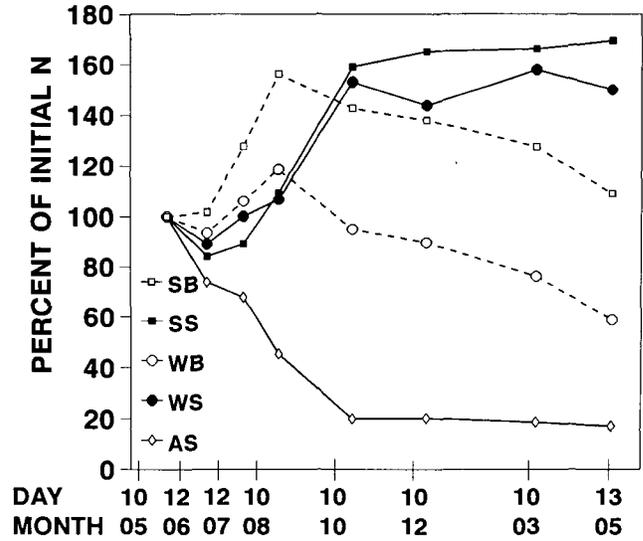


Fig. 6. Percentage of initial N content remaining in alfalfa, sorghum, and wheat residues. Data are averaged across water regimes. AS, alfalfa surface; SB, sorghum buried; SS, sorghum surface; WB, wheat buried; WS, wheat surface.

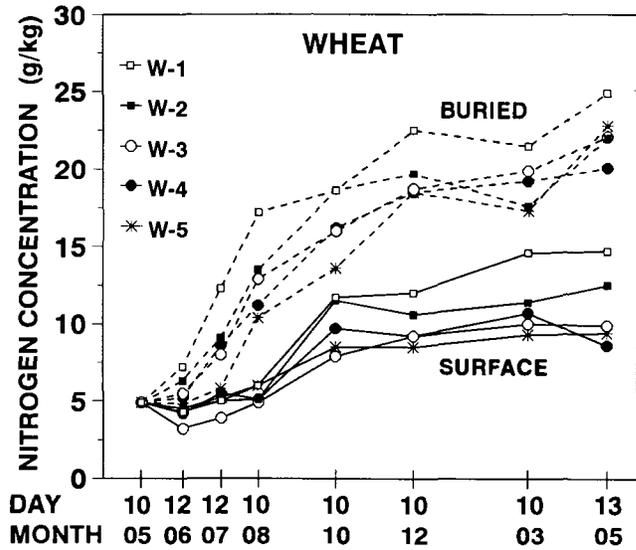


Fig. 7. Change in N concentration of surface and buried wheat residue decomposing in five water regimes. See Fig. 1 for location of water regimes W-1 through W-5 in relation to the line-source sprinkler system.

limited alfalfa data indicated net N mineralization was occurring from these residues (Fig. 6).

Water regime, placement, and time influences on the N concentrations of wheat and sorghum were similar. Initial differences in the N concentrations of these two residues (Table 1) remained relatively constant throughout the experiment; therefore, only data for wheat are shown in Fig. 7. The interaction between water and placement effects on N concentration had a significant linear trend with the response being greater for the buried residues. This is indicated by the more rapid increase in N concentration for buried than for surface residues during the first 92 d, with the greater effect occurring

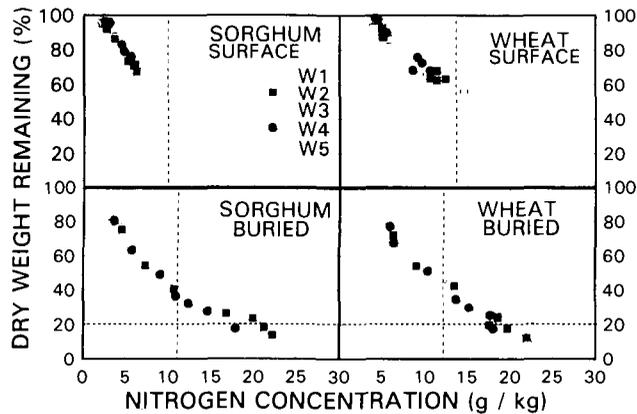


Fig. 8. Biomass remaining vs. N concentration of remaining residue for surface and buried sorghum and wheat residues ($n = 3$). Vertical line is the N concentration at maximum N immobilization (averaged across water regimes). Data below the horizontal line at 20% mass remaining was not used for fitting slopes and intercepts.

in the wetter regimes (Fig. 7). A substantial increase in surface residue N concentration occurred between the August and October sampling dates. This may have been due to lower soil temperatures and improved conditions for microbial growth within the residues resulting from fall precipitation. More than two-thirds of the 305 mm of precipitation was received during July to October (Fig. 3).

Crop and placement influences on N content averaged across water treatments are shown as a function of time in Fig. 6. Water regime differences for N content were not as great as those observed for N concentration (Table 3) but had similar trends (Fig. 7). Nitrogen content of surface alfalfa residues declined continuously during the first 150 d and then remained constant at about 20% of the initial N content. Buried alfalfa residue showed a similar decline in N content during the first 90 d (data not shown). Nitrogen content of buried sorghum and wheat residues increased during the first 92 d, and the increase was greater for grain sorghum than for wheat (1.6 vs. 0.8 g N kg⁻¹ initial residue). Subsequently, net N content declined, with the decrease being slightly greater for wheat residues. Nitrogen content of surface grain sorghum and wheat residues continued to increase until the October sampling with little change thereafter. Net accumulation of N within surface residues was 2.0 g N kg⁻¹ for grain sorghum and 2.3 g N kg⁻¹ for wheat.

Nitrogen immobilization dynamics of the sorghum and wheat residue were evaluated by the methods of Aber and Melillo (1982), Melillo et al. (1984), and Aber et al. (1990). Mass remaining vs. the N concentration of the mass remaining for wheat and sorghum are presented in Fig. 8. Nitrogen concentration of the decomposing wheat and sorghum residues increased as biomass decreased, with the relationship following the inverse linear function previously found with other litter types. The relation between N concentration and mass remaining for alfalfa (not shown) did not follow the inverse linear pattern probably because of the high initial N content and the rapid rate of mass loss.

Slopes and intercepts were used for estimation of

parameters associated with the point of maximum N immobilization within the residues (Table 5). Biomass remaining was greater for surface residues than for buried residues. Water regime appeared to have a greater effect on surface residues than buried residues based on the wider range of biomass remaining for surface residues when maximum N immobilization occurred.

The length of the immobilization phase was estimated by solving for time in the first-order decomposition model using the mass remaining at maximum N immobilization and the k values for mass loss (Tables 2 and 5). Time to reach maximum N immobilization was a function of crop, placement, and water regime (Table 3). Linear relationships describing water regime influence on days to maximum N immobilization are presented in Table 6. Buried residues of wheat and sorghum reached the point of maximum N immobilization much faster than surface residues (Table 5). The average period of time for N immobilization was >1 yr for both wheat and sorghum on the surface but was about 0.33 yr when buried. Water regime and placement effects on days to reach maximum N immobilization were greater for sorghum than for wheat (Table 6).

Crop \times placement interaction and water regime influenced N concentration at maximum N immobilization (Table 3). The N concentration for wheat was slightly greater for buried than for surface residues (Table 5 and Fig. 8). The opposite trend was observed for sorghum residues. The N concentration tended to increase as the amount of water decreased. The N concentrations averaged across crops and placements were 12.7, 11.5, 12.0, 11.4, and 10.8 g kg⁻¹ for the wettest to driest water regimes.

Both N_{max} (grams N immobilized per kilogram of original biomass) and N_{eqv} (grams N immobilized per kilogram of biomass loss) were influenced by crop and placement but not by water regime (Table 3). The N_{max} value was similar for surface residues of wheat and sorghum but was 50% lower for buried wheat residues than for buried sorghum residues (Table 5). Nitrogen use efficiency of microorganisms appeared to be greater within buried residues than within surface residues, as indicated by the smaller N_{eqv} of the buried residues.

DISCUSSION

Water application by the line-source sprinkler system enhanced decomposition of surface and buried alfalfa, grain sorghum, and wheat residues. The line-source provided a range of environments at one location to study water effects on microbial processes in situ. Our biggest problem with the line-source occurred because of windy conditions in the region. The repeated-measures analysis eliminated an original problem of line-source studies (Hanks et al., 1976; Fernandez, 1991).

Water application had a positive linear influence on the decomposition rate, which was greater for alfalfa and for buried residues (Table 3). Stott et al. (1986) observed in a laboratory study that wheat residue decomposition was linearly related to the logarithm of soil water potential, but the relationship was different for

Table 5. Decay rates (k) and parameters associated with the point of maximum N immobilization for grain sorghum and wheat residues.

Crop placement	Water regime	$-k$ $\times 10^{-3} \text{ d}^{-1}$	Maximum N immobilization				
			Biomass remaining %	Time d	N concentration g kg^{-1}	N_{max}^{\dagger}	N_{eq}^{\ddagger}
Sorghum buried	1	8.87	43.5	93	11.8	2.3	4.0
	2	7.99	42.2	108	12.1	2.2	3.8
	3	6.74	42.0	128	11.5	1.9	3.3
	4	5.92	46.7	131	9.6	1.6	2.9
	5	4.87	44.3	169	10.1	1.6	3.0
	Mean SE§			43.8 0.8	125 7	11.1 0.4	1.9 0.2
Sorghum surface	1	2.04	51.3	328	11.0	2.7	5.6
	2	1.35	55.7	433	8.2	1.7	3.8
	3	1.54	52.6	418	11.8	3.2	6.9
	4	0.93	54.1	660	9.8	2.4	5.2
	5	1.08	57.0	522	8.7	2.0	4.6
	Mean SE			54.1 0.8	472 32	9.9 0.5	2.4 0.2
Wheat buried	1	9.98	45.0	80	13.4	1.2	2.3
	2	8.69	46.9	87	11.5	0.6	1.1
	3	7.98	47.8	92	11.6	0.7	1.4
	4	6.20	47.2	122	11.7	0.7	1.4
	5	6.86	45.2	116	12.4	0.8	1.4
	Mean SE			46.4 0.8	100 5	12.2 0.3	0.8 0.1
Wheat surface	1	1.96	55.6	300	14.4	3.2	7.2
	2	1.67	55.1	357	14.1	3.0	6.6
	3	1.52	54.3	402	13.3	2.4	5.2
	4	1.30	54.7	465	14.5	3.1	6.9
	5	1.18	60.1	432	11.9	2.3	5.7
	Mean SE			55.9 0.8	391 17	13.7 0.4	2.7 0.2

$\dagger N_{\text{max}}$ = maximum N immobilized per kilogram original biomass.

$\ddagger N_{\text{eq}}$ = N immobilized per kilogram biomass loss.

§ SE = standard error of mean.

buried and surface residues. The interaction between crop and water regime in our study indicates that the effect of water availability on decomposition also depends on residue quality.

Decomposition rate differences between crops are well documented and are usually attributed to differences in total N, C/N ratio, N/lignin ratio, or other measures of residue quality. Differences in residue quality (Table 1) undoubtedly contributed to differences in decomposition rates between alfalfa, grain sorghum, and wheat. Alfalfa residues had a higher concentration of soluble components and showed a greater response to water application than did grain sorghum or wheat. Rapid mass loss from the alfalfa residue probably resulted from a combination of leaching and decomposition. Placement effects on decomposition rates were expected because surface residues dry much more quickly following irrigation or rainfall than do buried residues (Douglas et al., 1980; Douglas and Rickman, 1992). Rapid drying of surface residues undoubtedly contributed to the interaction between water regime and placement in our study. Differences between surface and buried residue decomposition rates for a particular crop provide a relative measure of environmental differences between the two placements. The differences we measured agree with the 60 to 70% differences between surface and buried residue decomposition rates used in the residue decomposition model of Douglas and Rickman (1992).

Loss of soluble components from surface residues

probably contributed to the influence of placement on the change in k with increasing water application. Christensen (1985) showed that cold water extraction decreased the N content of barley (*Hordeum vulgare* L.) straw 20% and caused a 50% reduction in CO_2 respired during a 203-d period at 15 °C. Leaching of soluble components may have been partially responsible for the initial decline in N content (Fig. 6) and slower decomposition (Fig. 5) of grain sorghum and wheat residues on the soil surface.

Our data, which indicate that 45 to 55% of the initial residues remain at maximum N immobilization, agree with other residue decomposition studies, most of which have demonstrated that N content of low-N residues decreases after 50 to 60% of the residue is decomposed

Table 6. Linear relationship between millimeters of water (w) and days (d) to reach maximum N immobilization where $d = b + m \times w$.

Treatment	b	m	SE b^{\dagger}	SE m^{\ddagger}	R^2
<u>Buried</u>					
Sorghum	212	0.18	13.7	0.03	0.77
Wheat	158	0.12	9.94	0.02	0.74
<u>Surface</u>					
Sorghum	814	0.71	83.3	0.16	0.58
Wheat	593	0.43	40.5	0.08	0.67

\dagger Standard error of b . All intercepts significant at $P < 0.01$.

\ddagger Standard error of m . All slopes and regressions significant at $P < 0.01$.

(Christensen, 1986; Douglas et al., 1980; Cochran, 1991). Andren et al. (1993) found that net N mineralization from buried barley straw occurred when the residues reached an N concentration of about 10 g kg^{-1} , which agrees with our data on sorghum and wheat but is slightly lower than the data for wheat straw observed by Holland and Coleman (1987). Andren et al. (1993) also found that the amount of N immobilized within buried barley straw was dependent on the soil water regime. Our wheat and sorghum data indicate a similar trend for buried residues, but the significance level was 0.12. This trend could be attributed to reduced rates of microbial activity and, therefore, reduced N immobilization under dryer conditions as indicated by Andren et al. (1993).

Mineralization of N from buried residues occurred within 100 to 150 d of incorporation. This would occur during fallow periods of the wheat-sorghum-fallow cropping system practiced on much of the southern Great Plains. Nitrogen loss potential is, therefore, great but actual loss is probably low because of limited rainfall in the area. Nitrogen mineralization from the surface residues was estimated to occur from 300 to 660 d after application to the soil surface, which would be late in the following cropping season or during the subsequent fallow period. Surface placement and water availability influences on N mineralization and immobilization would be important for evaluating availability of N from both soil and residues in fallow cropping systems.

Nitrogen accumulation in grain sorghum and wheat residues during decomposition indicates that initial residue N was inadequate to support the microbial community. The long-term accumulation of N in microbial biomass associated with surface residues represents a potential temporary sink to reduce N loss from leaching. Holland and Coleman (1987) found an increase in N content of surface and buried wheat straw residues during a 425-d period. Our N_{max} for sorghum and wheat and that of Holland and Coleman (1987) for wheat indicate N_{max} is greater for surface residues. They attributed the greater N immobilization in surface residues to a greater abundance of fungal decomposers and hypothesized that hyphal bridges between soil and straw allowed use of soil N and residue C during decomposition. Also, the abundance of fungal decomposers in the surface residues might contribute to increased organic matter stability because of the slower decomposability of fungal biomass. Some N accumulation in the surface residues may also have occurred by biological N_2 fixation (Roper, 1985), sorption of fixed N gases from the atmosphere, deposition from rain or soil, or movement of N to the soil surface with water (Parker et al., 1957). Our N content data were adjusted for N in adhering soil based on residue ash content and the N concentration of bulk soil samples. However, the N concentration of wind-blown material or soil at the surface may have been different from that of bulk soil. Movement of N to the surface residues probably occurred through a combination of physical and biological mechanisms.

Although the mechanism of N transfer into the residues is not known, the amount of N accumulated is important for optimizing crop management. The predominant crop

rotation in the southern Great Plains is wheat-sorghum-fallow, so two crops are produced in each 3-yr period. Average residue production in this cropping system at Bushland is 5.3 Mg ha^{-1} for sorghum and 6.5 Mg ha^{-1} for wheat (P.W. Unger, 1993, unpublished data). Leaving these residues on the soil surface could result in the immobilization of $12.7 \text{ kg soil N ha}^{-1}$ in the grain sorghum residues and $17.5 \text{ kg soil N ha}^{-1}$ in the wheat residues. Most of this soil N would be immobilized during the fallow period. However, release of the N may not occur during the following cropping season, as indicated by the time to reach maximum N immobilization (Table 5) and should, therefore, be accounted for when evaluating N requirements of the following crop.

Optimum residue management strategies must consider the influence of water on the impact of residue on both nutrient management and soil protection. Greater water availability to buried residues enhances their decomposition and nutrient release compared with surface residue placement. However, maximum soil protection requires minimal residue incorporation, so practices that promote rapid residue drying, such as leaving residues standing, should be encouraged on highly erodible lands. Nutrient management under these conditions may become more critical. The influence of residue quality should also be considered; i.e., residues that decompose rapidly protect soils for shorter periods but accelerate the return of nutrients to the soil. Knowledge of the multiple interactions between nutrient availability, soil protection, and residue decomposition will improve residue management strategies.

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