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## Simple Formulation of the Soil Water Effect on Residue Decomposition

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*Soil water content,  $\theta$ , is a major factor affecting residue decomposition, but simple formulation of this factor is often lacking. We observed that  $\theta$  significantly ( $P < 0.001$ ) affected the residue decomposition constant,  $k_d$ . When  $\theta$  varied from  $0.09 \text{ g g}^{-1}$  to  $0.23 \text{ g g}^{-1}$ ,  $k_d$  ranged from  $0.009$  to  $0.013 \text{ d}^{-1}$  and from  $0.009$  to  $0.022 \text{ d}^{-1}$  for residues with carbon to nitrogen ratio (C/N)  $> 30$  and  $C/N < 25$ , respectively. A  $\theta$  factor was formulated in terms of the field capacity  $\theta_{FC}$  and the air-dry  $\theta_d$  in the form  $f_w = (\theta - \theta_d) / (\theta_{FC} - \theta_d)$ , and this was used to modify the potential  $k_d$  as  $\theta$  varied. Coupling  $f_w$  with a first-order residue decomposition equation resulted in the prediction of the decomposition of four residue types in the greenhouse ( $R^2 = 0.94$ ; relative root mean square error, RRMSE, = 0.06) and in the field ( $R^2 = 0.93$ ; RRMSE = 0.11).*

**Keywords** Prediction, residue decomposition, soil water

### Introduction

Residues constitute one of the major ways by which organic matter or carbon (C) is introduced into the soil. In tropical agricultural systems, where application of fertilizer to crops is often negligible, the soil organic matter (or organic C) is the main reservoir of nutrients for plant growth (Bandaranayake et al. 2003). Hence, managing of residues to increase soil organic carbon (SOC) is economically relevant in tropical agriculture. Though residue addition and its subsequent conversion to soil C attracted much research attention in the past, there is now a renewed interest in the subject in response to global warming and climate change, which is attributable to the increasing carbon dioxide ( $\text{CO}_2$ ) load of the atmosphere. It is thought that increasing soil C by increasing residue additions to the soil might mitigate climate change (Lal 2004). If residues must be managed to enhance the buildup of soil C, then the factors that affect the conversion process must be assessed. The bulk of

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evidence indicates that residue decomposition is determined by two factors: (i) the residue quality (Palm and Sanchez 1991; Seneviratne 2004) and (ii) environmental factors, such as soil moisture and temperature (Stroo et al. 1989; Stott et al. 1990).

In this study, we focused on the role of soil water, given that in the tropics the variability in rainfall, and hence soil water, far exceeds the variability in temperature; therefore, residue decomposition patterns would largely be determined by soil water. To predict residue decomposition dynamics, we needed to formulate the soil water effect. In the past, indirect approaches were taken to formulate the soil water effect, apparently because of the paucity of soil water measurements in residue decomposition studies. For example, several researchers (e.g., Gregory et al. 1985; Douglas and Rickman 1992; Steiner et al. 1999) used the concept of decomposition days (DCD), a composite variable of temperature and precipitation, to describe the time variation of residue mass loss under field conditions. In this approach, a precipitation coefficient was used as proxy for a soil water factor. The precipitation coefficient varied when the precipitation was less than or exceeded set thresholds. Bristow et al. (1986) formulated the water factor in terms of soil and residue water content; however, data on residue water content is often not available.

Our aim was to develop a simple formulation of the water factor that would require only the minimum measured or estimated soil water information. We assumed that the decomposing residue is in direct contact with the soil and would therefore equilibrate with the current soil moisture. Thus, the knowledge of soil water content alone would be sufficient to describe the effect of water on residue decomposition. Further, given that the residue decomposition is rapid at field capacity, slow when soil moisture declines to less than 40% field capacity, and stops when the soil is air-dry (Vigil and Sparks 2002), we hypothesized a linear decline of the decomposition rate between the field capacity and the air-dry soil water content. The aim of this study was to test these hypotheses and derive a simple soil water factor that could be used for predicting residue decomposition under variable soil water conditions.

## Materials and Methods

### *Data Sources*

Residue decomposition was studied under both greenhouse and field conditions in Ghana from 2004 to 2005. From June to December 2004, greenhouse studies were conducted at the Departments of Soil Science and Crop Science, University of Ghana. Four residue types, (i) elephant grass (*Pennisetum purpureum*), R1; (ii) pigeon pea (*Cajanus cajan*), R2; (iii) cowpea (*Vigna unguiculata*), R3; and (iv) mucuna (*Mucuna puriens*), R4, were obtained from a long-term maize–fallow rotation study aimed at characterizing the effect of fallow residue management on maize productivity and soil carbon accretion (Table 1). The residues, which were harvested at their mature stages, were chopped into 2- to 3-cm lengths and oven dried. Then, 8-g portions were placed in litter bags (10 cm × 6 cm) made from 1-mm nylon mesh for subsequent incubation studies. Subsamples of the plant materials were used to determine C and total nitrogen (N) using standard analytical procedures.

About 400 kg of a sandy loam topsoil (0–20 cm), sampled from the site of the maize–fallow trial, was air dried for 72 h, ground, and passed through a 2-mm mesh

**Table 1.** Description and composition of plant residues

Type	Description	C (%)	N (%)	C/N ratio
R1	Elephant grass	47.0	1.58	29.8
R2	Pigeon pea	40.5	2.03	19.9
R3	Cowpea	42.1	1.79	23.5
R4	Mucuna	33.5	1.79	18.7

before used in the subsequent greenhouse experiment. The field capacity (FC) of the soil was determined by saturating samples in pots, allowing drainage for 2 days, and then measuring gravimetric soil water content (Table 2). The air-dry water content was also determined gravimetrically. Next, 800-g portions of the sieved soils were packed to a bulk density of  $1.10 \text{ g cm}^{-3}$  into 1.2-L plastic pots, leaving about 2.0 cm at the brim. The litter bags and their contents were buried in the potted soils to a depth of about 2.0 cm, and thereafter, three water treatments were imposed as follows: W1 (100% FC or  $\theta = 0.23 \text{ g g}^{-1}$ ), W2 (70% FC or  $\theta = 0.16 \text{ g g}^{-1}$ ), and W3 (40% FC or  $\theta = 0.09 \text{ g g}^{-1}$ ). The water treatments were maintained throughout the study period by regular weighing and replenishing any loss of water detected. There were 96 pots in all, arranged in a completely randomized design. The greenhouse temperature was between 28 and 32 °C, with an average of 30 °C.

Triplicate litter bags for each water treatment and residue type were retrieved at 10, 20, 30, 50, 80, 120, 150, and 180 days after the commencement of the experiment. At each time of retrieval, the bags were gently shaken to remove all attached soil particles, after which the contents were emptied into paper envelopes, dried at 60 °C for 72 h, and weighed.

Assuming that the rate of residue mass loss was proportional to the current mass, then

$$\frac{dY_t}{dt} = -k_d Y \quad (1)$$

where  $Y_t$  is the residue mass (g) at time  $t$  (d) and  $k_d$  is the decomposition rate constant. The analytical solution to equation (1) is

$$Y_t = Y_o e^{-k_d t} \quad (2)$$

with  $Y_o$  being the initial mass (g). In this study, the  $k_d$  was expressed either per day ( $\text{d}^{-1}$ ) or degree day [ $(^\circ\text{C d})^{-1}$ ]. Curves were fitted to the mass loss with time, and Excel was used to determine the  $k_d$  for the different residue types and soil water treatments.

The field studies were carried out at the University of Ghana Farm, Legon, from July to September 2005. Daily weather data, including rainfall and temperature,

**Table 2.** Description and composition of soil

Soil	Sand (%)	Silt (%)	Clay (%)	$\theta_{\text{FC}}$ ( $\text{g g}^{-1}$ )	$\theta_d$ ( $\text{g g}^{-1}$ )	Bulk density ( $\text{g cm}^{-3}$ )
Greenhouse	65.0	15.0	20.0	0.23	0.02	1.10
Field	64.0	25.0	5.0	0.19	0.02	1.35

were obtained from the Ghana Meteorological Services Department, which was situated about 4 km from the farm. The soil at the farm was loamy sand with moisture constants given in Table 2. The field capacity and air-dry soil water contents were determined using the same procedure as outlined for the greenhouse study. There was no irrigation during the field study.

For the field study, only residue types R1, R2, and R4 were used. Three hundred fifty grams of plant residues were chopped to about 30 cm long and placed in litter bags made of 1-mm nylon mesh with dimensions of 72 cm  $\times$  42 cm. The bags were buried at a depth of 3.0 cm below the soil surface. The litter bags were retrieved at 10, 20, 30, 50, and 80 d after the beginning of the study. At each retrieval time, the remaining residue was oven dried at 60 °C for 72 h and weighed.

### **Formulation of the Soil Water Factor**

To formulate the effect of soil water on residue decomposition, we expressed the rate constant  $k_d$  in terms of a potential rate constant under nonlimiting soil water conditions,  $k_{dpot}$ , and a soil water factor,  $f_w$ :

$$k_d = k_{dpot} f_w \quad (3)$$

Further, assuming that  $k_d$  declines linearly with soil water content between the field capacity  $\theta_{FC}$ , and air-dry,  $\theta_d$ , then  $f_w$  may be expressed as

$$f_w = \left[ \frac{\theta - \theta_d}{\theta_{FC} - \theta_d} \right] \quad (4)$$

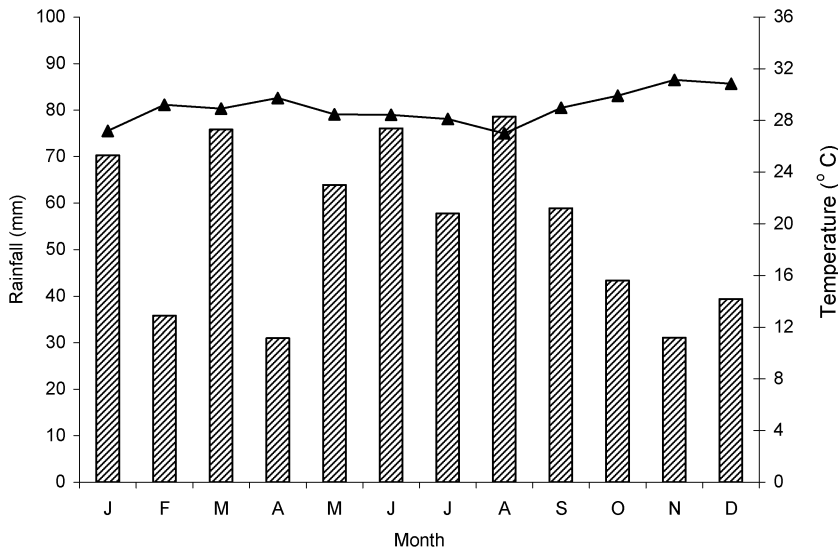
In the greenhouse, where  $\theta$  was maintained at specified levels throughout, the calculation of the  $f_w$  was straightforward. With  $k_{dpot}$  taken as the rate constant at field capacity for each residue type, the coupling of Eqs. (2) to (4) enabled the prediction of residue mass loss with time for the different water treatments.

However,  $\theta$  in the field varied with time and had to be calculated at each time step (in this case daily). We applied a simple bucket-type water balance equation to estimate the daily change in the soil water storage,  $\Delta S$ , to the depth of 100.0 cm, using

$$\pm \Delta S = P_r - ET - D - R \quad (5)$$

where  $P$  is rainfall rate,  $ET$  is evaporation rate,  $D$  is drainage rate, and  $R$  is runoff rate. All the terms in Eq. (5) have units of  $\text{mmd}^{-1}$ . With the exception of  $P_r$ , no measurements of the other terms in Eq. (5) were made. We proceeded to estimate  $D + R = 0.20 \times P_r$ , considering that the field was flat with low runoff potential, acting as a large soil bucket that would minimize drainage. The potential evaporation  $ET_o$  was calculated from the weather data using Cropwat (Smith 1992). The  $ET$  equaled  $ET_o$  when soil water was at field capacity. However, when soil water fell below field capacity,  $ET$  was obtained as the product of  $ET_o$  and  $f_w$ . The daily average change in water content of the soil was calculated as  $\Delta\theta = \pm \Delta S/z$  with  $z = 100.0$  cm.

With the  $\theta$  known,  $k_d$  and  $f_w$  were calculated using Eqs. (3) and (4). Equation (1) was then solved numerically using the Euler method, with a time step of 1 d in a Fortran program (IBM, Armonk, N.Y.). Input variables were  $k_{dpot}$  for different residue types, field soil moisture constants, and the weather data. Without any soil water measurements at the beginning or during the field study, the simulations



**Figure 1.** Rainfall (bars) and mean temperature (line) during the field experiment.

started by assuming that the soil was initially at field capacity, given the ample rainfall in the month of June prior to the study (Figure 1).

## Results

### *Variation of $k_d$ with Soil Water Content*

The  $k_d$  values for the different residue types were comparable to those obtained in other studies (Table 3). For the grass residue R1,  $k_d$  values ranged from 0.009 to 0.013  $d^{-1}$  when the water treatment increased from W3 to W1. For example, Mubarak et al. (2002) obtained the  $k_d$  value of 0.099  $week^{-1}$ , equivalent to 0.014  $d^{-1}$  for the field decomposition of maize straw, which was close to our observation at W1. Others obtained  $k_d$  values between 0.0002 to 0.0006  $^{\circ}C d^{-1}$  for corn-fallow

**Table 3.** Decomposition rate constants  $k_d$  ( $d^{-1}$ ) under varying water treatments

Water	Residue type			
	R1	R2	R3	R4
W1	0.013a (0.0007) <sup>a</sup>	0.021a (0.0011)	0.020a (0.0012)	0.022a (0.0012)
W2	0.012a (0.0006)	0.016a (0.0008)	0.014b (0.0007)	0.014b (0.0007)
W3	0.009a (0.0005)	0.008b (0.0004)	0.008c (0.0004)	0.009c (0.0005)
LSD (P < 0.05)	0.011	0.009	0.005	0.003

<sup>a</sup>Numbers in parentheses indicate  $k_d$  in ( $^{\circ}C d$ )<sup>-1</sup>.

Note. For columns, numbers with the same letters are not significantly different at P < 0.05.

rotations (Ma et al. 1999). Even though our values are somewhat greater [0.0005 to 0.0007 ( $^{\circ}\text{C d}^{-1}$ )], the order of magnitude is similar. In the case of legume residue decomposition, Mubarak et al. (2002) obtained a  $k_d$  value of 0.158 week $^{-1}$  (or 0.023 d $^{-1}$ ), whereas others obtained values between 0.027 and 0.036 d $^{-1}$  for soybean under wet soil conditions (Thonningsen et al. 2000). Again, these data are in agreement with our data for the legume residues (R2, R3, and R4).

Soil water content had a significant ( $P < 0.001$ ) effect on the decomposition rate constants (Table 3). When soil water was at field capacity (W1), mucuna residue (R4) had the highest  $k_d$  of 0.022 d $^{-1}$ , whereas the grass residue (R1) had the lowest  $k_d$  of 0.013 d $^{-1}$ . Decreasing soil water content resulted in the decline of the  $k_d$  for all residue types, but this decline was more rapid for the residues with lower C/N ratios (R2, R3, and R4) than for the grass residue (R1). Although the analysis of variance (not shown) indicated that the effect of residue type on  $k_d$  was not significant, we must note that the range of C/N ratios in the residues studied was rather narrow. In general, the variation of the  $k_d$  with soil water could be described by a linear function (Figure 2):

$$\frac{k_d}{k_{d\text{pot}}} = 0.82 \left( \frac{\theta}{\theta_{\text{max}}} \right) - 0.18, \quad R^2 = 0.85 \quad (6)$$

where  $\theta_{\text{max}}$  is the  $\theta$  at W1. The scatter in the data may be attributed to the differences in residue types.

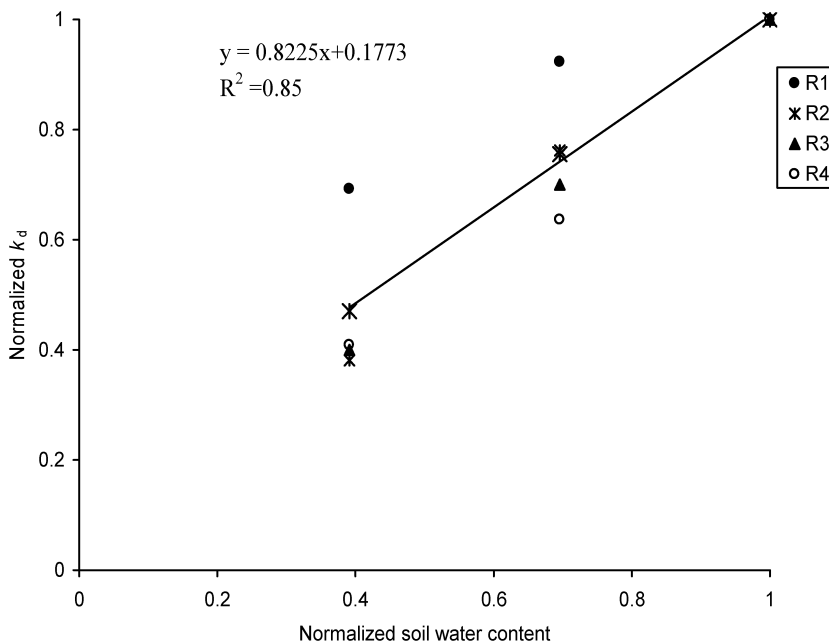


Figure 2. Variation of the decomposition rate constant with soil water content.

## Discussion

### Prediction of Residue Decomposition in Varying Soil Water Conditions

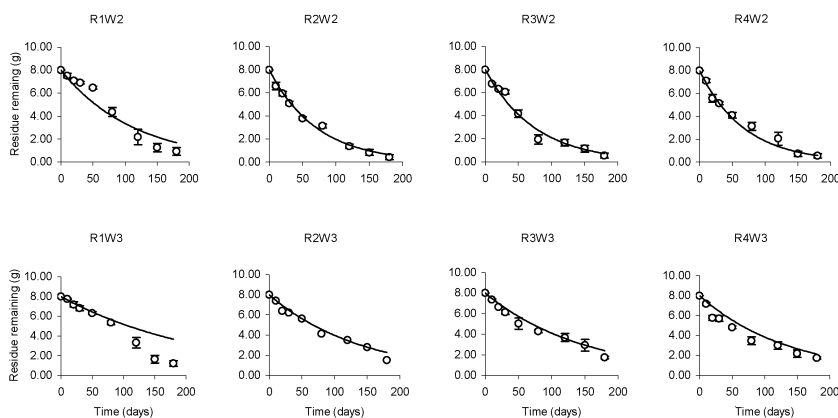
The residue mass declined exponentially with time in all treatments under greenhouse conditions (Figure 3). For water treatment W2, all treatments lost more than 80% of the initial mass by the end of the greenhouse studies. The residue types R2, R3, and R4 in particular lost more than 90% of the initial mass. For water treatment W3, residue decomposition was reduced but did not cease completely, with greater amounts of residues remaining undecomposed after 180 d than was the case in water treatment W2. About 25% of the R1 residue and slightly more than 25% of the other residue types remained after 180 d. These patterns of residue decomposition with time and soil water were well predicted ( $R^2 = 0.94$ ; RRMSE = 0.06) despite the slight overestimation for R1 at W3.

A comparison of the observed and predicted time course of residue decomposition (Figure 4) showed that the simple formulation of the soil water factor was also adequate for describing field-scale residue decomposition ( $R^2 = 0.93$ ; RRMSE = 0.11). The residues lost between 65 to 80% of their initial mass by 80 d, which was well captured by the model. Although we lacked data to test the model performance in the dry periods after September, the simulated trends indicate that the model would predict a further but very slow decline in residue mass under such conditions.

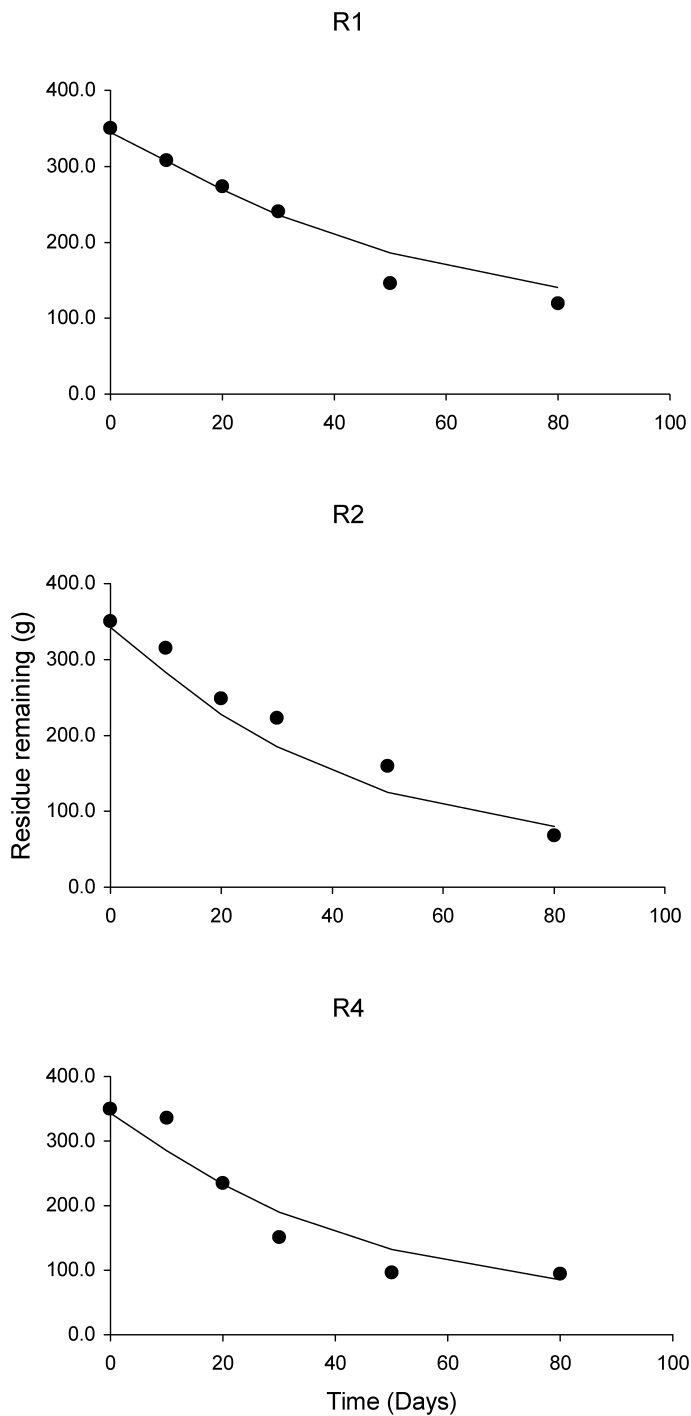
It is worth noting that the simple assumptions made about the terms in Eq. (5) led to good prediction of the residue mass loss with time. Undoubtedly, a more detailed soil water model, which would provide  $\theta$  as a function of soil depth, would enable the use of the topsoil  $\theta$  to control the  $k_d$ , rather than the average  $\theta$  of the whole profile used in this study. Such a detailed soil water model, however, would not invalidate our concept for formulating the soil water factor.

## Conclusions

We investigated the effect of soil water content on the rate of residue decomposition and concluded that soil water significantly ( $P < 0.001$ ) affected



**Figure 3.** Observed (symbols) and predicted (lines) patterns of residue mass loss with time for the different residue types at water treatment W2 (top row) and W3 (bottom row).



**Figure 4.** Observed (symbols) and predicted (lines) of residue mass loss under field conditions.

the  $k_d$ . Residue decomposition was enhanced by increasing soil water and vice versa. Our analysis shows that the  $k_d - \theta$  relation could be described by a linear equation and that a simple soil water factor could be formulated to predict residue decomposition in the greenhouse and in the field under variable soil water conditions.

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