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A simple model for predicting plant residue decomposition based upon their C/N ratio and soil water content

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This paper develops and tests a simple relationship for predicting the decomposition of plant residues of diverse composition under varying soil water conditions. Known weights of four plants samples comprising of groundnut (Gn), mucuna (Mc), maize (Mz) and bush fallow (Bf), were put in nylon bags and randomly buried in three plots with varying soil moisture conditions (*viz:* W1 = 60% field capacity (FC); W2 = 75% FC and W3 = FC) and the weight losses of the samples in the bags determined at different time intervals. At the field capacity state, plant residue composition was the major controlling factor on decomposition rate constants (k_d), with Gn (0.032 d^{-1}) and Mc (0.022 d^{-1}) having significantly higher k_d than Mz (0.019 d^{-1}) and Bf (0.016 d^{-1}). Decreasing soil water reduced the k_d values of the plant residues. Using a modified first order decay equation that included C/N ratio and soil water content, the patterns of plant residue decomposition of diverse composition under varying soil water conditions were adequately simulated (R^2 = 0.95 and RMSE = 8.84). We conclude that plant residue decomposition patterns can be described using simple relationships that required knowledge of the routinely determined C/N ratio of the residues and the soil water content only.

Key words: C/N ratio, soil water content, field capacity, plant residue, decomposition rate constant.

INTRODUCTION

Plant residue returned to the soil is the primary source of the soil organic matter (SOM). In low- input agricultural systems, the SOM is the main repository of plant nutrients (Bandaranayake et al., 2003) and apart, other soil properties such as soil structure, porosity, and water holding capacity are enhanced with increasing SOM (Skjemstad et al., 1996). Whether the SOM will increase or not depends largely on the quantities of residue input, as well as the rate at which the residue decomposes. In the northern Ghana where with an average temperature of 30 ± 4°C, decomposition rates are high, whereas the annual plant biomass production is often low because the rainfall is limited to only one season (May to September), lasting 5 to 6 months. Plant growth during the non-rainy period is negligibly low. Much of the residue generated during the rainy growing season decomposes before the commencement of the next season. As a result, the equilibrium SOM at 0 to 20 cm depth is often less than 5 g/kg (Jones et al., 2007). A major challenge is how to manage residues to minimize losses during the fallow period. This requires not only an understanding of the factors that affect residue loss, but also the prediction of

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Table 1. Sources of residue decomposition and C/N data.

Plant residue	C/N	*kd* (per day)	Source
Bean trash	48.0	0.018	Karanja et al. (2006)
Clitoria	15.0	0.029	Njunie et al. (2004)
Dolichos	17.0	0.071	”
Maize	40.6	0.014	Mubarak et al. (2002)
Ground nut	26.9	0.023	”
Sesbania	21.0	0.053	Chikowo (2004)
Acacia	24.0	0.039	”
Soybean	12.2	0.009	Thonninsen et al. (2000)
Ingofera	10.6	0.020	”
Peach palm	10.4	0.021	Soto et al. (2005)

the loss rates of residues under varying environmental conditions.

Residue decomposition has been a subject of many studies and the factors that control the process are generally well known. The major determinants are plant composition and environmental factors such as temperature and soil moisture. Hitherto, the C/N ratio of plants has been considered as the main plant composition factor that determines decomposition rates (Severatine, 2000; Trinsoutrot et al., 2000). Increasingly, other residue constituents such as lignin and polyphenol content, especially of tropical residues, are considered to play important roles in the decomposition process (Palm and Sanchez, 1991; Tian et al., 1995; Vanlauwe et al., 1996; Kumar and Goh, 2003). Tian et al. (1995) derived a composite residue quality parameter, the Plant Residue Quality Index (PRQI), a linear combination of C/N ratio, lignin and polyphenol content. Yet, there is hardly any improvement in residue mass loss prediction using the PRQI instead of the C/N ratio. The apparent lack of prediction improvement could be attributed to the significant correlation between the plant composition constituents so that the inclusion of one factor partially explains the effects of the others. Nourbakhsh (2006) observed that the lignin content is significantly correlated with the C/N ratio and this may also be valid for polyphenol content. The combination of correlated parameters presents effects of multi-colinearity and violates regression rules. Alternative approaches such as the principal component analysis may be required to examine the separate effects of the factors on residue decomposition but this is not the focus of this study. Thus, in this study, we use the C/N ratio as the plant factor.

Temperature and soil water are the major environmental factors that affect residue decomposition (Angle et al., 1984). Given that in the tropics, rainfall and hence soil water is more variable than temperature, it is conceivable that residue loss patterns will follow soil water variation. There has been much progress in the description of environmental effects on residue decomposition as a component of SOM models, but these formulations often require information that are not easily available.

What we seek in this study is to develop and test a simple relationship for predicting the decomposition of residues of diverse composition under varying soil water conditions, especially for tropical conditions, where there is often data paucity, or where only routinely determined plant residue and soil properties are often available.

Formulation of residue type and soil water factors

Literature data on the C/N and k_d for different plant residue types were assembled (Table 1) to derive a general relationship of the dependence of k_d on C/N ratio. In doing so, we limited the data sources to those where soil water was reported as non-limiting, so that only plant factors controlled the decomposition rates. Several researchers (Anderson and Ingram, 1993 and Mubarak et al., 2002) have determined *kd* by fitting residue decomposition data to:

$$R_t = R_o e^{-k_d t} \qquad (1)$$

Where; R_t was mass remaining (g) at time t, R_0 is the initial residue mass and k_d is the decomposition rate constant (d^{-1}).

The plot of k_d vs. C/N (Figure 1) showed a rapid decline of the k_d as C/N ratio increased and the relation could be described by the power function of the form:

$$k_d = 0.16\,(C/N)^{-0.72} \quad R^2 = 0.70 \qquad (2)$$

The effect of soil water on the k_d was formulated according to the observation that the microbial mediated processes such as residue decomposition are rapid when soil water content, θ was near the field capacity, FC (θ_{FC}) but ceased when θ was near air-dry (θ_d) (Vigil and Sparks, 2002). Based on this, Adiku et al. (2008) derived a soil water function, f_w:

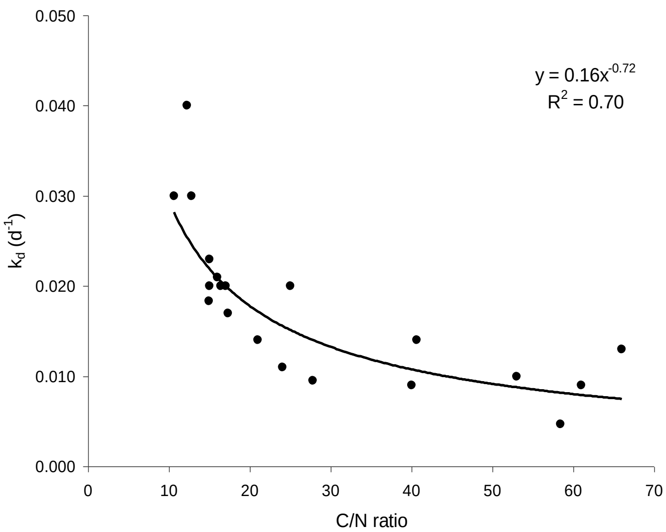

Figure 1. Relationship derived between k_d vs C/N ratio from literature data (Table 1).

Table 2. Plant residues and their chemical composition.

Residue type*	C (g/kg)	N (g/kg)	C/N
Bf	403	9.3	43.5
Mz	435	12.0	36.3
Mc	392	18.0	21.8
Gn	405	28.0	14.5

*Bf = Bush fallow, Mz = Maize, Mc = Mucuna and Gn = Groundnut residues.

$$fw = \frac{(\theta - \theta_d)}{(\theta_{FC} - \theta_d)} \quad (3)$$

which we adopt in this study. The combination of Equations (1) to (3):

$$R_t = R_0 \exp - \left\{ 0.16(C/N)^{-0.72} . \left[\frac{(\theta - \theta_d)}{(\theta_{FC} - \theta_d)} \right] t \right\} \quad (4)$$

would generally describe the decomposition of residues of diverse composition under variable C/N and soil water conditions.

MATERIALS AND METHODS

Residue decomposition studies and determination of rate constant

Field incubation studies were carried out using residues of groundnut (*Arachis hypogea*) Gn, mucuna (*Mucuna pruriens*) Mc, maize (Zea mays) Mz, and fallow bush, Bf. The latter comprised a mixture of Cyperus rotundus,

Tridax procumbeus, Andropogon gayanus and Digitaria horizontalis but the dominant species was *Cyperus rotundus.* The residues were harvested from a previous crop-fallow rotation trials at Savanna Agricultural Research Institute (SARI), Wa, (Lat. 10°N, Long. 2°5' E, and 323 m above sea level) located in the Guinea savannah zone of Ghana. Some chemical properties of these residues are given in Table 2. The plant residues were chopped to about 2 to 3 cm long and filled in 500 cm^3 nylon bags of 1 mm mesh with quantities; 11.45, 11.82, 10.48 and 8.9 g residues, respectively for groundnut, mucuna, maize and fallow bush per litter bag. The quantities of residue used were calculated based on the average biomass production of the various plant species in the field. The biomass production values were 4.58, 4.73, 4.2, and 3.6 t/ha, for groundnut, mucuna, maize and bush fallow, respectively.

The litter bags were buried 5.0 cm in a field plot at the SARI experimental fields during the period of low rainfall from, 8th March to 12th July, 2007 (Figure 2b). The mean monthly weather condition throughout year 2007 is shown in Figure 2a. The field soil was sandy and classified as *Ferric Lixisol* whose properties are in Table 3. Three water treatments were imposed, namely, watering every other day (W3) which maintained the soil water at field capacity (FC), watering every 4 days (W2) maintained the soil water at 75% FC and zero watering (W1) maintained the soil water at natural field-scale conditions (it was about 60% FC). A split-plot design was used with water treatments as main plots and residue types as sub-plot treatments and replicate litter bags were retrieved at 7, 28, 56, 91 and 126 days from the commencement of the experiment. The factorial combination of 4 residue types, 3 water treatments, 4 replicates, and 5 litter bag retrieval times resulted in a total of 240 litter bags. At each time of removal, adhering soil particles were shaken off gently and the contents emptied into labeled paper envelopes. The envelopes with the residues were oven-dried at 60°C for 72 h, cooled, emptied onto an aluminum container and weighed.

The mass of residues from the field studies under different water treatments were plotted against time and fitted with a first order decay equation (Equation 1). The half-life, $t_{½}$ was calculated using the formula:

$$t_{½} = 0.693/ kd \quad (5)$$

Statistical analysis

The decomposition constants, *kd* and the half-life, $t_{1/2}$, analyzed by analysis of variance using GENSTAT 5 released 3.2 (Lawes Agricultural Trust, 1995). When statistically significant difference at 5% level of probability existed, the means were separated using the Fisher protected LSD method.

RESULTS

Decomposition patterns of different residues

The decomposition rate constants determined for the residues used in the incubation varied with residue type (Table 4). The ANOVA indicated significant higher (P < 0.05) k_d values for the legume residues (mucuna and groundnut) than the non-legumes (fallow bush and maize). This could be attributed to the lower C/N ratio for the legumes (Table 2). There were also within legume differences with groundnut having significantly higher k_d than mucuna. The higher decomposition rate constant for Gn can be attributed to the higher biodegradability of groundnut residues induced by higher N content. Indeed, nitrogen is a key nutrient substance for microbial growth has a tremendous effect on residue breakdown by

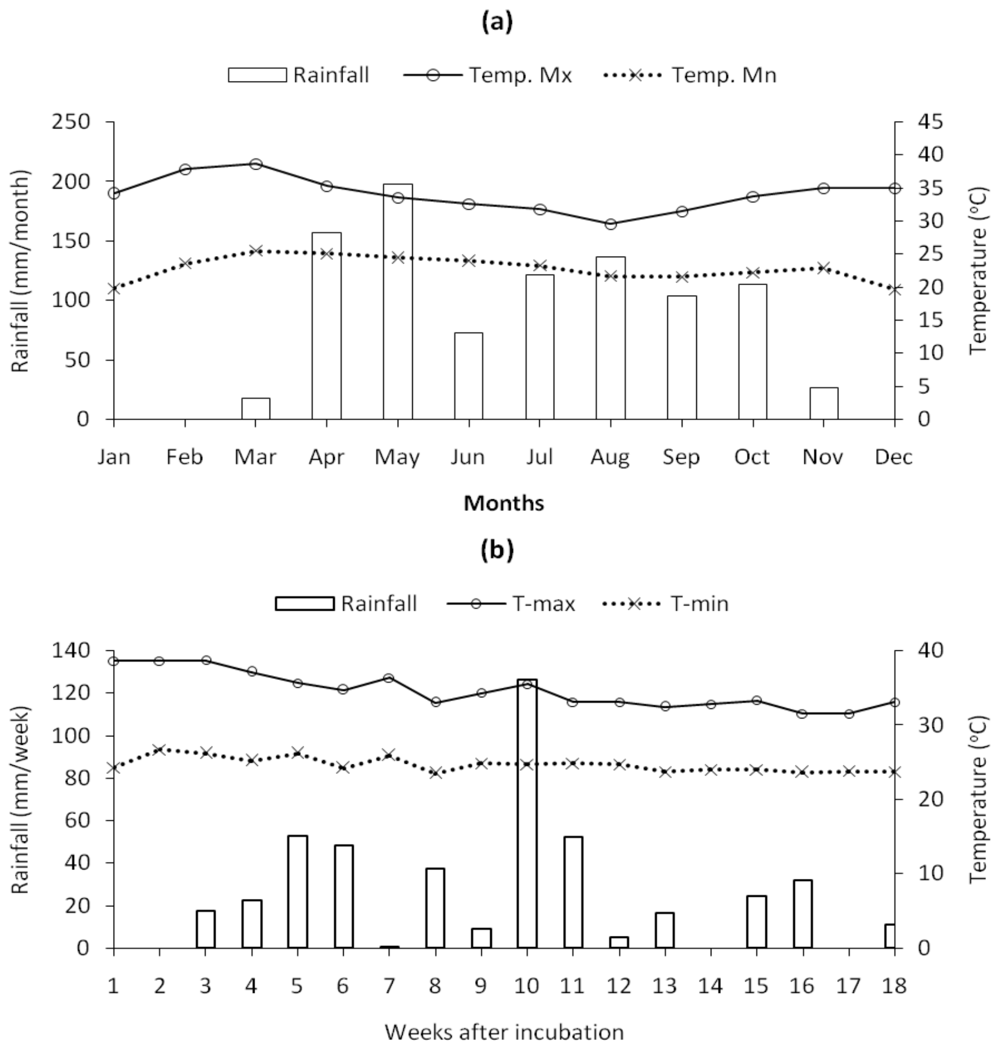

Figure 2. Weather conditions of Wa, Ghana, during the year, 2007: (a) monthly mean precipitation and temperatures, and (b) weekly mean precipitation and temperatures during the period of the experiment (that is, from 8th March to 12th July, 2007).

Table 3. Some chemical and physical properties of soil in Wa, used for the study.

Sand (%)	Silt (%)	Clay (%)	C (g/kg)	N (g/kg)	C/N	Field capacity (g/g)
86.2	11.4	2.5	5.7	0.6	9.5	0.20

Table 4. Effects of residue type on the decomposition rate constant, *kd* (d^{-1}) and half-life, $t_{1/2}$ (days) under non-limiting soil water conditions*.

Plant residue	*kd*	$t_{1/2}$
Bf	0.016^{d}	44^{a}
Mz	0.019^{c}	36^{b}
Mc	0.022^{b}	32^{c}
Gn	0.032^{a}	22^{d}

*Values in a column followed by different letters are significantly different at 5% level of significance using LSD method. Bf = Bush fallow, Mz = Maize, Mc = Mucuna and Gn = Ground nut residues.

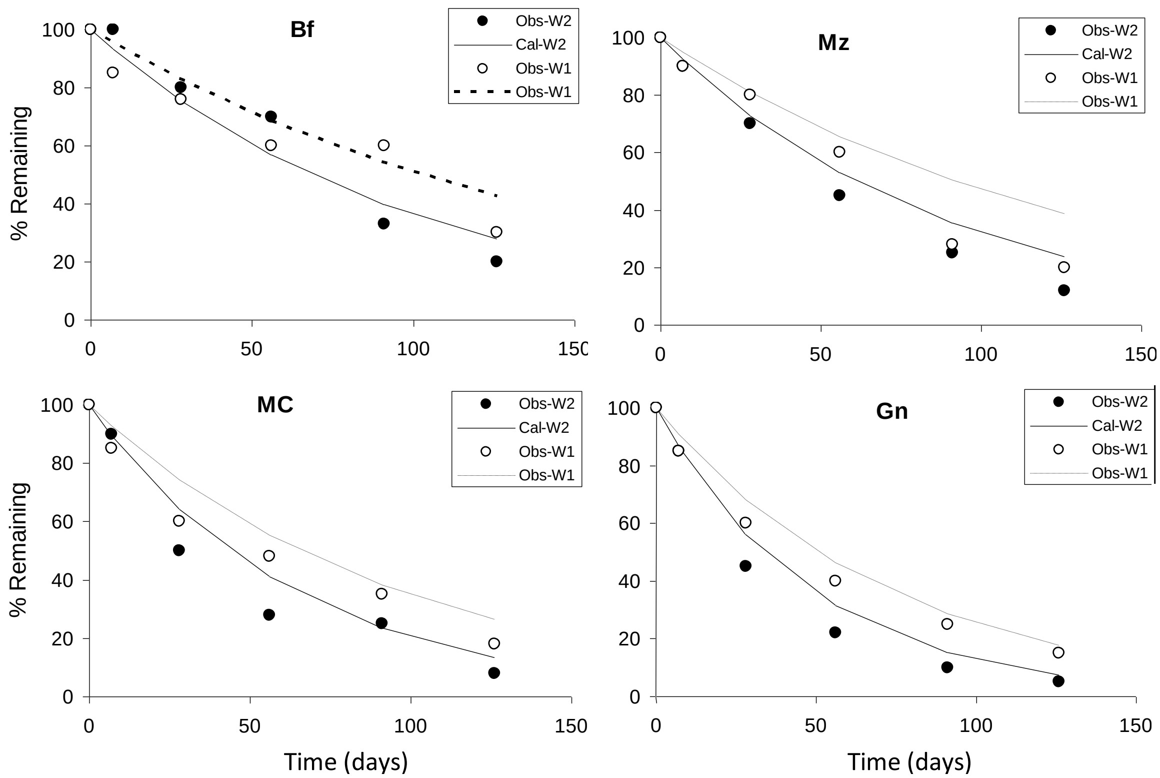

Figure 3. Time-course of observed (symbols) vs. calculated (lines) percent residue remaining for W2 and W1 for the different residue types.

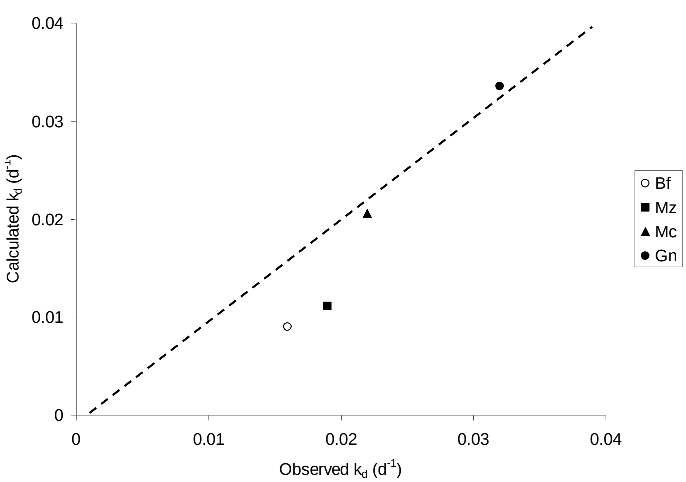

Figure 4. Calculated vs. observed k_d at FC for the different residue types.

microbes. Residues with high N contents are more sensitive to biodegradation. The higher k_d values for the legumes also translate to smaller residence time when soil water was high (Table 4). The half life for the groundnut residue was 22 days, indicating that half of the initial mass was lost within 3 weeks. The bush fallow grass and maize had $t_{½}$ of 44 and 40 days, respectively, and are likely to remain on the field over a longer period of time.

Residue decomposition was affected by soil water content. By the end of the 126-day incubation period, more than 25% of the non-legume residues (Bf and Mz) remained un-decomposed under W1 conditions compared with about 16% under W2 conditions (Figure 3). In the case of the legumes, percent residue remaining under W1 and W2 were 15 and 7, respectively. The initial rates of residue mass loss were also higher under W2 than W1, for most cases.

Test of prediction equation

The application of Equation (4) in conjunction with the residue composition data (C/N ratio in Table 2) under FC conditions (W3) showed generally a good agreement (Figure 4) between the observed and the calculated k_d. The Bf and Mz residues had lower k_d values while the legumes (Mc and Gn) had higher k_d values. Despite a slight overestimation of the k_d for Bf and Mz, the agreement was generally good. This gives an indication that the C/N ratio alone is adequate to account for plant composition effects on decomposition.

The prediction of soil water effect on residue decomposition was also well captured by Equation (4).

As shown in Figure 3, the predicted % mass remaining at the end of the 126 days was higher for W1 than W2 in all cases, reflecting the observed trends with R^2 = 0.95 and RMSE = 8.84 (or 15% of observed mean). It should be mentioned that we assumed that for the water treatment W1, the initially determined water content of 60% FC would pertain throughout the study period, there were indeed slight rainfall periods (Figure 2b) that may accelerate the decomposition that we have predicted. This may account for the higher predicted % mass remaining than actually observed.

DISCUSSION

Residue mass loss was generally well described by Equation (4). Legumes were shown to decompose faster than the non-legumes and the rate of mass declined with decreasing soil water content. The simple C/N-dependent k_d function adequately described the effect of residue type on mass loss. For nutrient such as N release, other plant constituents such as lignin and polyphenol content may enhance the model prediction. Whereas we recognize the efforts of researchers such as Tian et al. (1995) and Vanlauwe et al. (1996) among others, to include polyphenol content as additional decomposition-rate determining factor, our observations indicated where such data are unavailable, the simple C/N ratio could be adequately used as the plant factor. Also, the simple soil water formulation could adequately account for soil water effect on decomposition.

Both the observations and predictions show that more than 80% of residues will decompose within a 4 months after application to field soils. The non-legumes had a higher residence period and may have a longer mulch effect than the legumes. Fallow bush residues, if left on the field are often lost by grazing or burning. Hence, it is necessary to develop management practices that would retain these residues. Provided labour is available, harvesting the residue at the end of the growing season, air-drying and protecting the material from rewetting could ensure the availability of residues for mulch in the following cropping season.

Conclusion

Overall, our investigation of the residue mass loss under varying soil water conditions indicated that high C/N ratio residues decompose more slowly and are likely to contribute more to SOM than the low C/N residue types. Increasing soil water increased the decomposition rate. If technically feasible, residues must be harvested and kept dry during the fallow period and applied as mulch during the cropping season to prevent losses during the fallow time. Residue decomposition patterns under variable environment could be described using a simple equation that required knowledge of the routinely determined C/N ratio and the soil water content only. Even where the soil water content data is unavailable, it can be estimated from the water balance equation.

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