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Adapting the potentially mineralizable N concept for the prediction of fertilizer N requirements

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Abstract

Quantification of N dynamics in the ecosystem has taken on major significance in today's society, for economic and environmental reasons. A major fraction of the available N in soils is derived from the mineralization of organic matter. For decades, scientists have attempted to quantify the rate at which soils mineralize N, but the complexity of the N cycle has made this a major task. Further, agronomists have long sought soil test methods that are practical, yet will provide accurate means of predicting the amounts and rates of release of N from soils. Such tests would allow us to make more precise fertilization decisions. This paper discusses the potentially mineralizable N concept, first promoted by Stanford and colleagues [61, 62, 64], and suggests how it may be incorporated into deterministic models, such as CERES and LEACHM, so as to provide more accurate estimates of N mineralization under field conditions. We also suggest how the potentially mineralizable N concept may be coupled to quick, routine laboratory methods of determining available soil N, such as the hot 2 *M* KCl extracted NH_4-N method recently developed by Gianello and Bremner [35], and used together with deterministic N models, such as CERES, for predicting probable fertilizer N requirements.

Introduction

Nitrogen (N) is one of the most important plant nutrients. Crops obtain N primarily from the decomposition of soil organic matter but, also from added fertilizers, manures, and through N fxation by legumes, and from dry and wet deposition. Throughout the world, soil degradation associated with improper management has resulted in the diminution of the N-supplying capacity of many soils; this, plus the desire to increase production, has led to an increase in N fertilizer requirements and use [25]. In turn, the increasing use of fertilizers has resulted in considerable concern by society regarding the possible negative influence that N can have on the environment and health. The scientific community has responded by seeking crop management methods that producers may adopt to increase the efficient use of N.

Because soils are major sources of plant available N, and because excess N may impair the environment, it is imperative that we be able to quantify N mineralization. Due to the very dynamic nature of N, this has been a very challenging problem for scientists throughout the decades. This paper discusses: (i) how the concept of potentially mineralizable N may be adapted into deterministic models that have been designed to quantify all aspects of the N cycle, and (ii) how this concept may be adapted to provide more accurate soil tests for N fertilizer requirements.

Balance method of estimating N fertilizer requirements

The amount of N fertilizer to be applied depends on the attainable dry matter yield (Y_{dm}), the N concentration of the crop (N_y), the amount of residual mineral N present in the soil at seeding (N_{rm}), and the amount of N that the soil will mineralize from organic matter during the growing season (N_s) [58]. The crop does not recover all of the fertilizer N (N_f) nor soil N that is available to it (i.e., efficiency (E) of use of the various sources of N is less than 100%). Therefore, E will influence the quantity of N that must be applied in order to achieve a certain yield. If plant N at harvest is given by $Y_{dm} \times N_y$,

$$Y_{\rm dm}N_{\rm y} = E_{\rm rm}N_{\rm rm} + E_{\rm s}N_{\rm s} + E_{\rm f}N_{\rm f} \qquad (1)$$

Rearranging gives:

$$N_f = [Y_{\rm dm}N_{\rm y} - E_{\rm rm}N_{\rm rm} - E_{\rm s}N_{\rm s}]/E \qquad (2)$$

We can set a target yield and measure N_{rm} at seeding. As well, we can make reasonable estimates of the efficiencies even though these will vary depending on weather, fertilizer and crop management factors [53, 58]. The greatest difficulty in solving equation 2 is quantifying N_s.

Long before fertilizer use became commonplace, scientists have sought quick, routine tests for quantifying the N-supplying capacity of soils so as to determine the influence of crop rotations, legumes, and manure additions on fertilizer N requirements [10, 59]. This need is even more pressing today because, as producers adopt better management principles, they are likely to gradually increase the N-supplying capacity of their soils over time [18, 26, 27, 45, 51]. As well, where poor management is practised, the fertility of soils will be degraded [18]. It is unlikely that empirical methods such as the NO_3-test that is commonly used on the Canadian prairies and in some regions of the USA to determine fertilizer N requirements will adequately reflect the positive or negative changes in soil fertility. At present we have no simple soil tests that will reflect these changes in soil fertility but we will make some suggestions later in this paper. It is worth noting that, most of the routine soil tests used to assess available N have proven inadequate because they do not measure the potential of the soil to mineralize N over the growing season. Furthermore, such indices do not allow us to quantify N_s as a function of weather conditions. This is a prerequisite of any system if it is to be used in a predictive manner.

Estimation of N mineralization from potentially mineralizable N

Although there are several thousand kilograms N per hectare in most fertile agricultural soils, only 1 to 2% of this becomes available to crops each year [10]. The N that is mineralized comes from a heterogeneous pool of components varying in stability [10]. The organic components in soil include fresh crop and animal resiidues, microbial biomass, microbial metabolites and cell wall constituents adsorbed to colloids, physically protected material in small pores, and the very stable humus. Although fresh residues and microbial biomass are important as mineralizable substrates, specific compounds in the mineralizable pool have not been directly identified.

Stanford and Smith [64] proposed an incubation-leaching technique for use in quantifying the active N pool of soil organic matter. Stanford and co-workers [61, 62 64] advanced the concept of potentially mineralizable N, denoted as N_0, and a related mineralization rate constant (k), for use in characterizing soil-available N. Since then this concept has also been used to assess soil N availability in cropland, forests, and waste-disposal sites [7–9, 16, 29, 34, 55].

Stanford and Smith [64] suggested that N_0 and k could be estimated by statistical techniques if the soil was incubated at optimum moisture and temperature conditions for mineralization and the N mineralized (N_s and time of incubation (t) measured. They assumed that organic N mineralization under optimum conditions followed first-order kinetics, i.e.,

$$N_{\rm s} = N_0[1 - e^{-kt}] \qquad (3)$$

Stanford [58] suggested that the potentially mineralizable N concept could be used to estimate N_f by replacing N_s in equation 2 by N_0 $(1-e^{-kt})$. We could then modify k as a function of temperature and soil water [15] and calculate the probable N_s by using historical, long-term records of temperature and precipitation. Other soil characteristics that are required to allow estimation of N_s are field capacity and wilting point, and if these are not available they can be estimated from soil texture [65].

Use of this type of model requires that values of N_0 be known for each soil and it is desirable that these values do not change markedly from year to year. Few experiments have been conducted in which N_0 has been measured at regular intervals. In one such study conducted in Australia [30], N_0 decreased rapidly from 200 to 105 mg kg^{-1} soil during the first 20 yr after breaking and cultivating a Waco soil; however, during the following 50 yr of cultivation N_0 was essentially constant.

Equation 3 only holds when the mineralization process is conducted under optimum conditions for mineralization [64] for a long enough period ($\geq$ 24 wk) [14, 33]. If the incubation period is shorter than about 20 wk, the possibility of obtaining an inverse relationship between N_0 and k is great [32, 50]. Some scientists, in France [39] and also in Canada [32] did not obtain a first order relationship; rather, they obtained a zero order relationship for net N mineralization. However, Houot et al. [39] did not cite their temperature of incubation, while Ellert [32] incubated soil at 28 °C (might be too low) and worked with a forest soil where immobilization may have contributed to the observed departure from the first order relationship most frequently reported for cultivated soils. Low temperatures tend to favour immobilization over mineralization, especially early in the incubation, leading to an S-shaped type of curve.

The rate constant (k) in equation 3 must be adjusted for environmental conditions experienced *in situ* in order to predict the actual amount of N mineralized. For North American soils, optimum temperature for mineralization is assumed to be about 35 °C and optimum soil water content is field capacity (-0.03 to -0.01 MPa). The k is temperature-dependent [16, 19, 62]. Stanford et al. [62] found Q_{10} to vary between 1.8 and 1.9 for 39 US soils and suggested a Q_{10} of 2 could be used to represent most soils. The most precise results will be obtained if Q_{10} determined for a particular soil is used [15]; however, Q_{10} of a soil zone, or a Q_{10} of 2, will provide acceptable results if specific values for the soil are not available.

Prediction of N_s in the field also has to take into account the effect of soil water content. Stanford and Epstein [61] suggested that if the values of cumulative N_s were expressed on a relative basis with respect to maximum N_s, then the effect of water content could be described as:

$$\textit{Relative } N_s = \textit{Soil water content/ Optimum Water content} \qquad (4)$$

Similar results were obtained for nine Chilean soils [28]. However, the above expression was not suitable for 5 Australian and 32 Canadian soils [46]. Myers et al. [46] proposed a model similar to that in equation 4, except that they divided the available water in the soil by the possible available water for the soil, where the lower limit of available water was assumed to equal the water held by the soil at -4.0 MPa and the upper limit was taken as water held at -0.01 to -0.03 MPa. Myers et al. [46] obtained a linear relationship between N_s and this water quotient in the soils they tested, except for one Australian and nine Canadian soils, in which N_s showed a curvilinear response to the water quotient. Thus, in certain cases, the simple approach proposed by Stanford and Epstein [61] may not be adequate to represent the effect of soil water content.

There is some debate concerning the method used to correct N_s for soil water content. In some studies [15, 38] the water content factor was used to correct the rate constant k, but others [47] suggest that the water factor should be used to correct N_0. There is insufficient experimental data available to guide us in rationalizing this problem. Intuitively, however, it seems reasonable to expect such intensity factors as temperature, water and aeration to influence the rate of reaction rather than N_0. The potentially mineralizable N, which is a capacity factor, is a discrete quantity for each particular soil; its value is determined by the conditions (climate, edaphic, management) under which the soil has developed so that the moisture conditions in an incubation or in the field in a particular year merely determines what proportion of this factor will be mineralized in unit time. In any event, adjusting k for moisture resulted in only slightly larger predictions than when the correction was applied to N_0 [15, 38].

The correction by temperature and soil water content has been performed using hourly [15, 16], daily [7], weekly [44, 57], monthly [48, 52, 60], and yearly [66] time steps. Most workers have used Euler' s integration method, whereas Campbell et al. [15, 16] used the integrated form of the model to estimate N mineralized within each time step.

Stanford [59] summarized the first studies that attempted predictions of N mineralized from soil organic matter under greenhouse [63] and under field conditions [52, 60]. We shall report on some of the subsequent studies. Campbell et al. [16] used measured N_0 and k values for the top 2.5 cm of a loam soil to predict N mineralized in plastic bags in the laboratory and buried in the field, taking into account soil moisture and temperature conditions. The model predicted well the amounts of N mineralized in the laboratory but tended to under-predict the amounts of N mineralized in the field at the two lowest water contents. These underpredictions were attributed to the accidental entry of water into some bags, which could have caused wetting and drying cycles and induced flushes of N mineralization [16].

In another study [15], a more rigorous field evaluation of Stanford and Smith's approach was conducted with moisture effect calculated according to Myers et al. [46]. The N_0 and k values for the upper two 7.5-cm layers of a loam soil were used together with estimated temperature and soil water content, to predict N mineralized in lysimeters (0.15 m diameter, 1.2 m long) subjected to summer fallow, dryland spring wheat (*Triticum aestivum* L.) and irrigated spring wheat treatments. Predicted N mineralized closely agreed with measured values during the first 45 to 60 days, but tended to under predict observed values afterwards. Under predictions for the entire growing season amounted to 16, 26, and 31% of irrigated wheat, summer fallow, and dryland wheat treatments, respectively. The authors explained the under predictions as due to the model not accounting for the flushes in N mineralization that typically occur as a result of wetting/drying cycles on the Canadian Prairies.

In a Japanese study, N mineralized from soil organic matter during the corn (*Zea mays* L.) growing season in four soils was measured [55]. N_0 and k values were estimated and the dependence of k on temperature evaluated so as to predict N mineralized with adjustment for field temperature. In general, predicted amounts of N mineralized agreed closely (-1% to 8% of measured values) with observed amounts when the measured values ranged from 52 to 85 kg N ha^{-1}. Predicted amounts tended to be larger (1% to 51%) than measured amounts when mineralized N ranged from 103 to 226 kg N ha^{-1}. The authors attributed part of the over predictions to the existence of dry conditions which decreased N mineralization in the field. Because the model used did not make adjustments for soil water content, it would be expected to over predict N mineralized under dry field conditions.

Cabrera and Kissel [7] evaluated Stanford and Smith's approach in three Kansas soils during two sorghum (*Sorghum bicolor* [L.] Moench) growing seasons. Using the upper three 15-cm layers (0-45 cm total depth), they obtained over predictions ranging from 114 to 343% of the actual amounts of N mineralized (32 to 51 kg N ha^{-1}). When only the upper 15 cm layer was considered, the over predictions ranged from 9 to 181% [6]. It was hypothesized that the over predictions could have been due to an improper function of adjustment of the amounts of N mineralized based on soil water content, and to the crushing of the clay soil (to pass 2-mm sieve) before incubation [7]. In a follow-up study, it was found that, even after subtracting the initial N flush, samples that had been dried and crushed to pass through a 2-mm sieve showed higher N mineralization than undisturbed soil samples [9]. It was concluded that field-moist samples, as undisturbed as possible, should be used for determination of mineralization parameters.

This concept has been used, modified, criticized and discussed in great detail [5, 7-10, 15, 19, 31, 33, 43, 46-47, 50]. However, the foregoing research results indicate that there is a good chance we may be able to predict N mineralized under field conditions by following Stanford and Smith's approach. Much research remains to be conducted so as to improve the accuracy of predictions by this technique [14]. This type of model has been criticized for various shortcomings discussed elsewhere [14], but most of these may either not be quantitatively signifcant [15], or can be overcome if proper sample handling, incubation and calculation procedures are employed [14]. For example, soil samples should be air-dried and stored near freezing until analyzed. The incubation temperature is best at 35 °C, and the length of incubation should be at least 24 wk [32]. When the model proposed by Campbell et al. [15] is used for estimating N_s, two factors that can lead to low estimates of N_s is the failure to account for the N accruing from the most recent crop residues, and N lost by denitrification. However, these can be estimated by various commonly used simulation models such as LEACHM, CERES, EPIC and others.

Estimating N mineralization in long-term rotation studies

The use of the potentially mineralizable N concept to estimate N_s under laboratory, greenhouse and field conditions has been generally encouraging; however, most field studies have been one-season experiments. If the potentially mineralizable N concept is to be useful in a practical sense, it must perform credibly for systems that are degrading or aggrading as a consequence of crop management over time.

To test the usefulness of this concept under natural field conditions over several years requires the use of dynamic models that will allow accounting for the main components of the N cycle. Numerous deterministic models, appropriate for this task, have been developed (e.g., EPIC, NTRM, NLEAP, CERES, LEACHM). At Swift Current, Saskatchewan, we have tested LEACHM and CERES for simulating N min-

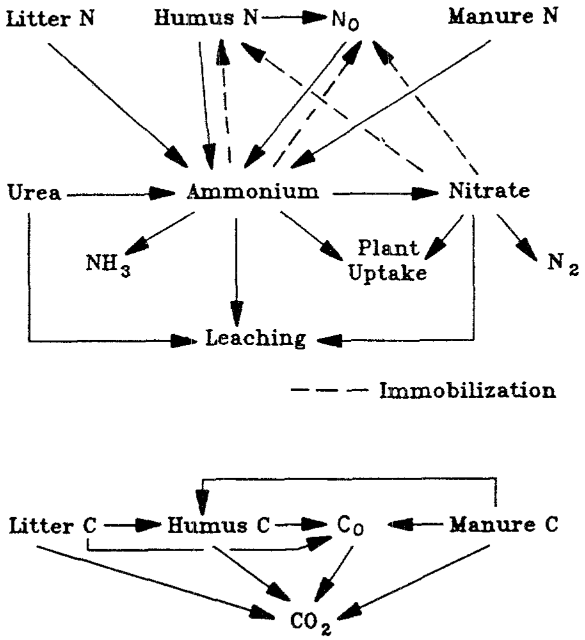

Fig. 1. Nitrogen submodel of LEACHMN [40] after modification [1], showing potentially mineralizable nitrogen (N_0) and potentially mineralizable carbon (C_0). (The CERES N submodel [37] was also modified as shown here).

eralization in two crop rotations from our long-term crop rotation study [23, 26]. We used the NO_3 leaching version of LEACHM (i.e., LEACHMN) to model N dynamics in the well-fertilized continuous spring wheat (Cont W) and fallow-spring wheat (F-W) rotations over the period 1967 to 1991 [1]. In the case of CERES, we only simulated a wet and a dry year.

The mechanisms describing mineralization and immobilization processes in CERES and LEACHMN are very similar [37, 40]. Both models simulate the decay of two types of organic matter: fresh organic matter (FOM) which includes crop residues or green manure, and a humic pool (HUM). However, in CERES, the FOM is further divided into three pools: carbohydrate, cellulose and lignin. Each pool has a different decay rate. In LEACHMN, FOM is treated as a single pool with one decay rate. Input data required for the models are the amount of straw added, its C/N ratio, its depth of incorporation into soil and the amount of root residue from the previous crop. These data are used to initialize FOM and the N contained within the fresh organic matter (FON), for each soil layer.

The mineralization routine also requires the amount of soil organic C in each layer as an input. This is used with a simplifying assumption of bulk soil C/N ratio of 10 to estimate the N contained in the humus pool. In testing CERES and LAECHMN models, our preliminary results showed that a single humus pool was inadequate. Therefore, both models were modifed by splitting the humus pool into two components: an active component (potential mineralizable-N), and a slow-N release fraction (humus-N). The characteristics of N_0 and k in the active pool were measured for this soil in a previous study (15, 16). The amount of humus-N was the total N contained in the soil less N_0. In the modified models (Fig. 1), the immobilized N and C were sent into the active N_0 pool, instead of into the FOM pool as it was done in the original models. The simulation results obtained from this modified model were much more plausible than that obtained from the original unmodified models.

Simulation with LEACHMN model

The water movement sub-routine of LEACHMN model was calibrated using data gathered in 1976 in an experiment conducted to measure Cl movement in lysimeters in the field (Campbell, unpublished data) and was validated using data from another lysimeter experiment [13]. The results obtained for water, Cl and NO_3 distribution in the soil profile throughout the growing season, under summer fallow and cropped systems, indicated a realistic representation of the system had been achieved using the modifed model [1].

We used this modified, calibrated model to simulate water and N in the rotation study. Total soil N (0.185%), assumed to be the starting value [4], was used to initialize the model for the year 1967. This was split into two fractions, an active fraction (potentially mineralizable-N) and a stable fraction (humus-N) based on the ratio of N_0/total N measured on the same soil in 1982 [16]. In that study, the ratio of N_0 to total N was 0.08, hence the initial value of total N in 1967 of 0.185 (or 1850 mg kg^{-1}) was split into 148 mg kg^{-1} as N_0 and 1702 mg kg^{-1} as humus in the 0-0.15 m layer. A similar calculation was made for the 0.15-0.30 m depth. For C, this was initialized using the value of organic C measured in 1967 and assuming the C/N ratio of the potentially mineralizable fraction was 10. The potentially mineralizable carbon (C_0) was subtracted from the total C to derive the humus C at the beginning of the experiment. It was assumed that very little N mineralization occurred below the 0.30 m depth [11].

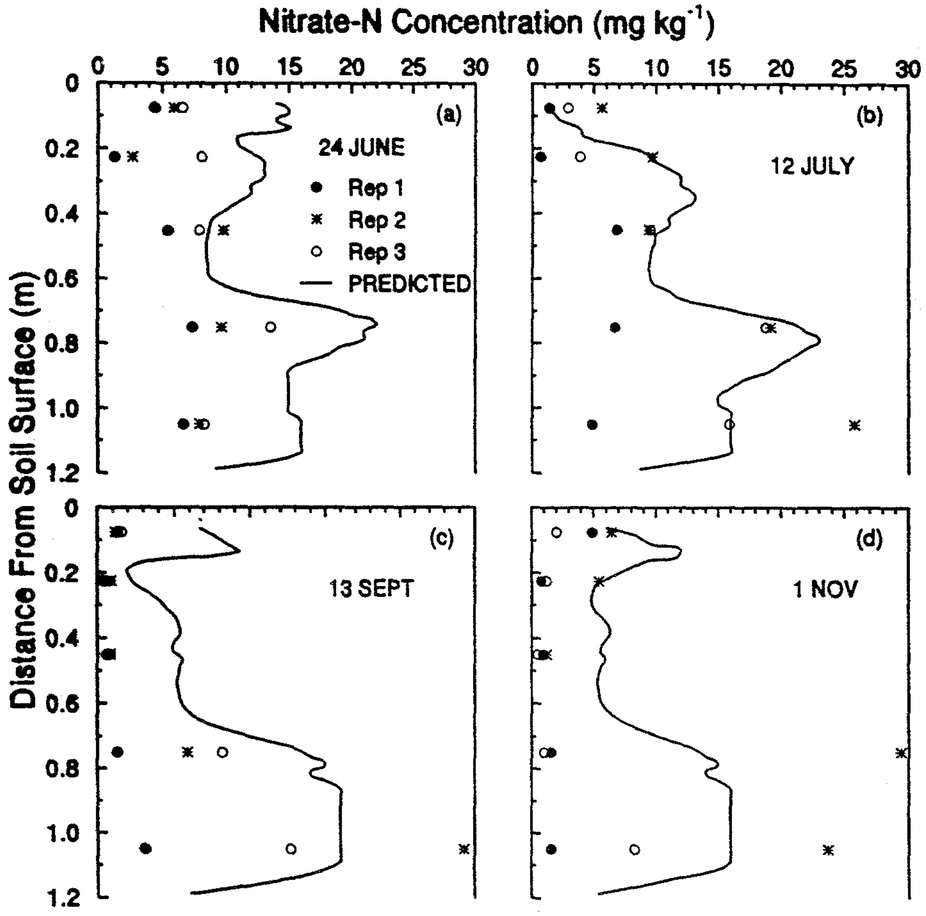

Fig. 2. Simulated soil nitrate distribution under Cont W in 1982 at Swift Current, Saskatchewan (wet year). Rainfall from 6 May to 24 June = 11 cm, 24 June to 12 July = 8.4 cm, 12 July to 13 September = 9.4 cm, and 13 September to 1 November = 6.7 cm [1].

The rate constant (k) associated with N_0 for the 0-0.15 m layer was taken as 0.013 day^{-1} [16]. The k value for the 0.15-0.30 m layer was assumed to be one-tenth of that for the surface 0.15 m [1]. The rate constant for the mineralization of humus-N (k_h) was not measured; it was obtained through calibration of the model (k_h = 0.00035 day^{-1}). It was assumed that the rate constant did not vary between growing seasons nor during a growing season.

The amount of straw-N available at the start ofthe experiment was estimated from straw yield of an adjacent field in 1966 [21]. Akinremi et al. [1] assumed that 50% of the 1966 straw remained at the start of the experiment in 1967 and that the straw was uniformly distributed within the plow layer (0-0.15 m) with about one-tenth located in the 0.15-0.30 m layer. The measured straw dry weights and straw N concentrations were used in the model calculations. The straw plus roots was assumed plowed into the soil and made available for decomposition a day after harvest as specified for this model. Root dry matter was estimated from the grain and straw dry matter by assuming that the root constitutes 16% of total plant weight at harvest [13]. Straw and root C concentrations were assumed to be 45% and root N concentration assumed to be 1% [12].

When the modified model was used to simulate water and N disposition in the soil in the two designated crop rotations at Swift Current, the model performed well for water (data not shown) and reasonably well for NO_3 (Fig. 2). But, as is readily seen in Fig. 2, even in this apparently uniform site, spatial variability of NO_3-N in the field can be quite large, especially in the 0.6-1.2 m depth. Therefore, striving for extreme precision in these types of analyses does not seem warranted.

We used the modified LEACHMN to estimate changes in N_0 during the growing season. Few studies have been conducted to follow changes in N_0 during the course of the growing season. In Sweden, the N mineralized in a 13-wk incubation for soils taken in April, June, August and October, decreased during the growing season but increased again after harvest [5]. The latter increase was attributed to the input of crop residues after harvest. Our simulation results for 1982 in the continuous wheat system (Fig. 3, top) followed the trend observed by Bonde and Rosswall [5]. The year 1982 was wet and this favoured N-mineralization; accordingly, the model predicted that N_0 declined gradually during the growing season until harvest (13 September), after which N_0 increased in response to the fresh residues. But, as shown by the results for the same rotation in 1978 (Fig. 3, bottom), the pattern of change in N_0 during a growing season will depend upon the amount of crop residues occurring in the previous year. Because N_0 is reduced by mineralization and increased through immobilization, the process that predominates during the growing season will dictate the trend of N_0. In years when crop residues are low, the build-up of N_0 may not compensate for its decline. In such situations N_0 will decline throughout the growing season, then increase after harvest when inputs of crop residues occur. These hypotheses remain to be tested in field studies.

The simulations predicted that, over the 24-yr period, N_0 will decline by 40% under F-W, but by only 10% under continuous wheat (Fig. 4). The rapid decline in N_0 in the first 4 yr of the experiment was due to low yields during the first 3 yr. While N_0 recovered in Cont W after the fourth year, N_0 in the F-W rotation continued to decline for about 10 yr. The higher annual production of crop residues under Cont W and the rapid decomposition of residues during the fallow phase of the two-year rotation account for this difference. These results are in accord with reports in the literature [12].

The model predicted a decline in the humus-N of about 2% under continuous wheat and 4% under F-W during the 24-yr period, with the trend being similar to that predicted for N_0 (data not shown). Although the humus fraction declined very little during the period simulated, the model suggests that the contribution of this fraction to the mineralized N was very important. In several years, mineral N produced from humus-N constituted about 50% of net mineralized N because of the magnitude of the humus fraction. Studies of N mineralization-immobilization using ^{15}N, showed that the relative contribution of various N fractions to the mineralized-N pool were: biomass 24%, metabolites 4%, active-N 32%, and stabilized-N, 40% [49].

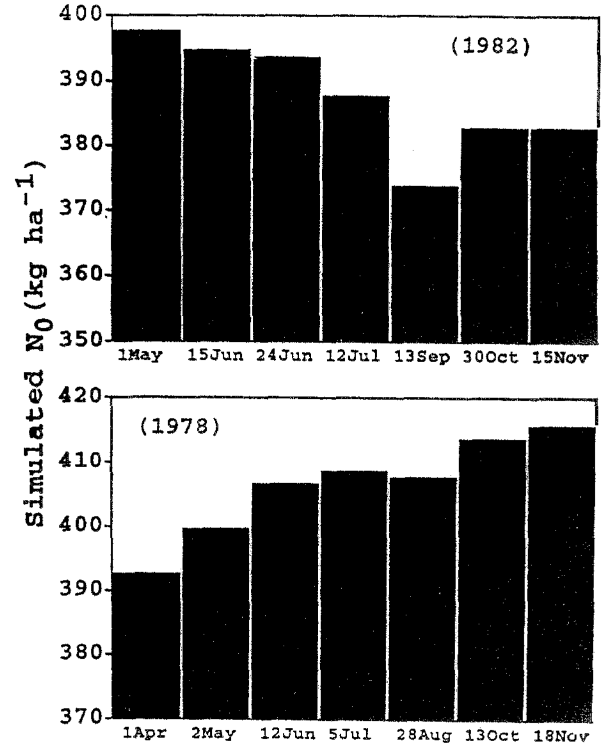

Fig. 3. Changes in simulated potential mineralizable nitrogen (N_0) in the 0–0.3 m depth, under Cont W at Swift Current, Saskatchewan, during the growing season of two dissimilar years [1].

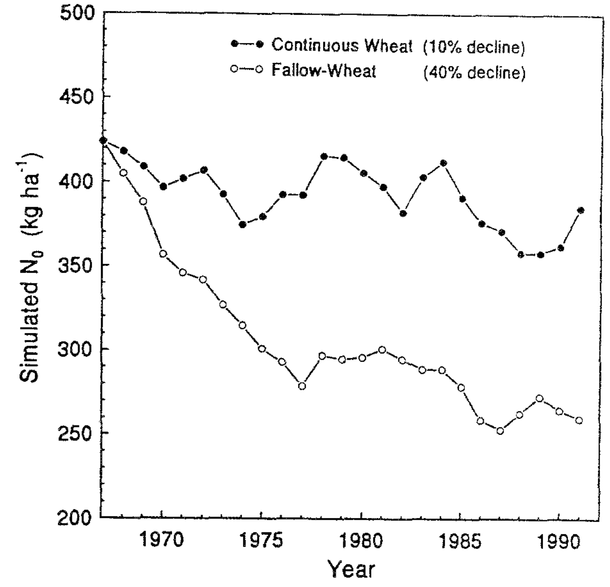

Fig. 4. Trends in simulated potentially mineralizable N (N_0) during 24 yr under F-W and Cont W rotations at Swift Current, Saskatchewan values are for 0–0.3 m depth) [1].

The first 3 pools can be assumed to be approximately equivalent to N_0 in our model. The relative contribution of humus-N to the mineral-N fraction as predicted by this modified LEACHMN model, was therefore in reasonable agreement with that reported [49].

The simulated amount of N_s for the period between spring thaw and freeze-up each year was estimated for Cont W, the fallow phase of F-W [(F)-W], and the wheat phase of F-W, [F-(W)] (Table 1). The results for F-(W) and Cont W were reasonable compared to estimates of N_s made for this soil by balance sheet methods [15, 20, 22, 24, 26]. However, values for (F)-W were lower than for F-(W). We had expected the (F)-W, with its longer period of moist soil conditions, to accumulate the most mineral N in this period. The F-(W) system should accumulate more N_s than Cont W in years when the previous fall and winter were dry such that stored water in surface soil of fallow exceeded that in surface soil of Cont W; otherwise, both of these systems should produce similar N_s. Our simulation results support the latter hypothesis. We have not yet identified the reason for the apparent inadequacy in simulating N_s in the (F)-W system. However, it could be because all the residues from the previous years' crop are being soil-incorporated at harvest making it immediately available for decomposition. (In Saskatchewan this rarely happens unless there is fall tillage.) This could result in overestimation of N immobilization in the short term. A more realistic accounting of residue decomposition, such as that used in CERES [67], might improve N simulation in LEACHMN.

Simulations with CERES model

The LEACHMN model simulates most of the major soil N transformations as well as N uptake by the crop; however, it is defcient because crop growth and yield responses are not incorporated in the model. It uses an empirical function to simulate plant N uptake. To simulate N dynamics adequately in a range of diverse cropping environments, a model capable of describing the major soil N transformations, as well as the plant component, is required. The CERES-wheat model satisfies the latter constraint. CERES also describes most of the major water and N cycles but does so less rigorously than LEACHMN [54].

Since 1987, Jame *et al.* [42] have been testing CERES at Swift Current and have calibrated and modified it for use on the Canadian Prairies. We used this modified version of CERES to estimate the net N mineralization during a wet year (1982) and a dry year (1973) for the same two rotations tested with LEACHMN.

The crop was seeded on 15 May in 1973 and on 5 June in 1982; however, we simulated periods from Spring soil sampling (3 May, 1973 and 6 May, 1982) to the date of crop physiological maturity (9 August, 1973 and 3 September, 1982). The soil water contents in the profile (0–1.2 m), measured on the date of sampling, were used as the initial values in the simulation. These water contents were much higher in 1973 (250–270 mm) than in 1982 (131–212 mm). Total precipitation received during the simulation periods were 62 mm in 1973 and 310 mm in 1982.

In the simulation with CERES, we assumed that 70% of the straw produced in the previous crop year were present at the start of the simulation run for (F)-W and Cont (W) (cropped the previous year) and 15% for F-(W) (cropped 2 yr previously). We also assumed that the straw was uniformly incorporated within the 0.1 m layer during seedbed preparation. Root dry matter was estimated as 16% of the straw weight [13]. The C concentration of straw and root was assumed to be 45%, and N concentration of the straw assumed to be 0.6% [13].

CERES requires that the soil organic C in each soil layer be specified. This is used to calculate the initial humic pool for each layer and, together with a simplifying assumption of bulk soil C/N ratio of 10, to estimate the N associated with the humic pool (NHUM). In CERES it is assumed that 20% of the gross amount of N mineralized each day is transferred from FON pool into the humic pool. As organic matter decomposes some N is required by the decay process and this amount is incorporated into microbial biomass which is included in the FON pool. The balance between the N immobilized and the N mineralized from FON and NHUM determines whether net mineralization or immobilization occurs.

When we used CERES without modifying the N sub-model, the largest amount of net N mineralized during the growing season from the three cropping systems was only 21 kg N ha^{-1} [(F)-W in 1982] and the smallest amount was 5 kg N ha^{-1} for Cont W in 1973 (Figs 5 and 6). These values are substantially lower than values generally reported for this soil [15, 20, 24, 26]. These low estimates of N_s were mainly associated with the very small k value for humus (k_h = 0.000083 day^{-1}). This value was adopted from the PAPRAN model [56]. In the SOIL-SOILN model, a

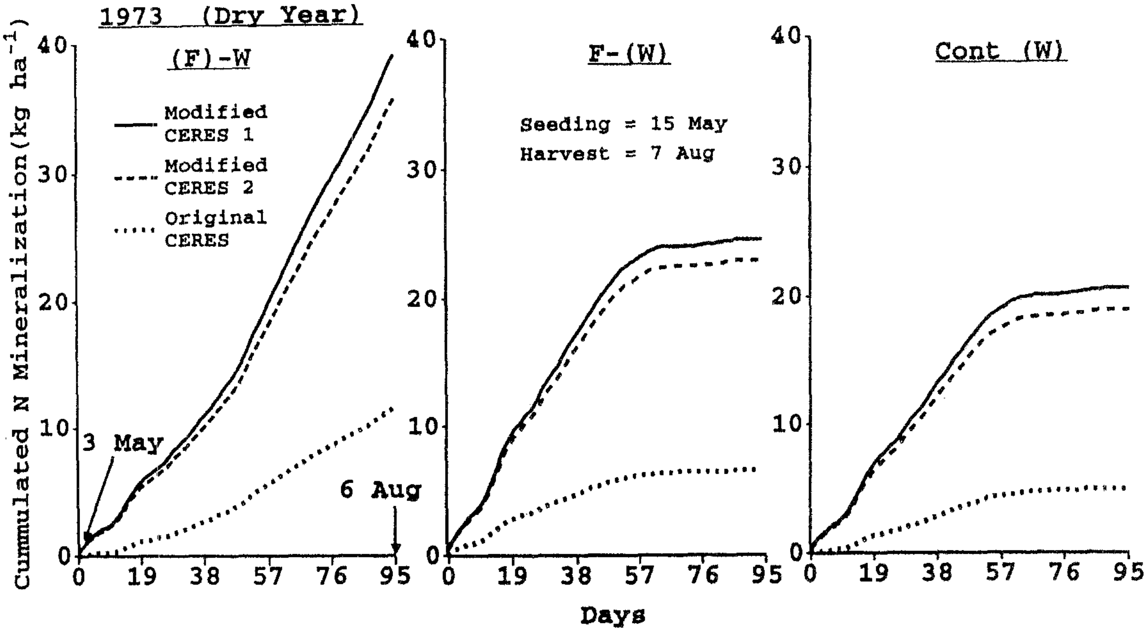

Fig. 5. Simulated N mineralized in fallow-spring wheat (F-W) and continuous wheat (Cont W), during the growing season of a dry year (1973), at Swift Current, Saskatchewan. [The initial water content in the 0–1.2 m soil depth was 248 mm in (F)-W, 262 mm in F-(W) and 270 mm in Cont W. (Modifed CERES 1 refers to case where N and humus pool used, and modified CERES 2 uses only N_0.) Precipitation received between 4 May and 9 August was 62 mm].

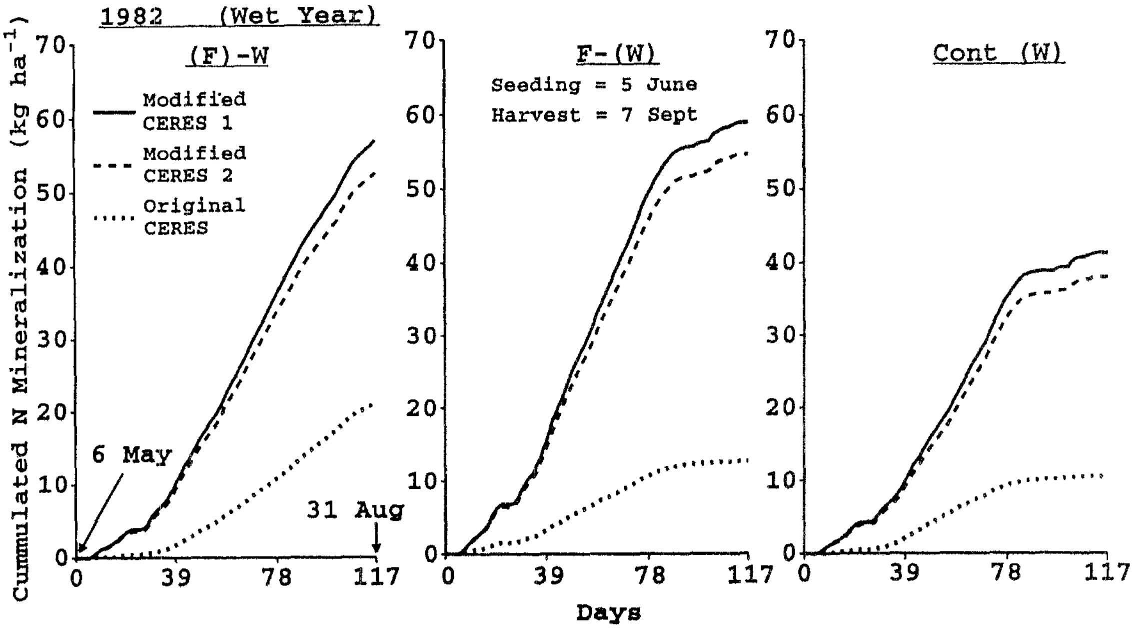

Fig. 6. Simulated N mineralized in fallow-spring wheat (F-W) and continuous wheat (Cont W), during the growing season of a wet year (1982), at Swift Current, Saskatchewan [The initial water content in the 0–1.2 m soil depth was 131 mm in (F)-W, 212 mm in F-(W) and 163 mm in Cont (W). Precipitation received between 7 May and 2 September was 309 mm. (Modified CERES 1 refers to case where N_0 and humus pools are used, and modifed CERES 2 uses only N_0].

Table 1. Net *N* mineralized (N_S) from Spring thaw to wheat harvest for fallow-wheat (both phases) and continuous wheat as estimated by simulation with the LEACHMN model [1].

Year	(F)-W[a] (kg ha^{-1})	F-(W)[a] (kg ha^{-1})	Cont W (kg ha^{-1})
1967	47	27	27
1968	26	40	18
1969	41	42	34
1970	48	55	40
1971	28	37	22
1972	33	29	23
1973	22	36	36
1974	34	41	47
1975	23	40	27
1976	26	43	23
1977	25	46	25
1978	18	36	5
1979	27	30	24
1980	26	37	30
1981	24	33	32
1982	43	48	49
1983	15	36	9
1984	21	21	5
1985	42	28	37
1986	41	37	43
1987	33	33	27
1988	20	27	30
1989	37	29	37
1990	40	32	24
1991	22	45	15
Mean	31	36	28

[a] Each phase of the fallow-wheat rotation was present each year. The values pertain to the phase in parenthesis. (F)-W means N mineralized during fallow phase; F-(W) means N mineralized during wheat phase.

greater value for the rate constant k_h (0.0003 day^{-1}) was used [3].

We modified the N sub-model of CERES as we did with LEACHMN (Fig. 1). The rate constant associated with N_0 for the surface layer (0–0.1m) was 0.013 day^{-1} as discussed previously, and k_h was 0.000083 day^{-1} as used in the original CERES model. However, the rate constant for the 0.1 to 0.2 m layer was assumed to be 0.3 of that in the 0.0 to 0.1 m layer and for the 0.2 to 0.4 m layer it was assumed to be 0.1 of the rate constant of the 0.0 to 0.1 m layer. We assumed that no N mineralization occurred below 0.40 m [11].

When this modified CERES model was used to predict N_s during the growing season, it predicted 39, 25, and 21 kg N ha^{-1} produced by (F)-W, F-(W) and Cont(W), respectively, in the dry 1973 (CERES 1, Fig. 5); LEACHMN had predicted the corresponding values of 22, 36, and 36 kg N ha^{-1} (Table 1). In the wet year (1982), the corresponding values for the modified CERES simulation were 58, 59, and 42 kg N ha^{-1} (CERES 1, Fig. 6), while LEACHMN had predicted 43, 48, and 49 kg N ha^{-1}, respectively (Table 1). The results obtained with CERES are more plausible, both in terms of the relative size of N_s for (F)-W compared to the other two systems tested, and in terms of N_s in the wet year compared to the dry year.

We re-examined our premise for revising the LEACHM and CERES N submodels (Fig. 1) and reasoned that because the measured N_0 was derived from all available pools of N (except litter, most of which is usually removed and discarded during soil preparation for incubation), then we should really only be replacing the "humus" in Fig. 1 with N_0. That is, in Fig. 1 we are in essence double-counting the humus fraction. If we wished to use the result from incubation in the manner shown in Fig. 1, then we should have partitioned the active pool of N into a more labile and a more stable N fraction, as has been done by others [8, 31].

We therefore conducted another simulation with the CERES model modified to replace humus with N_0. This simulation resulted in N_s over the growing season being about 5 kg N ha^{-1} less than in CERES 1 (CERES 2, Figs 5 and 6). This indicates that even if the revised model in Fig. 1 is invalid, the error is small because k_h in CERES is so small (0.000083 day^{-1}).

When the rate constants for biochemical constituents of crop residues used in the original CERES (Table 2) were used to estimate the amount of N mineralized, we obtained values of 8.6 kg ha^{-1} for (F)-W, 5.3 for F-(W) and 4.9 for Cont(W) in the dry 1973 growing season while for the moist 1982 the corresponding values were 18.2 kg ha^{-1} for (F)-W, 3.7 for F-(W) and 9.0 for Cont(W). Recently, Vigil *et al.* [67], working with grain sorghum, concluded that the decomposition rate constants of the residue constituents are an order of magnitude smaller than those originally used in CERES (Table 2). When the constants of Vigil *et al.* [67] were used in CERES, the values obtained for N mineralized from (F)-W, F-(W) and Cont (W) in 1973 were 6.6, 2.3, and 2.1 kg ha^{-1} respectively and corresponding values in 1982 were 13.6, 2.6, and 4.8 kg ha^{-1} respectively. Whether the lower values of Vigil et al. [67] were due to the difference in crop (Sorghum vs. wheat) is uncertain.

The validity of the N_s values obtained in the simulations is not easily verified because most balance sheet estimations are very crude, using various gross assumptions. However, the values obtained by LEACHMN and CERES were generally well within the range of N_s estimated for this soil in previous studies [15, 20, 24, 26]. The advantage of using these dynamic models, as compared to the simple model used by Campbell et al. [15], is that we are able to include N mineralized from recent crop residues, and also to account for N lost by leaching, gaseous means and N immobilized. These models require further fine-tuning, but the results we have obtained by incorporating the N_0 concept into the N submodel appear to have resulted in more credible outputs than when a balance sheet approach is used, especially in the case of CERES.

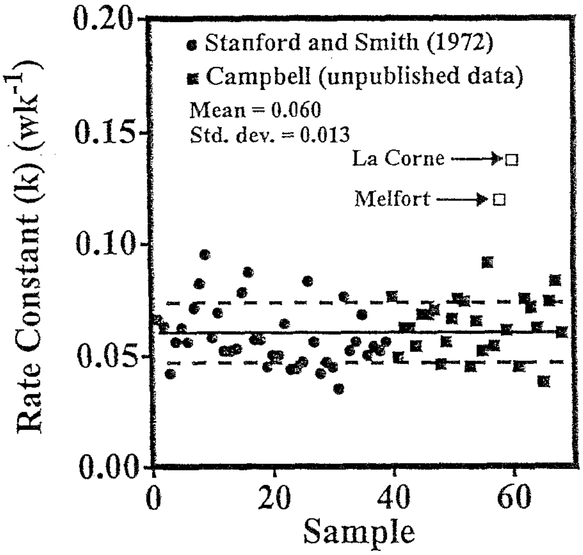

Fig. 7. Relationship between rate constant (k) as measured in a recent Saskatchewan study (C.A. Campbell, unpublished data) compared to k reported for an array of US soils [64].

Estimating potentially mineralizable N by chemical methods for soil testing purposes

In the foregoing discussion we demonstrated that the concept of potentially mineralizable N can be used in simulation models to quantify the amount of N that a soil will mineralize during a growing season under field conditions. Of the factors required to make this estimate, the most difficult to obtain is N_0 because it differs for each soil [16, 64], and because its determination requires long-term incubation. The latter would make this technique impractical for use in soil testing laboratories. Estimating the k value is less difficult because it appears to be less variable among soils, averaging about 0.06 for cultivated land in North America (Fig. 7). In general, a Q_{10} of 2.0 is a reasonable approximation for most soils, even though if the Q_{10} for the specific soil is available, the results will be more accurate [15].

If the potentially mineralizable N approach is to be used by soil testing laboratories, a quick, effective method for estimating N_0 must be developed. Two promising methods have been proposed [35, 36]. One involves determination of the NH_4-N produced when the soil is digested with 2 *M* KCl at 100 °C for 4 h [35].

Table 2. Crop residue decomposition rate constants used in CERES compared to other values used by others.

Source	Carbohydrates	Cellulose	Lignin
		(day^{-1})	
Seligman and Van Keulen [56]	0.8(0.2)[a]	0.05	0.0095
Vigil *et al.* [67]	0.05	0.0043	0.00095
Beek and Frissel [2]	0.075	0.005	0.00095

[a] CERES model uses Seligman and Van Keulen's values, except for carbohydrates where 0.2 is used.

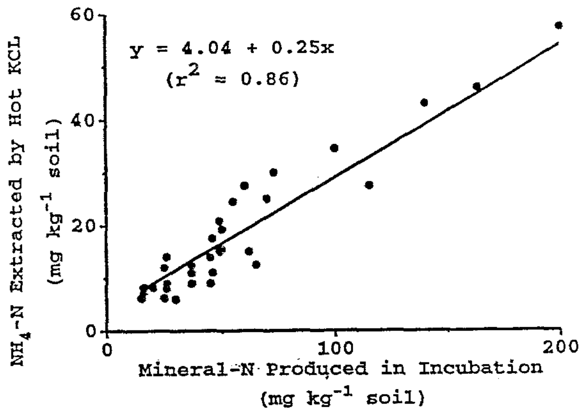

Fig. 8. Relationship between NH_4-N extracted with hot, 2 *M* KCl and mineral N produced by aerobic incubation of soil at 35 °C for 14 days in 33 Brazilian soils [35].

The second involves measuring NH_4-N produced by steam distillation of soil with pH 11.2 phosphateborate buffer solution for 8 min [36]. Both methods were tested using 33 Brazilian soils [35] and 30 diverse Iowa soils [36] with encouraging results. Recent unpublished research with 29 diverse Canadian prairie soils supported these conclusions (C.A. Campbell, unpublished data). Thus, excellent agreement was obtained [35] between the hot, KCl-extracted N and the amount of N mineralized during the first 14 days of aerobic incubation at 35 °C for the 33 Brazilian soils (Fig. 8). A close relationship was also found between the chemically extracted N and N mineralized under anaerobic incubation [36]. The latter was confirmed by others using some infertile upland soils in Thailand [41].

Although these results are promising, the relationship was not made relative to N_0 which is what is required. If a close relationship between N_0 and the NH_4-N extracted with hot 2*M* KCl or phosphate-borate buffer can be demonstrated, then it should be possible to determine N_0 for major soils of a region, develop the relationship between the chemically extractable N and N_0 in these soils, and store this information in the computer files of soil test laboratories for discrete soil regions. We could then determine the chemically extracted N on the soil of a farmer once every 3 to 5 years and estimate N_0 from the known chemically extractable-N vs. N_0 relationship. All the characteristics for each farmer's fields could be determined once, and stored in computer files for use in estimating fertilizer N requirements each year based on the soil test mineral N, the yield goal, and the degree of risk the farmer is willing to take (i.e., in terms of precipitation and temperature). From the grain yields of the previous year it would be possible to estimate the amount of N that would be derived from the most recent crop residues. Some account may need to be made for the timing of release of N from the latter source, especially in colder climates where very limited decomposition occurs between harvest and seeding. Crops such as Spring cereals which take up most of their N early in their growth (by heading stage) may only use a portion of the N from the previous year's residues for yield; by time the remaining N becomes available it may more likely go to increase grain protein instead of yields.

We used data from two previous studies [16, 64] to determine the relationship we might expect to find between N_0 and N mineralized during the 0 to 2-wk period of aerobic incubation. The results (Fig. 9) were very encouraging, with about 85% of the variability in N_0 being accounted for by N mineralized in 0-2 wk. Thus, it seems probable that a close relationship may also exist between N_0 and the hot KCl and/or phosphate-borate extractable NH_4-N; however, this remains to be determined experimentally.

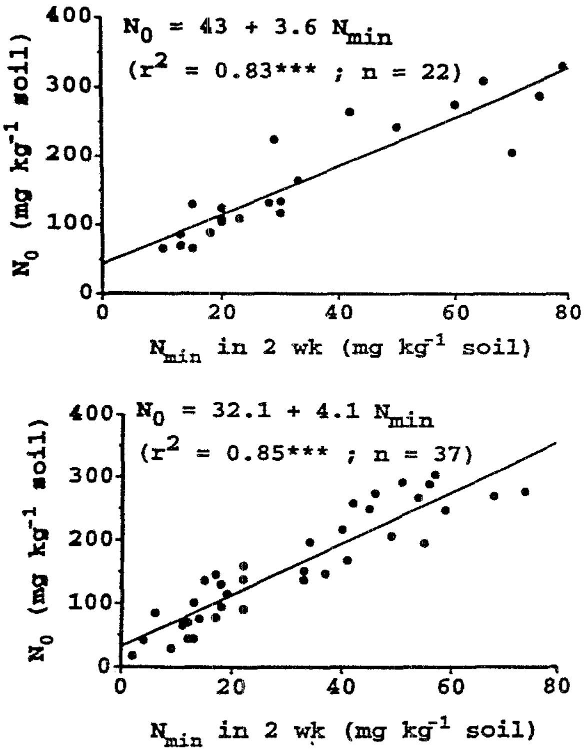

Fig. 9. Relationship between N_0 and N mineralized during the first 2 weeks of aerobic incubation at 35 °C: (top) adapted from Campbell et al. [16]; (bottom) adapted from Stanford and Smith [64].

Conclusions

The need to develop accurate methods for quantifying the rate at which soils will mineralize N cannot be overemphasized. A solution to this problem is required if farmers are to make more efficient use of N fertilizer, thereby maximizing net returns and reducing environmental pollution. Scientists have similar goals to producers but they have the added obligation of trying to improve understanding of the mechanisms that control N behaviour in the soil-plant-air system so as to facilitate our predictions of N behaviour in the environment.

This paper has demonstrated that significant progress is being made towards achievement of these goals. It demonstrates that the potentially mineralizable N concept can be used, together with deterministic models such as LEACHMN and CERES, to estimate N mineralization in field experiments. The paper further suggests ways in which it might be possible to couple the potentially mineralizable N concept with routine laboratory methods of measuring available N, such as the hot KCl or phosphate-borate extractable N procedures proposed by Gianello and Bremner, so as to provide an improved soil test for N. If this latter approach proves fruitful, it offers the advantage over current soil tests in that it would allow modification of estimates of N mineralization to be made based on probable temperature and soil water for an area. It would also prove advantageous in humid areas where such commonly used tests as NO_3-N in soil are not feasible because of leaching.

Much research remains to be done, however, both to improve the N sub-models of the deterministic models, as well as to establish whether the routine chemical extraction procedures are effective on a universal basis, and if they can be quantitatively related to potentially mineralizable N.

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