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Carbon and Nitrogen Mineralization and Persistence of Organic Residues under Conservation and Conventional Tillage

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Crop Residues

ABSTRACT

A combination of high biomass cover crops with organic mulches may be an option for no-till vegetable production, but information on mineralization rates from these residues is lacking. The objective of this study was to assess nutrient release rates and persistence from mimosa (*Albizia julibrissin* Durazz.), lespedeza [*Lespedeza cuneata* (Dum. Cours.) G. Don], oat (*Avena sativa* L.) straw, and soybean [*Glycine max* (L.) Merr.] residues under conventional and conservation tillage. The experiment was conducted in Tallassee, AL using litterbag methodology in a split-plot design (main plots: two tillage systems; subplots: four residue types). Comparison of rate constants showed that labile portions of residues was more affected by tillage than recalcitrant portions. In spring, mimosa residue contained 78 kg N ha^{-1} when buried the previous fall, compared to 123 kg N ha^{-1} when surface placed; soybean residue showed similar results (39 vs. 72 kg N ha^{-1}, respectively). Results were similar for lespedeza (72 vs. 101 kg N ha^{-1}, respectively), but not for oat straw (24 vs. 26 kg N ha^{-1}, respectively). After 1 yr, surface placed mimosa residue mineralized 33% of initial N compared to 71% when buried, while surface placed lespedeza mineralized 36% of initial N compared to 64% when buried. Soybean residue mineralized N quickly regardless of placement (73 vs. 87%, respectively). This study demonstrates that cut-and-carry mulches may be used under conservation tillage for the enhancement of soil organic matter (SOM), soil organic carbon (SOC), and soil N status.

Traditionally, organic and other limited-input vegetable producers use cultivation or hand weeding for weed control. Feasible methods of weed control in organic conservation tillage systems also include brush weeding, mowing, cutting, flaming (Bond and Grundy, 2001; Peigne et al., 2007), and the use of plastic, fabric, or organic mulches (Feldman et al., 2000). One alternative to tillage for weed control is the utilization of high biomass cover crops and organic mulches. Applied in sufficient quantities, high biomass residues, either grown as cover crops or applied as mulches, have been shown to suppress weeds, limit erosion, and conserve soil moisture (Rathore et al., 1998).

Mulches may include living mulches, plastic, paper, or loose organic materials and are employed primarily for weed control. Living mulches are mainly used for perennial crop production (Ingels et al., 1994), and require careful selection and management to limit competition with the main crop (Costello and Altieri, 1994). Woven polypropylene mulches are also used for persistent weed control in perennial crops (Bond and Grundy, 2001). Polyethylene plastic mulches are widely used for both conventional and organic vegetable production, but cleanup and disposal are problematic. Paper mulches have been shown to suppress weeds in transplanted vegetable production, with control similar to that of black plastic (Runham and Town, 1995). Most annual and some perennial weeds were suppressed using 0.8 to 1.4 t ha^{-1} of shredded newspaper during sweet corn [*Zea mays* L., var. Saccharata (Surt.)], field corn (*Z. mays* L.), soybean, and tomato (*Lycopersicon esculentum* Mill.) production (Munn, 1992). Paper mulches are biodegradable, thereby eliminating the labor and cost associated with plastic mulch removal while improving environmental sustainability.

Loose organic mulches are also biodegradable, but have the advantage of releasing nutrients as they decompose. The quantity needed to suppress weeds may make them cost prohibitive if they are purchased and transported to the production area, but may be economically feasible if they are produced in situ (Merwin et al., 1995). It was found that using cut ryegrass (*Lolium* spp.) as mulch was more economical than cultivation for weed control during tomato and pepper (*Capsicum annuum* L.) production (Edwards et al., 1995). It is important to ensure that straw does not contain seeds to circumvent volunteer infestation (Yordanova and Shaban, 2007).

Decomposition of the organic mulch residue may have allelopathic effects on weeds as well as on the cash crop by releasing natural phytotoxins (Wallace and Bellinder, 1992). Russo et al. (1997) found that mulching with fresh kenaf (*Hibiscus cannabinus* L.) chips reduced cabbage (*Brassica oleracea* L.) yields but did not affect onion (*Allium cepa* L.) yields, a phenomenon tentatively attributed to allelopathy of the fresh mulch. The same study showed similar weed control between black plastic mulch and kenaf chips.

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Abbreviations: ADF, acid detergent fiber; ADL, acid detergent lignin; AFDW, ash free dry weight; AIA, acid insoluble ash; HC, hemicellulose; NDF, neutral detergent fiber; SOC, soil organic carbon; SOM, soil organic matter.

Additionally, the decomposition of C rich mulches such as straw may result in reduced N availability as the soil microbial community temporarily immobilizes ammonium and nitrate in competition with plants (Cheshire et al., 1999). The use of N rich mulches may circumvent this problem by lowering the C to N ratio, though residue with higher N contents tend to decompose faster. Therefore, it is desirable to strike a balance between mulch N content and mulch persistence. On the other hand, C rich mulches can reduce nitrate leaching after harvest via immobilization (Doring et al., 2005).

There is evidence that mulching several weeks after transplanting bell pepper (*Capsicum annuum*) can improve weed suppression mainly by improving mulch persistence later into the growing season (Law et al., 2006), but mulch application should be done with care to prevent lodging of the crop (Boyhan et al., 2006) and shading of prostrate crop growth (Pedreros et al., 2008). Inhibition of light transmittance appears to be the greatest factor for weed suppression by mulches (Steinmaus et al., 2008).

Decomposition of organic residue occurs in two phases. Initially, a labile portion of the residue, such as sugars, starches, and proteins, is readily consumed by soil microbes, leaving behind a recalcitrant portion of the residue, such as cellulose, fats, waxes, lignin, and tannins (Wieder and Lang, 1982). This recalcitrant portion is slowly decomposed and contributes to the development of SOM. Such decomposition systems are best described by double exponential decay models, with one exponential term describing labile portion decay and the other exponential term describing the recalcitrant portion of the residue (Wieder and Lang, 1982). The double exponential decay model is represented by the equation:

$$Y = Ae^{-k_1 t} + Be^{-k_2 t} \quad [1]$$

where Y is the nutrient or mass remaining, A is the labile portion, B is the recalcitrant portion, k_1 and k_2 are rate constants fitted to the data, and t is time in days after application. Such models have adequately described field litterbag decomposition studies in Haiti (Isaac et al., 2000). When litter decomposes quickly, resulting in a nearly linear response from the recalcitrant portion of the residue, k_2 becomes very small, and the double exponential decay model collapses into a single exponential decay model.

More research is needed before limited-input vegetable producers are able to widely adopt conservation tillage. Creative approaches to achieve adequate weed control may include the use of high-biomass winter cover crops, followed by high-biomass summer cover crops for fall vegetable production. If summer and winter cover crops, as well as organic mulches, are chosen carefully with regard to persistence and nutrient content, it seems possible to keep land agriculturally productive while simultaneously improving soil quality.

Previous work has demonstrated the feasibility of high biomass cover crop mulches under conservation tillage production systems. No-till, herbicide-free broccoli production under high biomass cover crops produced yields similar to conventional tillage without a cover crop in Maryland and Virginia (Abdul-Baki et al., 1997). Such a system could achieve even greater weed suppression by using organic mulches in conjunction with high biomass cover crops, such as forage soybean. Ideally, mulches may be grown in situ to minimize transportation costs. These mulches could be obtained from invasive species already present in the production area, such as lespedeza and mimosa cuttings, and used as mulch material before seeds become viable. Lespedeza and mimosa may achieve a balance between mulch persistence and N contribution due to the woody nature of the stems in conjunction with the N-rich leaves.

The objective was to quantify mass loss and C and N release rates from decomposing organic residues under conservation and conventional tillage. The hypotheses of this study are (i) in situ organic mulches can increase SOC and release N in synchronicity with crop needs and (ii) SOC and N synchronicity is increased by the application of in situ organic mulches under conservation tillage compared to conventional tillage.

MATERIALS AND METHODS

A field decomposition study was conducted at the E.V. Smith Research Center Plant Breeding Unit (32°29'17" N, 85°53'17" W, 65 m elevation) south of Tallassee, AL, on a Wickham fine sandy loam with 0 to 2% slopes (fine-loamy, mixed, semiactive, thermic Typic Hapludults). The study site soil had an initial pH (1:1 soil/H_2O) of 6.3, 0.088 g N kg^{-1} soil and 1.0 g C kg^{-1} soil on a dry weight basis. Four organic residues, lespedeza (cuttings taken at flowering), mimosa (leaves and stems <1 cm in diameter), oat straw, and soybean [*Glycine max* (L.) Merr. var. Stonewall, group VII] were obtained locally to supply residue. Air-dried residues were packed into nylon mesh bags measuring 20 by 10 cm with 50- to 60-μm openings at a rate equivalent to 6.7 Mg ha^{-1} (3.0 tons acre^{-1}) (28.3 g bag^{-1}) on an air-dry basis. While packing the bags, residues were kept as whole as possible. Fiber analyses were conducted on time zero mulch subsamples using detergent fiber procedures as described by Goering and Soest (1970).

The site was maintained under no-till for at least 3 yr before placement. Conventional till plots were disked immediately before placement. The treatments were arranged in a split-plot (main plots: two tillage types; subplots: four residue types) design with four replicates; 288 sealed litterbags were placed on the soil surface (to represent conservation tillage) or buried at 10-cm depth (to represent conventional tillage) on 9 Oct. 2007. The plots were irrigated periodically by gun as would normally be the case under vegetable production. Bags were periodically retrieved from the field at 0, 3.5, 7, 14, 28, 56, 112, 224, and 364 d after application. The contents of each bag were oven-dried and weighed for dry matter determination. Residues were then ground to pass a 16-mesh sieve and analyzed for total C and N by LECO TruSpec CN (Leco Corp, St. Joseph, MI). Sample contamination by soil was accounted for by converting all data to an ash-free dry weight basis by ashing approximately 1.0 g of the samples in muffle furnace at 400°C for 12 h and determining the ash-free dry weight (AFDW) (Cochran, 1991). Weather data was collected at the E.V. Smith Research Station in Alabama at 32°27' N, 85°53'17" W, 66 m above sea level.

Means, standard errors, and statistical significance of treatments were determined using mixed model procedures as implemented by Proc Glimmix (SAS Institute, 2003) at the 95% confidence level. The Slicediff option within Proc Glimmix was used to determine the differences of one effect within another effect (e.g., differences between residues holding placement constant, or vice-versa) at the 95% confidence level holding placement, residue type, and time as fixed effects. Time zero samples were truly replicated in the field and the data obtained from them were included in ANOVA procedures. Least squares estimates for nonlinear models were determined using four parameter double exponential decay models (Systat Software, 2008). The double exponential decay model served as the basis for comparison of N, C, and mass loss between conservation and conventional tillage in this study. Correlations were estimated using Proc Corr (SAS Institute, 2003). Pairwise comparisons of fiber analyses were made using orthogonal contrasts as implemented within Proc GLM (SAS Institute, 2003).

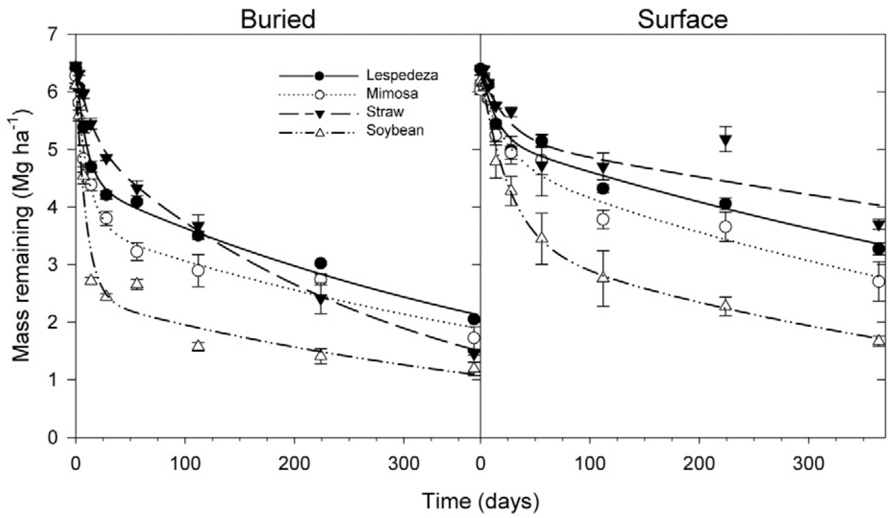

Fig. 1. Mass loss from surface and buried residue on an area basis. Residues were placed at a rate equivalent to 6.7 Mg ha^{-1} on an air-dried basis, but results are reported on an oven-dry basis. Error bars represent standard errors of the mean.

RESULTS AND DISCUSSION

Buried residue decomposed faster than surface residue, especially the labile portion. This was evidenced by the steeper slopes and the greater k_1 values (Fig. 1) (Table 1) during the initial decomposition phase compared to the recalcitrant phase. The slopes of the recalcitrant portions, however, tended not to differ much between buried and surface residue. This indicates that labile material in particular was more resistant to decay when residue was placed on the soil surface compared to burying it.

There is slight variation in the mass remaining at time = 0 d since different residues absorb atmospheric moisture at different rates. The parameters for double exponential decay curve equations that were fit to the data are shown in Table 1. Sometimes it is more convenient to represent decay patterns on a percent of original material basis such that researchers can easily convert for various amounts of residue in the field. For this reason, Table 1 also shows residue persistence normalized to 100% of initial AFDW. The normalized equations facilitate an approximation of the labile portion of the residue (A) and the recalcitrant portion (B) on a percent basis. Note that the decay rate constants do not change, only the coefficients. The difference in the rate of decay is apparent by comparing the k_1 and k_2 values from Eq. [1]. Buried residue exhibited faster mass loss in both the labile and recalcitrant portions of all residues, as shown by the greater rate constants k_1 and k_2 for buried material compared to surface residue (Table 1). However, the k_1 values tended to show a greater increase than the k_2 values (comparing buried to surface residue), evidence again that the labile portion exhibited the greatest increase in decay when buried. Isaac et al. (2000) also showed that in environments that facilitated rapid decomposition, the labile portion of residue was more affected than the recalcitrant portion. All regression equations were significant ($p < 0.02$) and were good approximations of the data (R^2_{adj}) (Table 1).

The ANOVA for mass loss on a per area basis showed that all effects (residue, placement, time, and their interactions) were significant ($p < 0.05$). The significant main effects and placement by residue interaction signified that not only did buried residue decompose faster than surface residue, but also that the effect varied by residue type. For example, the rate of mass loss for straw was disproportionately higher when buried in comparison to the other residues (Fig. 1). That is, whether one residue type decomposed faster than another residue type depended on placement.

Mass loss pairwise comparisons between residue placement (holding residue constant) showed that buried residues lost mass at a significantly faster rate than surface-placed residues ($p < 0.0001$) (Fig. 1). Pairwise comparisons of residue type (holding placement constant) showed that all residues decayed at significantly different rates from each other ($p < 0.04$). That is, each residue decomposed faster when it was buried compared to surface placed ($p < 0.0001$), and all residues decomposed at significantly different rates regardless of placement ($p < 0.04$). Similar findings have been reported elsewhere (Carter and Rennie, 1982; Skjemstad et al., 1997).

Buried C loss models (Fig. 2) appeared similar to buried mass loss models (Fig. 1) because most mass loss was due to microbial respiration of C (Wood and Edwards, 1992), which was then lost to the environment as CO_2. Conservation tillage has the effect of sequestering more C as SOM compared to conventional tillage, which results in greater microbial mineralization of SOC and respiration as CO_2. Since there is a direct relationship between SOM and SOC, producers interested in accumulation of SOM will find that conservation tillage will increase SOM content compared to conventional tillage (Balkcom et al., 2004). The results of this study imply that SOC, and by extension SOM, will accumulate over time if residues are applied annually. Should conservation tillage be employed over several years, the effect on SOM would be additive. That is, the accumulation of recalcitrant SOC over several years of conservation tillage would have the effect of increasing the SOM content in the surface horizons compared to conventional tillage. It is possible that the effect may not be noticeable after a single year, such as in the case of soybean residue, which retains less C when surface placed compared to other organic residues (Fig. 2). It has been reported that after 10 yr of conservation tillage in Crossville, AL (34°18′ N, 86°01′ W), SOC concentrations were 67% higher than conventionally tilled plots at the 0- to 10-cm depth (Wood and Edwards, 1992), so it seems reasonable that

Table 1. Equations regressed on time (days) for mass, C, and N loss from mulches incubated in litter bags under field conditions. Double exponential decay equations are of the form $Y = Ae^{-k1t} + Be^{-k2t}$, where Y = mass loss, A = the labile portion, B = the recalcitrant portion, k_1 and k_2 are rate constants fitted to the data, and t = time in days after application.

Parameter/species	Equation	$P > F$†	R^2_{adj}	S_{yx}‡
Mass buried, Mg ha^{-1}				
Lespedeza cuneata	$Y = 2.07e^{-0.1061X} + 4.44e^{-0.0020X}$	<0.0001	0.990	0.1
Albizia julibrissin§	$Y = 2.64e^{-0.0890X} + 3.67e^{-0.0018X}$	<0.0001	0.981	0.2
Avena sativa straw	$Y = 1.29e^{-0.0719X} + 5.24e^{-0.0034X}$	<0.0001	0.997	0.1
Glycine max	$Y = 3.93e^{-0.1063X} + 2.43e^{-0.0022X}$	0.0004	0.947	0.4
Mass surface, Mg ha^{-1}				
Lespedeza cuneata	$Y = 1.28e^{-0.0761X} + 5.20e^{-0.0012X}$	0.0002	0.959	0.2
Albizia julibrissin§	$Y = 1.34e^{-0.0428X} + 4.81e^{-0.0015X}$	0.0002	0.957	0.2
Avena sativa straw	$Y = 1.25e^{-0.0459X} + 5.20e^{-0.0007X}$	0.0129	0.784	0.4
Glycine max	$Y = 2.96e^{-0.0385X} + 3.42e^{-0.0019X}$	<0.0001	0.987	0.2
Mass buried, % remaining				
Lespedeza cuneata	$Y = 32.2e^{-0.1061X} + 69.2e^{-0.0020X}$	<0.0001	0.990	2.3
Albizia julibrissin§	$Y = 42.0e^{-0.0890X} + 58.4e^{-0.0018X}$	<0.0001	0.981	3.3
Avena sativa straw	$Y = 20.0e^{-0.0719X} + 81.3e^{-0.0034X}$	<0.0001	0.997	1.4
Glycine max	$Y = 64.3e^{-0.1063X} + 39.8e^{-0.0022X}$	0.0004	0.947	6.9
Mass surface, % remaining				
Lespedeza cuneata	$Y = 20.0e^{-0.0761X} + 81.3e^{-0.0012X}$	0.0002	0.959	3.4
Albizia julibrissin§	$Y = 22.2e^{-0.0428X} + 79.7e^{-0.0015X}$	0.0002	0.957	4.1
Avena sativa straw	$Y = 19.8e^{-0.0459X} + 82.2e^{-0.0007X}$	0.0129	0.784	6.6
Glycine max	$Y = 47.7e^{-0.0385X} + 55.3e^{-0.0019X}$	<0.0001	0.987	3.2
C buried, kg ha^{-1}				
Lespedeza cuneata	$Y = 673.8e^{-0.1173X} + 1980.4e^{-0.0029X}$	<0.0001	0.985	78.9
Albizia julibrissin§	$Y = 906.6e^{-0.1006X} + 1754.4e^{-0.0030X}$	<0.0001	0.997	38.5
Avena sativa straw	$Y = 210.2e^{-0.0952X} + 2276.1e^{-0.0046X}$	<0.0001	0.991	71.2
Glycine max	$Y = 1328.0e^{-0.1178X} + 1048.8e^{-0.0039X}$	0.0004	0.947	166
C surface, kg ha^{-1}				
Lespedeza cuneata	$Y = 257.0e^{-0.0911X} + 2373.3e^{-0.0018X}$	0.0005	0.942	116
Albizia julibrissin§	$Y = 274.4e^{-0.0461X} + 2291.0e^{-0.0020X}$	0.0002	0.960	103
Avena sativa straw	$Y = 288.9e^{-0.0280X} + 2162.6e^{-0.0012X}$	0.0014	0.913	116
Glycine max	$Y = 1030.5e^{-0.0298X} + 1313.1e^{-0.0021X}$	<0.0001	0.978	95.9
C buried, % remaining				
Lespedeza cuneata	$Y = 25.8e^{-0.1173X} + 75.8e^{-0.0029X}$	<0.0001	0.985	3.0
Albizia julibrissin§	$Y = 34.2e^{-0.1006X} + 66.2e^{-0.0030X}$	<0.0001	0.997	1.5
Avena sativa straw	$Y = 8.6e^{-0.0952X} + 93.0e^{-0.0046X}$	<0.0001	0.991	2.9
Glycine max	$Y = 58.2e^{-0.1178X} + 46.0e^{-0.0039X}$	0.0004	0.947	7.3
C surface, % remaining				
Lespedeza cuneata	$Y = 9.9e^{-0.0911X} + 91.5e^{-0.0018X}$	0.0005	0.942	4.5
Albizia julibrissin§	$Y = 11.0e^{-0.0461X} + 91.7e^{-0.0020X}$	0.0002	0.960	4.1
Avena sativa straw	$Y = 12.1e^{-0.0280X} + 90.8e^{-0.0012X}$	0.0014	0.913	4.9
Glycine max	$Y = 45.5e^{-0.0298X} + 57.9e^{-0.0021X}$	<0.0001	0.978	4.2
N buried, kg ha^{-1}				
Lespedeza cuneata	$Y = 61.9e^{-0.0028X} + 65.5e^{-0.0028X}$	0.0010	0.923	8.3
Albizia julibrissin§	$Y = 40.3e^{-0.3053X} + 132.6e^{-0.0026X}$	0.0010	0.922	10.7
Avena sativa straw	$Y = 8.4e^{-0.0005X} + 18.0e^{-0.0005X}$	0.9156	0.000	6.2
Glycine max	$Y = 104.4e^{-0.0873X} + 76.2e^{-0.0033X}$	0.0007	0.935	14.2
N surface, kg ha^{-1}				
Lespedeza cuneata	$Y = 61.9e^{-0.0012X} + 66.9e^{-0.0012X}$	0.0047	0.857	6.3
Albizia julibrissin§	$Y = 74.4e^{-0.0011X} + 79.3^{--0.0011X}$	0.0724	0.560	13.8
Avena sativa straw	$Y = 44.4e^{-0.0014X} - 20.6e^{-0.0053X}$	0.9008	0.000	4.3
Glycine max	$Y = 68.2e^{-0.0239X} + 114.0e^{-0.0023X}$	0.0003	0.956	10.4
N buried, % remaining				
Lespedeza cuneata	$Y = 47.3e^{-0.0028X} + 50.1e^{-0.0028X}$	0.0010	0.923	6.4
Albizia julibrissin§	$Y = 23.4e^{-0.3053X} + 77.0e^{-0.0026X}$	0.0010	0.922	6.2
Avena sativa straw	$Y = 29.7e^{-0.0005X} + 63.2e^{-0.0005X}$	0.9156	0.000	21.9
Glycine max	$Y = 62.0e^{-0.0873X} + 45.2e^{-0.0033X}$	0.0007	0.935	8.4
N surface, % remaining				
Lespedeza cuneata	$Y = 45.9e^{-0.0012X} + 49.6e^{-0.0012X}$	0.0047	0.857	4.7
Albizia julibrissin§	$Y = 47.3e^{-0.0011X} + 50.5e^{-0.0011X}$	0.0724	0.560	8.8
Avena sativa straw	$Y = 157.1e^{-0.0014X} - 72.8e^{-0.0053X}$	0.9008	0.000	15.4
Glycine max	$Y = 39.1e^{-0.0239X} + 65.4e^{-0.0023X}$	0.0003	0.956	6.0

† Significance of regression.

‡ Standard error of the estimate of *Y* on *X*.

§ Stems <1 cm in diameter.

SOC accumulation, if not observed after a single year, may show significant accumulation over a longer period of time after conversion to conservation tillage.

Buried residue exhibited faster C loss in both the labile and recalcitrant portions of all residues, as shown by the greater rate constants k_1 and k_2 for buried material compared to surface residue (Table 1). All regressions were significant ($p < 0.002$) with high R^2_{adj} values (Table 1). Carbon was sequestered longer when residue was left on the surface compared to residue incorporation, in both labile and recalcitrant portions of residue. This should result in greater SOM accumulation from surface residue over time compared to buried residue. On a more speculative note, in an age when producers may be compelled to participate in a C market, conservation tillage practices may provide producers with a C offset or credit, while also enhancing SOM. If or when a monetary value is associated with C sequestration, producers using conservation tillage may be able to avail themselves of the monetary benefit while simultaneously improving SOM and soil fertility.

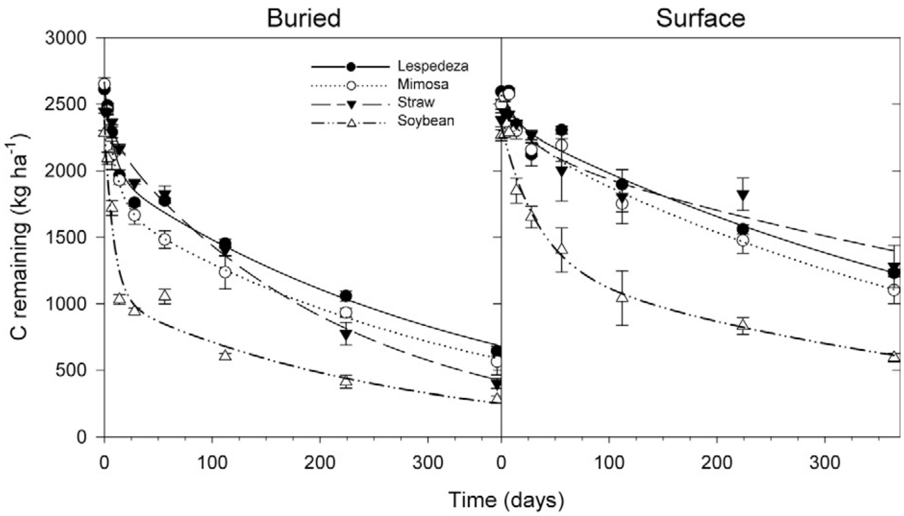

Fig. 2. Carbon loss from surface and buried residue on an area basis. Error bars represent standard errors of the mean.

All main effects for C loss were significant ($p < 0.0001$), although the interaction between placement and residue was not ($p = 0.2585$). Every residue had a significantly different C loss rate whether buried or surface placed ($p < 0.0001$). However, when residues were surface placed, only soybean residue lost C at a significantly higher rate than any of the other residues ($p < 0.0001$). In other words, lespedeza, mimosa, and oat straw all had statistically similar rates of C loss when placed on the soil surface. The effect can be seen in Fig. 2. When the residues were buried, only lespedeza and straw lost C at statistically similar rates ($p = 0.2942$).

When these data were normalized to represent C loss on a percent of original C remaining, a different story emerged. The interaction between placement and residue was significant ($p = 0.0158$), indicating that whether one residue type lost C at a significantly faster rate than another residue type depended on placement. In addition, only surface placed lespedeza and mimosa lost C at statistically similar rates ($p = 0.7217$). This is easily seen when graphed (data not shown) because the regression lines and data points are similar between surface-applied mimosa and lespedeza. When buried, all residues lost C at different rates ($p < 0.03$). As with mass loss, all residues lost C at different rates depending on whether they were surface placed or buried ($p < 0.0001$). As expected, the rate constants did not change depending on how the data is shown, either on an area or a percent (normalized) basis, but the coefficients did (Table 1). It is worth pointing out that the coefficients on a percent basis did not always add up to exactly 100. This is because the regression lines were fitted to the data, and in the attempt to model the data as closely as possible, the intercept can vary within a few percent of 100. The slight sacrifice in model accuracy near time zero should allow for a better fit of the model as time progresses compared to fixing the intercept to exactly 100.

Nitrogen loss from organic residues under conservation and conventional tillage on an area basis is shown in Fig. 3. The decay equations describing the data are shown in Table 1. Buried residue generally exhibited faster N loss in both the labile and recalcitrant portions of all residues. This is evidenced by the greater rate constants k_1 and k_2 for buried material compared to surface residue (Table 1), though notable rate constant exceptions exist in cases where the curve fit ($R^2_{adj.}$) is exceptionally low, such as in the case of straw, which had a low original N content and negligible labile N pool. For residues with an appreciable N content, the models described the data better. All regressions were significant regardless of placement, except for straw ($p > 0.9$) and surface placed mimosa ($p = 0.0724$, $R^2_{adj} = 0.56$). The reason for the relatively low fit for surface placed mimosa was likely due to outlying data points at time = 112 d (Fig. 3), where N content was just above 100% of the original N contained in mimosa residue. It appears

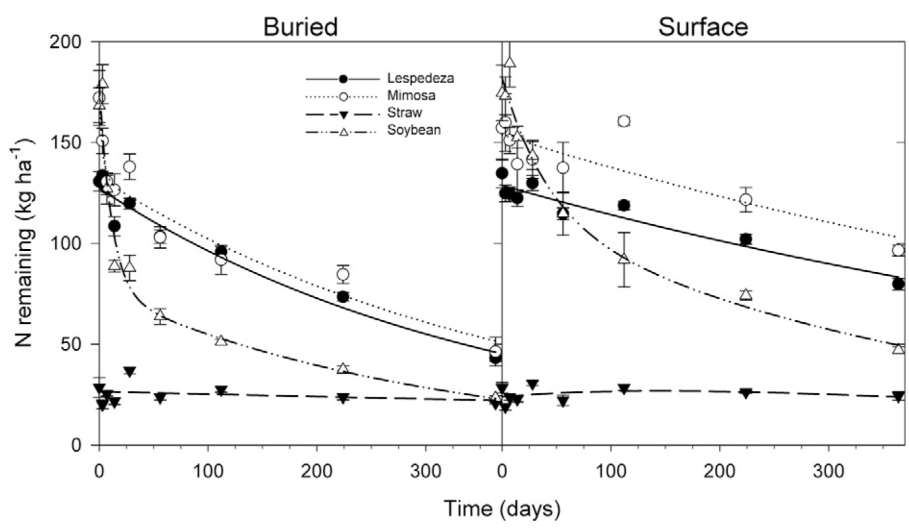

Fig. 3. Nitrogen loss from surface and buried residue on an area basis. Error bars represent standard errors of the mean.

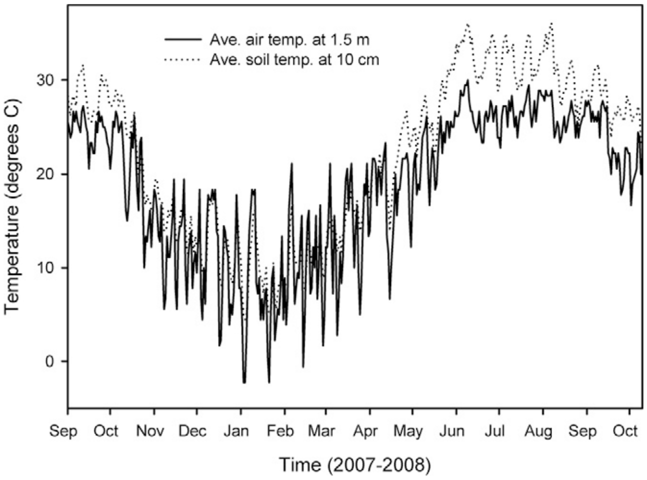

Fig. 4. Average air temperature at 1.5 m and soil temperature at a 10 cm depth near the study site.

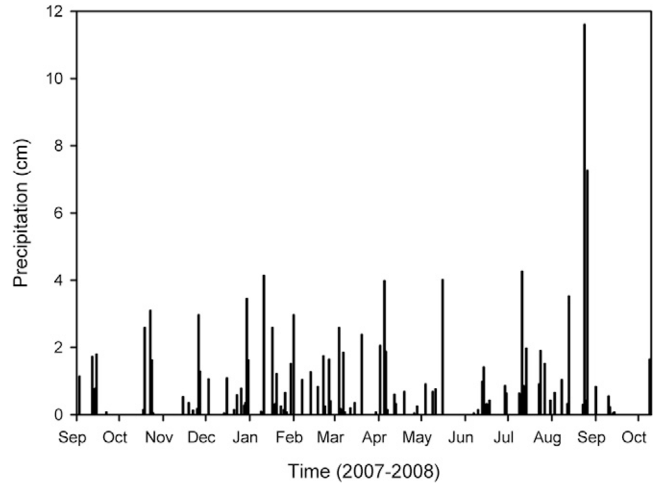

Fig. 5. Daily precipitation near the study site.

Table 2. Persistence of mass, C, and N from 6.7 Mg ha^{-1} residue under conservation or conventional tillage at various dates after placement based on decay parameters.

Date	Days†	*Lespedeza cuneata*	*Albizia julibrissin*‡	*Avena sativa* straw	*Glycine max*
		Mg ha^{-1}			
		Mass buried			
9 Oct. 2007	0	6.5	6.3	6.5	6.4
1 May 2008	205	2.9	2.5	2.6	1.5
7 Oct. 2008	364	2.1	1.9	1.5	1.1
9 Oct. 2010§	1096	0.5	0.5	0.1	0.2
9 Oct. 2010§¶	1096	3.7	3.4	2.1	1.8
		Mass surface			
9 Oct. 2007	0	6.5	6.1	6.5	6.4
1 May 2008	205	4.1	3.5	4.5	2.3
7 Oct. 2008	364	3.4	2.8	4.0	1.7
9 Oct. 2010§	1096	1.4	0.9	2.4	0.4
9 Oct. 2010§¶	1096	6.9	5.3	9.6	3.0
		kg ha^{-1}			
		C buried			
9 Oct. 2007	0	2654	2661	2486	2377
1 May 2008	205	1093	949	886	471
7 Oct. 2008	364	689	589	427	254
9 Oct. 2010§	1096	82	65	15	15
9 Oct. 2010§¶	1096	1008	849	519	328
		C surface			
9 Oct. 2007	0	2630	2565	2451	2344
1 May 2008	205	1641	1520	1692	856
7 Oct. 2008	364	1233	1106	1397	611
9 Oct. 2010§	1096	330	256	580	131
9 Oct. 2010§¶	1096	2198	1892	2877	1025
		N buried			
9 Oct. 2007	0	127	173	26	181
1 May 2008	205	72	78	24	39
7 Oct. 2008	364	46	51	22	23
9 Oct. 2010§	1096	6	8	15	2
9 Oct. 2010§¶	1096	68	79	56	32
		N surface			
9 Oct. 2007	0	129	154	24	182
1 May 2008	205	101	123	26	72
7 Oct. 2008	364	83	103	24	49
9 Oct. 2010§	1096	35	46	10	9
9 Oct. 2010§¶	1096	171	218	49	80

† Days after residue placement.
‡ Stems <1 cm in diameter.
§ Extrapolated data to time = 3 yr.
¶ Assuming residues were placed at the same rate and date each year for 3 yr.

that there may have been some N immobilization occurring at that time, though it may simply have been an artifact of the data obtained in the field. Day 112 corresponds to 27 Jan. 2008, and although there was a temperature spike at that time (Fig. 4) accompanied by moderate rainfall (Fig. 5), it is unclear why only one residue would have an increase in N immobilization at that time. Nitrogen immobilization was readily apparent in Fig. 3, where buried straw N content reached 130% of original residue N at Day 28. Immobilization was dampened when straw residue was surface placed, reaching only 108% at that same time. Surface placed straw has been shown to immobilize N in Alberta, Canada as well (Soon and Arshad, 2002). The effect of N immobilization partly accounts for the poor fit of straw residue N release on a percent basis by double exponential decay models in Fig. 3. However, straw N release appears to be linear when the data was expressed on an area basis because of the low initial N content.

The ANOVA for N loss on an area basis showed that all effects were significant, including interactions ($p < 0.0001$). There was no difference in N release when straw was buried or surface placed ($p = 0.9152$). All other residues released N at different rates when they were buried compared to placed on the surface ($p < 0.0001$). Additionally, the pairwise comparisons between residue types were all significant ($p < 0.001$) regardless of placement. That is, all residue types released N at significantly different rates compared to each other when compared on an absolute (per area) basis. Though all effects were significant when the data were normalized ($p < 0.008$), the pairwise comparisons were less distinct. When residues were surface placed, N from lespedeza, mimosa, and straw was released at the same rate ($p > 0.39$) when compared on a percent of original N (normalized) basis. The only residue to release N at a significantly different rate was soybean ($p < 0.0001$). However, when residues were buried, they all released N at different rates ($p < 0.0003$), even when compared on a percent basis. Straw released N at the same rate whether buried or surface placed ($p = 0.7670$) on a normalized basis. Net N mineralization from straw was minimal (Fig. 3), confirming observations of previous work (Soon and Arshad, 2002).

Table 2 shows the persistence of C, mass and N from residue under conservation or conventional tillage at various dates after placement based on decay parameters. Although caution should be applied when extrapolating data beyond the time frame of the study, two estimates of persistence at time = 3 yr are provided.

One is an estimation of the persistence of the residue placed 3 yr previously. The second estimate is based on the assumption that a producer may apply the residues each year at the same time and rate. The accumulation of recalcitrant material after 3 yr of residue application should be appreciable. For example, although buried oat straw would contain 15 kg ha^{-1} of C after 3 yr of decomposition, yearly application would increase that value to 519 kg C ha^{-1}. When surface placed, the effect would be even greater: 580 vs. 2877 kg C ha^{-1}, respectively. A study conducted in Alabama found that 10 yr of conservation tillage resulted in approximately 8745 kg C ha^{-1} within the top 5 cm of soil (Wood and Edwards, 1992). Although the present study supports those observations, further studies are needed to confirm extrapolated results regarding the mass and nutrient residence time after extended periods. Table 2 also allows the calculation of the increase in mass, C, and N under conservation tillage compared to conventional tillage along the chronosequence.

A producer may be interested to know how much mass, C, and especially N remains at spring planting, and how much of the remaining N will be mineralized over the season. Suppose that spring planting occurs on 1 May, which corresponds to Day 205 in this study. Table 2 shows that there remained 78 kg N ha^{-1} potentially available to spring crops from mimosa prunings on 1 May, even if the residue is buried the previous fall. Under conservation tillage, the value increased to 123 kg N ha^{-1} potentially available. By the end of the season on 7 Oct. 2008, 20 kg N ha^{-1} had been mineralized from surface placed mimosa residue (Table 2). A producer may therefore elect to reduce N fertilization by an equivalent amount for a crop grown between 1 May and 7 October if employing mimosa prunings as mulch under conservation tillage. Extrapolating the decay rates to the second season, from 1 May to 7 October, surface placed residue may release 13 kg N ha^{-1}, and in the third season, 9 kg N ha^{-1} may be mineralized from the surface placed mimosa residue. If a producer continued to apply the mulch at the same rate and same time over 3 yr, these N release patterns become additive, such that in the third year of production from 1 May to 7 October, 42 kg N ha^{-1} would be mineralized from surface placed mimosa. Similarly, surface placed lespedeza residue had 18 kg N ha^{-1} mineralized over the first season from 1 May to 7 October but if lespedeza residue were placed on the surface for three consecutive years, 36 kg N ha^{-1} may be mineralized during the third growing season. That would be the same amount as soybean residue would release over the third growing season if it were applied annually.

Interestingly, the recalcitrant N pool of surface placed mimosa was greater than any other residue used in this study. At the end of a year, 51 kg N ha^{-1} had been mineralized from surface placed mimosa, or only 33% of the original N content, leaving 103 kg N ha^{-1} potentially mineralizable (Table 2). Buried mimosa residue mineralized 122 kg N ha^{-1} after 1 yr (Fig. 3), or 71% of the initial N content (data not shown). Surface placed lespedeza behaved similarly: 46 kg N ha^{-1} was mineralized at the end of a year, or only 36% of the initial N content, leaving 83 kg N ha^{-1} potentially available to subsequent crops. These residues compared favorably to soybean residue, which lost N at a much faster rate and therefore did not have a large recalcitrant N pool. Even if soybean residue was placed annually, by the end of 3 yr the N pool would be an estimated 80 kg ha^{-1}, whereas mimosa may have 218 kg N ha^{-1} and lespedeza 171 kg N ha^{-1}.

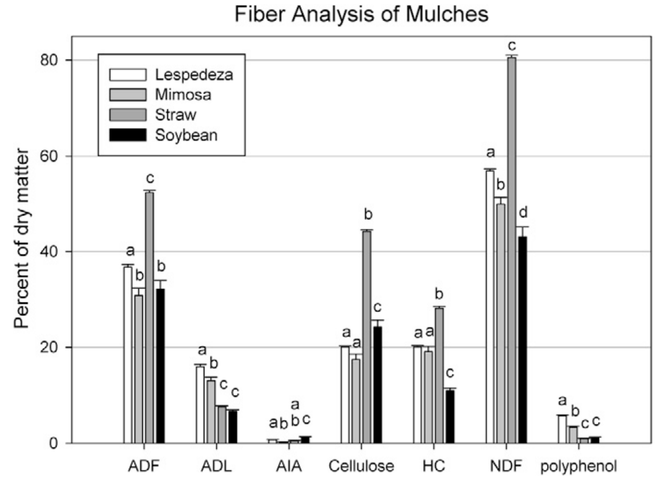

Fig. 6. Initial fiber content of residues. ADF = acid detergent fiber; ADL = acid detergent lignin; AIA = acid insoluble ash; HC = hemicellulose; NDF = neutral detergent fiber. Error bars represent standard errors of the means. Means followed by the same letter are not significantly different at $p < 0.05$

The advantage of a recalcitrant N pool is that it may act as a slow release N fertilizer, so that larger recalcitrant N pools slowly release more N to subsequent crops.

A caveat is worth mentioning at this point: this study did not determine N fate. Though the double exponential decay model does consider the recalcitrant nature of the remaining N residing in residue, this study did not determine the portion of mineralized N that may be plant unavailable due to leaching, volatilization, denitrification, or subsequent immobilization. However, the slow release nature of recalcitrant N should improve N use efficiency in a similar manner to that novel controlled release fertilizers do (Morgan et al., 2009).

Mass, C, and N residence times from organic residues under conservation tillage were increased compared to conventional tillage (Table 2). A notable exception existed for N content in oat straw, for which there was no difference between conservation and conventional tillage ($p = 0.9152$).

Figure 6 shows the initial fiber content of the residues used in this study. Straw had a significantly higher portion of acid detergent fiber (ADF), cellulose, hemicellulose, and neutral detergent fiber (NDF) than all other residues, which, along with a low initial N content, accounted for the slower decay rates observed by straw. The negative correlation between the mass of buried straw 28 d after placement (Table 3) with initial acid detergent lignin (ADL) (−0.610) closely resembled that observed in the laboratory by Stubbs et al. (2009) (correlation = −0.600), though that study correlated the parameters based on ADL at the time of sampling, not initial sampling. Similarly, the correlations between the mass of buried straw 28 d after placement with initial C and C/N (0.062 and −0.285, respectively) closely resembled that observed by Stubbs et al. (2009) (0.108 and −0.332, respectively) 28 d after placement. By 112 d after placement (data not shown), buried straw mass correlations with ADF (−0.588), ADL (−0.601), C (0.473), N (0.676), and C/N (−0.815) were in excellent agreement with those reported by Stubbs et al. (2009): −0.497, −0.400, 0.378, 0.277, and −0.379, respectively.

A few notes regarding the methodology are warranted. It seems possible that decay rates for buried residue are underestimated using litterbag methodology, a possibility also noted

Table 3. Pearson correlation of initial fiber analyses to residue type and placement 28 d after placement. ADF = acid detergent fiber; ADL = acid detergent lignin; AIA = acid insoluble ash; HC = hemicellulose; NDF = neutral detergent fiber.

Residue	Placement	NDF	ADF	HC	Cellulose	ADL	AIA	Polyphenol	C/N	N	C
					C						
L. cuneata	surface	0.426	0.612	−0.860	0.820	0.205	−0.837	−0.857	−0.397	0.395	−0.501
L. cuneata	buried	0.683	0.599	−0.190	−0.026	0.702	0.649	0.268	0.482	−0.486	0.504
A. julibrissin	surface	−0.632	−0.595	0.002	−0.694	−0.360	0.939	0.899	−0.553	0.597	−0.103
A. julibrissin	buried	0.793	0.243	0.351	−0.337	0.838	0.217	0.817	0.324	−0.469	−0.032
A. sativa straw	surface	0.760	0.699	−0.621	0.830	0.196	0.567	0.993	0.049	0.046	0.919
A. sativa straw	buried	−0.150	−0.847	0.467	−0.592	−0.009	−0.753	0.952	−0.535	0.640	0.642
Glycine max	surface	0.867	0.771	0.944	0.748	0.724	0.779	−0.604	0.021	−0.131	−0.638
Glycine max	buried	−0.807	−0.988	0.424	−0.999	−0.687	−0.463	0.660	−0.999	0.985	−0.027
					N						
L. cuneata	surface	0.641	0.487	−0.146	−0.663	0.812	0.807	0.772	0.238	−0.231	−0.295
L. cuneata	buried	0.414	0.627	−0.862	−0.265	0.827	0.674	−0.344	−0.437	0.467	0.419
A. julibrissin	surface	0.438	0.576	−0.308	0.469	0.641	0.522	0.236	0.375	−0.473	−0.648
A. julibrissin	buried	0.653	0.378	0.062	0.296	0.381	−0.854	0.518	0.459	−0.301	0.940
A. sativa straw	surface	0.974	0.950	−0.913	0.994	0.627	0.122	0.935	−0.418	0.502	0.997
A. sativa straw	buried	−0.650	0.141	−0.963	0.124	−0.104	0.366	−0.451	−0.301	0.161	−0.417
Glycine max	surface	0.042	0.198	−0.638	0.235	0.357	−0.502	−0.343	0.695	−0.562	0.937
Glycine max	buried	0.465	0.556	−0.217	0.578	0.009	0.731	−0.622	0.641	−0.568	0.239
					Mass						
L. cuneata	surface	0.427	0.612	−0.861	0.820	0.206	−0.836	−0.857	−0.398	0.396	−0.502
L. cuneata	buried	0.221	0.136	0.101	−0.480	0.337	0.207	0.661	0.644	−0.593	0.845
A. julibrissin	surface	−0.625	−0.615	0.053	−0.702	−0.399	0.922	0.877	−0.593	0.629	−0.127
A. julibrissin	buried	0.961	0.513	0.148	−0.033	0.956	−0.003	0.967	0.599	−0.677	0.331
A. sativa straw	surface	0.876	0.830	−0.767	0.926	0.391	0.388	0.996	−0.155	0.247	0.980
A. sativa straw	buried	−0.498	0.100	−0.731	0.467	−0.610	0.624	−0.239	−0.285	0.084	0.062
Glycine max	surface	0.783	0.669	0.973	0.642	0.622	0.741	−0.480	−0.128	0.016	−0.704
Glycine max	buried	−0.889	−0.871	0.016	−0.820	−0.985	−0.369	0.668	−0.770	0.745	−0.260

by Wieder and Lang (1982). When residues are incorporated during conventional tillage, the residue is distributed more uniformly in the surface horizons, with more intimate soil contact. That intimate contact with the soil may have an increased effect on residue decomposition because more surface area is exposed to microbial activity. Additionally, the efficiency of synchronicity is reduced when nutrient supplies are evenly distributed in the soil (Myers et al., 1997). On the other hand, litterbag methodology may have the effect of increasing labile decomposition because of the increased oxygen content surrounding the residue within the litterbag. The additional oxygen supply, however, can be expected to become rapidly depleted and should not have an appreciable effect on recalcitrant decomposition. By contrast, the decay rates for surface placed residue using litterbag methodology should be representative of actual field decomposition under conservation tillage.

CONCLUSIONS

Labile material in particular was more resistant to decay when residue was placed on the soil surface compared to burying it. Buried C loss models were similar to buried mass loss models because most mass was lost through microbial respiration of organic C. Organic C was sequestered for longer periods when residue was left on the soil surface, as in conservation tillage, compared to burying the residue, as in conventional tillage. Caution should be used when interpreting results on a relative basis because some residues may not appear to decay differently, when in fact they have entirely different decay coefficients on an absolute basis. Double exponential decay equations described both surface and buried residue decay data well, except when N immobilization occurred or when residues had a low N content. Surface residues may act as a slow release N fertilizer and contribute to organic matter accumulation on the soil surface, particularly if residues are applied annually. This study demonstrates that in situ cover crops and mulches may be used for the enhancement of SOM and soil N status. Further studies need to be conducted to determine if the decay rates remain valid for extended periods of time. Information on timely release of nutrients from organic residues will help producers make informed decisions regarding residue management, including the adoption of conservation or conventional tillage.

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