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Defining the relation between soil water content and net nitrogen mineralization

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Summary

Simulation models of net mineralization of nitrogen (N) in soil need to be able to incorporate the effect of soil water. Our objective was to identify and define the best way of expressing soil water and its effect on net mineralization across a range of soil types. We collated data from 12 laboratory incubation studies, including a total of 33 different soils, where rates of net mineralization of N were determined from the net accumulation of mineral N under a range of water contents at near-optimal temperatures. Measurements of water potential and limits of water content observed in the field were available for most of these soils. The percentage of pore space filled with water was estimated from measurements of soil bulk density. We found that relative water content, particularly when expressed relative to an upper and lower limit of water content observed in the field, was the best descriptor for net mineralization. The next best descriptions were soil water potential, water content relative to the optimal water content for mineralization, and percentage of pore space filled with water, with water content alone being poor. Although various functions may be used to describe the relation between relative water content and net mineralization of N, an equation for a sigmoidal curve provided the best fit, and explained 78% of the variation.

Introduction

Water, or its absence, controls microbial activity in soil and thus rates of gross mineralization and immobilization of organic nitrogen (N), the balance of which determines rates of net mineralization. These processes, in turn, influence the availability of mineral N for plant growth and the amount that might be leached. Defining a general relation between soil water content and net mineralization of N would greatly increase the utility of empirical models for rates of decomposition, nitrate leaching, plant growth and plant response to application of N fertilizer. This is because in many models, relations between soil water content and net mineralization have been based on empirical observations of one specific soil type.

Currently, most predictive models use a dimensionless scaling function, W_{m}, to simulate the effect of water content on net mineralization:

$$N_{\min} = kT_{\mathrm{m}}W_{\mathrm{m}}\beta, \tag{1}$$

where $N_{\min}$ is the rate of net mineralization of N, k is the rate of mineralization under optimal conditions of temperature and moisture, T_{m} is a dimensionless quantity that describes effect of soil temperature on microbial activity, scaled between 0 and 1, W_{m} is a dimensionless quantity that describes effect of soil water on microbial activity, scaled between 0 and 1, and β represents other factors which could include, for example, a C:N ratio factor, again scaled between 0 and 1.

By rearranging Equation (1) we obtain W_{m} as

$$W_{\mathrm{m}} = \frac{N_{\min}}{kT_{\mathrm{m}}W_{\mathrm{m}}\beta}. \tag{2}$$

A complicating factor for modelling the effect of soil water on the net mineralization of N is that soil water can affect the separate processes of gross mineralization and gross immobilization differently in different soils and under different conditions. The quantity W_{m} may depend on substrate quality: the more easily decomposable the substrate is, the more sensitive mineralization is likely to be to water content. Difference in quality of substrate might explain why microbial activities of fresh plant residues and soil are not similarly affected by water content (Quemada & Cabrera, 1997), and why the effects of water on microbial activity are greater in surface soil than in underlying mineral soil layers (Leirós *et al*., 1999). Given that functions of W_{m} are usually calibrated on short-term laboratory

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incubations, the influence of water on decomposition of only the ‘active’, or ‘decomposable’, soil organic matter pool is measured. It is therefore important to ensure that the value of k, and the time over which Equation (1) is applied, reflects this.

Although some field (e.g. Kowalenko *et al.*, 1978) and laboratory (Cassman & Munns, 1980; Quemada & Cabrera, 1997) studies have shown that the effect of water content on decomposition or net mineralization of N in soil varies with temperature, others (Kladivko & Keeney, 1987) have revealed no interaction of temperature and water content on net mineralization. Furthermore, no physical explanation has been given for any water–temperature interaction. For the purpose of application, a simple relation between soil water content and net mineralization with few input requirements is probably adequate.

Although there is a large amount of literature on laboratory experiments in which the effects of soil water content on mineralization of N have been examined, the results are difficult to collate because the variables used to describe soil water have varied from study to study, and the incubation conditions have differed. However, there have been attempts to define a generalized W_m function of net mineralization of N for nine soils from one incubation study (Stanford & Epstein, 1974), for five soils from another (Myers *et al.*, 1982), and for 12 soils from 12 different incubation studies (Walse *et al.*, 1998). Stanford & Epstein (1974) found that one linear W_m function of mineralization could be used for the range of soils studied ($R^2 = 0.93$), although in this study all nine soils were loams, ranging from fine sandy loams to silty clay loams. Both Walse *et al.* (1998) and Myers *et al.* (1982) concluded that variation in their data could not be adequately explained by a single W_m function of mineralization.

Rodrigo *et al.* (1997) showed that, regardless of model structure, W_m functions of mineralization are one of the main causes of differences in prediction among the models. For example, in the three previous studies (Stanford & Epstein, 1974; Myers *et al.*, 1982; Walse *et al.*, 1998) that attempted to define a generalized W_m function of mineralization across five to 12 soil types, the variable used to describe soil water content or the type of function fitted to data, or both, differed between the studies.

There has been no previous collation of data from laboratory incubations in which net N mineralization was determined under a range of soil water contents, and which accounted for differences between studies in temperature, substrate quality and availability, and duration of incubation. An extensive database might be the best source of information from which to ascertain whether a single generalized W_m function of mineralization could apply across a range of soil types and climates in order to minimize the need for site-specific calibration.

We first review mathematical descriptions of the effect of different variables for describing availability of soil water on net mineralization of N. We used data collated from 12 incubation studies, some of which had soils that had been sampled to a range of depths. Data were available for a total of 33 different soil horizons or layers. These data were used to identify and describe the best way of expressing soil water and its universal effect on relative rates of net mineralization.

Expressions for soil water and their effect on net mineralization of N

There are several interrelated mechanisms that cause a decrease in microbial activity in fairly dry soil, including reduced diffusion of soluble substrates, reduced microbial mobility and consequent access to substrate, and a direct effect on microbial growth. Decreases in activity of aerobic microbes in very wet soil are usually attributed to oxygen deprivation caused by slow diffusion (Grant & Rochette, 1994). Hence, the relation between soil water content and microbial processes in soil is complex because it varies from soil to soil, depending on the slope of the moisture retention curve, porosity, concentration of organic matter, pH and soil depth (Gonçalves & Carlyle, 1994; Rodrigo *et al.*, 1997; Leirós *et al.*, 1999). Also, microbes appear to be able to adapt to markedly varying water contents in the field (e.g. Sulkava *et al.*, 1996; Paul *et al.*, 1999). These issues raise the question as to what is the most appropriate expression of soil water to use in a W_m function for a range of soil types. Possible variables are discussed in turn below.

Gravimetric or volumetric soil water content. Although using gravimetric (θ) or volumetric (θ_v) soil water content may be satisfactory for a particular soil type (e.g. Myers *et al.*, 1982) or type of litter (O’Connell, 1990), it is difficult to apply either generally because of the wide variation in soil structure, texture and pore-size distribution among soils. For example, the same θ value results in markedly different wetness, i.e. matric suction, of soils of different texture.

Per cent pore space filled with water. If a particle density of 2.65 g cm^{-3} is assumed then the per cent pore space filled with water (PSF) can be estimated from measurements of the soil’s bulk density (in g cm^{-3}) and the volumetric water content. Per cent pore space filled with water has been used in W_m functions of mineralization by Grant & Rochette (1994), Rasiah & Kay (1998) and O’Connell & Rance (1999) because they thought that it described the influence of oxygen diffusion on mineralization and the volume of soil supporting aerobic microbial activity. However, since the availability of water and organic substrate may differ between large and small pores, PSF is not necessarily directly related to mineralization or decomposition. Also, Weier *et al.* (1993) and Rodrigo *et al.* (1997) found that the value of PSF that coincided with the onset of decreased activity of aerobic microorganisms varied from soil to soil (ranging from 60 to 90%), probably because of differences in structure.

Water content relative to a reference water content. Other soil water variables are water content expressed as a proportion of a reference soil water content ($\theta/\theta_{\mathrm{ref}}$), such as soil water-holding capacity, field capacity, porosity, and an optimal water content for mineralization (e.g. Stanford & Epstein, 1974; Myers *et al.*, 1982; Gonçalves & Carlyle, 1994). This variable might allow a better comparison between soil of various structures, textures and pore-size distributions than using water content itself.

Soil water potential. Soil water potential (ψ) is the most commonly used soil water variable in W_{m} functions (e.g. Cassman & Munns, 1980; Orchard & Cook, 1983; Theodorou & Bowen, 1983; Quemada & Cabrera, 1997; Sierra, 1997). This is because it, or equivalent quantities (e.g. relative humidity), is the most suitable measure for expressing availability of water for microbial activity (Orchard & Cook, 1983; Rodrigo *et al.*, 1997) in dry soils of varied textures. However, in wetter soils in which there is ample water for microbial activity, the water content takes on an independent importance because of its influence on transport.

Relative soil water content. A more sophisticated approach is to use a relative water content (e.g. Myers *et al.*, 1982; Walse *et al.*, 1998; Paul *et al.*, 2001). In it soil water is expressed in terms of its availability relative to the total available range. Relative water content (RWC) is usually defined in terms of a nominal permanent wilting point (i.e. θ at -1.5 MPa, $\theta_{-1.5}$) and saturation (i.e. θ at -0.01 MPa, $\theta_{-0.01}$):

$$\mathrm{RWC} = \frac{(\theta - \theta_{-1.5})}{(\theta_{-0.01} - \theta_{-1.5})}. \tag{3}$$

Relative field water content (RFWC) may be defined in terms of lower (θ_{LL}) and upper (θ_{UL}) limit of θ observed in the field:

$$\mathrm{RFWC} = \frac{(\theta - \theta_{\mathrm{LL}})}{(\theta_{\mathrm{UL}} - \theta_{\mathrm{LL}})}. \tag{4}$$

We may estimate the total available water range also by integrating several physical properties into a single variable called least limiting water range, LLWR (e.g. Zou *et al.*, 2000). This quantity is defined (i) at the wet end by the soil water content at an arbitrary value of non-limiting air-filled porosity (0.10 $\mathrm{cm^3\,cm^{-3}}$) or $\theta_{-0.01}$, whichever is the smaller, and (ii) at the dry end by the water content at an arbitrary value of limiting soil strength (3.0 MPa) or $\theta_{-1.5}$, whichever is the smaller. The LLWR may be used to define a least limiting relative water content,

$$\mathrm{LLRWC} = \frac{(\theta - \theta_{-1.5})}{\mathrm{LLWR}}. \tag{5}$$

Mathematical descriptions of W_{m}

Many functions have been used to describe the influence of water on mineralization, with large differences between models, particularly for dry soil (Rodrigo *et al.*, 1997). The simplest functions, usually using $\theta/\theta_{\mathrm{ref}}$, are the linear relations in the available moisture range between wilting point and field capacity or saturation (e.g. Stanford & Epstein, 1974). Outside this range, W_{m} is often assumed to be constant. Log-linear W_{m} relations, usually with ψ, are also widely used (e.g. Orchard & Cook, 1983), as are simple power or exponential functions (e.g. Sierra, 1997). Others (e.g. Cassman & Munns, 1980; Myers *et al.*, 1982) have found that a quadratic relation, usually using RWC, better described N mineralization in soil. Another class of equations are logistic or sigmoidal functions using θ alone (e.g. O'Connell, 1990), $\theta/\theta_{\mathrm{ref}}$ (e.g. Gonçalves & Carlyle, 1994), or PSF (e.g. O'Connell & Rance, 1999).

Most functions of W_{m} do not describe a decline in microbial activity in wet soil. Exceptions are quadratic and linear functions defined for soils wetter than field capacity or saturation. Such functions are most suitable for soils subject to waterlogging. However, for most soils it is probably not necessary to define W_{m} over the full range of possible water contents if the main objective is to predict rates of net mineralization predominantly in the surface 10 cm of soil. This is especially true for models that use average weekly or monthly estimates of surface soil water content, which are unlikely to be near saturation.

Methods

We have compiled incubation data from published and unpublished sources for 33 different soils, in which net mineralization of N was determined under a range of water contents at temperatures between 25 and 35°C (Table 1). Of these soils, 94% had measurements of ψ and a measure of $\theta_{-1.5}$ and $\theta_{-0.01}$, 89% had estimates of soil bulk density, and 68% had field measurements of soil water content from which θ_{LL} and θ_{UL} could be estimated.

Kirschbaum (1995) and Rodrigo *et al.* (1997) reviewed functions describing the influence of temperature on observed relative rates of mineralization, T_{m}, across a range of soil types. They showed that over a large temperature range the Lloyd & Taylor (1994) function was the most universal. Kirschbaum (2000) normalized this function to a reference temperature of 40°C and calibrated the function using data from a wider range of studies:

$$T_{\mathrm{m}} = \exp\left\{3.36\left(\frac{T-40}{T+31.79}\right)\right\}, \tag{6}$$

where T is the temperature of incubation (°C).

We removed temperature limitations on mineralization by dividing all observed rates of N mineralization by T_{m}, calculated using Equation (6). This effectively gave the estimated rate of mineralization at a temperature of 40°C. To compare soils that had differing substrate qualities, we expressed this

Table 1 References for studies of net mineralization of nitrogen under a range of soil water contents: location, land use (LU: pine plantation, Pi; eucalypt plantation, E; pasture, Pa; crop, C), depth of soil layer (cm), soil textural class (sand, S; sandy loam, SL; sandy clay, SC; fine loam, FL; coarse loam, CL; fine silty, FS; coarse silty, CS; clay loam, L; clay, C), soil bulk density (BD, g cm^{-3}), organic carbon content (OC, %), number of days of incubation, temperature during incubation (Temp., °C), soil water content (g 100 g^{-1}) at permanent wilting point ($\theta_{-1.5}$, defined as −1.5 MPa), saturation ($\theta_{-0.01}$, defined as −0.01 MPa), lower limit of water content observed in the field (θ_{LL}), upper limit of water content observed in the field (θ_{UL}), and at the optimum water content for mineralization (θ_{ref}), and maximum rates of mineralization of nitrogen (N_{min}, mg N g^{-1} day^{-1})

No	Location	LU	Depth	Texture	BD	OC	Days	Temp.	$\theta_{-1.5}$	$\theta_{-0.01}$	θ_{LL}	θ_{UL}	θ_{ref}	N_{min}	Reference
1	South Australia	Pi	0–7.5	S	1.26	1.60	60	25	NA	NA	2.6	31.5	31.5	0.79	Gonçalves & Carlyle (1994)
2	South Australia	Pi	0–20	S	1.47[c]	1.00	56	25	NA	NA	2.8	21.3	21.3	0.36	Theodorou & Bowen (1983)
3	North Dakota, USA[a]	C	0–20	L	1.42[c]	1.32	14	35	8.0	22.0	NA	NA	23.3	3.58	Stanford & Epstein (1974)
4	Georgia, USA[a]	C	0–20	C	1.58[c]	0.34	14	35	4.0	13.0	NA	NA	11.6	3.48	Stanford & Epstein (1974)
5	Idaho, USA[a]	C	0–20	CS	1.47[c]	1.00	14	35	6.0	34.0	NA	NA	24.2	6.66	Stanford & Epstein (1974)
6	Minnesota, USA[a]	C	0–20	FS	1.31[c]	2.19	14	35	12.0	34.0	NA	NA	26.6	7.09	Stanford & Epstein (1974)
7	Minnesota, USA[a]	C	0–20	FL	1.28[c]	2.43	14	35	9.0	32.0	NA	NA	25.5	5.41	Stanford & Epstein (1974)
8	Texas, USA[a]	C	0–20	FL/CL	1.46[c]	1.06	14	35	12.5	36.0	NA	NA	22.4	7.50	Stanford & Epstein (1974)
9	Argentina	C	0–5	L	1.31[c]	2.18	35	25	16.6	30.0	NA	NA	50.7	2.09	Sierra (1997)
10	Georgia, USA	Pa	0–10	SL	1.49[c]	0.88	21	28, 35	4.0	14.8	NA	NA	12.1	0.34	Quemada & Cabrera (1997)
11	Queensland, Australia	C	0–15	C	NA	0.65	14	35	27.5	57.0	NA	NA	52.8	0.92	Myers *et al.* (1982)
12	Queensland, Australia	C	0–15	C	NA	0.75	14	35	8.0	25.0	NA	NA	40.4	2.35	Myers *et al.* (1982)
13	Queensland, Australia	C	0–15	SC	NA	0.67	14	35	4.0	14.0	NA	NA	11.0	1.29	Myers *et al.* (1982)
14	Queensland, Australia	C	0–15	C	NA	2.22	14	35	25.0	53.0	NA	NA	67.6	3.60	Myers *et al.* (1982)
15	Queensland, Australia	C	0–15	C	NA	1.76	14	35	17.0	42.0	NA	NA	34.6	2.11	Myers *et al.* (1982)
16	Wisconsin, USA	C	0–15	SL	1.34[c]	1.93	14	30, 35	8.5	24.5	NA	NA	24.3	2.84	Kladivko & Keeney (1987)
17	Wisconsin, USA	C	0–15	CL	1.26[c]	2.63	14	30, 35	21.6	40.5	NA	NA	33.1	4.70	Kladivko & Keeney (1987)
18	South Australia	Pi	0–3	S	1.26	3.59	90	30	NA	NA	1.5	27.7	27.7	2.13	Hopmans *et al.* (1980)
19	South Australia	E	0–3	S	1.26	4.43	90	30	NA	NA	1.5	23.3	23.3	3.65	Hopmans *et al.* (1980)
20	California, USA	C	0–18	FS	NA	NA	14	25, 30	14.0	33.0	14.0	28.6	28.6	1.62	Cassman & Munns (1980)
21	West Australia[b]	E	0–5	SL	0.76	7.65	7–56	28–35	16.2	40.1	4.9	42.6	38.0	9.22	O'Connell & Rance (1999)
22	West Australia[b]	E	5–10	SL	1.20	4.81	7–56	28–35	11.5	26.0	4.7	26.1	24.5	2.95	O'Connell & Rance (1999)
23	West Australia[b]	E	10–20	SL	1.29	3.33	7–56	28–35	9.1	20.6	5.5	22.9	16.3	1.02	O'Connell & Rance (1999)
24	West Australia[b]	E	0–5	SL	1.09	4.24	7–56	28–35	8.2	21.3	2.2	20.9	17.2	4.11	O'Connell & Rance (1999)
25	West Australia[b]	E	5–10	SL	1.37	3.12	7–56	28–35	6.2	15.6	2.3	13.8	15.1	2.46	O'Connell & Rance (1999)
26	West Australia[b]	E	10–20	SL	1.53	2.03	7–56	28–35	4.7	9.6	3.4	11.8	7.7	0.54	O'Connell & Rance (1999)
27	West Australia[b]	E	0–5	SL	0.76	6.02	7–56	28–35	18.8	37.0	7.5	39.6	35.1	9.04	O'Connell & Rance (1999)
28	West Australia[b]	E	5–10	SL	1.17	4.21	7–56	28–35	11.8	28.1	8.0	26.4	22.7	2.12	O'Connell & Rance (1999)
29	West Australia[b]	E	10–20	SL	1.32	2.81	7–56	28–35	10.9	24.8	7.8	22.8	24.2	1.93	O'Connell & Rance (1999)
30	New South Wales, Australia	C	0–2	L	1.31	2.13	35	30	11.9	18.0	1.8	18.0	18.0	3.04	Purnomo (1996)
31	New South Wales, Australia	C	2–4	L	1.31	1.91	35	30	11.9	18.0	1.8	18.0	18.0	1.64	Purnomo (1996)
32	New South Wales, Australia	C	4–6	L	1.31	1.86	35	30	11.9	18.0	1.8	18.0	18.0	1.80	Purnomo (1996)
33	New South Wales, Australia	E	0–10	L	1.31	1.31	88	25, 30	11.9	18.0	4.9	23.7	33.3	2.63	P. Polglase (unpublished)

[a]Information on soil properties was obtained from Stanford & Smith (1972).
[b]Data for the soil water retention curve was provided by A.M. O'Connell (unpublished).
[c]Estimated using the relation given by Adams (1973).
NA, data not available.

rate of mineralization in relative terms (i.e. to derive W_m) by dividing by the calculated rate of mineralization at optimal soil water content. We determined the optimal soil water content for each individual soil layer incubated by fitting a polynomial through a plot of the rate of mineralization ($mg\,N\,kg^{-1}\,day^{-1}$) against θ. Across the 32 soils, the fitted polynomial functions explained an average of 91% of the variation in net mineralization rates.

In most cases, the rate of net mineralization is likely to decrease with increase in the duration of incubation, as readily decomposable substrate is exhausted and waste products accumulate. As these effects are likely to develop rapidly in soils incubated at near-optimal water content, sensitivity of net mineralization to water content may be underestimated (Cassman & Munns, 1980). To limit this potential problem, we collated data from incubation experiments where incubation was less than 90 days.

All studies had been made on sieved soil under varying water contents. Sierra (1997) suggested that aeration in such disturbed soil may be more favourable for mineralization than in undisturbed soils, and that, consequently, the response might be biased. However, recent work by Paul *et al.* (2001) has shown that for 11 different soil types (many of which we tested) there was very little difference in rates of mineralization between disturbed and undisturbed soils.

As the percentage of air-filled pore spaces decreases, so the active microbial population changes from aerobic to facultative or obligate anaerobic organisms. The relative importances of the processes that transform N also vary because nitrification (aerobic) is restricted at water contents near saturation and denitrification (anaerobic) increases as the soil water content increases (Rodrigo *et al.*, 1997). Therefore, we excluded from our analysis relatively wet soils in which mineralization appeared to be limited by lack of oxygen. We therefore could not describe how rates of mineralization of N decline in wet soil across a range of soil types. This inability is largely immaterial for predicting rates of net mineralization in well-drained soil in the field.

To determine the best way of expressing soil water content for inclusion in a generalized W_m function of mineralization, we plotted the value of W_m calculated for each soil layer against the soil water variables θ, PSF, θ/θ_{ref}, ψ, RWC, RFWC and LLRWC.

Variation of W_m between soils remained large regardless of the variable used to describe soil water content. Given this variation, the simplest possible function was fitted to each data set (Table 2). We assumed that there was a linear increase of W_m with the soil water variable within a specified range, outside of which W_m was assumed to be 0 in drier soils and 1 in wetter soils. We determined the slope, intercept and range of the fitted linear regression by concurrently minimizing the total sums of squares of the difference between predicted and observed W_m.

After fitting these simple functions to each data set shown in Table 2, we determined the extent to which the soil water variables explained relative rates of net mineralization, W_m, by calculating the model's efficiency (E, as defined by Soares *et al.*, 1995). This efficiency is analogous to R^2, and provides a simple index of performance on a relative scale on which 1 indicates a perfect fit and 0 indicates that the model is no better than a simple average. The deviations of predicted W_m from the true mean were assessed by the mean squared error (MSE), for which the smaller the values, the better the model explains the data.

Results

Measures of performance (E, MSE and R^2) indicated that some variables were much better than others in providing a

Table 2 Variables used to describe generalized W_m functions, linear models fitted within the ranges specified, data not used in model parameterization (see Table 1), number of data points available (n), and various measures of model performance (E, MSE, R^2). For explanation of abbreviations see text

Variable	Data not used	Function fitted to data, and range	n	E	MSE	R^2
θ		$W_m = 0.07\theta - 0.33,\ 5 < \theta < 20$	415	0.19	0.09	0.47
PSF	14–18, 23[a]	$W_m = 0.02\mathrm{PSF},\ 0 < \mathrm{PSF} < 50$	369	0.37	0.07	0.45
θ/θ_{ref}		$W_m = 1.67\theta/\theta_{ref} - 0.33,\ 0.20 < \theta/\theta_{ref} < 0.80$	415	0.59	0.04	0.67
ψ	1, 2, 21, 22[b]	$W_m = -0.15\log_{10}\psi + 0.55$	390	0.61	0.04	0.61
LLRWC	14–18, 23[a]	$W_m = 0.83\mathrm{LLRWC} + 0.42,\ -0.50 < \mathrm{LLRWC} < 0.70$	369	0.68	0.03	0.74
RWC	1, 2, 21, 22[c]	$W_m = 0.83\mathrm{RWC} + 0.42,\ -0.50 < \mathrm{RWC} < 0.70$	390	0.72	0.03	0.75
RFWC	3–20[c]	$W_m = \mathrm{RFWC} + 0.10,\ -0.10 < \mathrm{RFWC} < 0.90$	283	0.74	0.03	0.76
RFWC	3–20[c]	$W_m = 1/[1 + 6.63\exp(-5.69\mathrm{RFWC})]$	283	0.78	0.03	0.78

[a]Estimates of soil bulk density were unavailable.

[b]Measures of ψ were unavailable.

[c]Measures of θ_{LL} and θ_{UL} were unavailable.

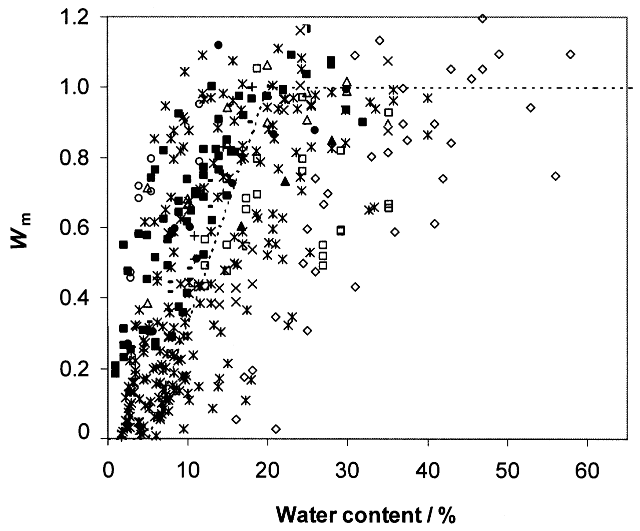

Figure 1 The relation between W_m and gravimetric water content, θ, of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

generalized response of different soil types to changes in water content (Table 2).

Gravimetric water content, θ, was poorly related to W_m across the range of soil types (Figure 1). The linear function that provided the best fit explained less than half (47%) of the variation in W_m, with an E and MSE of only 0.19 and 0.09, respectively (Table 2).

Using PSF as the independent variable (Figure 2) did not explain much more of the variation in W_m than using θ alone. The E and MSE of the fitted linear function were only 0.37 and 0.07, respectively (Table 2).

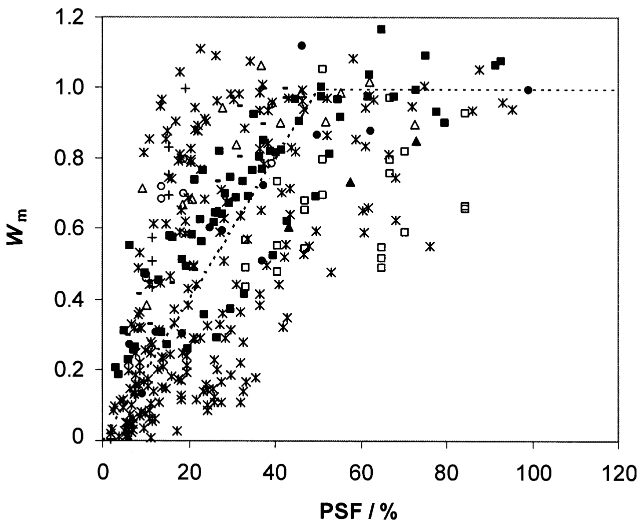

Figure 2 The relation between W_m and pore space filled with water (PSF) of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

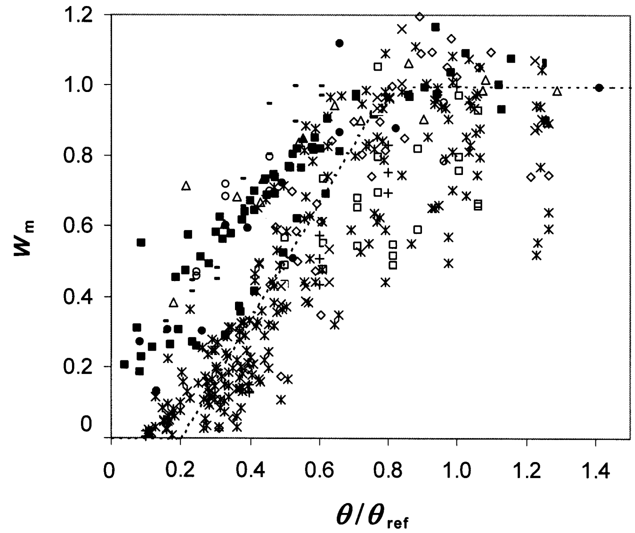

Figure 3 The relation between W_m and water content relative to the optimal water content for net mineralization of N (θ/θ_{ref}) of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

The relation between θ and W_m was improved when θ was expressed in terms of the optimal gravimetric water content for net mineralization, θ_{ref} (Figure 3). The linear function provided the best fit and explained 67% of the variation in W_m, with an E and MSE of 0.59 and 0.04, respectively (Table 2).

As expected, using ψ as the independent variable was also better than using θ (Figure 4). The log-linear function of W_m provided the best fit to these data, explaining 61% of the variation in W_m. The E and MSE of prediction were 0.61 and 0.04, respectively.

When LLRWC or RWC were used as the independent variable (Figures 5 and 6), between 74 and 75% of the variation

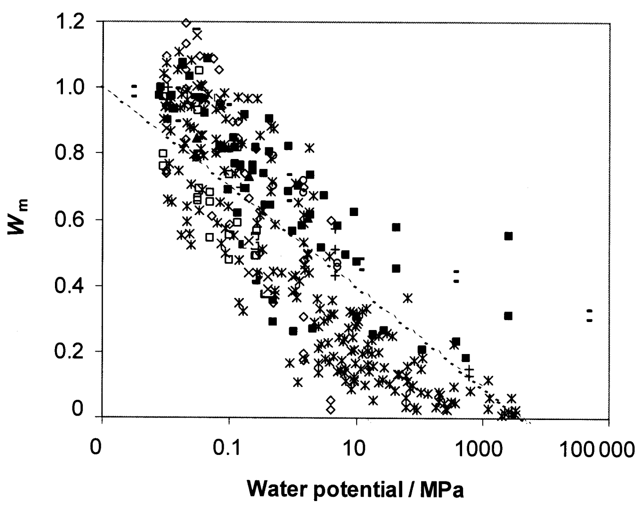

Figure 4 The relation between W_m and water potential (ψ) of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

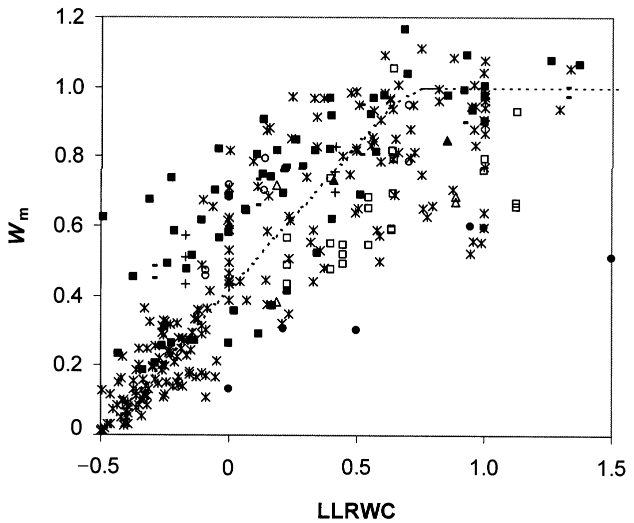

Figure 5 The relation between W_m and least limiting relative water content (LLRWC) of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

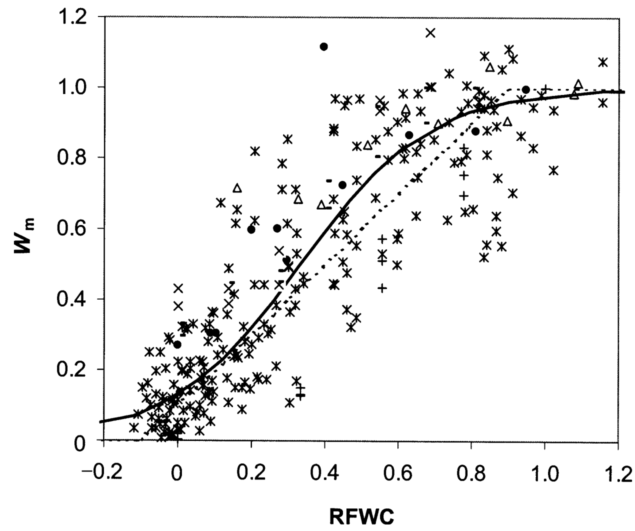

Figure 7 The relation between W_m and relative field water content (RFWC) of the soil during incubation. The fitted equation (dashed and solid lines), measures of the model performance, and the data used are given in Table 2.

in W_m was explained by the linear function given in Table 2. Accounting for soil strength and air-filled porosity (i.e. LLWR) in the estimated total available range of water did not improve the model's performance relative to simply using the difference between $\theta_{-1.5}$ and $\theta_{-0.01}$. Consequently, regardless of whether LLRWC or RWC were used as the independent variables, the fitted linear function had an E of 0.68–0.72 and an MSE of 0.03.

We gained a further improvement by using the upper and lower limit of water content observed in the field to define

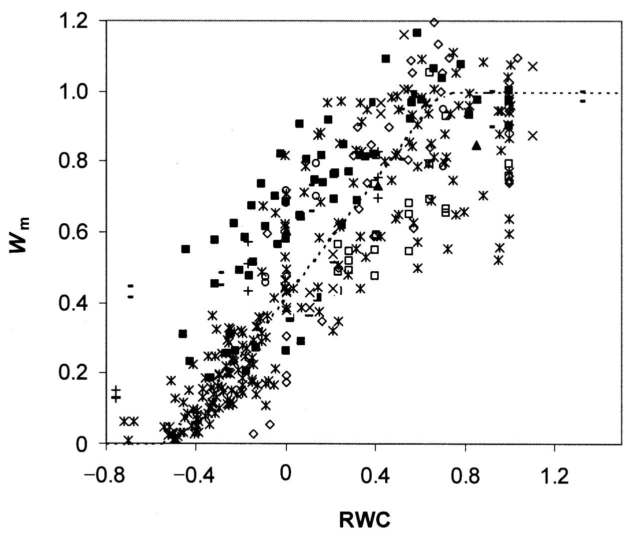

Figure 6 The relation between W_m and relative water content (RWC) of the soil during incubation. The fitted equation (dashed line), measures of the model performance, and the data used are given in Table 2.

RFWC (Figure 7). The fitted linear function explained 76% of the variation in W_m, with an E of 0.74 and an MSE of 0.03 (Table 2). Although the linear function given in Table 2 explained the data well, the best fit was obtained with a sigmoidal function of the form described by O'Connell & Rance (1999) (Figure 7). This function explained 78% of the variation in W_m with an E and MSE of 0.78 and 0.03, respectively. However, only 68% of the sets of data had measurements of θ_{LL} and θ_{UL} from which we could calculate RFWC. It is possible therefore that the reduced variation in the relation between relative mineralization and water content arises because we had fewer sets of data.

Discussion

One of our main findings is that although PSF, θ/θ_{ref} and particularly ψ have been widely used in W_m functions calibrated to particular soils, they are not the best variables in a function that is to be applied across a wide range of soil types. Using θ/θ_{ref}, and particularly PSF, provided only a slightly better description of net mineralization of N than using θ alone. Consistent with these findings, Kladivko & Keeney (1987) noted that there was little difference between N mineralization rates estimated from a linear function of soil θ and from a logarithmic function of ψ. Also consistent with our findings, Walse *et al.* (1998) found that θ/θ_{ref} was poorly related to relative mineralization or decomposition across 12 soil types.

We conclude that measures of relative water content (i.e. RWC, LLRWC and RFWC) were the best variables for describing how the net mineralization of N responds to water across a range of soil types. By contrast, in an incubation study, Myers *et al.* (1982) found that RWC could not account for the variation in net mineralization of N between five different soils. The lack of a general response to change in RWC observed by Myers *et al.* (1982) might have been because they assumed drier θ_{LL} and θ_{UL} of -4.0 and -0.03 MPa, respectively, compared with our θ_{LL} and θ_{UL} of -1.5 and -0.01 MPa, respectively. In addition, the water content relative to the water content at specific water potentials was not the best means to allow for comparison between soils of differing texture.

Using RFWC in a generalized W_m function not only allows comparison among soils of different textures but is also useful for describing processes, such as the diffusion of nutrients and oxygen, which can limit microbial activity. Furthermore, it is often suggested that sensitivity of microbial communities to changes in soil water content generally decreases with increasing mean annual rainfall (e.g. Lomander *et al.*, 1998). Microbes may adapt to variations in the frequency of wetting and drying cycles (Paul *et al.*, 1999). Using RFWC allows for microbial adaptation to the climatic environment since microbes are likely to be adapted to the lower and upper limit of water content observed in the field (θ_{LL} and θ_{UL}).

Conclusion

Defining soil water content in terms of an upper and lower limit observed in the field (i.e. RFWC) was the most accurate way to describe the generalized effect of soil water on net mineralization of N across a range of soil types. For the data collated, we found that a sigmoidal curve provided the best fit for the relation between RFWC and relative rate of mineralization of N. The function is suitable for models that aim to have a water modifier that can be applied to a range of soil types and climatic conditions without the need for calibration at every site of interest.

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