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## Crop Residue Decomposition in No-Tillage Small-Grain Fields

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### ABSTRACT

Conservation tillage fields provide different environments for biological and chemical processes than tilled fields. Our understanding of decomposition does not adequately account for post-harvest residue distributions or field environment variability. We hypothesized that temperature and moisture could be used to normalize field environments to optimal conditions that produce maximum decomposition rates; and biomass density could be normalized based on the fraction of initial biomass remaining over time. Four small grains were grown at Bushland, TX, to produce high-, medium-, and low-biomass densities in 36 field subplots using different seeding rate, fertilizer, and irrigation on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). During decomposition, differential irrigation increased environmental variability (13, 5, and 0 applications to sub-subplots). Ash-free crop residue biomass was measured seven times during 14 mo. Climate indices related field to optimal conditions, based on the daily minimum of air temperature and precipitation coefficients. First-order decomposition coefficients,  $k$ , were determined by plot, using the cumulative climate index to represent time. Irrigation did not affect  $k$  ( $P < 0.45$ ), indicating that the moisture index accounted for irrigation effects; but crops had different coefficients ( $P < 0.062$ ). Initial biomass density was inversely related to  $k$  ( $P < 0.008$ ), indicating that climate-based indices inadequately normalized environments across density treatments. The  $k$  was correlated to initial biomass ( $r = -0.49$ ), fraction-standing initial biomass ( $r = -0.37$ ), and initial N concentration in standing biomass ( $r = 0.32$ ). Climate indices may allow normalization of field environments important to decomposition and other agroecosystem processes if density effects on atmosphere-soil-residue interactions can be better quantified.

MANAGEMENT of grain crops in the USA has changed substantially from traditional practices involving intensive tillage following harvest to practices such as no-tillage, ridge tillage, and other conservation tillage systems that leave residues undisturbed following harvest. These management systems have been adopted to increase production efficiency and reduce water and

wind erosion. Soil microenvironments are different in fields that have surface-crop residues than in tilled fields with incorporated residues. Natural-resource simulation models that address soil erosion, water quality, integrated pest management, nutrient management, and other issues need to consider the impacts of residues on the agroecosystem and ecosystem impacts on residue decomposition (Steiner, 1994).

Much of our understanding of decomposition is based on controlled-environment studies, or field studies using bagged residues or labeled isotopes. Mass loss over time has been reported for few studies in natural field distributions because of inherently high variability of such data and the high labor requirement to collect and process residue samples. However, it is important that we gain a better understanding of decomposition in realistic field environments. For example, Stott et al. (1990) reported that about 16 to 18% of total residue biomass was in standing stubble, following harvest in decomposition studies at Pullman, WA; but the fraction of remaining biomass increased to 85% after 49 wk during 1 yr, contrasted to 0% by 32 wk in the next year. In the second year, the stems fell during winter snows; but in the first year, when the stubble didn't fall during winter, the mass loss was extremely low from stubble, compared with the residues that were on the soil surface. Most decomposition models cannot account for this type of interaction between the plant material and the environment.

Organisms that drive decomposition experience cycles of population growth and activity due to variable field environments, and these cycles may impact decomposition rates in ways that are not accounted for in current agroecosystem models. Taylor and Parkinson (1988a) conducted decomposition studies of leaf litter

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**Abbreviations:**  $A$ , constant in temperature coefficient equation; Biomass Density Treatments: H, high; M, medium; L, low. Crops: B, barley; O, oat; S, spring wheat; W, winter wheat. DAH, days after harvest; DD, decomposition day;  $k$ , decomposition coefficient;  $M_0$ , initial biomass;  $M_t$ , total biomass at time  $t$ ;  $P$ , precipitation (or irrigation); PC, precipitation coefficient;  $T$ , temperature;  $TC$ , temperature coefficient;  $T_{opt}$ , optimum temperature for decomposition.

in microcosms and reported that litter absorbed water and decomposed faster following 14 freeze–thaw cycles than after a single freeze–thaw cycle. Differences in water absorption and decomposition did not persist past the first 2 to 3 mo and a single freeze–thaw cycle was more important than the number of cycles in causing physical changes in the plant litter that affects decomposition. However, Taylor and Parkinson (1988a) concluded (based on a series of studies) that freezing before permanent snow cover and decomposition beneath snow remained important parts of the litter mass loss that are not well understood. Microcosm studies of wetting and drying cycles (Taylor and Parkinson, 1988b) indicated that pine (*Pinus contorta* Loud. × *P. banksiana* Lamb.) needles that went through 14 wet–dry cycles absorbed water and decomposed faster than needles that went through a single cycle, but the reverse was true for aspen (*Populus tremuloides* Michx.) leaves. For both species, the effect was only important during the first 2 to 3 mo of decomposition. In forest sites in western Canada, litter layers exhibited trends of increasing moisture content with depth, and only the top 1 cm went through wetting and drying cycles (about 10–15 yr<sup>-1</sup>), indicating to the authors that wet–dry cycles are probably not a significant factor for their environment.

Many researchers have developed temperature and moisture factors to quantify climatic limitations to decomposition. An advantage of normalizing weather data to optimal temperature and moisture conditions is that it allows the use of decomposition coefficients developed in controlled environments to predict decomposition in field environments. Hunt (1977) calculated decomposition in grasslands as an empirical function of soil water tension, a quadratic effect of temperature from 0 to 38°C and as an empirical function of N in the soil. He calculated a maximum potential decomposition rate and then multiplied it by the moisture, temperature, and N factors to determine an actual rate. In developing and testing a crop-residue decomposition model, Gregory et al. (1985) and Ghidry et al. (1985) multiplied temperature and moisture factors and then divided by the initial C/N ratio of the residue and accumulated this factor over time to calculate residue decomposition. Andrén and Paustian (1987) found that a one-compartment model using a Q<sub>10</sub> temperature factor and a log-linear function of soil water potential described mass loss of barley (*Hordeum vulgare* L.) straw decomposed in bags at 10 to 15 cm below the soil surface better than other decomposition models (e.g., multi-compartment) and climate factors. In an analysis of environmental limitations on wheat (*Triticum aestivum* L.) residue decomposition, Stroo et al. (1989) applied the *law of the minimum* to temperature and moisture factors and found that accumulating the daily *minimum* of temperature and moisture factors was better related to observed mass loss than a cumulative factor based on multiplication of the daily factors. Data reported by Summerell and Burgess (1989) on decomposition of wheat straw across a range of controlled temperature and moisture conditions fit the Stroo decomposition model well when the environment data were used to calculate the cumula-

tive minimum environmental factor (data not shown). The treatments fell on a single decomposition line, except for (i) the highest temperature, which was above the model optimum temperature, and (ii) the wettest moisture treatment, which perhaps was oxygen-limited. In an analysis of persistence of standing stems (Steiner et al., 1994), precipitation and air temperature served as reasonable parameters to normalize climatic effects over time, similar to the model of Stroo et al. (1989). For surface-placed bagged residue decomposition studies, a precipitation-based index performed as well as a soil water content-based index to normalize environmental conditions across irrigation treatments (Schomberg et al., 1996).

Small grains are predominant crops in the Great Plains and the Pacific Northwest regions of the USA, and managing small-grain residue is critical to controlling wind erosion in these regions. Small grains are also important in Upper Midwest and southeastern cropping systems, contributing to the control of water erosion because of the good groundcover and relatively slow decomposition rates of the residues, compared with those of other crops grown in these regions. Smith and Peckenpaugh (1985) measured the decomposition rate of 23 small grain straws in bags buried 15 cm at Kimberly, Idaho. They reported 54 to 75% decomposition during a 384-d period, with hard red winter wheat and triticale (*Triticale hexaploides* Lart.) straw decomposing faster than soft white wheat or barley straw. Decomposition rate for these varieties was not consistently related to the C/N ratio (33:199) or N concentration (2.2–12.5 g kg<sup>-1</sup>) of the initial residues.

Clark (1968) reviewed literature regarding the *rate of addition* effect (varying amounts of fine plant material mixed with a constant volume of soil) on soil organic matter decomposition that indicated an inverse relationship of the rate of addition to the decomposition rate. However, studies on the related *soil volume effect* (a constant amount of plant material mixed with varying amounts of soil) indicated a decrease in percent-C evolved as CO<sub>2</sub> as soil increased, an apparent contradiction to the rate of addition studies. Jenkinson (1971) reviewed C-14 studies and found mixed results, but concluded that when the rate of addition does not exceed about 1.5% of the dry weight of the soil, the decomposition rate can be assumed to be independent of the quantity of plant material added. In subsequent work, Jenkinson (1977) reported that the percent labeled-C evolved as CO<sub>2</sub> tended to increase slightly as the rate of addition increased, but concluded that except for short-term incubations of N-poor material, percentage decomposition of organic matter in the soil would be substantially independent of loading rate.

Brown and Dickey (1970) reported that percentage mass loss was inversely related to the initial amount (1121–6726 kg ha<sup>-1</sup> equivalent) of bagged wheat straw in above-soil, soil-surface, and buried-field exposures. Stott et al. (1990) also reported an inverse relationship of initial wheat straw biomass (1680–6000 kg ha<sup>-1</sup>) to percentage mass loss using grab samples from no-tillage fields. Stroo et al. (1989) reported that surface-placed

**Table 1. Growing season treatments used to produce three residue biomass densities at harvest for small grain decomposition plots.**

Density	Seeding rate	Fertilizer <sup>†</sup> (N, P)	Growing season irrigation	Biomass at maturity	Non-grain biomass	Head number
	kg ha <sup>-1</sup>		mm	g m <sup>-2</sup>		m <sup>-2</sup>
Barley (winter)						
High	112	135, 168	435	750 (50) <sup>‡</sup>	480 (31)	360 (44)
Medium	84	55, 168	335	480 (23)	330 (33)	300 (23)
Low	67	0, 168	95	270 (52)	207 (28)	180 (71)
Oat (spring)						
High	112	135, 168	320	450 (75)	290 (40)	300 (25)
Medium	84	55, 168	235	420 (23)	260 (12)	370 (7)
Low	67	0, 168	95	250 (66)	140 (39)	200 (57)
Spring Wheat						
High	112	135, 168	320	700 (4)	460 (15)	340 (15)
Medium	84	55, 168	235	510 (81)	320 (54)	230 (7)
Low	67	0, 168	95	310 (102)	190 (63)	150 (20)
Winter Wheat						
High	112	135, 168	435	840 (174)	500 (97)	560 (152)
Medium	84	55, 168	335	600 (19)	360 (25)	500 (27)
Low	67	0, 168	95	350 (82)	250 (42)	330 (76)

<sup>†</sup> Fertilizer N was applied as anhydrous ammonia, and P as triple super phosphate (0-46-0).

<sup>‡</sup> Mean (standard deviation).

wheat straw (1- to 2-cm segments) decomposed faster for 1500 and 3000 kg ha<sup>-1</sup> rates than for 6000 kg ha<sup>-1</sup>, based on percent-C evolved as CO<sub>2</sub> in laboratory studies. In contrast, Wagner-Riddle et al. (1996) reported a linear relationship between time and fraction of initial mass remaining for rye (*Secale cereale*) cover crops (1–8 Mg ha<sup>-1</sup>, across years, sites, and treatments), which implies no impact of initial residue mass on decomposition rate. Parr and Papendick (1978) summarized literature from laboratory and field studies that indicated that residue decomposition is inversely related to the amount of residue, but concluded that mechanisms, processes, and relationships to explain such a relationship were lacking, which is still the case today.

Because of the importance of small grains for conservation cropping systems, we established a study to improve our understanding of residue decomposition of four small grains in varying field environments. Our overall goal is to develop simple decomposition models that can be applied across a wide range of climates and management systems. Specific objectives of this paper are to determine residue-density effects and temperature and moisture limitations on small grain residue decomposition, and to normalize field environments to environmental conditions that produce maximum decomposition rates.

## MATERIALS AND METHODS

### Field Experiments

Crop residue biomass was monitored for 14 mo for winter wheat (*Triticum aestivum* L.) 'TAM-107'<sup>1</sup>, spring wheat 'Oslo', winter barley (*Hordeum vulgare* L.) 'Post', and spring oat (*Avena sativa* L.) 'Lew' at the USDA-ARS, Conservation and Production Research Laboratory, Bushland, TX (35°N, 102°W, elevation of 1170 m, mean annual precipitation of 476 mm, mean annual temperature of 13.3°C). Crops were grown on a Pullman clay loam (fine, mixed thermic Torrertic Paleustoll) in 0.25-m rows, oriented north-south as described by Steiner

et al. (1994). In summary, twelve 12- by 70-m main plots were arranged in three randomized complete blocks of the four crops. Before this study, all plots had been uniformly cropped to dryland sorghum [*Sorghum bicolor* (L.) Moench]. Each main plot was split into three subplots before planting, to establish density treatments with minimal irrigation pipe and labor required to flood-irrigate level-border plots. High (H), medium (M), and low (L) initial crop-residue biomass densities were obtained for each crop by differentially managing seeding rate, fertilization, and growing-season irrigation (Table 1). The L-treatment plots received an establishment irrigation (13 December for fall-sown crops and 2 April for spring-sown crops). The H-treatment plots were irrigated when about 50% of plant-available water was depleted, as determined by neutron probe readings from access tubes centered in each subplot (10 December for fall-sown crops and 18 March, 12 April, and 2 May for all crops). The M-density plots received irrigations on 12 December (fall-sown crops), 5 April, and 14 May. Grain was harvested from all crops during June 1991.

To provide a range of environments during the decomposition phase of the study, each crop-density subplot was divided into thirds with berms for treatments consisting of no-irrigation, full-irrigation, and alternate-date irrigation treatments, randomly assigned to sub-subplots. Full-irrigation sub-subplots were irrigated to maintain a moist surface (as often as weekly) with the minimum amount of water (about 50 mm) required to flow across a 12- by 22-m sub-subplot. Full-irrigation plots were irrigated on 49, 59, 77, 82, 160, 114, 168, 269, 281, 292, 346, 382, and 388 days after harvest (DAH), while alternate-date irrigation plots were irrigated 58, 107, 169, 282, and 387 DAH. We did not irrigate when the daily mean air temperature was at or near freezing.

Ten 1.0- by 1.0-m sites were established in controlled traffic areas of each sub-subplot. Sample sites were from rows centered during planting and harvest operations, to minimize variability among samples. At approximately 60-d intervals, residue biomass was measured from one site per sub-subplot. Initial biomass was measured in July 1991 (24 DAH) and additional samples were collected about 92, 156, 224, 301, 365, and 401 DAH (biomass sampling required more than one day, depending on the age of the residue and labor availability).

We used the following procedure for a biomass sample collection. Intact stems that were *fallen* or leaning near the ground at an angle of 10° or less were collected. The remaining intact *standing* stems were counted and collected by cutting or lifting them from the soil. Remaining *surface* biomass was collected with as little soil as possible. Any remaining *dirty*

<sup>1</sup> Reference to a trade or company name is for specific information only and does not imply approval or recommendation by the USDA to the exclusion of others that may be suitable.

residue was raked and picked up by hand. This fraction contained a high percentage of soil and a small proportion of the total residue mass.

The fallen, standing, and surface components were sieved on a 1-mm fiberglass screen to remove soil. Soil and residue that passed the screen was added to the dirty fraction from that plot. The dirty fraction was washed on 0.5-mm screens under an array of spray nozzles (6-mm nozzles mounted 0.25 m above the sample trays produced a 0.5-m diam. conical pattern, with an average flow rate of 0.1 L s<sup>-1</sup>, at 330 kPa). This was the lowest force that maintained an even pattern without producing splash. Wash time was about 2 to 5 min, using the least water possible to minimize leaching. All components were dried at 60°C and weighed. Samples were ground to pass a 0.635-mm screen and subsamples were weighed, ashed in a muffle furnace at 500°C for 4 h, and weighed to determine the soil fraction of the sample. Residue mass for the fallen, surface, and dirty fractions were corrected to ash-free mass and summed with standing-stem mass to obtain the total crop-residue mass ( $M_t$ ).

Rainfall ( $P$ , in mm) was measured in a standard weather service rain gauge about 50 m east of the experimental area. Daily mean, maximum, and minimum air temperatures ( $T$ , in °C) at 2 m were measured either at the experimental area or at a Class A weather station located 1 km east of the experimental site.

### Calculating Decomposition Days

We used the concept of a decomposition day (DD) to normalize time based on climatic conditions, similar to the environmental coefficients developed by Stroo et al. (1989). Assuming that the most important environmental factors for decomposition are temperature and moisture, we calculated daily temperature and moisture coefficients. Each coefficient is constrained from 0 to 1, with 1 indicating conditions for maximum decomposition and 0 indicating no decomposition. Based on the principle of *most limiting factor*, the lower of two coefficients was used to represent the fractional decomposition for a given day, relative to a day at optimum conditions.

As described by Steiner et al. (1994), the precipitation coefficient is triggered by precipitation (or irrigation) and declines until the next event. Based on Schomberg et al. (1996), we decreased the coefficient to 40% of the previous day's value (giving the equivalent of about 1.66 *optimum moisture days* for each precipitation event that exceeded 4 mm, assuming moisture decreased to a negligible level after 7 d without rewetting). The value of 4 mm used as a threshold is adequate to fully wet even dense layers of surface residues (Schreiber, 1985; Savabi and Stott, 1995) and moisten the underlying soil (precipitation coefficient [PC] = 1, when precipitation  $\geq$  4 mm). Smaller amounts of precipitation are assumed to be intercepted by the residue layer where they dry relatively quickly and the initial coefficient is calculated as PC = precipitation/4. If another precipitation or irrigation event occurs during the decay of the PC coefficient over time, PC is reset based on precipitation amount.

The temperature coefficient (TC) was calculated (Eq. [1]) after Stroo et al. (1989):

$$TC = \frac{2(T + A)^2 (T_{opt} + A)^2 - (T + A)^4}{(T_{opt} + A)^4} \quad [1]$$

where  $T$  is the daily average air temperature;  $T_{opt} = 32^\circ\text{C}$ , and  $A = 0$ . The equation must be constrained to remain at 0 when  $T < A$ ; otherwise, it increases with decreasing low temperatures.

The daily fractional decomposition day was set equal to the minimum of temperature or moisture coefficient for that day,

and accumulated as DDs to normalize the *time scale* to environmental conditions.

### Determining Decomposition Coefficients

First-order exponential decomposition rates were determined using Eq. [2]:

$$M_t/M_0 = \exp^{-k(\text{DD})} \quad [2]$$

where  $M_t$  is total biomass at time  $t$ ,  $M_0$  is the initial biomass, and  $k$  is the decomposition coefficient ( $\text{g g}^{-1} \text{DD}^{-1}$ ), and DD is the decomposition days. The initial biomass was that collected on 24 DAH. Because decomposition period irrigation treatments had not been initiated at that time, only sub-subplots to be fully irrigated were sampled and that value was used for the other two irrigation sub-subplots. The 24 DAH biomass data for spring wheat plots were anomalously low, based on higher subsequent residue biomass samples and on higher values obtained from preharvest yield samples. Using a linear relationship developed from barley, oat, and winter wheat data for the preharvest and 24 DAH data, initial residue for spring wheat ( $M_{24}$ ) was estimated for each plot based on the preharvest mass ( $M_h$ ) as  $M_{24} = 1.43 M_h$ ,  $r^2 = 0.97$ . The slope  $> 1$  indicates that biomass passing through the combine was concentrated in the sampling rows. Residue distribution can be strongly affected by wind direction and speed, as described by Allmaras et al. (1985), and in our experiment, different crops were harvested on different days as they reached harvest maturity.

### Statistical Analysis

Analysis of variance of preharvest plant data and the initial biomass data (24 DAH) were conducted using the General Linear Models (GLM) Procedure of SAS (1989) with crop treatments as whole plots, and density treatments as strip plots with three replications. Analysis of variance of residue data on 224 and 404 DAH were also conducted using the GLM procedure in SAS (1989) for crop, density, and irrigation treatments and interactions as a strip-split plot design with three replications. The decomposition coefficient,  $k$ , was determined for each sub-subplot using the MODEL procedure in SAS (1988). Crop, initial biomass density, and decomposition-period irrigation treatment effects on  $k$  were analyzed using the GLM procedure of SAS (1989). The Correlation (CORR) Procedure (SAS, 1989) was used to determine correlation coefficients between  $k$  and initial residue properties. The heterogeneity of slopes was tested using the procedure described by Freund et al. (1986) solving linear models within the GLM procedure of SAS.

## RESULTS AND DISCUSSION

The growing-season treatments (Table 1) provided a reasonable range to represent high to low small-grain

**Table 2. Significance level of crop and density treatment effects on small grain residue samples collected on 24 d after harvest.**

Parameter	Crop	Density	Crop × density
			$P <$
Total mass ( $\text{g m}^{-1}$ )	0.0001	0.0008	0.0001
Standing mass ( $\text{g m}^{-1}$ )	0.0001	0.0001	0.0018
Surface mass ( $\text{g m}^{-1}$ )	0.0003	0.0144	0.0044
Fraction standing ( $\text{g g}^{-1}$ )	0.0024	0.0140	0.0044
Stem number ( $\text{m}^{-2}$ )	0.0001	0.0067	0.0033
Stem weight ( $\text{g stem}^{-1}$ )	0.0256	0.1357	0.5528
Standing mass N concentration ( $\text{mg g}^{-1}$ )	0.0099	0.0347	0.0178
Surface mass N concentration ( $\text{mg g}^{-1}$ )	0.4336	0.4226	0.0009

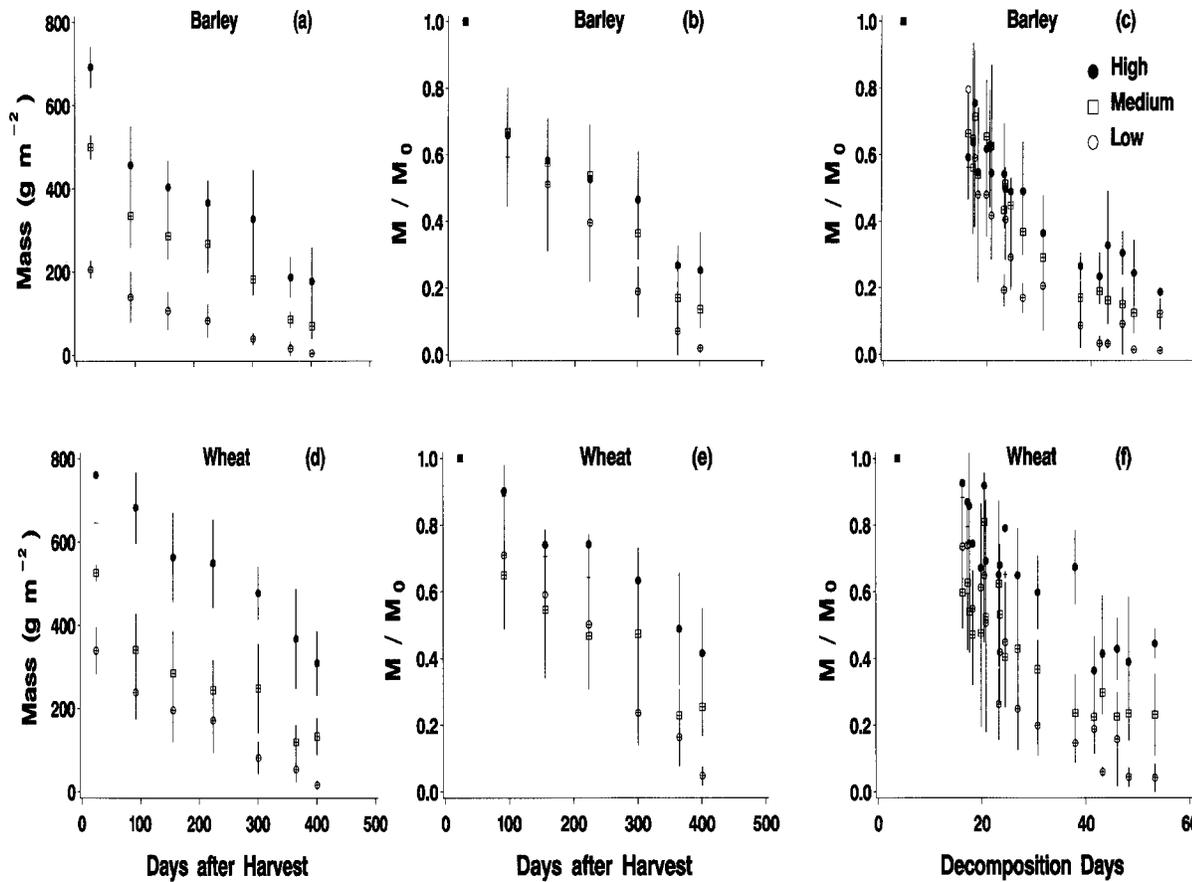


Fig. 1. Decomposition of barley and winter wheat residue, shown as mass vs. days after harvest (a and d); normalized mass ( $M/M_0$ ) vs. days after harvest (b and e); and normalized mass vs. decomposition days (c and f). Symbols are means and lines represent plus or minus one SE. For a, b, d, and e there are nine observations per mean (three irrigation  $\times$  three replications), and for c and f there are three observations per mean (replications).

biomass at maturity ( $840\text{--}250\text{ g m}^{-2}$ ), nongrain biomass ( $500\text{ to }<150\text{ g m}^{-2}$ ), and head number ( $560\text{--}150\text{ m}^{-2}$ ). The range of plant biomass achieved by density treatments was least for the oat crop, with high- and medium-management strategies producing similar biomass and head numbers. Growing-season crop and density treatments affected several properties of the residue at the initial biomass sampling on 24 DAH (Table 2) but significant interactions occurred between main treatment effects. A primary interaction was similar H and M biomass for oat, compared with a range of values for the

other crops. Another significant interaction was a very low proportion of surface biomass in the spring wheat crop, compared with the total biomass for those plots, relative to other crops. Across treatments, the trend was for the highest N concentration in standing biomass in the L-density treatment, but the L-density spring wheat had one of the lowest standing biomass N concentration levels of the experiment.

Decomposition of barley and winter wheat are shown in Fig. 1 (spring wheat and oat show similar trends, data not shown). Total biomass vs. days after harvest (Fig.

Table 3. Significance level of Crop (C), Density (D), and Irrigation (I) treatment effects on small gain residue samples collected on 224 and 404 days after harvest.

Parameter	Crop	Density	C $\times$ D	Irrigation	C $\times$ I	D $\times$ I	C $\times$ D $\times$ I
$P <$							
224 d after harvest							
Total mass ( $\text{g m}^{-1}$ )	0.0154	0.0001	0.0001	0.0131	0.5841	0.4559	0.8135
Standing mass ( $\text{g m}^{-1}$ )	0.0071	0.0485	0.2192	0.0001	0.0001	0.0810	0.0010
Fallen mass ( $\text{g m}^{-1}$ )	0.0789	0.0242	0.0933	0.0088	0.3246	0.3909	0.1169
Surface mass ( $\text{g m}^{-1}$ )	0.0128	0.0003	0.0003	0.1154	0.8173	0.4408	0.2280
Stem number ( $\text{m}^{-2}$ )	0.0337	0.1050	0.4894	0.0001	0.0099	0.1913	0.0399
404 d after harvest							
Total mass ( $\text{g m}^{-1}$ )	0.0043	0.0008	0.0003	0.0009	0.4045	0.1470	0.2639
Standing mass ( $\text{g m}^{-1}$ )	0.0104	0.0598	0.0092	0.0021	0.0092	0.0052	0.0985
Fallen mass ( $\text{g m}^{-1}$ )	0.0202	0.0007	0.0043	0.0312	0.6669	0.3706	0.3928
Surface mass ( $\text{g m}^{-1}$ )	0.1765	0.0130	0.0429	0.6833	1.0000	0.9106	0.9489
Stem number ( $\text{m}^{-2}$ )	0.0007	0.0430	0.0071	0.0079	0.1787	0.1152	0.4838

**Table 4. Summary of the analysis of variance of crop, density, and irrigation main† effects on the decomposition coefficient, *k*, of small grain residues.**

Source	df	SS(III)	MS	<i>F</i>	<i>P</i> > <i>F</i>
Crop	3	0.00120070	0.00040023	4.28	0.062
Density	2	0.00370847	0.00185424	20.82	0.008
Irrigation	2	0.00003893	0.00001946	0.84	0.446
Crop × Block‡	6	0.00056103	0.00009350		
Density × Block‡	12	0.00035619	0.00008905		
Crop × Density × Irrig. × Block‡	24	0.00069864	0.00002911		

† Crop × Density, Crop × Irrigation, Density × Irrigation, and Crop × Density × Irrigation interactions are not significant at *P* < 0.46, 0.62, 0.99, and 0.90, respectively.

‡ Error terms for main effects.

1a and d) show the range of initial biomass obtained and the decline of mass over time. To develop a more general relationship describing decomposition, mass for each date was normalized to initial mass for each plot; but irrigation treatment effects resulted in a large range in the fraction of mass remaining on any given day after harvest (Fig. 1b and e). In field environments, decomposition does not occur uniformly over time, but instead occurs when temperature and moisture conditions support biological activity or when precipitation leaches soluble material. When the time scale was normalized for environmental conditions using decomposition days, irrigation treatments converged, and the remaining variability appears to be related to density treatments (Fig. 1c and f).

Table 3 summarizes the analysis of variance of treatment effects on standing, fallen, surface, and total mass for samples from 224 DAH (the first post-winter sample) and 404 DAH (the final sample). As expected, crop, density, and irrigation treatments significantly affected most residue biomass components; and as expected, there were interactions among main effects. On 224 DAH, the two drier irrigation treatments had more biomass remaining (240 g m<sup>-1</sup>) than the wettest irrigation treatment (213 g m<sup>-1</sup>). Though they had essentially the same total biomass, unirrigated plots had more standing stems and more biomass standing than intermediate-irrigation plots. The intermediate-irrigation treatment

had more fallen biomass than the other treatments, presumably because fewer stems fell in the unirrigated plots, and stems that fell decomposed faster in the frequently irrigated plots (both irrigated treatments had similar initial standing-stem number and standing biomass, data not shown). On 404 DAH, the two irrigated treatments had similar biomass in all components, but dryland plots retained more standing stems and more standing and fallen biomass (data not shown).

The analysis of variance of treatment effects on the decomposition coefficient, *k*, is summarized in Table 4. Irrigation did not significantly affect *k* because of the normalization through use of DD; therefore, coefficients were determined again for crop (typically the only consideration for model inputs) and crop-density combinations (Table 5). The lower *k* indicates that decomposition for hard red winter wheat was slower than for barley, oat, and spring wheat. This differs from Smith and Peckenpaugh's (1986) report that hard red wheat (winter and spring varieties) decomposed faster than barley. Our spring wheat was a hard red variety and decomposed at a rate similar to barley. The overall average *k*-value across crop and density treatments (0.033 g g<sup>-1</sup> DD<sup>-1</sup>) could be used to estimate the decomposition rate of small grains when specific empirical data to calculate a *k*-value are not available.

The *k*-values indicate an inverse relationship to density (larger *k* and faster relative decomposition rates with lower initial biomass). Correlation analysis of *k* to initial residue properties (Table 6) indicated that initial biomass had the strongest relationship (*r* = -0.49) to *k*-values, followed by the fraction of biomass standing (*r* = -0.37) and N concentration in the standing biomass (*r* = 0.32). Residue quality is known to have a positive influence on decomposition rate, but the range of N concentration in these materials was relatively low. Treatment effects on N concentration were consistently related to patterns of *k*. For example, winter wheat

**Table 5. Crop decomposition coefficient (*k*) fit by crop, density, and crop × density treatments.**

Crop	Density	<i>n</i>	<i>k</i>
			g g <sup>-1</sup> DD <sup>-1</sup> †
Barley		27	0.035‡
Oat		27	0.033
Spring wheat		27	0.037
Winter wheat		27	0.028
	H	36	0.027†
	M	36	0.032
	L	36	0.041
Barley	H	9	0.028
Barley	M	9	0.032
Barley	L	9	0.042
Oat	H	9	0.031
Oat	M	9	0.028
Oat	L	9	0.041
Spring wheat	H	9	0.032
Spring wheat	M	9	0.035
Spring wheat	L	9	0.039
Winter wheat	H	9	0.015
Winter wheat	M	9	0.030
Winter wheat	L	9	0.036

† DD, decomposition day.

‡ LSD for *k* coefficient by crop is 0.006, and by density is 0.002.

**Table 6. Correlation coefficients of *k* with initial residue properties, measured 24 d after harvest.**

	<i>k</i>	Surface N	Standing N	Initial biomass	Fraction standing
	<i>r</i>				
<i>k</i>	1.00	0.16	0.32***	-0.49***	-0.37***
Surface N		1.00	0.52***	-0.15	0.01
Standing N			1.00	-0.40***	0.07
Initial biomass				1.00	-0.03
Fraction standing					1.00

\*\*\* Significant at *P* < 0.001, *n* = 108.

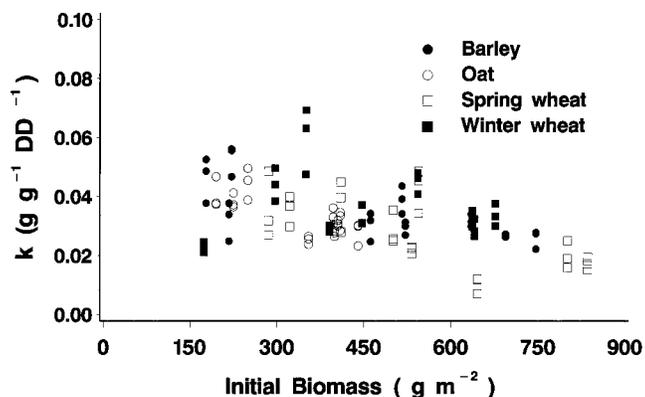


Fig. 2. Decomposition coefficients ( $k$ ) of barley, oat, spring wheat, and winter wheat as a function of initial biomass.

had the lowest N concentration of all the crops and decomposed at the slowest rate of all crops. In addition, there was a trend of the highest N for the L-density plots ( $9.9 \text{ mg g}^{-1}$ ) compared with M-density ( $9.1 \text{ mg g}^{-1}$ ) and H-density plots ( $8.1 \text{ mg g}^{-1}$ ), but the range was very small relative to the magnitude of the range in  $k$ .

To further investigate the biomass effect, we plotted the initial biomass of each plot to  $k$  (Fig. 2) and analyzed the relationship of  $M_0$  to  $k$  (Freund et al., 1986). Intercepts of linear regressions were not significantly different for the crops (data not shown), so we restricted intercepts to be equal and tested for heterogeneity of slopes across crops. For all crops, the decomposition coefficient decreased as initial mass increased, as indicated by the significant negative slopes of the regressions (Table 7). The slope of the equation for oat was not significantly different from that for winter wheat ( $P < 0.335$ ); but barley ( $P < 0.054$ ) and spring wheat ( $P < 0.001$ ) had smaller slopes than winter wheat, indicating less dependence of decomposition rate on initial biomass. The dependence of  $k$  on  $M_0$  is not reflected in the residue decomposition models of major erosion models (Stott et al., 1995; Foster, 1991; Hagen, 1991), nor to our knowledge in other natural resource models.

The results of our study support findings in the literature of an inverse relationship between the rate of loading and the percent decomposition, reported for a variety of controlled-environment and field studies, for which the mechanism has not been identified. An alternate explanation for the strong impact of the density treatments on the decomposition rate coefficient is that the use of climate factors to normalize the time scale for environmental conditions was inadequate. Our analysis assumed that all residues had the same temperature environment (based on air temperature) and that there was no interaction between residue density and the moisture environment. Both of these assumptions are questionable, and the simplified assumption that climate factors can be used to characterize decomposition environments in surface residue–soil systems might need further development. However, it is more difficult to measure and simulate temperature and moisture conditions in the near-surface soil layer and within the residue layer than to obtain representative air temperature and rainfall data. When climate data are the only data avail-

Table 7. Test of the heterogeneity of slopes across crops for the linear regression of decomposition coefficient ( $k$ ) on initial biomass ( $M_0$ ).

Parameter	Estimate of parameter	$t$	$P > t$	SEE $\ddagger$
Intercept $\S$	0.0476376	18.78	0.0001	0.00253673
Slope: Barley	-0.00002817	5.00	0.0001	0.00000564
Slope: Oat	-0.00004279	5.08	0.0001	0.00000843
Slope: Spring wheat	-0.00002153	3.62	0.0005	0.00000595
Slope: Winter wheat	-0.00003677	7.18	0.0001	0.00000512

$\dagger$  Equation tested:  $k = a + b (M_0)$ .

$\ddagger$  Standard error of the estimate.

$\S$  The unrestricted analysis indicated that the intercepts for barley, oat, and spring wheat were not different from the intercept for winter wheat at  $P = 0.99, 0.74,$  and  $0.14,$  respectively, so the relationships were analyzed with the restriction that all equations have the same intercept.

able, the decomposition day provides considerably more insight into rate-controlling factors to decomposition than simply using a time scale.

In our study, the lowest residue-density treatments provided a relatively thin layer in which a high proportion of residue elements were in contact with the soil, as well as with other residue elements or the atmosphere. For the high-density plots, the residue layer was quite thick ( $\approx 10 \text{ cm}$  or more, initially), and a high proportion of the residue elements was in contact only with the atmosphere or other residue elements, not directly with soil. It is widely recognized that conditions in the soil are much more favorable to decomposition than conditions on the soil surface, and one hypothesis could be that the degree to which residue elements equilibrate with soil vs. atmospheric conditions might be related to residue mass.

Overall, decomposition coefficients calculated from these field data are higher than those derived from a laboratory study where components of wheat residue (stem, leaf sheath, chaff, and leaf) were mixed and decomposed at  $20^\circ\text{C}$ , resulting in a  $k$ -value of 0.015 (Collins et al., 1991). However,  $20^\circ\text{C}$  produces a TC of 0.63, and if the laboratory  $k$ -value is adjusted by 0.63, the resulting 0.024 is very similar to the value of 0.028 for wheat in Table 5.

## CONCLUSIONS

The strategy used to predict residue decomposition using a decomposition-day concept appears reasonable, based on field observations of small-grain residue decomposition. In particular, irrigation treatments during the decomposition period were accounted for by the moisture factor in the decomposition-day calculation. However, using only climatic parameters to calculate DDs did not adequately account for the differences found with different amounts of residue. This indicates that if decomposition is being calculated in a model that provides soil water content or potential and soil temperature near the surface, this might provide better environmental drivers than climate data. Under the same climatic conditions, relative decomposition rate (percent of initial) was faster from lower initial biomass plots than from plots with higher initial biomass. Additional work is needed to characterize relative impacts of weather and soil on residue moisture and temperature

environments at various residue densities. Until that time, decomposition models will likely continue to be applied without regard to the effect of initial residue mass on decomposition rate and may overestimate residue amount and cover for cropping systems and environments that do not produce large amount of plant biomass and residue at harvest. Our data indicate slow decomposition of standing biomass, so if the residue amount is limited, then managing the harvest equipment to leave as much residue standing as possible may enhance the effects of the residue biomass to provide surface mulch and protect soil from erosion.

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