Acidification and Release of Nutrients from Organic Matter – a Model Analysis

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Abstract. A simple, phenomenological model is proposed to describe the behaviour of nett mineralization of nitrogen from the soil organic matter.

Experimental evidence shows that nett mineralization of nitrogen is increased following artificial acidification of soil forests. The model seems to describe appropriately this phenomenon and some testable predictions are derived from it. These predictions seem to give a clue to the intriguing difficulty of establishing effects of acid rain in coniferous forest ecosystems.

A discussion is also given on how the model can be extended to nutrient elements other than nitrogen.

Introduction

The release of nutrients from the organic matter of unfertilized soils is a key process controlling the growth of plants. Intimately associated with this process is the mineralization process, through which the nutrients are transferred from the organic to the water soluble – inorganic – state which is available for plant uptake.

Mineralization is a very complex process. First of all, since it consists of a host of enzymatically regulated steps, it depends on specific properties of the decomposer communities in the soil. Furthermore, Elliot et al. (1979) and others have observed that the mineralization of nitrogen in microcosms is increased by the predation of bacteria. Interactions between soil organisms are, thus, also of importance for mineralization.

This detailed level of resolution cannot be incorporated in mathematical formulations attempting to describe phenomena at the ecosystem level, especially if long-term predictions are expected from the theory. Sometimes, even if the complexity of the model is drastically reduced, relevant analyses can be carried out if the essential variables for the problem are retained in the theory (Bosatta 1981a, b). Another approach to the “tie up of different levels” problem is to start with a model using phenomenological (empirical) variables at the ecosystem level; the coupling to the actual mechanisms can then be achieved by relating these phenomenological variables to microbial parameters (Bosatta and Staaf 1981).

Incubation experiments carried out in the field (Bååth et al. 1980) and laboratory lysimeters experiments (Hovland et al. 1980) seem both to indicate that the rate of decomposition of pine litter is decreased by acidification. It is generally postulated that a decrease in the decomposition rate of organic matter will produce a decrease in the rate of mineralization.

Andersson et al. (1980) made use of this hypothesis in a model aimed to analyze the effects of acidification in the productivity of a forest, and they found that the system was most sensitive to perturbations of the mineralization rate of nitrogen in needle litter. Aber et al. (1982) also developed a simulation model to study the effects of acid rain on forest systems. Simulations with this model make apparent that even small changes in nitrogen availability due to acid precipitation cause a reduction in forest biomass accumulation.

Nevertheless, there are indications that the response of the system to acidification may be the opposite. Thus, Tveite (1980) has observed that the height growth of some species, during a period of some years, has been stimulated by increased rain acidity.

Furthermore, Tamm et al. (1977) observed that the nett mineralization of nitrogen was increased when humus samples from a coniferous forest soil were treated with sulphuric acid.

Nett mineralization is the difference between mineralization and immobilization, which is defined as incorporation – retention – of nitrogen in the decomposer biomass. Thus, the key to the availability of inorganic nitrogen lies in the nett mineralization being a positive quantity, i.e., in the extent to which mineralization exceeds immobilization (Swift et al. 1979; Bosatta 1981a). To explain the above phenomena i.e., the stimulation of nett mineralization following acidification, Tamm (1976) suggests that immobilization could be inhibited to a larger extent than the decomposition of organic matter. The inhibition of the latter is confirmed by a significant decrease in respiration observed in the acidified samples.

Furthermore, Bååth et al. (1980) have observed a lower nitrogen retention in the needle litter decomposed for a period of two years in acidified plots, a fact in agreement with Tamm’s suggestions about immobilization.

This paper presents a simple model of mineralization, adapted to the ecosystem level, which seems to describe correctly the above-mentioned stimulation phenomena and which enable the derivation of predictions feasible for experimental verification.

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Theory

Aber and Melillo (1979) found that the concentration of nitrogen in a large number of decomposing forest litter types increases linearly with the accumulated weight loss and that this relationship is very strong up to at least 50–60% of weight loss. Staaf and Berg (1982) found a similar relation for nitrogen concentration in decomposing pine litter.

Assume now that a certain litter structure with an initial C/N-ratio of Co/No contains C g of carbon and N g of nitrogen after t years of decomposition. If the material decays in an exponential way (Berg 1978) and if the carbon concentration in it remains constant over time, C will change in time according to

$$C(t) = C_0 e^{-kt}$$ (1)

where $k (yr^{-1})$ is the decomposition rate constant.

The linear increase of nitrogen concentration with the accumulated weight loss can now be expressed as

$$N/C = N_0/Co + a (1 - C/Co)$$ (2)

where $a$, a constant determined by the litter material, is a measure of how strongly nitrogen is retained in the substrate.

Calculated $a$-values for several litter materials showed a strong positive linear relationship with their $k$-values (Bosatta and Staaf 1982), i.e.,

$$a = a_0 + a_1 k$$ (3)

where $a_0 (gN.g^{-1}C)$ and $a_1 (gN.g^{-1}C.yr)$ are the coefficients of the regression model.

The dynamic properties of nitrogen in the litter that can be derived from Eqs. (1)–(3) are comprehensively discussed by Bosatta and Staaf (1982). So, introducing Eqs. (1) and (3) in (2), one gets the equation for the nitrogen dynamics

$$N = N_0 e^{-kt} + (a_0 + a_1 k) (1 - e^{-kt}) C_0 e^{-kt}.$$ (4)

Taking the time derivative of this expression one gets

$$\dot{N} = \dot{a}_N = -kN + bC$$ (5)

where

$$b = (a_0 k + a_1 k^2) e^{-kt}.$$ (6)

The nett mineralization rate of nitrogen, $m$, can be formulated

$$m = -\dot{N} = kN - bC.$$ (7)

Evidently, if $b$ is zero it means that nitrogen is mineralized at the same relative rate as carbon and $b$ will, hereafter be named specific immobilization rate ($gN.g^{-1}C.yr^{-1}$).

For litter materials such that $N_0/C_0 < (a_0 + a_1 k)$, $N$ given by equation (4) shall increase from $N_0$ and will reach a maximum at time

$$\tau_N = -\frac{1}{2} \ln \frac{N_0}{C_0 (a_0 + a_1 k) + 1}.$$ (8)

For $t < \tau_N$ nett mineralization $m$ is negative, i.e., immobilization predominates ($bC > kN$).

At time $\tau_N$, $m$ is zero and the material reaches a “critical” $N/C$-ratio given by

$$(N/C)_c = (N_0/C_0 + a_0 + a_1 k)/2.$$ (9)

Thereafter, $kN > bC$ and $m$ is positive.

Assume now that during the course of decomposition the $k$-value of the material is reduced by, i.e., acidification. Suppose the perturbation is applied at some time $t_p$; the perturbed system is that for which

$$k^* = k$$ \quad if \quad $t < t_p$$

$$k^* = k - \varepsilon$$ \quad if \quad $t \geq t_p$$

and

$$\varepsilon > 0$$

The difference between the mineralization of the perturbed system, $m^*(\varepsilon, t)$, and the unperturbed mineralization, $m(t)$, is defined as

$$\delta(\varepsilon, t) = m^*(\varepsilon, t) - m(t).$$ (11)

We now ask: are there any specific conditions under which the value of nett mineralization could increase if the value of $k$ is decreased?

If the perturbation is small, i.e., if $|\varepsilon| < < k$, the explicit evolution of $\delta(\varepsilon, t)$ can be obtained by means of a sensitivity analysis (Astor et al. 1976).

The value and sign of $\delta$ at the moment of the perturbation, $\delta(\varepsilon, t_p)$, is easier to obtain and also provides relevant information. This is given by

$$\delta(\varepsilon, t_p) = -\varepsilon C_p [N_0/C_0 - g(k, t_p)]$$ (12)

where

$$C_p = C(t_p)$$

and

$$g(k, t_p) = (a_0 + a_1 k) (2 - k t_p e^{-kt_p} - a_0).$$ (13)

The answer to the above question is provided by 12. Since $\varepsilon > 0$, $\delta(\varepsilon, t_p)$ will be greater than zero if

$$N_0/C_0 < g(k, t_p)$$ (14)

i.e., under conditions such that 14 is verified, nett mineralization of nitrogen will increase as a response to a decrease in $k$.

Results

If litter materials is characterized by its initial N/C-ratio, $N_0/C_0$, and specific decomposition rate $k$, Eq. (14) can be used to tell us how old a material can become and still react by increasing its mineralization when acidified for the first time – provided that the acidification leads to a reduced decomposition rate.

Figure 1 shows plots of $g(k, t_p)$ [Eq. (13)] in the two dimensional space $k$-$N_0/C_0$ for different values of $t_p$. The values given to the parameters $a_0$ and $a_1$ are those found by Bosatta and Staaf (1982) for nitrogen, i.e., $a_0 = 0.011$ ($gN.g^{-1}C$) and $a_1 = 0.059$ ($gN.g^{-1}C.yr$). According to Fig. 1 a material with, for example, $k = 0.2$ and $N_0/C_0 = 0.01$ will still satisfy inequality 14 if it is acidified 2.5 years after decomposition has started, or, in other words, it will react to acidification by increasing its mineralization up to an age of roughly 2.5 years.

One could ask now if the above theory should be regarded valid only for nitrogen.

It was discussed earlier that if $N_0/C_0$ lies under a certain level, nitrogen will accumulate in the substrate until it