DISSERTATION

SOIL-PLANT DYNAMICS RELATED TO N UPTAKE AND SOIL N AVAILABILITY

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY RODOLFO DELGADO ENTITLED "SOIL-PLANT DYNAMICS RELATED TO N UPTAKE AND SOIL N AVAILABILITY" BE ACCEPTED AS FULFILLING, IN PART, REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT OF DISSERTATION

SOIL-PLANT DYNAMICS RELATED TO N UPTAKE AND SOIL N AVAILABILITY

Evaluating the capacity of soil to supply N and the plant characteristics associated with N uptake are key to determining economical and environmentally sound fertilization practices.

I reviewed the literature to assess the effects of management practices (e.g., tillage, crop rotations and N fertilization) on soil N supply and to examine the utility of different biochemical assays to predict N availability (Chapter 1). Published work shows that management affects N supply by influencing inorganic and organic N pools, by modifying the activity of soil decomposers that mineralize organic N sources, and by influencing soil processes involved in N losses. Also, management can affect plant root properties associated with N and water uptake (e.g., root depth, root density). A variety of different methods for assessing potential N supply were evaluated, with an emphasis on field-applied methods that could be practical for soil testing and fertilizer management. The highest correlation between N uptake by crops and N supply were for aerobic incubations and mild extracts. The lowest correlations involved methods using anaerobic incubation and intensive extractions. Although traditionally-used indices of soil N supply based on biological and/or chemical assays work well in some circumstances, none work consistently in all cases due to variability associated with sample collection, handling, and processing, as well as site-specific circumstances.

Corn (*Zea mays* L.) yields in Venezuela are highly variable, and a better understanding of the multiple factors affecting yields is needed. In a field study, I studied corn response to N application during three successive years on a Mollisol soil of Venezuela (Chapter 2). I evaluated the effects of initial contents of soil mineral N and water, and different amounts and distribution of precipitation during the crop cycle on N uptake and soil N dynamics. Total N uptake by the crop was more closely associated with the initial soil mineral N content and soil water than was yield and dry matter production. This probably is because most of the N uptake occurred before silking, while a great proportion of the total dry matter production occurred later. Interannual variations in crop response to N application were associated with variations in soil capacity to supply N and variations in water availability during the crop cycle.

Soil factors affecting the amount and timing of N supply to plants were evaluated for 15 soils in Venezuela (Chapter 3). I attempted to identify measurable soil N fractions associated with soil N supply capacity, along with other measures such as initial soil mineral N content. Because organic N sources associated with macroaggregate size fractions have been found to be easily mineralizable, I hypothesized that some of these fractions could be used as an index of soil N availability measured by N uptake by a perennial grass *(Brachiaria brizanta)* in the greenhouse. Although initial mineral N content was closely associated with the N uptake by *Brachiarai*, it represented only a small proportion of the total N uptake so that most of the N came from an easily decomposable organic N source. In soils having a high capacity to supply N, high correlations between macroaggregation and N uptake were found, suggesting that macroaggregate-associated N was a significant labile N source. In contrast, a poor association between N in macroaggregates and N uptake was observed in the soils with low capacity to supply N. However, there was no single soil property that could reliably separate soils of high capacity from low capacity to supply N other than the initial content of mineral N. Future research should be oriented to identify and to isolate the organic sources of N responsible for soil N availability in different soils.

The plant root system is a primary determinant of plant growth, controlling the uptake of nutrients and water. Due to the diversity of factors that affect root growth, simulation modeling can be useful in evaluating root dynamics and crop responses to management. In Chapter 4, I describe a general root growth model that emphasizes root properties associated with water and nutrient uptake as a function of physical and chemical properties, C and N availability, plant phenology, and climatic variables. The model simulates vertical root development and lateral root proliferation, root depth and density distribution, and includes a full carbon budget. The model was parameterized for two different crops (corn and cotton) and different soil conditions. The simulated root length density and rooting depth were similar to the observed data, both in terms of the magnitude and the temporal patterns. The root model was sensitive to plant and soil parameters and it could be satisfactorily utilized to predict the root system dynamics in the soil profile for different crops.

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DEDICATION

To my family in Venezuela,
To my son Carlos Julio,
To my daughter Ana Maria,
To my wife Ana Mireya (Titina)

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CHAPTER I

ASSESSING MANAGEMENT EFFECTS ON SOIL N AVAILABILITY AND N SUPPLY FOR CROPS

1. Introduction

Accurate estimation of soil N availability is required for economically and environmentally sound N fertilizer applications. Different management variables such as tillage (Doran, 1980), N fertilizer application (Watson and Mills, 1998; Thicke et al., 1993), irrigation, crop sequence and types (Haynes, 1994), and cover crops (Hu et al., 1997) influence soil N availability, by affecting the amount and quality of organic-N sources returned to the soil, the availability of organic matter to soil decomposers, the distribution of the mineral N in the soil profile, and by altering plant access to soil mineral N.

Many chemical and biological methods have been used to evaluate soil N availability, often based on studies of crop response to varying N application. However, there is no universally accepted standard method of assessing N availability that has been proven under all situations of soil, crops, or management practices (Dahnke and Vasey, 1973). Moreover, although such methods normally seek to assay an "available" N-pool, the origin of the measured N and its relations to plant uptake is often poorly understood. This constitutes a limitation if we want to improve the soil capacity to supply N through different management practices. Other approaches like simulation models, where many different factors affecting soil N availability are included, usually define conceptual soil N pools rather than directly measurable ones, and generally some simplifications are made to include the factors affecting soil N uptake by the crop.

In this review, we analyze factors affecting soil N availability in the short-term (i.e., during a crop cycle) under different management practices, and commonly used methods to evaluate it. Hopefully this analysis will provide ideas for future development to improve our estimates of N soil availability.

2. Effect of Different Management Practices on Soil N Availability and Crop Response

The effect of management on soil N availability is associated with a variety of factors, including: 1) the amount, quality, and mineralization rate of plant residues; 2) soil conditions affecting microbial decomposition; 3) influences on soil processes such as leaching, denitrification, and immobilization; which affect soil N availability; 4) distribution of mineral N into the soil profile; and 5) accessibility of mineral N to plant uptake through influences on root growth. A summary of the reported effects of different management practices on soil processes and soil N availability is shown in the appendix.

A. Effects on soil N availability

Tillage systems: Tillage intensity has been shown to affect soil capacity to supply N, but with often contradictory results (Table 1). For example, Varco et al. (1989) found that total N uptake by corn (*Zea mays* L.) during the vegetative stage was more rapid with conventional tillage (CT) than with no-till (NT), although NT systems could have more potential to supply N in the grain-filling stage. Lock and Hons (1988) and Sweeney (1993) also noted that under NT, sorghum (*Sorghum bicolor* L.) growth was delayed, possibly due to N deficiency, and in the second year more N was accumulated across all the growth stages under CT. In contrast, Evanylo (1990) found that more N was available and taken up by corn under NT than under CT.

Variations in soil capacity to supply N under similar management practices are probably associated with specific conditions of the experimental site, although the length of time that the system has been under NT or CT is likely to be important. Where N supply was greater under NT (Evanylo, 1990), a higher soil capacity to supply N under NT could be associated with the build up of organic N sources over several years (six years), in contrast to the studies of Varco et al. (1989), Locke and Hons (1988), and Sweeney (1993) where the observations correspond to the first year of a NT evaluation. Moreover, in the case of Varco et al. (1989), where the CT plots were introduced into seven-year old NT plots, the high supply of N under CT is probably enhanced by decomposition of aggregate-associated organic matter which is protected in macroaggregates under NT systems (Six et al., 2000). More evidence of an increased capacity to supply N under NT systems due to a build up of organic N stocks was provided by Tracy et al. (1990) who found higher C-CO_2 released from incubations of 16-year old NT versus CT soil. The typically observed decreases in soil capacity to supply N under NT systems have been considered as a transient condition during the first years of conversion into no-till (Rice et al., 1986).

Decreases in soil capacity to supply N under NT could be associated with soil surface placement of plant residues, which could limit C supply to soil decomposers (Alvarez et al., 1998) and enhanced protection of C-substrates in soil aggregates (Elliott, 1986; Six et al., 2000). Six et al. (2000) found that the turnover time of plant residues was longer in NT systems than under CT. This sequestration of organic matter into aggregates, which is enhanced under NT, could be responsible for observed increases in potentially mineralizable N (Needelman et al., 1999). Incorporation of plant residues into the soil under CT could enhance N uptake by the crop (Varco et al., 1989) (Table 1).

Moreover, tillage systems could affect soil N availability by influencing other soil and plant processes involving N. No-tillage systems, in addition to affecting soil mineralization by protecting SOM as indicated before (Russell, 1988), could enhance processes such as denitrification and immobilization (Russell, 1977; Varco et al., 1989; Locke and Hons, 1988; Doran, 1980). An example of variation in soil N availability as a function of tillage is the immobilization of soil N by fungal biomass growing in the surface-applied plant residues in a no-tillage system (Holland and Coleman, 1987; Frey et al., 2000). Similarly, preferential allocation of plant roots in the surface soil layer of NT soil (Anderson, 1987) could affect macroaggregate formation (Oades, 1984), but also the volume of soil explored by roots, and thus the amount of water and nutrients that could be accessed by the plant.

Crop rotations, cover crops and N fertilizer application: Soil capacity to supply N is also affected by management practices such previous crops, N fertilizer application, and cover crops (Table 2), all of which alter the content of soil mineral N and the quantity and quality of organic N added to the soil. Effects of previous crops were studied by Strong et al.

(1986) (Table 2) who found that the largest amount of soil N was taken up by wheat (*Triticum aestivum* L.) sowed after legumes, followed by oilseeds, and finally cereals. They found also that soil mineral N (2M KCl), which was used as a soil N availability index, followed the same trend (Table 2). McCracken et al. (1989) found that with no N fertilizer, N uptake by corn was higher when it followed vetch (*Vicia* spp.) than rye (*Secale cereale* L.), although both were higher than when no residues were incorporated. When 100 or 170 kg N ha^{-1} were applied (Table 2) the relative effect of the different cover crops were the same. For example, Lory et al. (1995) found that corn sown after alfalfa showed no growth response to additional N fertilizer.

The effect of previous crops on soil N availability is a function of the N supplied through mineralization of the previous crops residues, and the previous crops effect on the amount and distribution of residual soil mineral N. The benefits of a legume crop, which adds additional N through fixation, on soil N availability for subsequent crops are well recognized. Other plant characteristics such as pattern of root growth and length of the growing season influence the amount of mineral N remaining in the soil profile after harvesting a crop. Hipp and Gerard (1973) found that the soil profile was more depleted of mineral N when it was sown with sorghum than with cotton, which affected the response of the following crop (mustard) to N application. They suggested that variations in the length of the growing season affected the amount and timing of evapotranspiration and thus, the exposure of soil mineral N to loss by leaching. Effects of cover crops on soil mineral N pools are evident from results of Crozier et al. (1998) who found that about 44% of the applied N in crop legume residues is mineralized rapidly (Crozier et al., 1998). Effects of cover crops on different pools of soil N, such as potentially mineralizable N pool (N_0) and surface residues, were large and agronomically significant, contrary to results for fertilized systems where variations in N_0 and other measured pools were much smaller (Crozier et al., 1994).

In other studies, where intensity of crop rotations and N fertilizer application were evaluated under no-tillage systems (Kolberg et al., 1999), net soil N mineralization in the fallow phase of a wheat-fallow (WF) rotation was higher than in the fallow phase of a wheat-corn-fallow (WCF) rotation (43 and 22 kg N ha^{-1} respectively), averaged for 2 sites. More plant residues, accumulated during 6 years were returned under the WCF rotation than under WF (15965 and 8823 kg ha^{-1} respectively), which probably was responsible for greater N immobilization in the more intensive system (WCF).

Nitrogen fertilizer applications affect soil N availability through changes in the content of mineral N in the soil profile (Hooker et al., 1983), the quality and amount of some fractions of the SOM (McCracken et al., 1989; Bonde and Rosswall, 1987; Reddy and Reddy, 1993), the amount and quality of C substrates returned to the soil from previous crops (Ledgard et al.,1998), and by affecting or enhancing different soil processes such as denitrification and nitrification (Watson and Mills, 1998). Net soil N mineralization rate was noted to be affected by previous N fertilizer doses by Kolberg et al. (1999), who found that in the wheat-corn-fallow (WCF) rotation the daily net mineralization rate increased with increasing N fertilizer rates, while in the wheat-fallow (WF) rotation, which had a higher mineralization rate than the WCF rotation, the effect of N fertilizer was not evident.

Vanotti et al. (1995) investigated the effect of previous application of N fertilizer on N uptake by corn (Table 2). In all the cases, N fertilizer rate applied in previous years (i.e., 1983 and 1985) significantly affected the total amount of N taken up by corn in 1986. The highest amount of N taken up by corn in 1986 was associated to the highest N fertilizer rate in 1983 and 1985. Nitrogen fertilizer rate applied in previous year also affected the content of soil mineral N accumulated through the 0-90 cm depth (Table 2).

Other effects of N fertilizer applications have been observed in the soil organic fractions where between 12 and 48% of the applied N is retained (Reddy and Reddy, 1993). In contrast to immediate impacts of fertilizers on soil mineral N, this more stable organic fraction could contribute to the long-term soil capacity to supply N (Reddy and Reddy, 1993; Ladd and Amato, 1986). Applied N fertilizer could affect mineralization of native organic N sources, known as the added N influence (ANI), but contradictory results have been observed (Haynes, 1986). Probably specific soil conditions such as SOM contents, soil C:N ratio, and contents of soil mineral N contribute to the magnitude of the ANI effect as suggested from results of Rao et al. (1991) and Woods et al. (1987).

B. Effects of management practices on soil N accessibility to plants

Management can also influence plant access to soil N by affecting root properties associated with N and water uptake (i.e., root length, and root length density) and the soil volume explored by roots. Comparing tillage systems, Ball-Coelho et al. (1998) observed that corn roots grew preferentially in the 0-10 cm soil layer under NT (root length of 17 km m^{-3}) compared to CT where mean root length was lower (7 km m^{-3}) and more uniformly distributed. In the 15-30 cm soil layer, root length density in NT was 4 km m^{-3} lower than in CT. Other studies have shown that annual plowing (CT) allows deeper root penetration and thinner roots are produced than in NT systems (Barber, 1971). Although root length density is generally higher in the surface soil layer of the NT systems, the greater stratification of roots may result in a lower soil volume explored by the root systems than under CT (Hughes et al., 1992).

Nitrogen fertilization and irrigation also had been noted to affect root distribution and morphology. Garcia et al. (1988) in greenhouse studies and Durieux et al. (1994) in field experiments found that N application enhanced root length in the area of application, although the total root length was not affected. Moreover, Sharma and Chaudhary (1983) evaluated different depths of N location in the soil profile and found that root length, root weight densities, and root diameter increased with deeper placement of N fertilizer. In regard to the effect of water supply on root distribution, Proffitt et al. (1985) found that high-frequency irrigation resulted in a shallower rooting system (110 cm) than the low-frequency irrigation treatment, which allowed a deeper root system (160 cm).

Although N uptake by plants is affected by different management practices (as discussed above), other factors, such as soil water availability, affect N uptake and may offset the effects of reduced soil volume explored by roots and the preferential allocation of roots in specific soil layers. This is suggested from findings where there were no differences in N uptake by crops under different management practices, although there were differences in root distribution (Varco et al., 1989; Olness, 1984; Locke and Hons, 1988). This could explain other findings under field conditions where as little as 10% of the total root system may be satisfactory to support plant growth (Burns, 1980). Other studies have shown that root parameters are more relevant to soil N uptake in conditions of low versus high N content in the soil (de Willigen and van Noordwijk, 1987). In this context, Tinker and Nye (2000) mention many cases where N uptake was not closely related to root proliferation or root length, supporting the idea that root length is not of enormous importance for uptake of mobile nutrients, so long as the roots are well distributed.

3. Indexes of Soil N Availability: Uses and Limitations

Soil N availability is usually evaluated by using biological and chemical indexes (Black, 1993), prior to sowing, at sowing time, or shortly after sowing. For this review, a variety of different methods were included, with emphasis on field-applied methods that could be practical for soil testing and fertilizer management. Thus, results from greenhouse studies and methods using long-term incubations (i.e., several weeks, as in Stanford and Smith (1972) were not included. Aerobic and anaerobic correspond to methods using short-term (one week) incubations. Chemical extracts were grouped based on the severity of the extraction, similar to the classification by Stanford (1982). In the intensive extractions, total soil N (TN), soil organic C (SOM), N in $K_2Cr_2O_7$ extraction, and 6M HCl extractions were included. In the intermediate intensity, we grouped methods where N was released by autoclaving, alkaline hydrolysis, alkaline and acid permanganate, phosphate borate buffer, formic/acetyl acetate, pyrophosphate, and procedures where heating and boiling were used. In the mild intensity group, we included procedures that extract the soil content of mineral N (NH_4-N, NO_3-N, or both).

Average correlation coefficients between N uptake by crops in field experiments and different soil N availability indexes are shown in Figure 1. The highest correlation between N uptake by crops and N were for aerobic incubation and mild extracts, and the lowest correlation was with N release by anaerobic incubation and intensive extractions. The intermediate extracts group showed an intermediate degree of correlation, with a wide range of variation. In general, the relative success of aerobic incubation had been associated with the fact that organisms responsible for mineralizing N in incubations are the same that mineralize N in the field (Duhnke and Vasey, 1973), although N release by incubation still represents a potentially mineralizable soil N since it is obtained under optimal conditions of soil moisture and temperature. The utility of aerobic incubation to predict soil N availability under different management practices was shown by Thicke et al. (1993) and Vanotti et al. (1995). Thicke et al. (1993) evaluated different N availability indexes in a crop rotation where corn followed other crops and found that aerobic incubation helped explain N uptake when N fertilizer was not applied, but its utility was reduced when N fertilized was applied. Vanotti et al. (1995) evaluated corn response to N fertilizer application and found that N obtained during the first week of aerobic incubation was well-correlated with N uptake by corn. However, some contradictory results in using aerobic incubations could result from soil processing which exposes organic C substrates to soil decomposers.

Concerning anaerobic incubations, contrasting results have been reported (Stanford, 1982). Fox and Piekielek (1984), analyzing 67 N fertilizer experiments in corn, found that the N mineralized 7 days after anaerobic incubation was not significantly associated with the field-measured N availability. However, they highlight its ability to estimate soil N availability in flooded rice and forest soils. Loss of initial content of mineral N (NO_3-N) by denitrification could contribute to the low correlations (Dahnke and Vasey, 1973).

The relative success of the intermediate intensity methods, which in some instances showed correlations close to those found for mild extracts and aerobic determinations, may be because these procedures are extracting an easily decomposable soil organic matter fraction (Dahnke, 1990). Some of the methods included in this group have shown their potential to predict under different conditions of soil and management practices (Figure 2). Soil N released by autoclave (0.01M $CaCl_2$) showed significant correlation ($r = 0.58$) with N uptake by corn sown on soil which had been under continuous corn, where sludge and fertilizer N had been applied, and for soils under CT and NT systems (Magdoff and Amadon, 1983; Figure 2A). Correlations were also significant for N uptake by corn ($r = 0.58$) when it was sown in soils after previous crops (legume, cereals, or not cropped), for difficult tillage systems (NT and CT), and for fertilized or unfertilized conditions (McCracken et al., 1989; Figure 2 B). Another procedure included in the intermediate extracts, which has shown potential to estimate soil N availability, is the N release by phosphate borate buffer (PBB), which was able to predict residual effect of previously applied N fertilizer ($r = 0.80$) (Vanotti et al., 1995; Figure 2C). Procedures like alkaline and acid permanganate extractions and alkaline hydrolysis show a similar degree of correspondence as autoclaving and PBB.

Modifications in some of these indices have been made by including the initial content of soil mineral N, which is normally subtracted in the original procedures. These modifications usually improve or do not affect the results obtained with the original method (Serna and Pomares, 1992). As an example, in Fig. 2D, N released by the modified PBB was significantly associated with N uptake by corn ($r = 0.76$), while N released by the unmodified method was not significantly correlated (r = -0.25). These findings show the importance of initial content of soil mineral N as an index of soil capacity to supply N.

Limitations in using some of these procedures are shown in data from Serna and Pomares (1992) where N uptake by corn was significantly associated with N released by autoclaving and acid permanganate for sandy (r = 0.89 and 0.73) and loamy soils (r = 0.85, and 0.67), but was not associated with N taken up by corn in the clay soils (r = 0.23, and r = 0.15), for the autoclaving and acid permanganate in each soil class, respectively.

The high average correlation between mild extraction procedures, which have the highest average correlation among the chemical procedures, and N uptake (Figure 1) are in accordance with results of Dahnke and Vasey (1973), who show a great number of successful applications when NO_3-N was used as an index of soil N availability, (in a review of studies from 1901 to 1969), although less success was found with NH_4-N. In general, this index seems to be sensitive enough to evaluate the effect of previously sown crops and cover crops on N uptake by a following crop (McCracken et al., 1989; Strong et al., 1986), as shown in Figures 3A and 3B respectively, or to evaluate soil capacity to supply N when plant response to N fertilizer application are carried out over a range of soils with very different management practices (Hong et al., 1990) as shown in Figures 3C and 3D.

The strong relationship between initial mineral N content, obtained by different extracts, with N uptake by the crop and crop responsiveness to N fertilizer suggests that this fraction is closely associated with the potentially available N during the crop cycle, as suggested by Black (1993). At the present time, mineral N soil tests are used in many areas to estimate N availability and provide fertilizer recommendations (e.g., Hergert, 1987; Magdoff

1991a; Magdoff et al.1983; Gerik et al., 1998). Initial content of mineral N extracted by AB-DTPA increased responsiveness to N fertilizer doses for proso millet (*Panicum miliaceum* L.) (Rodriguez et al., 1989). Also, results of Serna and Pomares (1992) suggest that indexes based on soil mineral N are more applicable across soils of different texture, as compared to the intermediate intensity extractions discussed above. The correlation coefficients between N uptake by corn and mineral soil N extracted by $NaHCO_3$ (measured at 200 nm to exclude organic N) were 0.92, 0.90, and 0.65 for sandy, loamy, and clay textured soils respectively.

Some of the limitations in using the initial content of mineral N have been associated with its small amount relative to the total amount taken up by crops, and that crop responsiveness to N fertilizer, and its relationships with soil mineral N content could be affected by the pattern and amount of precipitation. In this aspect, critical values of soil mineral N, which are the N concentrations above which no response to N application normally occurs, would be expected to change due to variations in soil water availability (Holford and Doyle, 1992).

Applications using the soil mineral N content as an index of soil N availability and responsiveness to N fertilizer include the pre-sidedress nitrate test (PSNT) (Magdoff 1991b), which is performed when plants reach between 20 to 30 cm tall. Average correlation between N uptake by crops and PSNT was similar to that obtained with aerobic incubation and initial content of soil mineral N (Figure 1). McCracken et al. (1989) and Binford et al. (1992) found significant correlations between PSNT tests with corn response and relative yield respectively. Binford et al. (1992), evaluating 45 sites in Iowa, found that the critical concentration of NO_3-N was between 23 to 26 mg kg^{-1} in the soil surface 0-30 cm depth.

Also, Fox et al. (1989) have shown that PSNT is a good indicator of crop response to sidedress N fertilization, and then were able to estimate a critical soil N level to separate responsive versus non-responsive sites. In studies evaluating manure application, Motavalli et al. (1989) found that content of mineral N measured four to six weeks after planting had the best correlation with N uptake by corn among several indexes. However, limitations in the use of PSNT are associated with the fact that in this procedure, soil N availability is measured when the plant has had a certain time in the field; thus determinations of PSNT, determination of N requirements, and purchase and application of fertilizer must be made in a short period of time.

Although several methods to evaluate soil N availability work well in some situations of soil or management practices, none of them seem to work consistently in all cases. Different factors, such as sampling, soil handling and processing, and specific conditions of the system affect the performance of the biological or chemical methods previously described. For example, Clay et al. (1990) found that N release by autoclave was significantly correlated with corn yield and N uptake by corn (r = 0.94 and 0.87) for the roto-till system where crop residues were incorporated, but correlations were not significant for the no-till systems where residues were retained on the soil surface. However, they found that N release by autoclave was consistently higher in the NT systems. Although, under this system, N uptake by the crop was lower than under roto-tillage which could be an indication that high, potentially mineralizable N under NT systems does not correspond with the real available N for the crop. Moreover, effects of soil handling could produce different effects in estimates of soil N availability as suggested from results of Cabrera and Kissel (1988) where disruption of the soil seemed to be more evident in some soil texture classes than in others. Thus, procedures to estimate real available soil N need to be improved to allow the evaluation of soil N availability under the conditions that would prevail in the field.

Some attempts to associate N supply capacity with specific soil organic matter fractions have been made, but contradictory results have been obtained. One fraction that has often been evaluated is soil microbial biomass (SMB) in a variety of systems, including different cereal cropping systems (Bending et al., 2000), grass production under legume or N fertilizer applications (Ledgard et al., 1998) and long-term fertilizer treatments (Glendining et al., 1996). Although there were differences in gross N mineralization among treatments or in specific mineralization rates, these studies suggest that the size of the biomass N pool could be a less useful estimator of potentially available N than the turnover of the biomass pool or in its action in releasing other soil-N fractions (Stockdale and Rees, 1994).

Variations in relationships between soil microbial biomass and N mineralization are likely affected by the activity of microbial biomass in the soil. Thus, active microbial biomass could be better associated with rate of soil N mineralization than total SMB. In comparing different grassland soils, Hassink (1994) found that active microbial biomass measured through the substrate-induced respiration method was well correlated with N mineralization rate. However, other factors such as interactions among soil trophic groups (nematode, protozoa, bacteria, etc.), which have been associated with soil N availability, could be responsible for contrasting results in using soil microbial biomass as a index of soil N availability.

Other fractions of soil organic C, such as non-biomass soil organic matter, have also been associated with soil capacity to supply N. Appeal (1998) found that mineralizable N extracted by $CaCl_2$ after the soil was subjected to a drying-rewetting procedure, was not of microbial origin or recently immobilized N. He suggested that this procedure, and the organic matter fraction obtained, could be used as an index of easily mineralizable N. Other fractions such as macroorganic matter (MOM), which is soil organic matter larger than 150 m, have been significantly associated with N mineralization rate (Hassink, 1994). Moreover, C and N mineralization were significantly associated with the amount of C and N in the light macroorganic matter, which normally has a high C:N ratio and is less protected by the soil (Hassink, 1995). More important, this association was found to hold for soils of different texture, and variations in the amount of MOM seem to be associated with different management practices (Barrios et al., 1997). In Figure 1, the average from two studies where MOM and POM were associated to N uptake by the crop is shown.

Other studies have shown significant relationship between water soluble organic C (WSOC) and N mineralization (Verstraeten et al., 1970; Verstraeten et al., 1971), probably due to preferential use of WSOC by soil microbial biomass as a C source (Liang et al., 1998). Liang et al. (1998) found a significant correlation between WSOC and microbial C and soil carbohydrates, but a negative correlation with long-chain aliphatic C. Relationships between availability of WSOC and use of soil N have been reported by DeLuca and Keeney (1994) who have shown that the ratio of the amount of soluble C-sugar and amount of mineral N (N-NO_3) could be used to predict soil N immobilization.

4. Some Consideration in Evaluating Soil N Availability

Different management practices, such as fertilization, cover crops, quality of plant residues, crop rotations, and tillage impact the soil capacity to supply N by acting on the mineral and organic N pools of the soil, by affecting the accessibility of C substrate to soil decomposers (i.e., superficial allocation of soil residues and protection of labile C substrates in soil aggregates), and by influencing different soil processes (i.e., soil N immobilization, leaching, and denitrification) (see Chapter II). Thus, methods used to evaluate soil N availability need to be adapted to try to measure it for conditions prevailing under specific management practices.

However, common methods used to evaluate soil N availability are based on disturbed soil samples and methods may be applied without taking into account specific properties of the systems. This probably contributes to the substantial variability shown by these methods and explains their inability to predict *in situ* soil N availability under different conditions of soil and management practices. Moreover, although the different methods try to obtain the labile soil N fraction, the chemical extracts could be extracting part of organic N pools of longer turnover time or protected organic matter, which normally do not contribute to *in situ* soil N availability.

Specific soil properties or soil processes enhanced under specific management practices (i.e., soil N immobilization, and denitrification under non-tillage systems) could be used to improve or develop new forms to evaluate soil N availability. Moreover, since soil processes, such as soil aggregation, are enhanced under certain management practices (NT), non-protected or weakly protected SOM fractions alike MOM and POM could be associated with soil capacity N under different soil and management conditions (see Chapter III).

Different management practices can affect soil N accessibility by affecting the development of the plant root system. However, the impact of plant root dynamics on soil N availability is difficult to directly measure. Plant growth models, which incorporate meaningful factors that drive root dynamics associated with N uptake, may be useful in this context. Models should be able to predict root growth on a daily basis because of the short crop cycle of many annual crops, and because of the short time under which most of the N is taken up by annual crops. In Chapter IV of this thesis, a root growth model developed to analyze soil N interactions is described.

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Table 1. Effects of different management practices on total N taken up by different crops.

Management Practice	N uptake by the crop (kg N ha^{-1})	Author(s)
	N uptake by corn at harvest.	Varco et al., 1989
1984		
Corn residues under NT	50	
Corn residues under CT	67	
Vetch residues under NT	92	
Vetch residues under CT	133	
1985		
Corn residues under NT	58	
Corn residues under CT	66	
Vetch residues under NT	131	
Vetch residues under CT	131	
	N uptake by corn at 5 leaf stage.	Eavanylo, 1990
1988		
Conventional tillage	0.83 b	
No-tillage	1.02 a	
1987		
Conventional tillage	0.63 b	
No-tillage	1.02 a	
	N uptake by sorghum Average across stages.	Locke and Hons, 1988
1985		
Conventional tillage	161.5 a	
No-tillage	164.7 a	
1986		
Conventional tillage	131.2 b	
No-tillage	116.5 a	
	N uptake by sorghum at harvest	Sweeney, 1993
Reduced tillage	22.9 a	
No-tillage	17.0 b	

Numbers followed by the same lowercase letter in each study and year are statistically similar.

Table 2. Effect of previous crops, N fertilizer applications, and cover crops on soil N availability and N taken up by a crop.

Management Practice	Initial soil mineral N (2M KCl) mg N kg^{-1}	N uptake by crop Kg N ha^{-1}	Author(s)
Previous crops	Soil layer 0-30 cm	Wheat	
Legumes[1]	11.4	43.2	Strong et al., 1986
Cereals[2]	6.6	24.4	
Oilseeds[3]	7.8	32.7	
[1,2,3] indicative that values are means of 8, 6 and 4 crops			
Cover crops, N fertilizer	Soil layer 0-15 cm.	Corn	McCracken et al., 1989
Without N*			
Vetch	18.6	87.7	
Rye	15.3	59.2	
None	12.3	54.8	
With N 100/170 kg N ha^{-1}*			
Vetch	23.7	104.5	
Rye	18.5	83.4	
None	16.7	75.0	
*Mean values across tillage treatment which were not significantly different for each cover crop			
Previous N applied Kg N ha^{-1}	Soil layer 0-90 cm	Corn (1986)	Vanotti et al., 1995
1983			
0	17.3	105.0	
134	17.7	114.0	
268	20.0	127.0	
402	18.5	126.0	
1985			
0	17.3	105.0	
78	18.1	117.0	
156	20.0	129.0	
Soil N concentration estimated using SBD=1.2 g cc^{-1}			

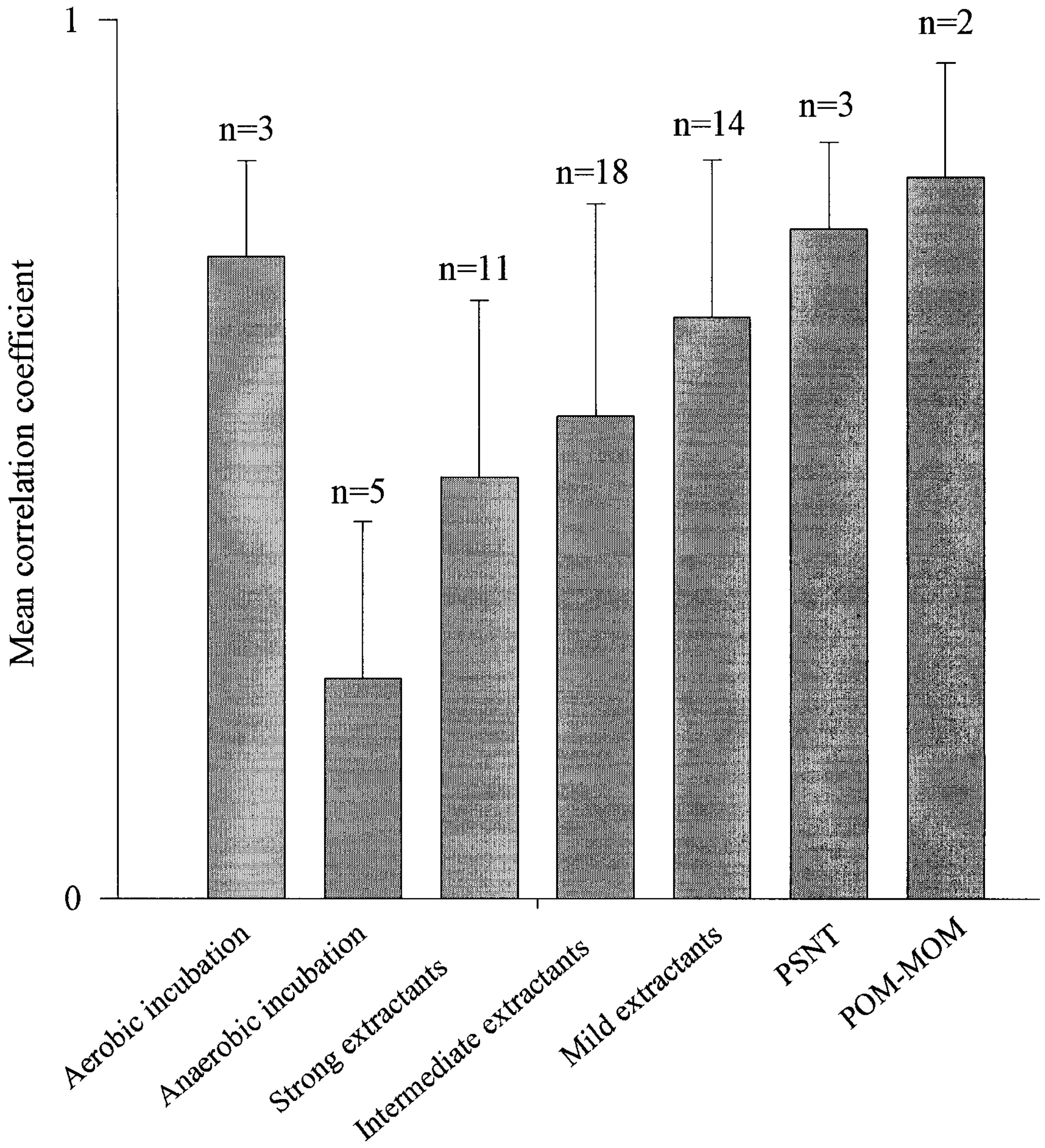

Figure 1. Average correlation coefficient between N uptake by crops grown in field with soil N availability measured by biological, chemical extractants, and soil organic indices.

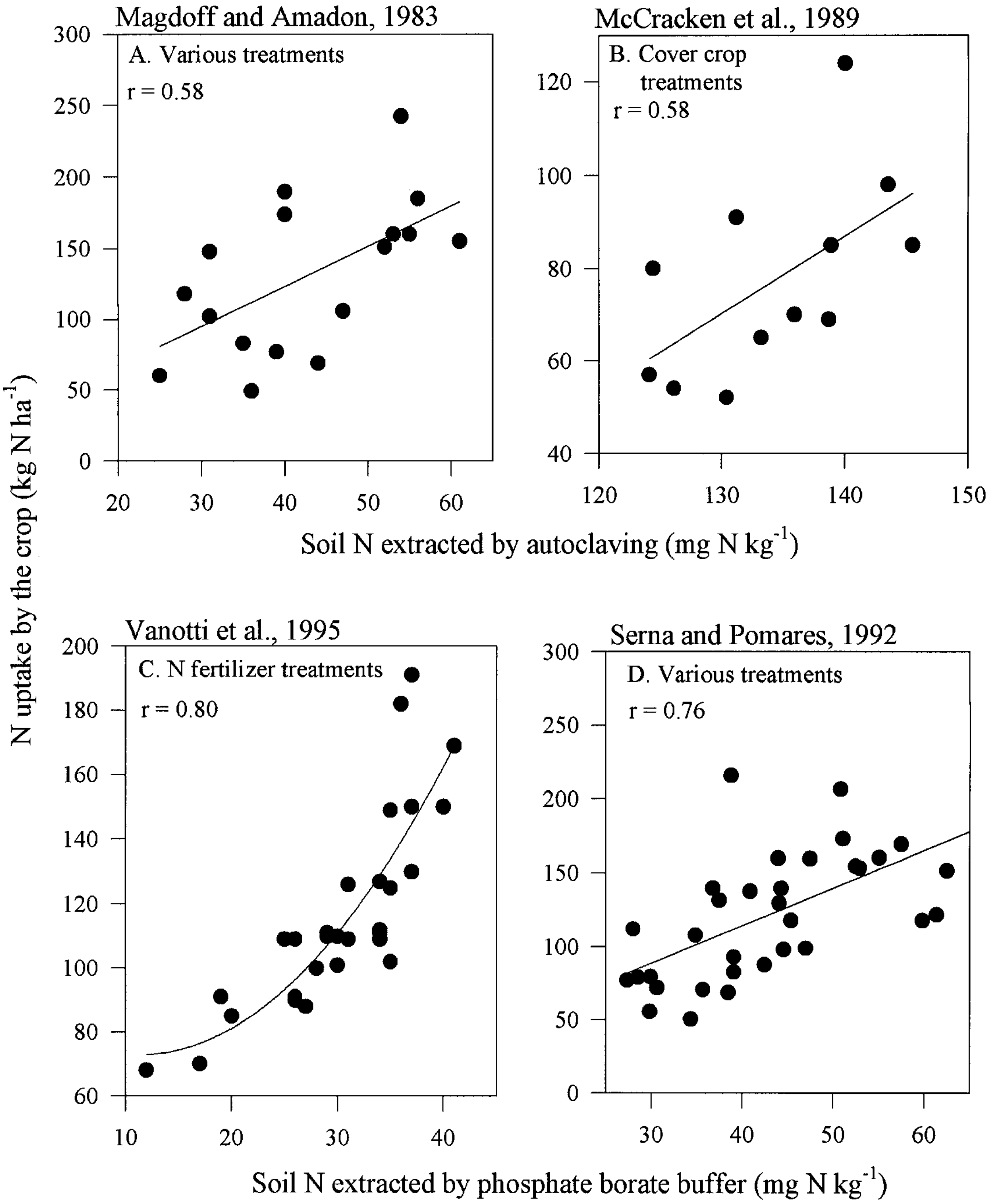

Figure 2. Relationships between soil N extracted by different chemical extractants and N uptake by the crop.

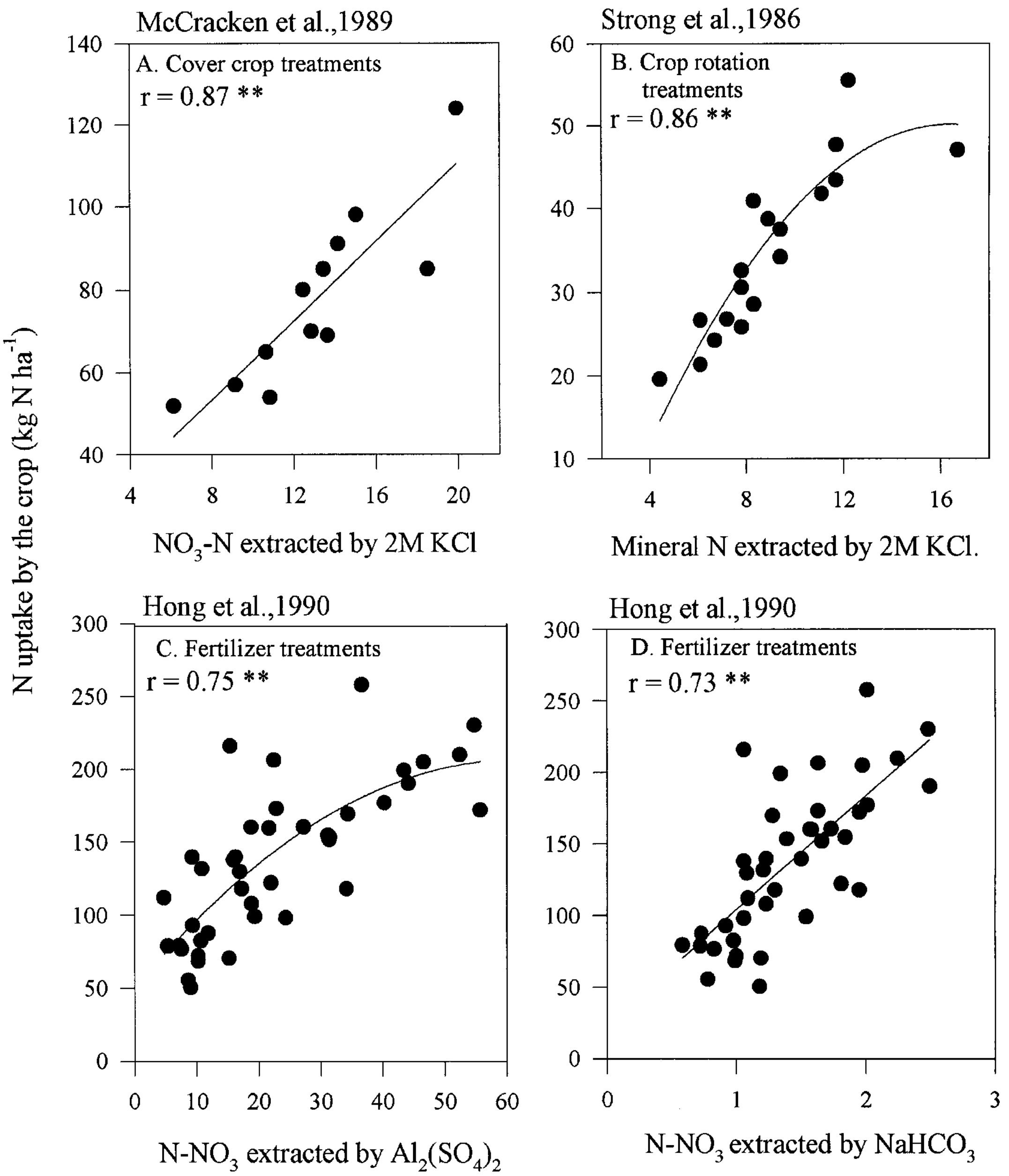

Figure 3. Relationships between initial content of soil mineral N measured by different indexes and total N taken up by the crop.

CHAPTER II

CORN RESPONSE TO N FERTILIZER APPLICATIONS ON A VENEZUELAN SOIL AND ITS' RELATIONSHIP WITH CLIMATIC AND SOIL FACTORS

1. Introduction

Corn (*Zea mays* L.) yields in Venezuela vary from year to year, due to differences in management practices, inappropriate N fertilizer rates, and variable weather. Although some work has related variations in corn production with variations in soil water (Medina and Ramirez, 1997; Rios, 1989), more attention is needed on the interaction of multiple factors affecting yields. Nitrogen fertilizer recommendations for corn in Venezuela are based on experiments conducted some years ago (Gonzalez et al., 1977; Gonzalez and Vonasek, 1974), but often other factors associated with soil (e.g., content of soil mineral N), plant (e.g., N requirements for specific cultivars), management (e.g., tillage system, irrigation), or climatic conditions were not taken into account. A great diversity of soils (Comerma, 1971) exist in Venezuela, and agricultural activities are carried out under diverse agroclimatic management conditions. Thus, N fertilizer recommendations must be adapted to specific conditions.

The effect of N fertilizer application on the short- and long term capacity of the soil to supply N is a site-specific soil property of importance for fertility management. Vanotti et al.

(1995) found that treatments receiving high rates of N fertilizer mineralized significant N quantities (in this case 78 kg N ha^{-1}) from a labile organic pool, much of which was derived from fertilizer previously applied. The content of mineral N at the beginning of the growing season, and corn response to fertilizer levels, can be affected by residual N from previous fertilizer applications (Bundy and Malone, 1988).

Limiting soil water content can directly affect plant growth, through water stress at different plant stages (Waldren, 1983). Water content also has indirect effects on growth by influencing soil N mineralization (Stanford and Epstein, 1973) and soil N availability related to leaching and denitrification (Jarvis et al., 1996). In areas of low precipitation, the amount of water in the soil profile at the start of the crop cycle is highly correlated with plant yield (Isfan, 1984). Thus, the impact of soil water content and its dynamics over the growing season represent a key aspect to understanding crop behavior. Other agronomic considerations, such as optimal rates of N and N use efficiency, are sensitive to rainfall level and hydrologic conditions (Bondavalli et al., 1970; Reddy and Reddy, 1993). Thus, variation in the soil water content during the crop cycle, which can be altered by changes in the sowing time and changes in rainfall distribution during the crop season, can greatly impact crop growth and the crop response to N fertilization. Effects of N applications on soil water use have been noted (Cantero-Martinez et al., 1999), which could affect the crop response to soil water content.

In this study, we evaluated crop response to N application under different initial contents of soil mineral N and water and different amounts and distribution of precipitation during the crop cycle. We hypothesized that initial availability of soil mineral N and water, and variations during the crop cycle would affect crop production and N uptake. In this study, corn response to N application was evaluated during three successive years on a Mollisol soil of Venezuela. Total dry matter production and N uptake by the end of the crop cycle were used as indicators of plant production and response to N application.

2. Material and Methods

Characteristics of the experimental site: The experiment was carried out between 1992 and 1994 on a Fluventy Haplustoll (Soil Survey Staff, 1994) soil located in Maracay, Venezuela, at 10°17' North, 67°37' West, at an elevation of 460 m above sea level. This site had been uncultivated and kept under natural vegetation (fallow) for about eight years. The main physical and chemical characteristics are presented in Table 1. Soil organic matter (SOC) was determined by Walkley and Black (Nelson and Sommers, 1982), and soil texture by the hydrometer method (Gee and Bauder, 1986). Soil available P and K were extracted by sodium bicarbonate (Olsen and Sommers, 1982) and measured colorimetrically and by atomic absorption, respectively. Available Ca^{++} was obtained using Morgan's extract modified by using NaOAc and 1M KCl (Nieves, L., personal communication), which is used for routine analysis in Venezuela.

Treatments and experimental conditions: The soil was tilled with a disk and harrowed 2 or 3 times at least 15 days prior to sowing. The treatments consisted of N rates of 0, 3, 6, 9, 12, and 18 g N m^{-2} (0, 30, 60, 90, 120, and 180 kg ha^{-1}), applied in the form of urea (46% N), combined with 9 and 8 g m^{-2} (90 and 80 kg ha^{-1}) of P and K, respectively, as triple superphosphate and potassium chloride, broadcast and incorporated into the soil at or just prior to sowing time. Corn (hybrid PB-8) was sown on August 8, June 17, and July 4 in 1992, 1993, and 1994, respectively. The treatments were arranged in a randomized complete block design (RCB) with 3 replications, in plots of 9.4*5 m where the corn was sown with 20 cm between plants and 0.8 m between rows. The final plant population, after thinning at 10-15 days from sowing, was 62,500 plants ha^{-1}. In 1994, some parts of the experiment were replanted due to failure to germinate because of dry soil. Each year, weed control consisted of post-emergent herbicides (Atrazine at 2 kg ha^{-1}). Control of *Spodoptera* sp. was done 25 days after sowing in 1992, at 12, 18, and 35 days in 1993, and at 20 days after sowing in 1994 using Dipterex (Trichlorfon) at 2 kg ha^{-1}. Precipitation during the crop cycle was measured at different intervals with a pluviometer located at the experimental site.

Plant and soil parameters evaluated: Each year, total aboveground dry matter (DM), grain yield (GY) and total N uptake in aboveground tissue and grain were measured at harvest time by harvesting 1 m in each of the 4 central rows. Plants were cut at the soil level and biomass was separated into aboveground foliage and grain. Total aboveground foliage was measured and a subsample analyzed for water content (in oven at 60°C until constant weight) and total N contents by Kjeldahl (Bremner and Mulvaney, 1982). Ears were allowed to air dry in a greenhouse and then the grain was weighed; cobs were included into the aboveground mass. A subsample of grain was used to determine water and N contents as indicated above. In 1993 and 1994, DM and N uptake by the crop was measured every 15 days during the crop cycle for the 0 and 12 g N m^{-2} treatments.

At the sowing date in each of the experimental units, the initial content of soil mineral N ($N\text{-}NO_3$) and $N\text{-}NH_4$), from 0 to 50 cm of depth in increments of 10 cm, was measured by extraction in 2M KCl (Bremner, 1965). Water content from the same depth increments was measured gravimetrically (Pla, 1977). Soil mineral N and soil water content in each soil layer were expressed in g m^{-2} and mm by using the soil bulk density (SBD) measured by the core method (Pla, 1977). In 2 of the treatments (0 and 12 g N m^{-2}), mineral N (N-NO_3 and N-NH_4) and soil water were measured every 2 weeks during the crop cycle.

Statistical analysis: Differences in total DM, grain yield, and N uptake among years were analyzed in the three-year experiment as a repeated measures design, using a mixed-effect, general linear model (SAS, 1998). Years and treatments (N rates) were considered as fixed effects. Also, it was assumed that the covariance between two periods (years) decreases exponentially and the option 'type=ar(1)' of SAS was used (SAS, 1998).

In each year, response curves for total DM, and N uptake by the crop were obtained by linear regression using procedure REG in SAS. Variables were allowed in the regression model if they were significant at 5% using the 'Backward' option in REG. The GLM procedure of SAS was used to enhance the model obtained by the Backward procedure to include simple effects of variables when only the quadratics or the interaction were allowed by the Backward procedure.

3. Results and discussion

Total dry matter (DM), grain yield (GY) and N uptake for each year, averaged across N rates, are shown in Figure 1. Total DM in 1994 was higher than in 1992 and 1993, but there was no difference in GY among the three years. However, total N uptake and N in grain in 1992 (38.6, and 10.5 g m^{-2} respectively) were higher than in 1993 (16.8 and 7.4 g m^{-2}), and

1994 (11.4 and 5.1 g m^{-2}). The contrast of low DM production and high N uptake in 1992, with high DM production and low N uptake in 1994, suggests that processes other than N availability were involved in DM production and N uptake.

Differences in weather could contribute to the differences observed in DM and N uptake among years. Corn yield has been shown to be most sensitive to weather conditions immediately before or during anthesis (Runge and Odell, 1958). In our study, total precipitation during the crop cycle was 436, 440, and 653 mm for 1992, 1993, and 1994, respectively. Moreover, there were differences in the amount of precipitation during the reproductive stage: 153, 76 and 241 mm for 1992, 1993, and 1994, respectively. Thus, soil water availability during sensitive crop stages, such as flowering and grain fill, probably affected DM production in 1992 and 1993.

The highest N uptake, which occurred in 1992, was associated with a large capacity of the soil to supply N. It is obvious that previous land use (eight years under vegetated fallow) affected soil N supply and thus crop response to N application. Net N mineralized during the crop cycle was calculated as N uptake in the unfertilized treatment plus the difference in soil mineral N (0-50 cm) between harvest and sowing time, assuming negligible losses of N (Figure 2). The net nitrogen mineralized in 1992 (29.5 g m^{-2}) was significantly higher ($p<0.05$) than in 1993 (2.6 g m^{-2}) and in 1994 (-3.3 g m^{-2}), when there was probably net immobilization or N loss. The high N mineralization in 1992 was undoubtedly associated with N release from organic matter accumulated under fallow (Campbell, 1983). These organic sources began to decompose when the soil is cultivated and much of the labile organic N is mineralized during the first years of cultivation.

The decrease in N mineralization from 1992 through 1994 is associated with a large export of N in grain (105, 74, and 51 kg ha^{-1} from 1992-94) and possibly some losses of N by denitrification and leaching. Also, since plant residues remained standing on the field until the next crop cycle, some N could have been lost directly from the plant residues into the atmosphere. Losses of N from 58% to 82% in non-incorporated plant residues have been reported (Watson and Lapins, 1972). This may include leaching losses and/or gaseous loss from plants tissues (Parton et al., 1988) through volatilization of amines, NH_3, and N oxides after senescence (Stevenson and Cole, 1999).

Corn response to N application, evaluated by regressing DM and total N uptake with N rate, showed that only 24 to 53% of the variability in DM, and 30 to 55% of variability in total N uptake was explained by N fertilizer rate (Table 2). For DM production in 1992 and 1994, only the significant ($p<0.05$) linear effect of N fertilizer rate was included in the models, and in 1993, where the highest coefficient of determination was observed, the linear and quadratic effects were significant. For total N uptake, only the linear effect was included in each of the three years. However, the relatively low coefficients of determination (R^2) of the models indicate that crop production and N uptake were affected by other variables. Among these, variation in amount and distribution of precipitation during the crop cycle probably affected soil water availability as well as N mineralization, leaching, and denitrification.

Regressions of total DM and total N uptake as affected by N fertilizer and initial content of mineral soil N and soil water are shown in Table 3. Total mineral soil N (0-50 cm) was not significantly associated with DM and N uptake (data not shown). For all years, 44%

of the variability in DM production was explained by N fertilizer rate and initial content of mineral N in the 20 cm of soil, and 74% of variability in total N uptake was explained by including all three factors and their interactions. The high coefficient of determination in the regression model suggests that N uptake is highly associated with soil variables measured at the beginning of the crop cycle, contrary to DM where initial soil conditions only explained a small proportion of its variation. This could be because most of the total N is taken up by corn occurs prior to silking stage (Hanway, 1962; Fageria et al., 1997) and thus N uptake is more affected by the initial soil conditions.

The effect of the initial soil water content of the first soil layer (0-20 cm) is probably associated with the preferential uptake of N plant by mass flow. Nitrogen movement from the bulk soil to roots has been found to be a limiting process in N uptake and it is affected by soil water content (Barraclough and Tinker, 1981). The relationship between the initial soil water content accumulated in the first 20 cm depth of the soil and total N uptake by the crop for all the three years is shown in Figure 3. At initial water contents less than 50 mm, there was no relationship with N uptake, but N uptake increased with increasing soil water above 50 cm.

Soil water availability could be responsible for some of the variability in crop response not explained by N fertilizer rates. Soil water content at sowing, averaged across treatments, was significantly greater in 1992 than in 1993, and amounts in 1993 were greater than in 1994 (Table 4). The influence of soil water content on N uptake may be greatest early in the crop cycle when N demand is high. During anthesis and grain-fill, direct effects of soil moisture on production may be more important. In 1992 and 1993, soil water was close to field capacity at the beginning of the crop cycle, but by the reproductive stage, soil water was below field capacity most of the time (Figures 4 and 5). In contrast, during 1994 there were water deficits at the beginning of the crop cycle, but soil water increased to field capacity or higher by the reproductive stage (Figure 6). Amount and timing of precipitation had the greatest effect on soil water. In 1992 and 1993, total precipitation was 436 and 440 mm, while in 1994 it was 653 mm (Table 4). Moreover, in 1993, only 76 mm of precipitation occurred during the reproductive stage compared to 153 and 241 mm in 1992 and 1994 respectively.

Estimated evapotranspiration (ET) for the whole crop cycle, averaged across treatments, was significantly higher in 1994 than in 1992 and 1993 (Table 4). Interannual variability of ET was greatest during the reproductive period of the crop cycle (Figure 7). ET during the reproductive stage, where evaporative demand is high (Denmead and Shaw, 1962), was lower in 1992 and 1993 than in 1994. In contrast, water availability and ET during the vegetative stage were lowest during 1994 and visual observations of the plant suggested there was water stress. Although soil water stress during the vegetative stages affects yield less than at other crop stages (Denmead and Shaw, 1960), small decreases in plant production (up to 25%) have been reported (Larson, 1975). Low water content could affect N uptake by the crop, much of which occurs through mass flow (Barber, 1984). In 1994, the lowest N uptake by the crop was observed (Figure1), although the initial content of mineral N across treatments (14 g N m^{-2}) was similar to that in 1992 and higher than in 1993. Potential nitrogen losses by denitrification when soil water content was above field capacity may have reduced by a high crop uptake in the 12 g N m^{-2} treatment (Figure 5F), in contrast to observations in the 0 g N m^{-2} treatment where total N availability decreased over the same period (Figure 5C). Paul and Clark (1996) mention that NO_3^- and water uptake by plants help decrease denitrification in cropped versus fallow soils. However, in 1993 we cannot discount the possibility that loss of N directly from plant tissues could alter evaluations of crop response to N application. In this year, plant N content in the treatment with 12 g N m^{-2} decreased continually from 30 g N m^{-2} at 63 days of the crop cycle to 18 g N m^{-2} at the harvest time (Figure 5F), whereas only a small loss was observed in the unfertilized treatment between 97 and 109 days (Figure 5 C). Losses of N directly from standing plants have been reported to vary between 3 to 9 kg N ha^{-1} in rice to as high as 45 kg N ha^{-2} in soybean (Weiland et al. 1982), and between 25 to 80 kg N ha^{-1} in winter wheat (Daigger et al., 1976).

In 1994, changes in soil water content appeared to drive changes in soil N availability (Figures 6C and 6F). In the unfertilized treatment, the increase in N availability during the first 20 days coincided with increased soil water and mineral N content (Figures 6A and 6B). During the period from 47 to 62 days, there was a net increase in soil N availability (6.1 and 8.6 g N m^{-2}) and N uptake (1.5 and 7 g N m^{-2}) in the 0 and 12 g N m^{-2} treatments, respectively (Figures 6C and 6F). These high N uptake rates in the crop were accompanied by daily ET rates as high as 13.2 and 12.4 mm d^{-1} for the 0 and 12 g N m^{-2} treatments, respectively (Figure 7). However, during this period, the high soil water contents could also have increased soil N losses by leaching and denitrification (Paul and Clark, 1996; Sexstone et al., 1985), thus reducing soil N availability. Estimates of N losses, using the initial and final soil mineral N (0-50 cm) and N taken up by the crop, were about 6 and 14 g N m^{-2} for the unfertilized and fertilized (12 g N m^{-2}) treatments, respectively. Although high soil water content in this period (days 62-77) probably affected soil N availability, there was little if any effect on plant production. Adverse effects of high water contents (i.e., flooded conditions) are more evident at early growth stages (Cannel and Jackson, 1981) with some effects during the tasseling/silking stage (Carter et al., 1990; Evans et al., 1990), late vegetative stage, flowering, and yield formation (Mukhtar et al., 1990).

4. Conclusions

Total N uptake by the crop was better associated with the initial soil mineral N content and soil water than was DM production. This probably is because most of the N uptake occurred before silking, while a great proportion of the DM production occurred after that. Dry matter production is more affected by factors acting in the reproductive stage of the crop cycle such as amount and distribution of precipitation.

Crop response to N application was affected by the soil capacity to supply N and factors affecting crop growth. In 1992 and 1993, although a high amount of N was taken up by the crop, water deficits in the reproductive stage prevented high yields and DM production. On the other hand, in 1994 when the lowest amount of N was taken up by the crop, the highest crop production occurred. In this year, high water availability during the reproductive stage enhanced crop production. Thus, variation in crop response to N application was associated with variations in soil capacity to supply N and variations in water availability during the crop cycle. Variations in the sowing time caused variations in the initial properties of the soil associated with N and water availability, and amount and distribution of precipitation during the crop cycle. Thus, determination of appropriate sowing time is a key factor in evaluation of crop production and evaluation of the effects of N applications.

Because soil properties and variation in weather conditions affect crop growth and response to N application, uses of simulation models where the main aspects affecting crop growth and dynamic of nutrient and water in the soil are considered, may help to evaluate crop response to N application. Using this approach, we could evaluate crop response to N application under different scenarios of amount and distribution of precipitation.

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Table 1. Chemical and physical properties of the soil at the experimental site.

Soil Layer (cm)	P	K	Ca	pH	SOC	Texture
		mg kg^{-1}			g kg^{-1}	
0-20	19 (m)[1]	232 (h)	615 (h)	6.5	1.3	Loam
20-40	4 (l)	84 (h)	475 (m)	6.8	0.7	Loam
40-60	4 (l)	44 (l)	375 (m)	7.1	0.2	Sandy clay loam
>60	3 (l)	28 (l)	415 (m)	7.5	0.2	Sandy loam

[1] Letters after nutrient content show the sufficiency level of the element: high (h), medium (m), and low (l) related to crop response to application of the element.

Table 2. Regression models for total dry matter production and N uptake of corn as a function of the amount of fertilizer N applied for different years.

Year	Best regression model adjusted	R^2
1992	DM ($g\ m^{-2}$) = 966.2 + 18.0 (TRT)	0.24 *
	Nabt ($g\ m^{-2}$) = 32.2 + 0.80 (TRT)	0.30 *
1993	DM ($g\ m^{-2}$) = 718.8 + 103.8 (TRT) - 4.1 $(TRT)^2$	0.53 **
	Nabt ($g\ m^{-2}$) = 9.39 + 0.93 (TRT)	0.55 **
1994	DM ($g\ m^{-2}$) = 1102.2 + 25.0 (TRT)	0.29 *
	Nabt ($g\ m^{-2}$) = 7.7 + 0.46 (TRT)	0.38 *

All the variables included in the models are significant at α=0.05.
** and * show significance at α=0.01 or 0.05 respectively.

DM and Nabt: Total dry matter produced and total N taken up by the crop at harvest.

TRT: Nitrogen rate ($g\ m^{-2}$) applied at sowing time.

Table 3. Regression models obtained for total dry matter production and N uptake of corn.

Year	Best regression model adjusted	R^2
1992	DM (g m^{-2}) = 871.6 + 19.1 (TRTN12)	0.27 *
	Nabt (g m^{-2}) = 28.6 + 0.79 (TRTN12)	0.30 *
1993	DM (g m^{-2}) = 476.9 + 111.7 (TRTN1) - 3.49 $(\mathrm{TRTN1})^2$	0.55 **
	Nabt (g m^{-2}) = 6.9 + 0.91 (TRTN1)	0.60 **
1994	DM (g m^{-2}) = 1019.1 + 24.7 (TRTN1)	0.36 **
	Nabt (g m^{-2}) = 6.27 + 0.45 (TRTN1)	0.45 **
All years	DM (g m^{-2}) = 655.2 + 46.7 (N12) + 59.9 (TRT) - 2.0 $(\mathrm{TRT})^2$	0.44 **
	Nabt (g m^{-2}) = -17.2 - 0.49 (SW12) + 0.01 $(\mathrm{SW12})^2$ +6.4 (N12) + 1.74 (TRT) - 0.079 (N12*SW12) - 0.191 (N12*TRT)	0.74 **

All the variables included in the models are significant at α=0.05.
** and * denote significance at α=0.01 or 0.05 respectively.

DM and Nabt: Total dry matter produced and total N taken up by the crop at harvest.

TRT: Nitrogen rate (g m^{-2}) applied at the sowing time.

TRTN1 and TRTN12: Nitrogen rate (g m^{-2}) plus mineral N content (g m^{-2}) of the 0-10, and 0-20 cm soil layer respectively.

N12: Amount of soil mineral N (g N m^{-2}) in the 0-20 cm layer.

SW12: Accumulated soil water content (mm) in the 0-20 cm soil layer at the sowing time.

Table 4. Soil water content, amount and pattern of rain and evapotranspiration in 1992-1994.

	Soil water at sowing (mm)	Soil water at flowering (mm)	Total rain (mm)	Rain during reproductive stage (mm)	Total ET (mm)	ET at reproductive stage (mm)
1992						
0 g N m^{-2}	187 a	152 a	436	153	491 b	175 a
12 g N m^{-2}	207 a	126 a	436	153	537 a	184 a
mean	197 A	139 A			514 B	180 B
1993						
0 g N m^{-2}	137 a	137 a	440	76	484 a	121 b
12 g N m^{-2}	145 a	139 a	440	76	505 a	138 a
mean	141 B	138 A			495 B	130 C
1994						
0 g N m^{-2}	82 a	136 a	653	241	612 a	255 a
12 g N m^{-2}	84 a	153 a	653	241	653 a	248 a
mean	83 C	145 A			633 A	251 A

Numbers followed by the same small case letter for the same year are statistically similar. Numbers followed by the same capital case letter are similar for different years in the same column.

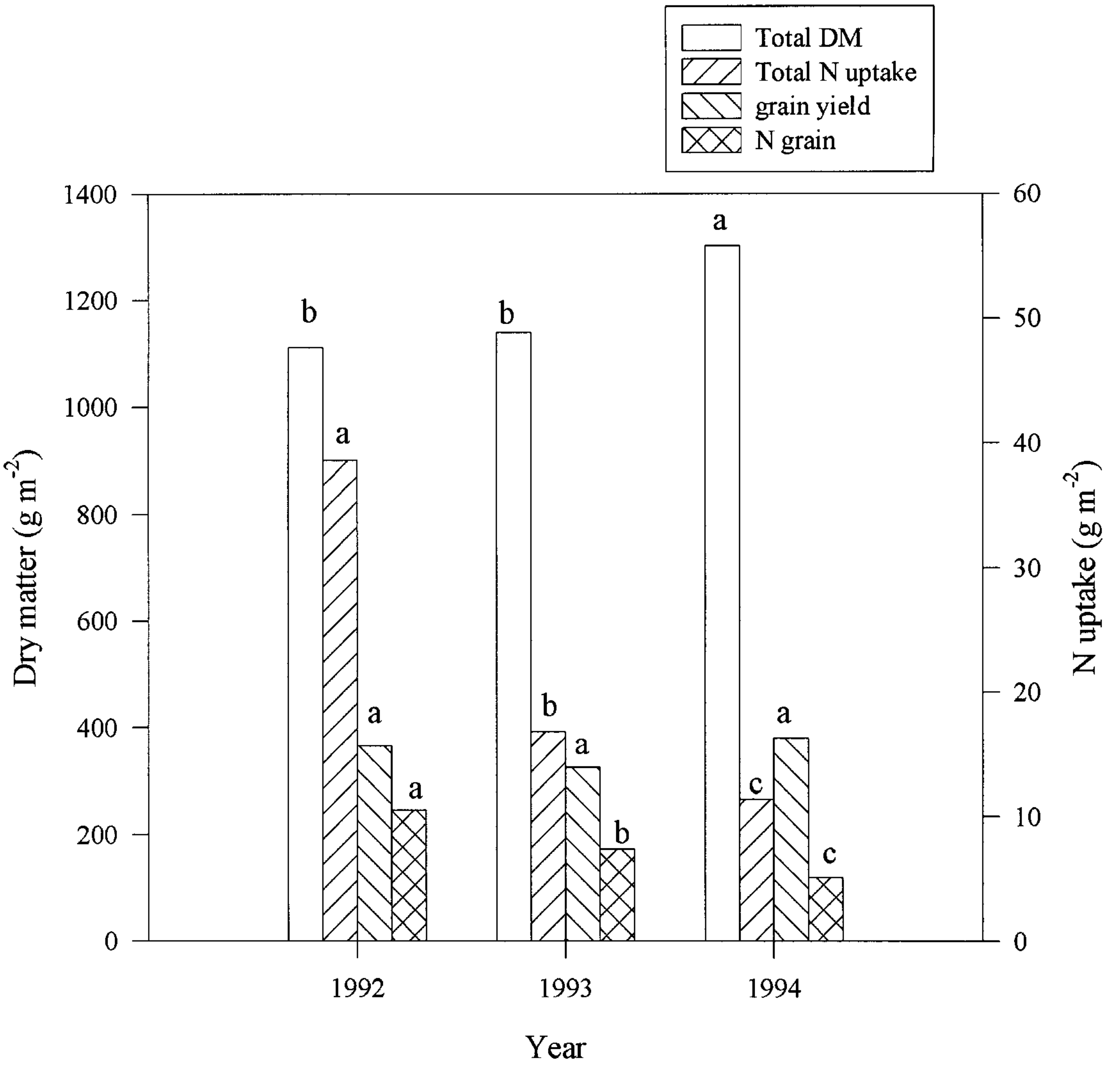

Figure 1. Total dry matter, grain yield, and total nitrogen uptake for corn in each year. Bars with different lowercase letters are significantly ($p<0.05$) different between years for each of the variables.

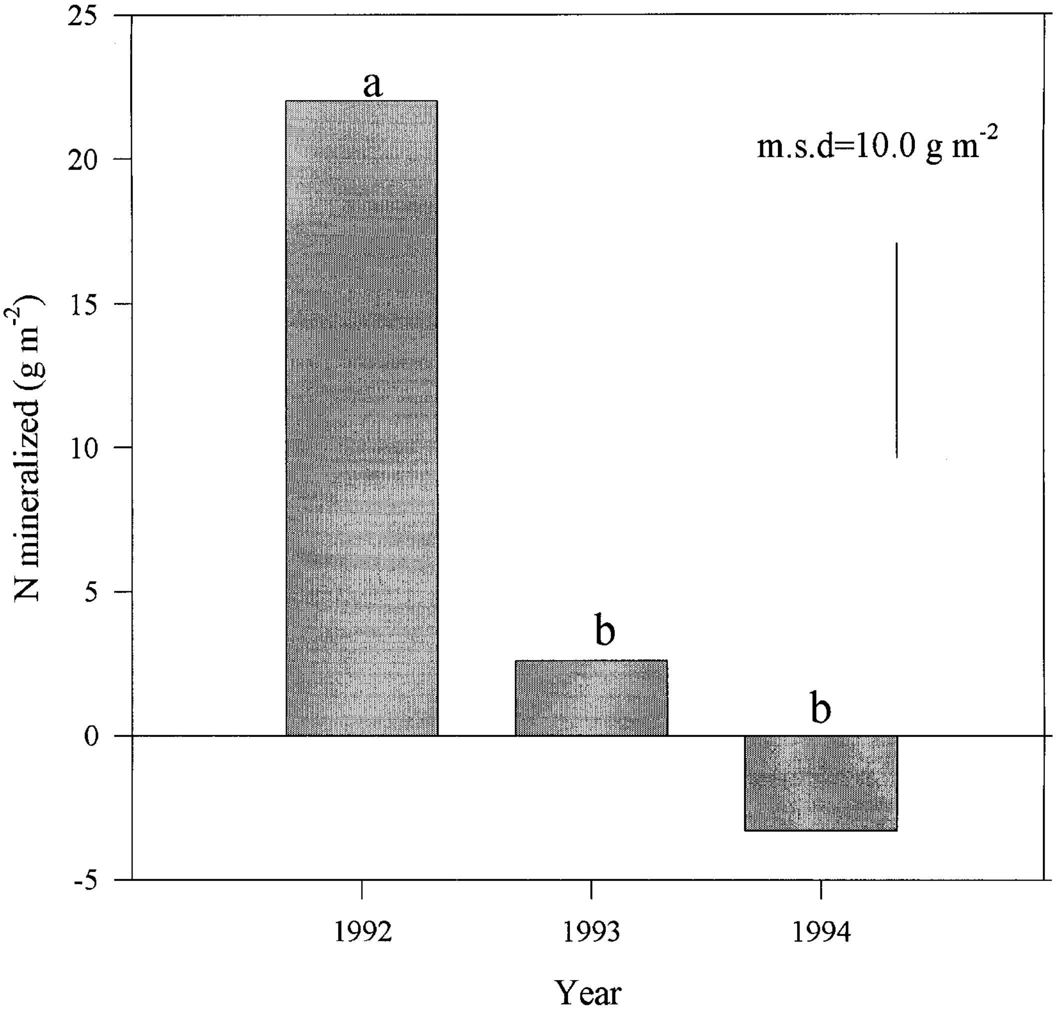

Figure 2. Estimated total nitrogen mineralized during the crop cycle in the treatment without N fertilizer for each year. Bars with different lowercase letters are significantly ($p<0.05$) different between years.

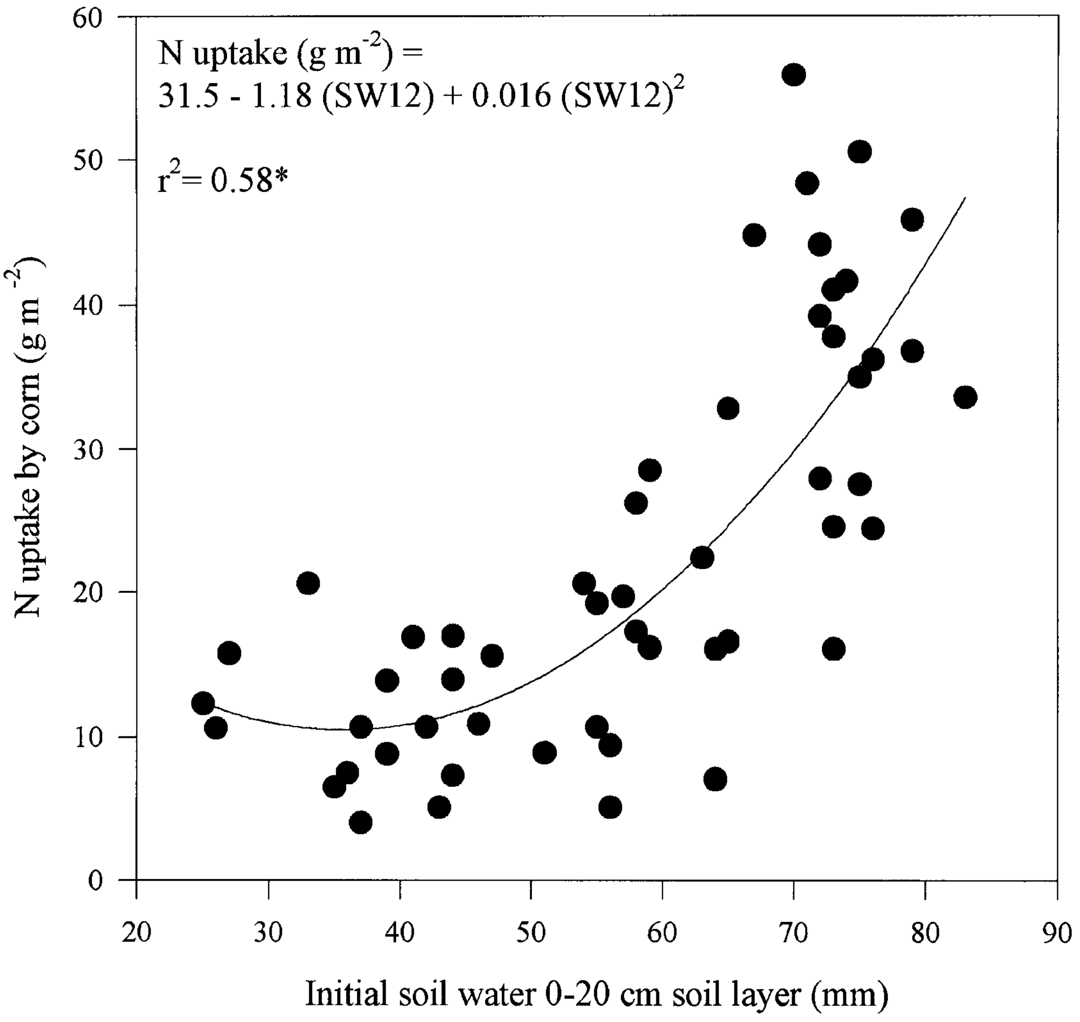

Figure 3. Relationship between initial soil water content in the surface soil layer (0-20 cm) and N uptake by corn during three years.

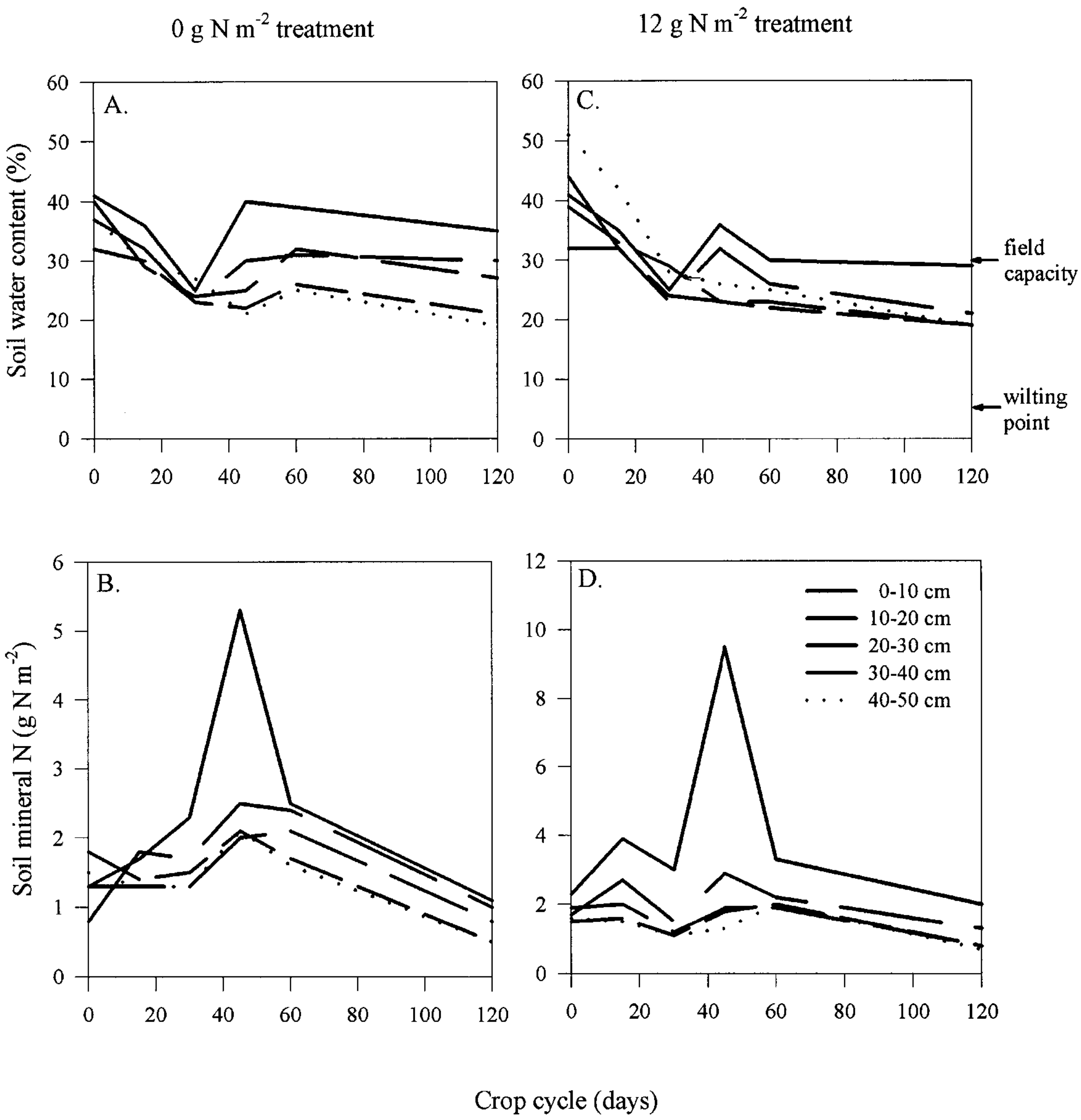

Figure 4. Variation in soil mineral N and water content in soil in different soil layers during the crop cycle in a) the unfertilized (0 g N m^{-2}) and b) fertilized (12 g N m^{-2}) treatments in 1992.

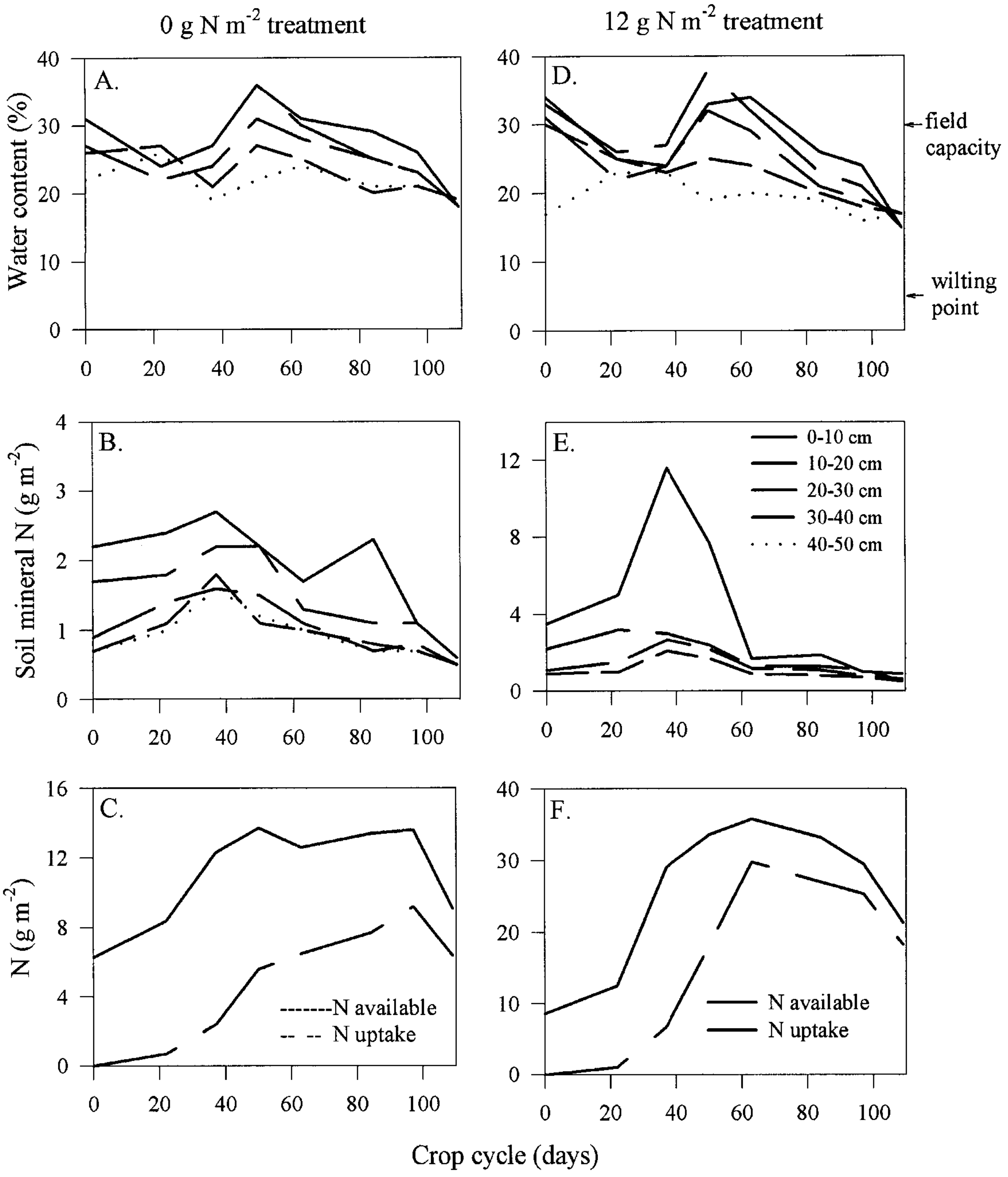

Figure 5. Variation in soil mineral N and water content in different soil layers, N uptake by the crop and total N available during the crop cycle in a) the 0 g N m^{-2} and b) fertilized treatments in 1993.

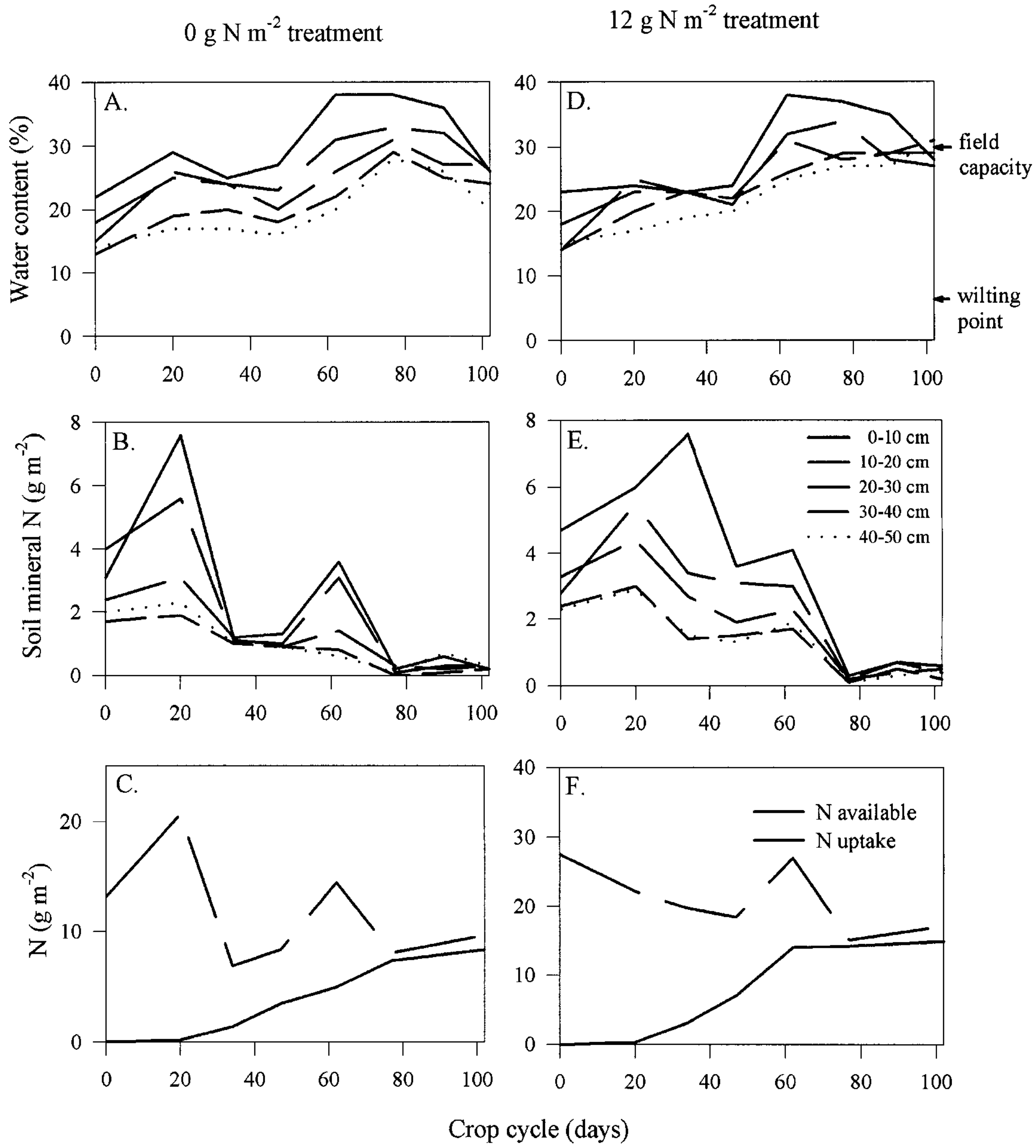

Figure 6. Variation in soil mineral N and water content in different soil layers, N uptake by the crop and total N available during the crop cycle in unfertilized and fertilized treatments in 1994.

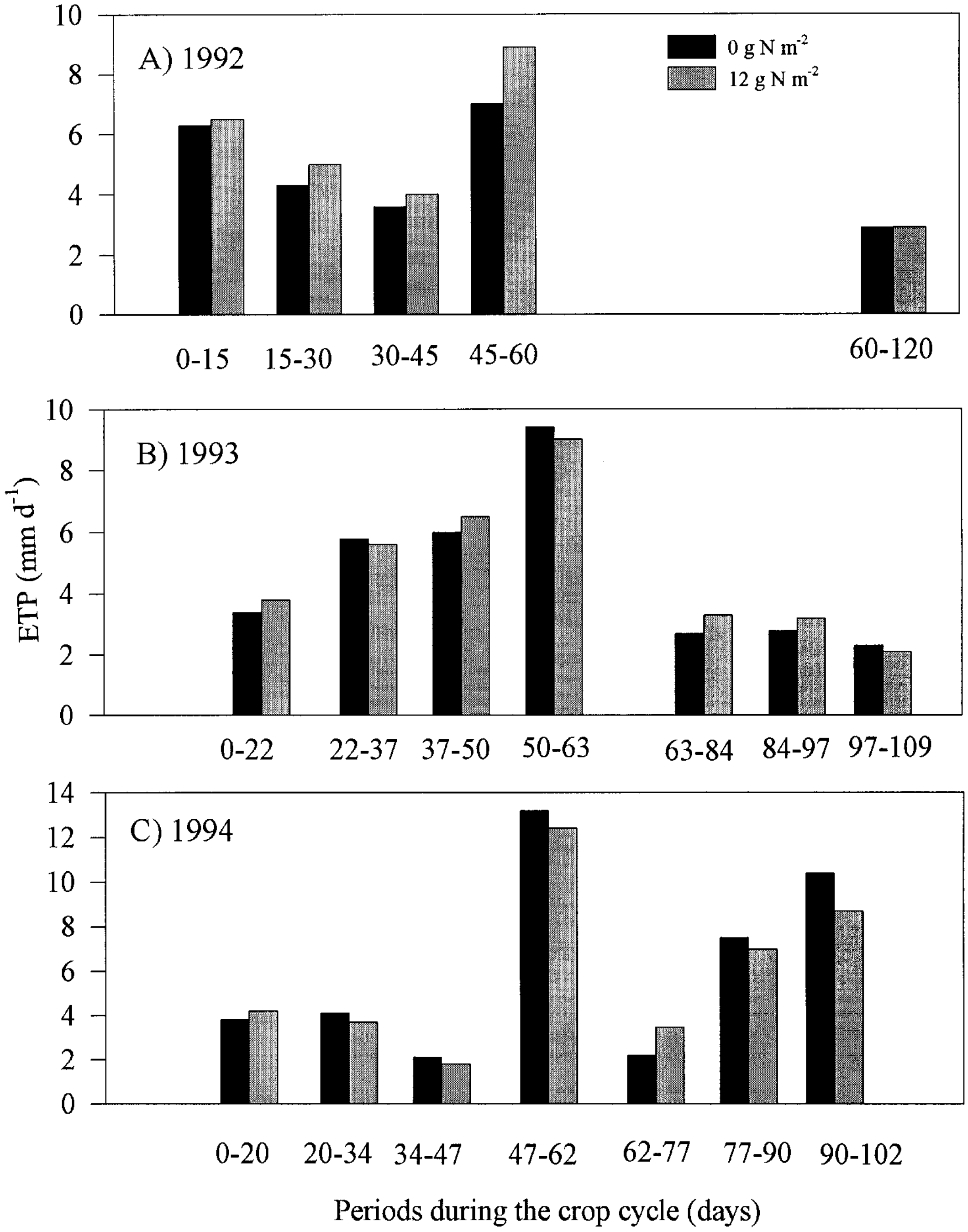

Figure 7. Estimated daily evapotranspiration by 15 days periods through the crop cycle in a) 1992, b) 1993, and c) 1994, for the unfertilized (0 g N m^{-2}) and fertilized (12 g N m^{-2}) treatments.

CHAPTER III

EVALUATION OF N SUPPLY CAPACITY OF DIFFERENT VENEZUELAN SOILS AND ITS' RELATIONSHIP WITH SOIL PROPERTIES AND N COMPARTMENTS

1. Introduction

The capacity of a soil to supply N for plant nutrition is related to the organic and mineral forms of the element in the soil. However, total soil organic matter (SOM) and total soil N (Magdoff, 1991) are often only weakly related to N availability or N supply capacity of soils. Soil aggregation has been found to play an important role in soil organic matter dynamics by affecting the microbial driven process of mineralization (Feller and Beare, 1997; Feller et al., 1996; Christensen, 1992; van Veen and Kuikman, 1990; Six et al., 1999). Thus aggregate-related soil N fractions may be useful indicators of N supplying capacity at the start of the growing season.

Although soil mineral N concentration (N-NO_3 and N-NH_4) represents a small proportion of the total N uptake by the crop, a significant positive relationship between these two variables has often been found (Binford et al., 1992; Fox et al., 1989). However, its utility as a soil N availability index has been questioned due to potential post-sampling changes of N distribution in the soil profile associated with soil water dynamics (Holford et al., 1997).

The contribution of organic N compounds to plant nutrition is, in addition to being affected by SOM quality, affected by the physical accessibility of soil organic N sources to decomposers (van Veen and Kuikman, 1990). Physical protection of organic N in soil has been identified as one of the main factors controlling N mineralization (Gregorich et al., 1997). Elliott (1986) and Beare et al. (1994) showed that C and N mineralization increased when macroaggregates were crushed, suggesting that SOM is physically protected in them. Franzluebbers and Arshad (1997a) found that macroaggregates contained more mineralizable C than microaggregates. The higher rates of C and N mineralization in macroaggregates are related to the age of the organic matter occluded in them. Organic matter in macroaggregates is generally younger, more labile, and has a faster turnover than in microaggregates (Monreal et al., 1997; Elliott, 1986; Six et al., 1999).

In this study, we tried to identify measurable soil N fractions associated with soil capacity to supply N. Because organic N sources associated with macroaggregate size fractions have been found to be easily mineralizable, we hypothesized that some of these fractions could be used as soil N availability indices. In this study, we used N uptake by a perennial grass *(Brachiaria brizanta)* as an index of soil N availability in different Venezuela soils, and related that with different mineral and organic soil N fractions obtained from the soils. We also investigated the relationships between different soil properties associated with soil N availability.

2. Materials and Methods

Samples were collected from the 0-20 cm layer from fifteen cultivated soils in Venezuela (Table 1). Soils were sampled at the beginning of the rainy season, brought to the lab and air dried and sieved through a 5 mm screen. During the sieving process the soils were gently broken up with a rubber hammer to pass through a 5 mm screen. On whole soil, organic carbon (SOC), texture, total soil N (TN), and pH were determined by Walkey and Black (Nelson and Sommers, 1982), hydrometer method (Gee and Bauder, 1986), Kjeldahl (Bremner and Mulvaney, 1982), and the soil-water solution method

(McLean, 1982), respectively. The soils represented a range of organic matter contents (SOM) (0.59 to 2.69%), textures (sandy to clay), TN (0.015 to 0.258%), and pH (5.4 to 8.7).

Soil aggregate size distribution: Soil aggregate size fractions (5000-2000μm, 2000-850μm, 850-425μm, 425-250 μm, 250-150μm, 150-106μm, 106-45μm, and <45μm) were obtained by dry-sieving 100 g of the air-dried soils in a vertical shaker (Portable sieve shaker, model RX-24, Tyler Industrial Products, Mentor, Ohio) for 15 minutes. Soil organic C and N contents of the soil aggregates were determined by the Walkey and Black method (Nelson and Sommers, 1982). Sand content, in each of the aggregate size fractions was measured by dispersing the aggregate fractions with 5% sodium hexametaphosphate and sieving through a 53 μm screen (Elliott et al., 1991). Aggregate distributions were evaluated on a sand-free basis. Nitrogen content in each aggregate size class was calculated by multiplying the N concentration of each aggregate size (Bremner and Mulvaney, 1982) with the mass of aggregates in that size class. For some analyses, aggregate classes were grouped into the same major classes identified by Elliott (1986): large macroaggregates (2000-5000 μm), small macroaggregates (250-2000 μm) and microaggregates (<250 μm).

The macro-organic matter (MOM), which is the soil organic matter >250 μm in the whole soil, was obtained by water flotation and sieving through a 0.25 mm screen, after soil dispersion with hexametaphosphate (Barley, 1955). Macroorganic matter of the four replicates of each soil was mixed to obtain N and C concentrations. Nitrogen was determined by Kjeldahl and C by combustion at 650°C.

Evaluation of soil N availability: Soil mineral N content was obtained using a KCl (2M) extraction (Bremner, 1965). Nitrate-N and ammonium-N in soil extracts were measured using a Perkin-Elmer flow injection analyzer. The total amount of mineral N, NO_3-N plus NH_4-N (NO_3NH_4), was used as a soil index of N availability.

The N uptake by *Brachiaria brizanta* was also used as an index of soil N availability (Warren and Whitehead, 1988; Jarvis et al., 1996). In a greenhouse experiment, with 4 replications for each soil, 30 plants of *Brachiaria brizanta* were grown in 5 kg of 5 mm dry-sieved soil. Soil water content was maintained at field capacity during the experiment. A nutrient solution, with all the main plant nutrient requirements except N, was applied at the beginning of the experiment and after each harvest. At 35, 60, and 90 days, shoot dry matter production of *Brachiaria* was measured by cutting the plant at about 3 cm over the soil surface and weighing the oven-dried (60°C) material. Nitrogen content in the tissue was measured by Kjeldahl. The amount of N uptake by the shoots during each period (Nab1, Nab2, Nab3) and the total for all three periods (Nabt) was calculated using the dry matter produced and the N concentration in the tissue.

Statistical Analysis: Statistical evaluation of differences among soils was made using the General Linear Models procedure (GLM) from SAS (1998). The Honest Significant Difference (HSD) of Tukey ($\alpha=0.05$) was used to establish significant differences among mean values. Regression and correlation (Pearson) were performed (SAS, 1998) to study the relationship among variables. Analysis of "influence" was performed using the Cook's distance test from the REG procedure in SAS (1998).

3. Results and discussion

Relationship between N uptake, aggregate fractions, and other soil properties across all the soils: Averaging across all the soils, approximately 60% of the soil mass and soil N were found in the macroaggregate fraction (250μm-5000μm), mostly in the small macroaggregate fraction (250-2000μm) (Table 2). This is similar to the results of Gijsman (1996) who found 30% of the total soil weight in the >2000μm fraction, 55% in the macroaggregate (250μm-2000μm) fraction, and only 10% in microaggregates

(<250μm) in an Oxisol soil. Cambardella and Elliott (1994) also found 49, 55, and 60% of the soil in small macroaggregates in a Mollisol soil under fallow, stubble mulch, and no tillage treatments. The mean C:N ratio, across soils, of the large macroaggregate fraction (5000-2000 μm) was significantly ($p<0.05$) higher than the C:N ratio of the microaggregate size fraction (<250 μm), but there was no significant difference between the C:N ratio of small macroaggregates (2000-250 μm) and microaggregates (Table 2). Organic matter contained in macroaggregates is predominantly plant-derived material (Monreal et al., 1997; Jastrow, 1996) whereas that in microaggregates is more microbially altered (Stevenson, 1994; Jastrow, 1996).

Total plant N uptake by *Brachiaria* varied from 101 mg N kg^{-1} soil in Uribeque to 736 mg N kg^{-1} in Arenales (data not shown), but across all the soils about 60% of this was taken up in the first harvest (Nab1), and only 23% and 17% in the second (Nab2) and third harvest (Nab3), respectively (Table 3). Across all soils, total N taken up by *Brachiaria* was about seven times larger than the initial content of mineral N (NO_3NH_4). Thus, most N must have been derived from mineralization of organic N. Since more of the N was taken up during the first 35 days, we suggest that this organic N source must be an easily mineralizable pool.

We estimated the proportion of the N uptake derived from mineralization after 35 days and 90 days (total) to be 61% and 83%, respectively. This is assuming that all of the initial mineral N was taken up by the first harvest and that the content of mineral soil N at the end of the first harvest and at the end of the experiment was low. For the first 35 days, this amount of N was utilized to calculate the net N mineralization rate (assuming negligible N losses), which varied from 9.4 mg kg^{-1} d^{-1} to 0.2 mg kg^{-1} d^{-1} for the Arenales and Uribeque soils, respectively (Figure 1). The mean net N mineralization rate across all the soils was 3.2 mg kg^{-1} d^{-1}.

Nitrogen taken up during the first 35 days (Nab1) and total accumulated N during the experiment (Nabt) by *Brachiaria brizanta* were significantly correlated with SOM, TN, MOM, and initial mineral N (Table 4). Also, they were correlated with the amount of soil in different aggregate sizes classes, and the grouped aggregate size classes, large macroaggregate (5000-2000 μm), and small macroaggregate (2000-250 μm) size classes (Table 4). No significant relationships were found between N uptake and microaggregate amounts. The initial mineral soil N ($NO_3 + NH_4$) content was significantly correlated with the same macroaggregate soil fractions (Table 3). The relationship between N taken up by *Brachiaria* and the large macroaggregate fraction, MOM, and initial content of mineral N (NO_3NH_4) are shown in Figure 2. Initial mineral N content explained about 93% of the variation in the amount of N taken up by *Brachiaria* (Figure 2B). This association is in agreement with other studies (Binford et al., 1992; Warren and Whitehead, 1988; Hergert, 1987). Although the Arenales soil (which had the highest uptake) acted as an influence point in Figure 2B (Cook and Weisberg, 1982), the close relationship between N taken up by *Brachiaria* and initial mineral N ($NO_3 + NH_4$) is still significant ($p<0.05$, $r^2 = 0.88$) when this soil was excluded from the analysis (data not shown).

The significant correlation between total N taken up by *Brachiaria* with the amount of soil in the large macroaggregate fraction (Figure 2A) and macroorganic matter (Figure 2C), in contrast to the lack of correlations with microaggregates, suggests that organic N in the coarsest aggregate fractions is more labile and available for plant uptake. Angers et al. (1997) showed that plant residues were initially incorporated in the largest aggregate fractions, but are still rapidly decomposed. Buyanovsky et al. (1994) also showed that turnover time of organic matter contained in macroaggregates was shorter compared to that in microaggregates. Also, they showed that the C:N ratio of macroaggregate associated SOM is larger than that associated with microaggregates, indicating that their characteristics are more closely related to plant fragments. In our study, the C:N ratio of the large- and small macroaggregates were higher (although not significantly different for small macroaggregates) than in microaggregates, suggesting that material in the macroaggregate fraction is enriched in plant-derived material, supporting the idea that N sources from this fraction are more easily decomposed. These findings are also supported by: 1) the initial content of mineral N (NO_3 + NH_4) was significantly ($p<0.05$) correlated with the amount of soil in the large and small macroaggregates and MOM; 2) there was significant ($p<0.05$) correlation between amount of MOM and amount of soil in the large and small macroaggregates; and 3) NO_3 + NH_4 and MOM did not correlate with the amount of microaggregates.

Across all soils, there was a weak, but significant, relationship between N uptake by *Brachiaria* and amount of soil and N in the aggregates >250 μm and MOM, which could represent the easily decomposable soil N. Soils fell into two distinct groups: one with a high amount of N taken up by *Brachiaria*, where N uptake was well correlated with the macroaggregate fraction and MOM, and another group having lower N uptake, which lacked a strong relationship between those variables. Probably the availability of organic sources of N for decomposition was limited by soil factors controlling the accessibility of organic N pool to microbial activity (Hassink, 1996; Franzluebbers and Arshad, 1997b).

Relationship among N uptake, aggregate fractions, and other soil properties in soils grouped by N supply capacity: Nitrogen mineralization rates for the different soils in the first 35 days after sowing (Figure 1) were used to group soils according to N supply capacity. From this, it was evident that a group existed with high N mineralization rates (i.e., Arenales and Maracay, 9.2 mg $kg^{-1}d^{-1}$), a second group with intermediate N mineralization rate (i.e., Tucutunemo, Barinas, and La Fe soils, 6.3 mg $kg^{-1}d^{-1}$), and a third group consisting of all the soils with the lowest N mineralization rate (<3 mg $kg^{-}d^{1}$).

Because differences between the first two groups were small, we grouped them into one group called high N supply capacity (HNSC) and the soils of the third group were called low N supply capacity (LNSC). The soils grouped into HNSC are Mollisols, with the exception of La Fe which is an Ultisol and Barinas which is an Alfisol. Probably a high supply of plant residues and N fertilizer for a long period of time improved the capacity of La Fe soil to supply N. This high input could have improved the amount of soil organic matter, soil aggregation, and capacity to supply N.

On the other hand, the soils included in the LNSC group were mainly Ultisols and Alfisols, with the exception of the San Carlos (Mollisol) and Turen I (Inceptisol). In the San Carlos soil, stabilization of soil organic C due to a high content of soil Ca^{++} and soil carbonates could possibly hamper N mineralization (Muneer and Oades, 1989a, 1989b; Clough et al., 1997). Also, in this group of soils, other factors such as the content of Al and Fe mineral complexes, could affect mineralization of the organic sources of N. This was suggested by Veldkamp (1994) who found, in evaluating organic C turnover in tropical soils, that variations in stable soil organic matter were associated with the content of Al and Fe.

Mean size distribution, N content, C:N ratios of aggregate size classes, and N uptake by *Brachiaria* for HNSC and LNSC soils are shown in Tables 2 and 3. For the HNSC soils, about 70 % of the total N taken up by *Bracharia* occurred in the first 35 days, and only 18 and 10% in the second and third harvest respectively. In the LNSC soils those proportions were 38, 31, and 31% for the same periods (Table 2). Moreover, the N taken up that was not derived from the initial mineral N (i.e., N uptake by *Brachiaria* 35 days after sowing minus initial mineral soil N) was significantly ($p<0.05$) higher in the HNSC group (261 mg N kg^{-1} soil) than in the LNSC group (34 mg N kg^{-1} soil), showing that the HNSC group has a greater potential to supply N during the growing season.

These differences in capacity to supply N could be associated with the quality and availability of organic N sources. In the HNSC group, the C:N ratio of aggregates decreased as a fraction of size, in contrast to the LNSC group where the C:N ratio was similar across aggregate sizes (Table 2). This finding suggests that more of an aggregate hierarchy exists in the HNSC soils, which indicates a close relationship between SOM and aggregation (Tisdall and Oades, 1982). That is, SOM acts as a binding agent for the formation of aggregates, which differentially protect SOM against decomposition depending on aggregate size. Thus, the larger aggregate sizes are a more labile source of mineralizable N. In contrast to the HNSC soils, the LNSC soils probably had more aggregate stabilization from mineral-mediated binding through hydrous oxides of aluminum and iron, aluminosilicate, and calcium carbonate (Tisdall and Oades, 1982). This weaker relationship between aggregation and SOM in the more highly weathered soils (e.g., Ultisols and Alfisols) could be one of the reasons for the relative lack of correlation between aggregation and N dynamics in the LNSC soils. Indeed, Motavalli et al. (1995) found significant differences in N mineralized among soils of different mineralogy. The lowest values were obtained for the kaolinitic and oxidic groups, and the high values in the smectitic and allophanic groups. This suggests that N availability indices need to be evaluated for the effect of mineralogy.

Correlation analysis showed that in the HNSC soils, N uptake by *Brachiaria* at 35 days (Nab1) and total N taken up (Nabt) were significantly ($p<0.05$) correlated with the amount of soil in the large and small macroaggregates, $NO_3 + NH_4$, and amount of macroorganic matter and N in MOM (Table 5), but was not significantly correlated with microaggregates (<250 μm) (Table 5). For the LNSC soils, only low positive correlations were found between N uptake at 35 days with SOM, initial content of mineral N and amount of N in microaggregates <250 μm. For these soils, N uptake was negatively correlated with the amount of soil in large macroaggregates (Table 5). Moreover, the initial content of mineral N ($NO_3 + NH_4$), which is often associated with the soil capacity to supply N, was significantly associated with the same soil variables associated with N taken up by *Brachiaria* in the HNSC group, but not in the LNSC group (Table 5). These findings in the HNSC soils highlight the importance of the macroaggregate size fraction in the soil capacity to supply N, and are in accordance with Gupta and Germida (1988) and Elliott (1986), who found more N mineralized in macroaggregates than in microaggregates. These data also agree with Patra et al. (1999) and Vanlauwe et al. (1998), who found that N released from organic materials was associated with macroorganic matter. The main significant relationships between N uptake by *Brachiaria* in HNSC soils and measured soil properties are shown in Figure 3. Similar associations were observed between the initial content of mineral N and the same soil parameters.

Although the amount of N in macroorganic matter and initial mineral N were closely associated with N uptake by *Brachiaria* for the HNSC soils, the N uptake in the first 35 days was 1.7 times higher than the amount of N that could be supplied by those sources together. Thus, at least 70% of the N taken up by *Brachiaria* came from sources other than N in macroorganic matter or mineral N. Because this N was taken up in the first 35 days, it must be an easily mineralizable organic N pool. Different authors have pointed out the importance of the particulate organic matter (POM), which is the fraction between 53 to 2000 μm, as a source of mineralizable C and N (Cambardella and Elliott, 1992). Vanlauwe et al. (2000) found a significant relationship between N taken up by maize and N in the POM, although it is evident from their results that other sources of N in the soil supply plant N. In our experiment, the small POM fraction (53-250 μm) was not included in the macroorganic matter. Consequently, we might have disregarded a significant part of the decomposable organic matter, and this could be responsible for a part of the N that it is not explained by MOM and initial content of mineral N.

In the LNSC soils, N uptake by *Brachiaria* was more uniform during the experiment (38, 31, and 31% of total N was taken at 35, 60, and 90 days, respectively), suggesting that there was not a predominant labile N pool. The association between N uptake and N in microaggregates could account for 32% of the variation in N uptake, and up to 62% when it was included together with initial content of mineral N.

Moreover, since the amount, N concentration, and C:N ratio of MOM were not significantly different between soil groups (Table 6), and this fraction seemed to represent a significant source of N in HNSC soils, our results suggest that different fractions of macroorganic matter could have been isolated in our experiment, or that MOM could be protected preferentially in the soil. Gregorich et al. (1997) and Golchin et al. (1994) have shown that two types of MOM could be separated from the soil: one is easily accessible to decomposition (free MOM), and a protected MOM. Barrios et al. (1997), studying different light fractions obtained from macroorganic matter >150 μm, found that the light fractions with density between 1.13 and 1.37 Mg m^{-3} were better descriptors of differences in management practices than heavier fractions (POM). However, physical protection of MOM also could affect N mineralization. Vanlauwe et al. (2000) found a significant relationship between N taken up by maize and content of N in particulate organic matter (POM) >53 μm for savanna soils, but not for humid forest soils and suggested that in these last soils POM was protected by aggregation. Also, Franzluebbers and Arshad (1997b) suggested that clay could protect the POM from decomposition.

4. **Conclusions**

Initial soil mineral N content was closely associated with the N taken up by *Brachiaria.* However, the amount of N in the initial mineral N pool only represented a small proportion of the total amount of N taken up by *Brachiaria*, suggesting that most of the N came from an easily decomposable organic N source. In soils having a high capacity to supply N, high correlations between macroaggregation and N uptake suggest that this easily decomposable fraction is associated with macroaggregate size fractions. In contrast, a poor association between N in microaggregates and N uptake was observed in the soils with low capacity to supply N.

In the HNSC group, made up of predominantly Mollisols, there was more of an aggregate hierarchy suggesting a stronger role for SOM binding agents involved in the formation and stabilization of large macroaggregates, which could be a significant source of N mineralization. In the LNSC soils, predominated by more highly weathered Alfisols and Ultisols, aggregation is mainly conferred by mineral-mineral bindings (e.g., hydroxides of aluminum and iron in soils of high sand content), resulting in less of a relationship between aggregrate fractions and labile sources of organic matter and N.

However, we were not able to identify a unique soil property that could reliably separate soils of high capacity from low capacity to supply N, other than the initial content of mineral N. Future research should be oriented to identify and to isolate the organic sources of N responsible for soil N availability in different soils.

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Table 1. Soil classification and main characteristics of the 15 evaluated soils in Venezuela.

Soil number	Soil Name	Taxonomic Order	Texture	PH	SOC gC kg^{-1}	Total N gN kg^{-1}	C:N ratio	CEC cmol kg^{-1}	Initial NO_3+NH_4 MgN kg^{-1}
1	Arenales	Mollisol	Clay	7.8	16±1.3	2.6±0.04	6±0.5	22	241±12.4
2	Maracay	Mollisol	Sandy Loam	5.9	12±0.7	1.0±0.03	12±0.6	12	76±8.0
3	La Fe	Ultisol	Clay Loam	5.4	10±0.4	1.0±0.06	10±0.8	11	99±10.4
4	Barinas	Alfisol	Sandy Loam	5.8	8±0.6	0.7±0.09	12±0.9	4.8	48±5.1
5	Tucutunemo	Inceptisol	Sandy Clay Loam	6.2	13±0.3	1.9±0.03	7±0.2	11	40±8.3
6	Chaguarama	Alfisol	Sandy Loam	5.7	11±0.4	1.1±0.04	10±0.3	14	42±6.7
7	San Carlos I	Inceptisol	Sandy Loam	8.5	12±1	1.5±0.05	7±0.9	9.0	30±5.3
8	Tigre	Ultisol	Sand	5.9	3±0.5	0.2±0.01	23±5.0	1.7	29±3.9
9	El Pao	Ultisol	Sandy Loam	5.5	6±0.3	0.5±0.02	10±1.0	3.5	21±11.0
10	Urachiche	Alfisol	Sandy Loam	8.6	10±0.9	1.2±0.07	9±0.5	6.5	14±4.4
11	Turen I	Mollisol	Sandy Loam	8.7	4±0.3	0.6±0.03	7±0.6	2.5	19±4.9
12	Iguana Arcillosa	Ultisol	Clay	5.4	8±0.6	1.0±0.02	9±0.6	13	26±13.0
13	Sta. Barbara	Ultisol	Sandy	6.0	5±0.6	0.2±0.02	22±4.5	2.7	18±12.0
14	Uribeque	Alfisol	Clay Loam	7.5	9±0.7	1.4±0.03	7±0.6	9.1	24±19.0
15	Iguana Arenoso	Ultisol	Sandy Loam	5.5	6±0.6	0.4±0.03	18±3.0	2.8	14±1.7

Table 2. Sand-free aggregates distribution and nitrogen distribution across all soils and soils grouped by N supply capacity.

	Aggregate distribution [a]			N distribution [b]			C:N [c]		
Soil	Agr1	Agr24	Agr58	Agr1	Agr24	Agr58	Agr1	Agr24	Agr58
		g kg^{-1}			mg kg^{-1}				
All soils	60±69 (13%) [b]	238±179 (50%)	174±78 (37%)	121±136 (10%)	634±367 (50%)	508±199 (40%)	12 A	11 AB	10 B
HNSC	102 a (16%)	343 a (53%)	202 a (31%)	206 a (12%)	933 a (54%)	576 a (34%)	13 A	10 B	9 B
LNSC	39 a (10%)	185 a (48%)	160 a (42%)	79 a (8%)	485 b (47%)	471 a (45%)	11 A	11 A	11 A

[a] Agr1, Agr24, and Agr58 are amount of soil in the large macroaggregate (5000-2000 μm), small macroaggregate (2000-250 μm), and microaggregates (<250 μm) fractions respectively.

[b] Numbers in parentheses ( ) are the proportion of the sand-free aggregates or aggregate-associated N contained in each aggregate size fraction and total N respectively.

[c] C:N ratios of different aggregate sizes, within the same soil group, followed by a similar uppercase letter are not significantly different according to Tukey's HSD mean separation test at $\alpha = 0.05$.

[d] HNSC and LNSC are groups of soils with high and low capacity to supply N.

Values in the same column followed by the same lowercase letter are not significantly different according to Tukey's test at $\alpha = 0.05$.

Table 3. Nitrogen uptake by *Brachiaria brizanta* across all soils and soils grouped by N supply capacity.

	N Uptake[a]			
Soil	Nab1	Nab2	Nab3	Nabt
		mgN kg^{-1}		
All soils	159±166 (60%)[b]	61±26 (23%)	47±14 (17%)	267±188
HNSC	362 a (72%)	90 a (18%)	48 a (10%)	499 a
LNSC	58 b (38%)	47 b (31%)	46 a (31%)	151 b

[a] Nab1, Nab2, Nab3, and Nabt are the N taken up by *Brachiaria* at 35, 60, and 90 days after sowing, and total accumulated N during the experiment respectively.

[b] Numbers in parentheses ( ) are the proportion of the total N uptake.

Values in the same column followed by the same lowercase letter are not significantly different according to Tukey's test at $\alpha = 0.05$.

HNSC and LNSC are groups of soils with high and low capacity to supply N.

Table 4. Correlation coefficients between N uptake by the crop and N content in different soil fractions using all the soils.

	N uptake[a]				Soil N sources [b]	
Soil N sources [b]	Nab1	Nab2	Nab3	Nabt	NO_3NH_4	MOM [c]
SOC[c]	0.67 **	0.55 **		0.68 **	0.64**	0.51**
TN[c]	0.59 **	0.49 **		0.60 **	0.66**	0.45
NO_3NH_4[c]	0.87 **	0.73 **		0.87 **		
MOM[c]	0.50 **	0.45 **	-0.38 **	0.49 **	0.67**	
Ag1	0.60**	0.51**	-0.40*	0.58**	0.73**	0.66**
Ag2	0.44**	0.38**	-0.47**	0.41**	0.50**	0.65**
Ag3	0.55**	0.48**	-0.31*	0.54**	0.58**	0.59**
Ag4	0.54**	0.44**		0.53**	0.50**	0.50**
Ag5	0.50**	0.38**		0.48**	0.41**	0.49**
Ag6	0.34*	0.33*		0.35*		0.38**
Ag24	0.51**	0.43**	-0.38**	0.49**	0.55**	0.65**
Nag1	0.56**	0.48**		0.55**	0.73**	0.55**
Nag2	0.62**	0.50**		0.60**	0.70**	0.61**
Nag3	0.73**	0.62**		0.74**	0.79**	0.57**
Nag4	0.54**	0.51**		0.58**	0.59**	0.31*
Nag5	0.29*			0.29*		
Nag6	0.32*			0.32*		
Nag7			0.28*			
Nag8			0.27*			
Nag24	0.70**	0.59**		0.70**	0.77**	0.58**
Nag58			0.31*			

*Significant at 0.05 level, ** Significant at 0.01 level.

[a] Nab1, Nab2, Nab3, and Nabt are the amount of N taken up by *Brachiaria* at 35, 60, and 90 days after sowing, and total accumulated in during the experiment.

[b] Ag1 through Ag8, and Nag1 through Nag8 are the amount of sand-free aggregates and N in the aggregates sizes classes 5000-2000, 2000-850, 850-425, 425-250, 250-150, 150-106, 106-45, and <45 micrometers respectively. Ag24, Nag24, and Nag58 are the accumulated aggregates and N of the aggregates size indicated previously.

[c] MOM is the amount of macro organic matter. SOC and TN are the carbon and N concentration of the whole soil. NO_3NH_4 is the initial content of soil mineral N ($N\text{-}NO_3 + N\text{-}NH_4$).

Table 5. Correlation coefficients between N uptake by the crop and N content in different soil fractions for the two groups of soils.

	N uptake[a]				Soil N Sources	
Soil N sources [b]	Nab1	Nab2	Nab3	Nabt	NO_3NH_4	MOM
HNSC soils:						
SOC	0.59**	0.56**		0.66**	0.72**	
TN	0.53**			0.60**	0.70**	
NO_3NH_4	0.85**	0.60**		0.87**		
MOM	0.73**	0.46**	-0.60**	0.70**	0.84 **	
NMOM[c]	0.98**	0.95*		0.99**	0.99**	
Agr1	0.86**	0.56*	-0.49*	0.86**	0.91**	0.77**
Agr13	0.79**	0.58*	-0.50*	0.79**	0.88**	0.88**
Agr58	-0.15	-0.17	-0.16	-0.20	-0.33	-0.03
LNSC soils:						
SMC	0.40*	0.03	-0.12	0.30	0.23	0.49**
TN	0.28	0.01	-0.15	0.19	0.21	0.33*
NO_3NH_4	0.65**	0.14	-0.39*	0.45**		0.06
MOM	-0.05	0.10	-0.14	-0.05	0.06	
NMOM	-0.09	0.35	0.14	0.04	0.03	
Agr1	-0.36	-0.11	-0.41	-0.47*	0.11	0.41
Agr24	-0.12	-0.16	-0.41*	-0.29	0.07	0.48**
Agr58	0.33	0.03	0.02	0.29	0.16	0.30
Nagr1	-0.29	0.10	-0.19	-0.27	0.20	0.33
Nagr24	0.14	0.05	-0.33*	0.02	0.14	0.42**
Nagr58	0.57**	0.23	0.06	0.58**	0.19	0.21

* and ** denote significant correlations at $\alpha=0.05$ and 0.01, respectively. MOM, and MOMN are amount of macroorganic matter, and N in macroorganic matter.

[a] Nab1, Nab2, Nab3, and Nabt are the amount of N taken up by *Brachiaria* at 35, 60, and 90 days after sowing, and total accumulated in during the experiment.

[b] Agr1, Agr24, and Agr58 are amount of soil in large macroaggregate (5000-2000 μm), small macroaggregate (2000-250 μm), and microaggregate (<250 μm) respectively. Nagr1, Nagr24, and Nagr58 are the amount of N in the Agr1, Agr24, and Agr58 respectively. SOM, TN, and NO_3 NH_4 are soil organic carbon, total soil N, and initial content of mineral N.

[c] Samples of different replicates for the same soil were mixed together to obtain N of MOM (NMOM).

Table 6. Main characteristics of macroorganic matter in the groups of high and low capacity to supply N.

Soil	Macroorganic matter (MOM) properties			
	Dry wt. (mg kg^{-1} soil)	Amount N (mg kg^{-1}soil)	N concentration (%)	C:N ratio
HNSC	8707a	155a	1.8 a	34a
LNSC	6317a	105a	1.5a	47a

Values in the same column followed by the same lowercase letter are not significant different according to Tukey's HSD mean separation test at $\alpha = 0.05$.

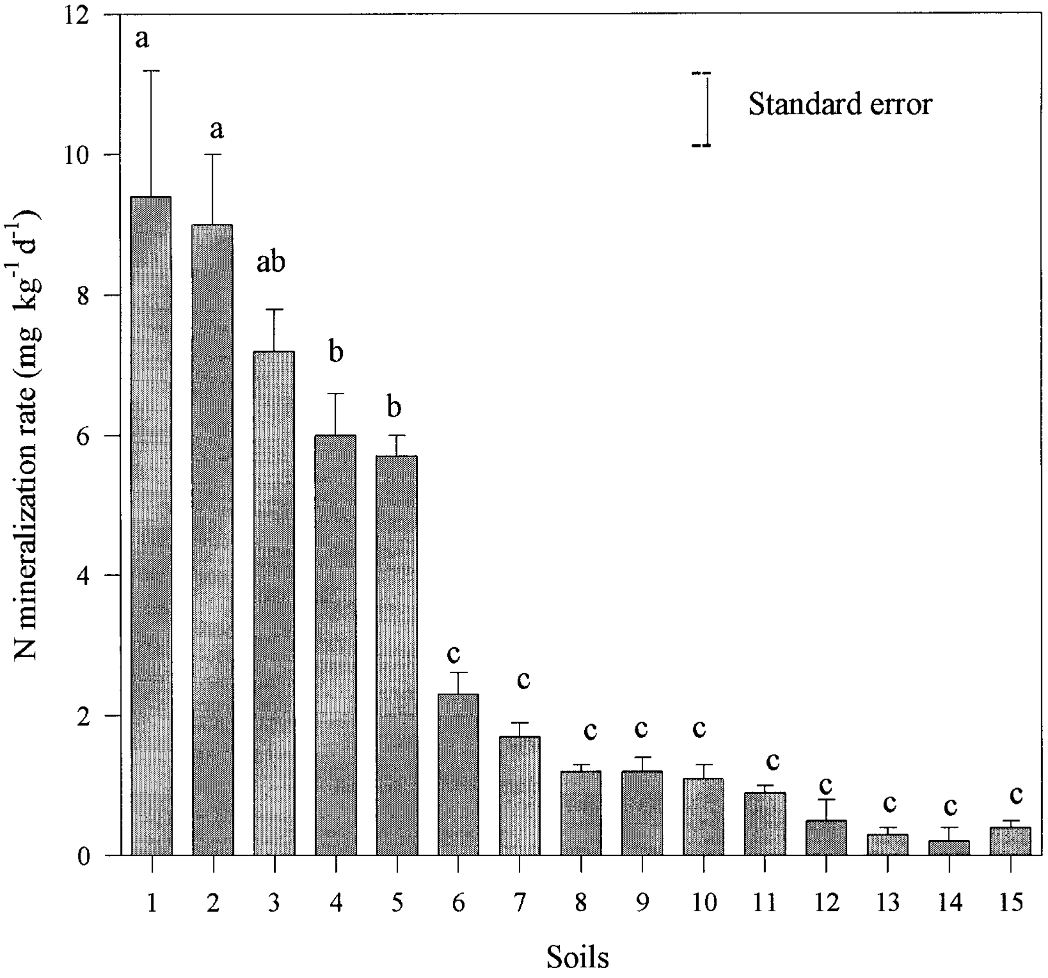

Figure 1. Estimated nitrogen mineralization rate for the different soils (in Table 1 soil identification) during the first 35 days of the experiment. Similar lowercase letters show no significant differences.

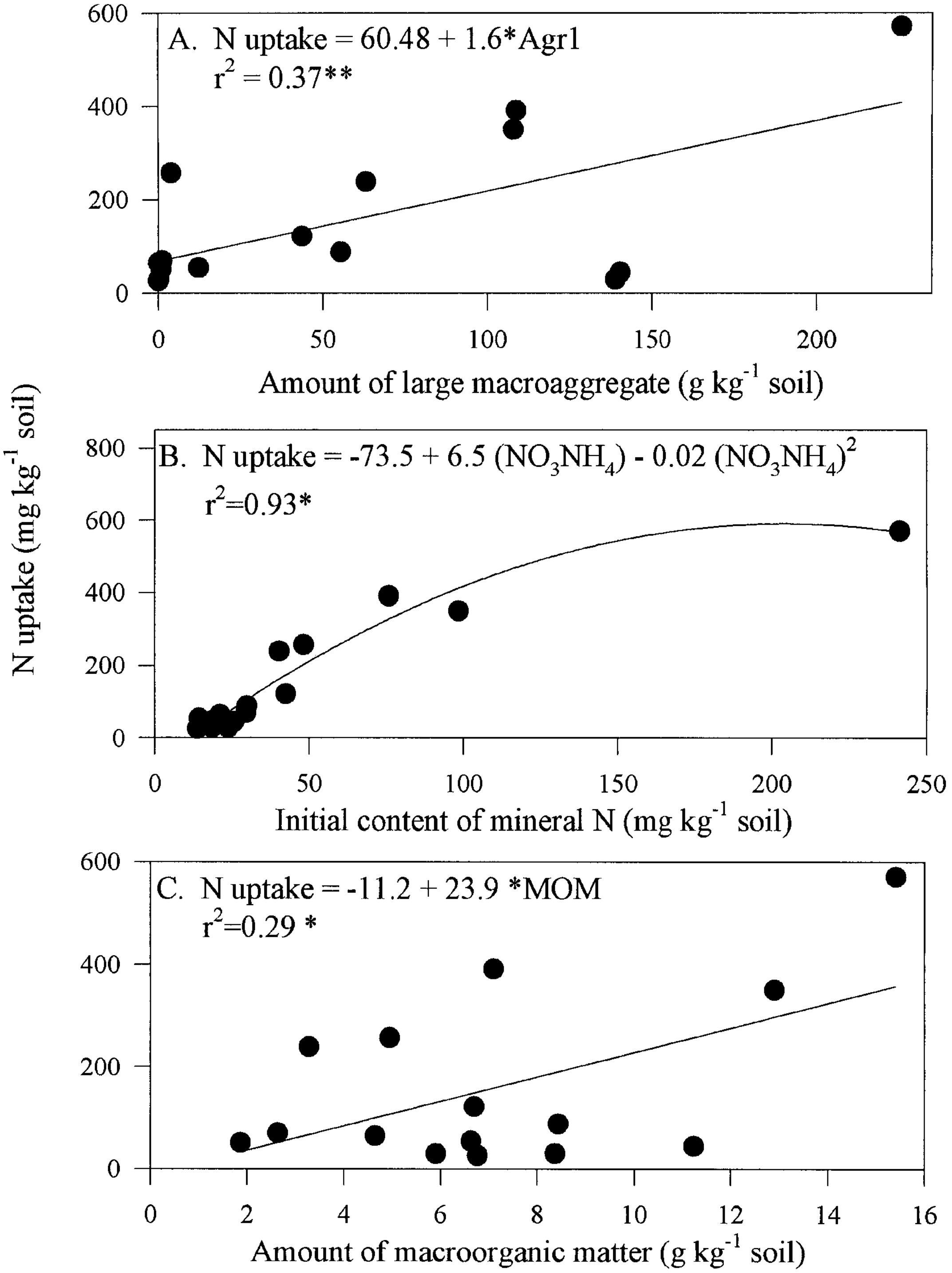

Figure 2. Relationship between N uptake by *Brachiaria* at 35 days with A) amount of large macroaggregate (Agrl), B) initial soil mineral N (NO_3NH_4), and C) macroorganic matter (MOM) for all the soils.

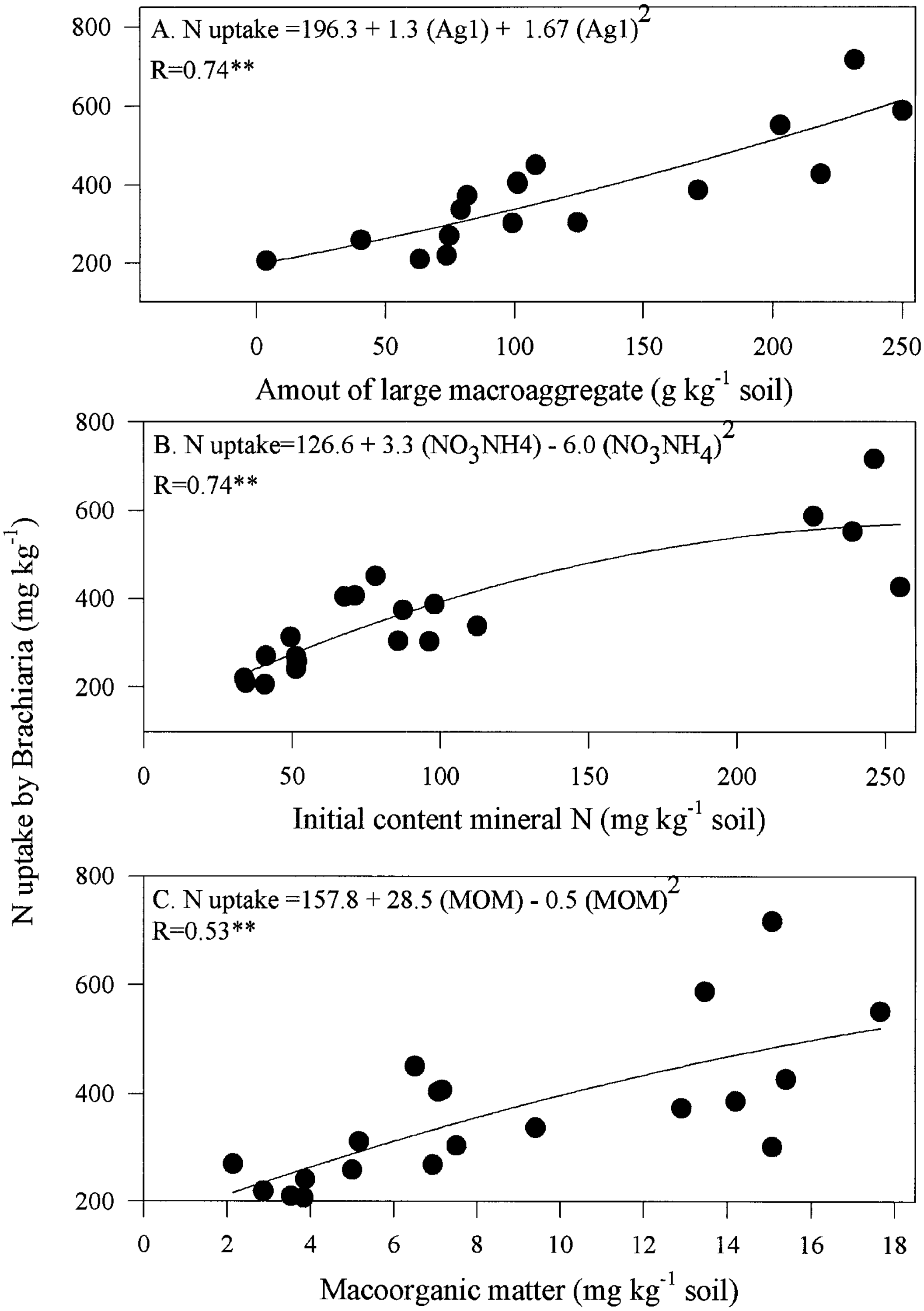

Figure 3. Relationship between N uptake by *Brachiaria* at 35 days with A) large macroaggregate, B) initial soil mineral N (NO_3NH_4), and C) macroorganic matter (MOM) in soils of high capacity to supply N.

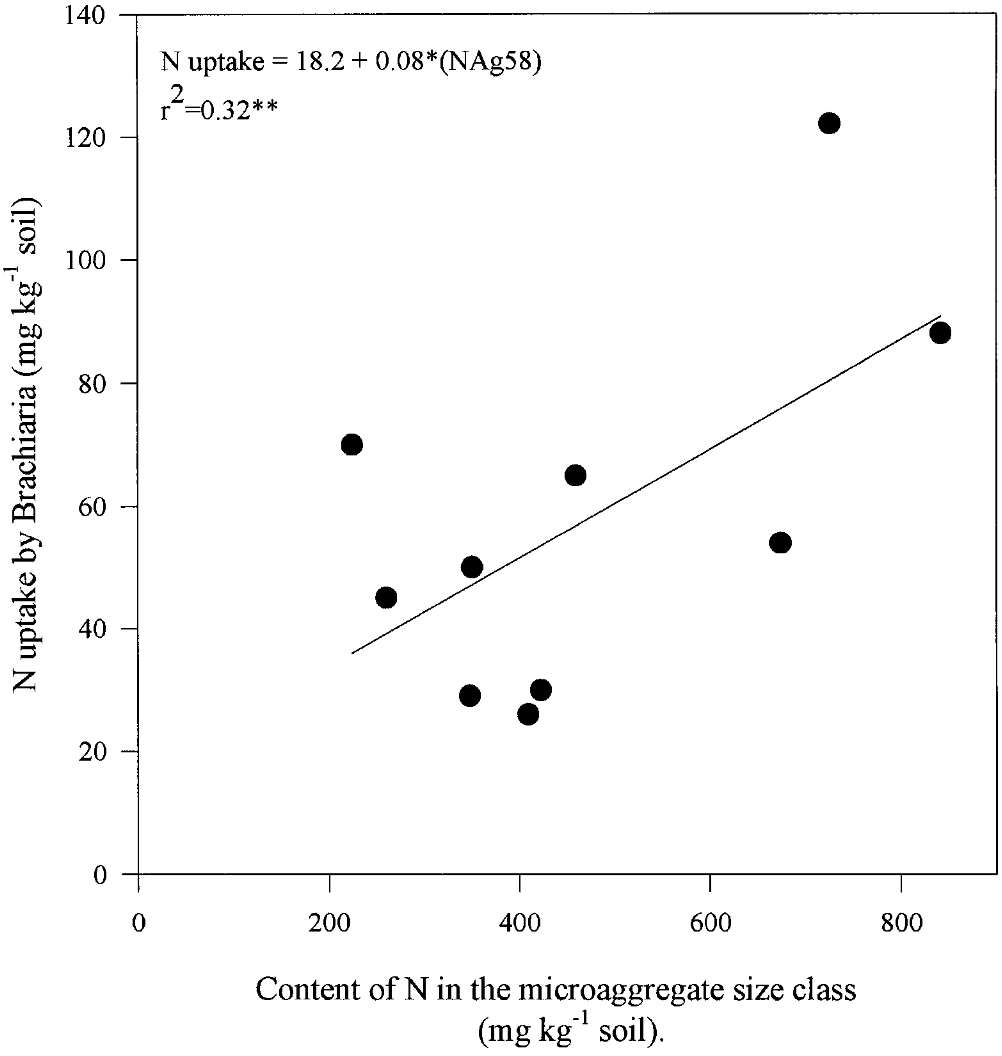

Figure 4. Relationship between N uptake by *Brachiaria* at 35 days with amount of N in microaggregates (NAg58) in the soils of low capacity to supply N.

CHAPTER IV

A GENERAL PLANT ROOT MODEL: PARAMETERIZATION AND SENSITIVITY ANALYSIS

1. Introduction

The plant root system is a primary determinant of plant growth, through providing nutrients and water to the plant (Klepper and Rickman, 1990; Miller, 1986). Relationships between root length density and water and nitrate depletion in the soil profile have been reported by Grimes et al. (1975) and Engels and Marschner (1995). The importance of plant root systems as a part of ecosystem C cycling is highlighted in global budgets where roots represent about 33% of the annual net primary productivity (Jackson et al., 1997). Quian et al. (1997) estimated that 33 to 20% of the total C fixed in corn (*Zea mays* L.) is allocated to the root system. In agricultural systems, some of this C remains after harvest of the crop and contributes to the sequestration of atmospheric CO_2-C into the soil. Knowledge of root growth patterns during the crop cycle and under various soil and management conditions is needed to accurately predict crop development and production, soil water and nutrient use, and allocation of photosynthetically-fixed C into the soil. Knowledge of root system response to variations in soil properties affected by different management practices, would allow better evaluation of the impact of these practices on crop development. Due to the diversity of factors that affect root growth, simulation modeling, where root properties controlling N and water uptake can be associated with meaningful soil, plant, and weather properties, is useful in evaluating root dynamics.

Of the root properties associated with water and nutrient uptake, rooting depth and root length density have received the most attention. Rooting depth is associated with the volume of soil explored, and thus is related to water and nutrient availability and the rate to which that availability changes over time as the plant grows (Jamieson et al., 1998). Deeper rooting has been associated with increases in yield in some years (Jordan et al., 1983), probably by enhancing water availability. From a practical point of view, the distribution of the root length density in the soil defines the limits of the root system in absorbing water and nutrients (Tinker and Nye, 2000). Root length density has been incorporated into transport models to simulate nutrient uptake (Barber, 1995; van Noordwijk and de Willigen, 1991).

Many soil properties influence root growth, including soil temperature (McMichael et al., 1996; Kaspar and Bland, 1992) and soil nutrient availability (Hanson et al., 1987; Hackett, 1968), mechanical soil strength and soil bulk density (Unger and Kaspar, 1994; Pabin et al., 1998). Other properties like soil texture, soil organic matter, and water content (Vepraskas, 1988; Gerard et al., 1982; Jones, 1983; Pabin et al., 1998; Meerigama et al., 1987) influence soil strength and soil bulk density. These soil properties normally vary with depth in the soil profile (as well as horizontally) and thus, affect the rate and extent of vertical root development and root proliferation into the soil. Soil physical characteristics, such as structure (Stypa et al., 1987) and aggregate size distribution (Youngh and Bengough, 1989), have been suggested as important in affecting root growth, but these have yet to be incorporated into dynamic root models. Moreover, most of these soil properties are affected by management practices such as irrigation (Pietola and Smucker, 1998; Kaigama et al., 1977), fertilization (Durieux et al., 1994), tillage (Allmaras and Nelson, 1971; Coale and Grove, 1986; Ellis et al., 1977; Rasse and Smucker, 1998; Ball_Coelho et al., 1998), and soil tillage (Bennie and Botha, 1986).

Dynamic elements of root growth include: 1) variable partitioning of fixed C into plant organs; 2) root morphology (in part, a genetically determined property); and 3) allocation of C and nutrients to specific root processes (root maintenance, new root growth, etc.) and preferential allocation of new root growth into soil layers with more suitable physical or chemical properties. In this paper, emphasis is on the second and third areas (i.e., root behavior subsequent to the allocation of C to the roots from above-ground plant parts).

With respect to root morphology, differentiation between mono- and dicotyledonous plants provides a first-order classification of the root morphology of different crops: in dicots the root system is basically formed by the primary roots and laterals (Zobel, 1992), while in monocots the root system is formed by seminal and nodal axes (Gregory, 1988). Moreover, differences in the number of axes of the secondary root system have been detected among cultivars of the same species (Weihing, 1935).

Adaptation of root systems to soil constraints, referred to as phenotypic plasticity (Zobel, 1992), has been well demonstrated (Masle, 1992). Taylor and Klepper (1974) and Proffitt et al. (1985) found that root length density of cotton and wheat reflected greater allocation into deeper soil layers because of dry surface soil layers. Also, as a response to a compacted soil layer, some crops such as maize and rice (Iijima et al., 1991) grow more higher-order lateral roots to compensate for restricted growth of main root axes. In wheat, Oussible et al. (1992) observed a higher root length density and length: mass ratio in the upper, less compacted soil layer.

There are several examples of simulation model of root growth, but in many cases, the models include for soil constraints (Porter et al., 1986) or else they have been developed only for specific crops (Asseng et al., 1997). In the agricultural system model EPIC (Williams et al., 1989), root growth and distribution into the soil profile is proportional to soil water used, which is estimated as a function of depth, soil water content, and a factor associated with water deficits. Soil strength, aluminum saturation, and aeration are additional factors that affect root functions. Rooting depth is estimated as a function of heat units and potential root zone depth. However, this approach does not include a C balance, and root properties such as root length density are not estimated. Moreover, since the root growth model is driven by water use, more roots are allocated to soil layers from which more water is been taken up.

In other approaches like the CERES models (e.g., Jones and Kiniry, 1986), a normalized weighting factor (supplied by the user), based on soil layers appropriate to support root growth, is used to distribute the C substrate to root growth into the different soil layers. In this model, water and N deficits affect the distribution of new daily root growth in the soil profile. Although root length density is obtained for each soil layer by using a constant factor to transform mass of C to root length, no C balance is calculated. Some attempts to improve the root distribution in this model have been made (Robertson et al., 1993) by using an exponential distribution of root length density similar to Gerwitz and Page (1974), where the decay constant of the negative exponential distribution is normalized for the maximum rooting depth and used as a weighting factor for each soil layer.

General root models have been developed by several authors. Jones et al. (1991) developed a model to be used for different crops where more of the physical, and chemical, soil properties affecting root growth were integrated. In this approach, root length distribution into the soil profile was simulated by an empirical negative exponential function (Gerwitz and Page, 1974), but no C balance was made and parameters associated with root capacity to overcome soil constraints and morphological differences among crop species were not taken in account. This approach has been incorporated into more integrated models like EPIC (Bland and Jones, 1992; Benjamin et al., 1996) with varying results.

In some ecological models (e.g., CENTURY) (Metherel et al., 1993), C is allocated to root growth as an empirically determined fraction of total assimilate. Although an explicit C balance is included, root morphology (i.e., root length density), root depth distribution, and effects of many soil properties on root dynamics are not taken into account.

In this paper, we describe a general root growth model with an emphasis on root properties associated with water and nutrient uptake driven by soil properties, C and N availability, plant phenology, and climatic parameters. Plant strategies, such as preferential uses of C by specific root processes and compensatory root growth to overcome soil constraints, were included. The model was parameterized for corn (Mengel and Barber, 1974) using field data evaluated under hypothetical soil conditions where the main soil factors affecting root growth were varied.

2. Model description

Overview: The root model has a generic structure to simulate different crop and soil situations, and it was designed to be coupled to aboveground crop growth, soil carbon, and nutrient and water balance models using a daily time step. In the stand-alone version of the model presented here, availability of photosynthate to the roots was generated by a forcing function to simulate the C supply from the aboveground part of the plant.

A key aspect of the model is the differentiation between vertical root development and the lateral proliferation of roots within soil layers. Vertical growth is carried out by 'primary' roots which can vary in number from one (i.e., plants with tap roots) to many (i.e., plants with fibrous root systems), while 'secondary' roots represent branching and lateral root development within a soil layer. Vertical growth is allowed only until a certain crop stage is reached, based on accumulated thermal time. In contrast, root proliferation occurs within a soil layer once it is reached by vertical roots and can continue until the end of the crop cycle. This latter aspect differs from other approaches (i.e., Hoogenboom et al., 1987) in which proliferation in a layer is allowed when the root length in a previous layer exceeds a minimum threshold value. Carbon allocated to root growth is preferentially done in a sequential order to: 1) maintain vertical growth (subject to plant and soil constraints); 2) maintain existing roots; and 3) support root proliferation.

Proliferation occurs subject to remaining resources (C and N), modified by density dependence and soil constraints to root growth.

Each soil layer offers certain conditions, referred to as root 'hospitality' that affect root growth. Hospitality is characterized in the model by constants (soil bulk density, texture, draining upper and lower limits to hold water) and variable (soil water, soil temperature, and N concentration) soil properties. A similar concept (termed favorability), was suggested by Hayhoe (1981) and Robertson et al. (1993) to characterize the capacity of soil to allow root penetration. In our approach, the soil factors controlling vertical development and root proliferation differ some, although in both cases, a multiplicative effect of factors involved was used. Normalization of hospitality among soil layers allows enhancement of root growth in soil layers having more favorable conditions based on the assumption of plasticity in the development of the root system. In Figures 1, 2, and 3, the main aspects involved in vertical root development and root proliferation, and in the estimation of soil capacity 'hospitality' to support roots, are shown. Description and definitions of parameters used in the model are given in Tables 1 and 2.

Vertical root growth and rooting depth: The daily vertical root growth (*Vertgrow*) (Equation 1) is the minimum of: 1) the potential daily vertical growth under non- C- and N-limitations (*Pverrootgr*) assigned into a layer; 2) C-limited vertical root growth; and 3) N-limited vertical root growth, i.e.,

$$Vertgrow = min\left(Pverrootgr,\ \frac{\dfrac{C\_avail * effic,}{P\_root\_den * PltPop}}{len\_mass\_v},\ \frac{\dfrac{N\_avail * highC:N}{P\_root\_den * PltPop}}{len\_mass\_v} \right) \quad (1)$$

where *C_avail* and *N_avail* are C and N available to root growth, and other terms are as indicated in Table 2. Carbon available for root growth is the C remaining after the maintenance requirement (*mrr*, Table 2) of existing roots has been satisfied.

The daily potential vertical root growth (*Pverrootgr* [cm per day]) (Equation 2) is derived from the maximum root depth (*Pmax_rooting* [cm]) and the 'thermal time' (degree-days [°C]) (*Max_rooting_stage*) at which maximum root depth is reached under optimal environmental conditions. This is equivalent to a potential rate of root extension per unit daily thermal time (*DTU*, °C d^{-1}), which is calculated from the maximum and minimum daily air temperature (°C) and a base temperature (10 °C for corn) (Jones et al. 1986). The potential rate is conditioned by the hospitality factor for vertical root growth (*Hf_v*) within a given layer, which is the product of soil strength (*HSST*) and soil temperature (*STeffect*) (Figure 3). The duration of vertical growth is normally associated with changes from the vegetative to the reproductive phase (Borg and Grimes, 1986). In our model, max_rooting is based on the accumulated thermal time to the onset of the reproductive phase.

$$Pverrootgr = \frac{Pmax\_rooting}{Max\_rooting\_stage} * DTU * Hf\_v \tag{2}$$

Since daily potential vertical root growth (*Pverrootgr*) can extend from one soil layer into the next within a time step, the potential root growth used in Equation 1 is the vertical root growth allowed to grow in that soil layer, and is compared against the C- and N-limited root growth. If the potential vertical growth exceeds the lower border of the layer, vertical growth is allowed to continue into the next soil layer.

The potential vertical root growth when limited by C and N availability (Equation 1) is a function of the number of primary roots per plant, plant density, and a specific length:mass factor (*len_mass_v*) for vertical roots. The number of primary roots per plant reflects differences in root morphology between different crop types and crop varieties. Differences between mono- and dicotyledonous plants, as discussed above, can be roughly associated with the capacity of monocots to produce seminal and nodal root axes, which dicots do not (Zobel, 1992). Previous attempts to use numbers of axes have been made (Hackett and Rose, 1972) in a root model for barley. Although the numbers of axes can be altered by external factors such a soil temperature (Reddy, 1997), root axes are largely a genetically controlled parameter and thus the general morphology can be established for specific species. However, differences have been found in the numbers of root axes for corn of different heights (Weihing, 1935), and for wheat (Robertson et al., 1979).

Where vertical root growth is limited by N availability, an additional parameter, i.e., the maximum allowable C:N ratio (*high C:N*), is used (Equation 1). Finally rooting depth is updated daily by summing the new vertical root growth in a day to the rooting depth of the previous day. Available C and N are updated to calculate the C and N remaining for root proliferation which will be described next.

Root proliferation and root length density: Similar to vertical growth, a potential daily root growth (*dPLenG*) for each soil layer is calculated from the minimum of: 1) the root length increment necessary to reach the maximum allowable total root length in a soil layer (*max_leng*); and 2) root proliferation calculated as a relative growth rate (*rrg*) of existing root length (*root_len*), and a density dependent factor, both modified by the soil hospitality for root proliferation (*Hf_p*) (Equation 3).

$$dPLenG = min\left(\begin{matrix} max\_leng - root\_len - dRLGrow, \\ rrgr * root\_len * 1 - \dfrac{root\_len}{max\_leng} \end{matrix}\right) * Hf\_p \qquad (3)$$

The maximum root length allowed in a soil layer (*max_leng*) is calculated from a maximum allowed root length density (*Max_root_den*) (Table 2) and *dRLGrow*, the current day's vertical length increment. The idea of a maximum root length density (*Max_root_den*) for a specific soil layer is based on evident differences in RLD for different crops (Gregory, 1988). A similar approach, but using maximum allowable amount of structural C, has been used by Thornley and coworkers (Brugge and Thornley, 1985; Thornley, 1990).

The soil parameters included to estimate the hospitality factor (*Hf_p*) are soil strength, soil water and temperature, and soil N content (Figure 3). Soil strength is assumed to affect lateral root development similarly to that for vertical root proliferation (Bengough, 1997), although others had reported that it affects only vertical root growth (Veen, 1982). Orientation of macropores, which mostly are vertically oriented, probably are associated with effects of soil strength.

The potential C required (*P_incC'*) for the estimated daily root proliferation in a specific layer (*dPLenG*) (Equation 3), calculated by a length to mass conversion constant for fine roots (*len_mass_p*) (Table 2) (Van Noordwijk and Brouwer, 1991), is matched against the C available for root growth (*C_avail*) and the maximum amount of C that could be fixed by the available N for root growth (*N_avail*), at a maximum allowable C:N ratio for root tissue. If the C available for root proliferation is equal or greater than the potential requirement for the full depth of rooting (*TprolC*), the new root proliferation will equal the potential. Otherwise the available C for root proliferation (*Climit*) will be distributed proportionally to the potential requirements of C in each soil layer (*P_incC'*) as indicated in Equation 4.

$$P\_incC = P\_incC' * Climit/TprolC \qquad (4)$$

Finally the C allocated to root growth (*P_incC*) in each soil layer is transformed to root length using the length to mass ratio for secondary roots (*len_mass_p*), and total root length and root length density (*RLD*) are updated for each soil layer.

Hospitality factor for root growth: The capacity of each soil layer to support root growth is referred to as hospitality, and it is the combined effect of physical, and chemical soil properties that affect root growth (Figure 3). The soil conditions include soil texture (sand content), soil bulk density (SBD), soil water parameters (soil water at the upper (DUL) and low (LL) limits of soil water availability), daily soil water content (SW), soil temperature (ST), and soil mineral N content (N_{act}). Functions for the effects of soil bulk density (*SBDeffect*), soil water content (*SWeffect*), and soil strength (*HSST*) were estimated as suggested by Jones et al. (1991). Soil temperature effect (*STeffect*) was calculated using the approach suggested by Thornley (1998) where the daily soil temperature (ST), maximum and minimum limiting soil temperatures above and below which root growth is inhibited, and a curve shape factor are used.

The effects of N and water availability on root growth were estimated combining the concept of plant available water, as defined by Grant et al. (1989), with the concept of a responsive zone to N availability given by Gregory (1988) and Marschner (1997). A coefficient for plant available water (*PAW*) is calculated as the ratio between the actual soil water content and the potential plant available water content (*PPAW*) where *PPAW* is the difference in soil water contents at field capacity and wilting point. The concept of a responsive zone on the other hand, implies a threshold in the soil solution N concentration over which initiation and extension of laterals roots are not limited (Marschner, 1997; Gregory, 1988). In our approach, if the concentrations of N in soil solution (N_{act}) and soil water content (SW) are higher than threshold limits for N and water content (N_{sat} and DUL respectively), root growth will not be affected by these factors. Otherwise, the product of N concentration in soil solution and water effect of each soil layer are normalized by the average of these products in the soil profile.

$$NWeffect\_n_{(layer)} = \frac{NWeffect_{(layer)}}{\sum NWeffect_{(layer)}} \tag{5}$$

where *NWeffect* is the product of soil water (*SWeffect*) and N concentration in soil solution, and *NWeffect_n* is the normalized effect of soil water and N concentration in each soil layer of the profile.

Root maintenance, root respiration, and root mortality: Daily requirements of C for root maintenance were estimated as a fixed fraction (*mrr*) of the total root C (Thornley and Johnson, 1990). The C used for root maintenance is considered to be a part of the total daily root respiration. Similarly daily root mortality was estimated as a fixed fraction (*rdr*) of the secondary root system. Primary (i.e., vertical) roots are assumed to die only at the end of the crop cycle.

The other source of root respiration is the growth respiration associated with the conversion of C substrate into root biomass (for both vertical growth and root proliferation). In this case, a fixed efficiency (*effic*) is used, thus the amount of C consumed by respiration will be a fixed fraction (*1-effic*) of the net carbon allocated to root growth. Total daily C respired is the total C allocated to root maintenance plus the C derived from root synthesis.

Carbon supply to root growth, in this stand-alone version, was simulated by a Poisson density function, with time since the beginning of the crop cycle as the independent variable. The value obtained from this distribution, which varied from 0 to 1, was multiplied by a constant value which represents maximum daily C supplied to root growth by the aboveground part of the crop.

3. RESULTS

Parameterization: The model was parameterized by comparing simulated and observed root length density (RLD) and total root biomass for corn, grown in a Chalmers soil in Indiana (Mengel and Barber, 1974) and RLD for cotton, grown in a Frio soil in Texas (Bland and Dugas, 1989). For the corn experiment, soil information was taken from previous studies conducted by Mengel (1972) and Mengel and Barber (1974), and a general description of the soil profile characteristics of the Chalmers soil series (Soil Survey Staff, 1994). For the cotton experiment, soil information was taken from Bland and Dugas (1989) and the soil survey description of the Frio series. Sand content for this soil was taken as the upper limit for a silty clay loam (20%), and 10% for layers lower than 90 cm. For soil N distribution for cotton, we assumed that there was 180 kg ha^{-1} of mineral N accumulated in the soil profile to 210 cm depth, and distributed it as 60% into the first soil layer (0-30 cm), 23% in the 30-50 cm layer, 9% in the 50-70 cm, and 4% in each soil layer below to the 210 cm depth. We also assumed that all fertilizer N was allocated to the first soil layer (0-30 cm). The base soil temperature, below which no root growth occurs, was set at 10 and 12.8°C for corn and cotton, respectively (Jones et al., 1986; Mullins, 1990). An initial set of parameters were obtained or derived from published papers, but in some cases the final parameter resulted from manual adjustment of parameters to improve the fit to observed data. In Table 3, the best fit set of parameters for corn and cotton are shown.

Maximum rooting depth (*Pmax_rooting*) for specific crops was obtained from Borg and Grimes (1986) and Gregory (1988). Initial values for accumulated thermal time (*Max_rooting_stage*) for cotton were taken from Gerik et al. (1988), but since vegetative growth in cotton persists even after the reproductive stage has begun, the final thermal time was obtained by adjusting the observed and simulated data. For corn we used the accumulated daily thermal time calculated by the model at flowering time based on the weather information of each experimental site and year (Jones et al., 1986). Parameters for efficiency (*effic*) of utilization of C-substrate into structural C in roots and C requirements for root maintenance (*mrr*) were taken from Brugge and Thornley (1985), and for daily root mortality (*rdr*) we used an estimate by Asseng et al. (1997) which is about 5%. However, mortality rates as low as 0.5% have been used in other models (Robertson et al., 1993).

Parameters to convert root mass to root length of secondary roots were taken from van Noordwijk and Bouwer (1991). Similarly, parameters to convert root mass to root length of primary roots were derived from the study of Granato and Raper (1989) where corn was grown at high irradiance, and all root axes were under the same N concentration. Values for maximum root length density (*Max_root_den*) were taken from Gregory (1988). For high and low C:N ratios of root tissues, we used values based on observations for barley (*Hordeum vulgare* L.) by Rutherford and Juma (1989) and other crops (*Medicago truncatula* L.; *Hordeum leporinum* L.; and *Vicia faba* L.) as reported by Crawford et al. (1997). For limiting soil N concentration (N_{sat}), we initially used the soil N concentration below which N uptake by maize roots is affected (3.75 mmol l^{-1}; 53 mg l^{-1}), based on simulation data of Barber (1995). However, to improve model fit it was necessary to increase it up to 75 mg l^{-1} for corn and to decrease it to 10 mg l^{-1} for cotton. Moreover, contradictory values for this value have been reported by Burns (1980) who found a range from 0.08 to 0.20 mmol l^{-1} and Kachi and Rorison (1991) who found 0.04 mmol l^{-1}. Values for branching (*rrgr*) and number of primary roots in corn were varied until simulated and observed RLD were close, while for cotton a single tap root for vertical development was used and only the branching factor (*rrgr*) was varied.

The simulated and observed root length density (RLD) in different soil layers and during the crop cycle for corn are shown in Figures 4 and 5, respectively. The model satisfactorily predicted the RLD as suggested by results of regression analysis of observed and simulated RLD data for all soil layers (Figure 5). A high coefficient of determination (r^2 =0.84) and a slope of the regression line (1.008) that did not statistically differ from 1 (p=0.90), indicate good agreement between the observed and simulated RLD data. Similarly, results of observed total root C, calculated from the total root dry matter and a C content of 0.46 g C g^{-1} DM, were close to the simulated data obtained by the model (Figure 6). In general, the simulated RLD were in the same order as the observed data, and had the same behavior with increasing RLD until after 80 to 90 days, followed by a decreasing trend. However, underestimation of RLD by the model was evident in the 60-75 cm layer, and some overestimation in the 15-30 cm layer. Also, it was evident that simulated RLD was slow during the first 50 days, which may be associated with C supply to root growth.

Discrepancies in simulating the RLD for the 60-75 cm layer could be due to inappropriate data utilized for simulation, as well as the influence of processes not considered by the model. In our case, the sand contents utilized for simulation were obtained from a general description of the soil series, and they might not reflect the actual values in the soil profile. A description of the experimental site (Mengel, 1972) reported the 40-75 cm soil layer as a yellow-brown clay loam containing sand and gravel. Given that the observed RLD in this layer was relatively high (over 1 cm cm^{-3}), the actual sand content may have been higher than the value utilized for simulation. An increase in the sand content allowed us reproduce the observed RLD values for that layer (data not shown). Influences of other soil factors on the root growth, particularly soil porosity, cannot be disregarded since they were not considered in the model.

Simulations of the root system for cotton resulted in good agreement between simulated and observed RLD values for the different soil layers during the first 80 days of the crop cycle (Figure 7). After 80 days, the model underestimated the RLD values in most soil layers. Deviation between observed and simulated root growth could be partially attributed to the assumed pattern of C supply to the root growth. With the Poisson forcing function utilized by the model, C supply for root growth decreases after 80 days of the crop cycle. This pattern of C allocation to the roots might not adequately represent the increasing demands for photosynthate in cotton roots during the latter stages of the crop cycle. This possibility is supported by studies showing that the root system of cotton requires significant amounts of C for maintenance and development of new roots at the flowering stage (Oosterhuis, 1996).

An examination of the root system dynamics in the observed data suggest the existence of some interactions with soil properties which were not taken into account by the model, and consequently might be responsible for uncertainties in the predictions. The data showed a decrease in the observed RLD of the upper soil layers (50-90 cm) after 60 days of the crop cycle associated with a low water availability in these layers (Bland and Dugas, 1989). Along with this water deficiency in the upper layers, a root proliferation was observed in the lower layers (110-190 cm) after 60 days, suggesting an interaction between water supply and root growth. This interaction has been suggested already for cotton roots by Taylor and Klepper (1974) who found an increasing RLD in the deepest soil layers as the water supply decreased in the top soil layers. The simulation of this type of interaction could not be properly represented by our model, since simulations were made using a constant value of soil water content during the crop cycle. In this regard, more experimental data is required to better quantify the influence of the soil water content of the top layers on the root growth into deeper soil layers. It is important to note at this point that model predictions could also be affected by the values assigned to other soil properties (sand content, soil mineral N content, soil temperature) as well as parameter estimates (N_{sat}, number of primary roots, maximum root length). In the cotton root growth simulations, for instance, values for soil mineral N content were assumed, and it was necessary to adjust the parameter controlling the effect of N on root growth (N_{sat}).

Sensitivity Analysis

Parameter sensitivity: The sensitivity analysis was made using the values of plant and soil parameters that allowed the best fit of the model to the observed data after the parameterization process. The parameters utilized were those related to root growth of corn (*rrgr*, *effic*, *mrr*, *rdr*, *Max_root_den*, *P_root_den*, *Pmax_rooting*, and *Max_rooting_stage*), as well as the soil solution N concentration over which there is no effect of N on root growth (N_{sat}). The nominal value of each parameter was varied ± 10% and the model predictions for root length density (RLD) and rooting depth were utilized to evaluate the effect of changing the parameters. The sensitivity to specific parameters was evaluated graphically by comparing the simulated data (output) obtained at ±10% variation of the nominal value. It is expected that the model will be more sensitive to the parameter(s) offering the widest range of variation in the response.

Root length density was relatively more sensitive to changes in the fraction of root allowed to proliferate (*rrgr*) (Figure 8A), maximum allowed root length density (Figure 8B), and daily root mortality (*rdr*) (Figure 8C), as compared with the effect of the limiting N factor (Figure 8D). The other plant parameters did not significantly change the estimated values of root length density. An increase of 10% in the nominal values of the branching factor (*rrgr*) and the maximum allowed RLD (Figures 8A and B) produced on average a change of 10% in the simulated values of RLD. Sensitivity analysis using rooting depth on the other hand, showed significant variations only when changing parameters associated with the potential maximum root depth (*Pmax_rooting*, Figure 8E) and the maximum plant stage allowing vertical root growth (*Max_rooting_stage*).

Sensitivity to selected soil properties: To test the model behavior under different soil physical conditions associated with root growth, the model was run using four hypothetical soil conditions resulting from variations in sand content only, maintaining the other plant parameters unaltered. Optimal conditions of soil water and N content were assumed. In addition, simulations were performed by combining different values of sand content (10, 20, 40 and 65%) with increasing values of soil bulk density (SBD = 1.25, 1.45, 1.55, and 1.65 g cm^{-3}). Soil properties such as soil water content at DUL and LL were estimated from sand, silt, and soil organic matter contents as indicated by Ritchie et al. (1986). The effect of increasing SBD on rooting depth also was investigated by using the same uniform soil profile as previously indicated. A limiting soil bulk density was set as the value of SBD at which the rooting depth was reduced to 20% of the maximum obtained when using optimal values of SBD (Jones et al., 1991).

The model was sensitive to variations in sand content and soil bulk density. Different root length density, root respiration, C allocated to roots, and rooting depth were predicted for the different soil profiles (Figure 9). The model was particularly sensitive to changes in values of sand content between 10 and 20% (Figures 9A-9C). Similarly, an increase in soil bulk density values from 1.2 to 2.0 g cm^{-3}reduced the rooting depth by up to 80% (Figure 9A). This indicates that the model was able to differentiate among a wide range of soils having different soil conditions or parameters that could potentially affect the root growth constants (i.e., soil temperature, N content, and even C supply to root growth). However, we recognize that generalization about soil texture effects on root growth and behavior is difficult, since many effects can be indirect and attributed to complex interactions with other soil properties such soil water availability, mechanical impedance, nutrient contents, etc., (Glinski and Lipiec,1990).

The estimated limiting soil bulk densities at which rooting depth was reduced to 20% of the maximum obtained with optimal soil bulk density were: 1.55-1.60, 1.60-1.65, 1.65-1.70, and 1.75-1.80 for the clay (10% sand), silt loam (20% sand), loam (40% sand), and sandy loam (65% sand), respectively (Figure 9E). These results closely correspond with values of limiting soil bulk densities previously found for soils of different textures under experimental conditions (Miller, 1986) and early studies of root growth in sunflower grown in different soils (Veihmeyer and Hendrickson, 1948).

4. Conclusions

The model was parameterized for two different crops (corn and cotton) and different soil conditions. The simulated root length density and rooting depth were similar to the observed data, both in terms of the magnitude and the temporal patterns. This showed the potential to use the model under different condition and crops, but more evaluations are required.

The root model was sensitive to plant and soil parameters and it could be satisfactorily utilized to predict the root system dynamics in the soil profile for different crops. Predicted root length density was sensitive to root branching, maximum allowed root length density, daily root mortality, and limiting soil N concentration, while rooting depth was sensitive to the maximum root depth and maximum crop stage allowing vertical root growth. Estimates of root growth (root length density and root proliferation) were relatively less sensitive to changes in the number of primary roots, but appropriate values had to be provided for each crop in order to fit the model to the observed data. The root model was sensitive to variations in soil conditions (sand content and soil bulk density).

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Table 1. Specific site soil properties required in the root model.

Parameter symbol	Parameter Description / units
Sand	Sand content in the soil layer (%)
SBD	Soil bulk density in specific soil layer (g cm^{-3})
SW	Soil water content (cm^3 cm^{-3})
DUL	Soil water content a field capacity (cm^3 cm^{-3})
LL	Soil water content a wilting point (cm^3 cm^{-3})
dLayr	Depth of soil layer (cm)
Zlayr	Depth to bottom of layer (cm)
ST	Actual soil temperature (degrees Celsius)
N_{act}	Actual content of soil N (kg ha^{-1})

Table 2. Crop, management and soil parameters required in the root model.

Parameter symbol	Parameter Description / units
Max_rooting_stage	Maximum plant stage until where vertical root growth is allowed (°C)
Pmax_rooting	Potential maximum root depth (cm)
mrr	Fraction of C used for root maintenance (dimensionless)
effic	Conversion efficiency of C to root tissue (g g^{-1})
rrgr	Fraction of actual root length allowed to branch for horizontal root proliferation (dimensionless)
rdr	Specific rate of daily root mortality (dimensionless)
Max_root_den	Maximum root length density allowed for specific plant (cm cm^{-3})
Len_mass_v	length to mass ratio for vertical roots (cm g^{-1})
Len_mass_p	length to mass ratio for fine (proliferation) roots (cm g^{-1})
P_root_den	Number of primary root per plant (# roots $plant^{-1}$)
highC:N	Maximum root C:N (dimensionless)
lowC:N	Minimum root C:N (dimensionless)
PltPop	plant density (plants m^{-2})
N_{sat}	limiting N concentration in soil solution (mg N l^{-1})

Table 3. Specific plant parameters used to simulate root growth for different crops, and in different places.

Parameter Description / Units	Experimental	Site
	Chalmers soil series Corn	Frio soil series Cotton
Maximum rooting of the crop (cm)	300	300
Crop stage (thermal time) until where vertical root growth are allowed (°C)	1200	700
Efficience factor in conversion of no structural C into structural C	0.65	0.65
Factor related to the branching of secondary roots	0.37	0.5
Proportion of C allowed to maintenance of previously grown roots	0.02	0.02
Daily root mortality	0.07	0.07
Maximum root length density (cm cm^{-3})	5	1.2
Length : mass factor for primary roots (cm / g C)	1000	1000
Length : mass factor for secondary roots (cm / g C)	16000	16000
Number of primary roots (# / plant)	150	1
High C:N ratio in roots	25	25
Low C:N ratio in roots	20	20
Limiting soil solution N concentration (mg l^{-1})	75	10
Plant density (Plants m^{-2})	5	15

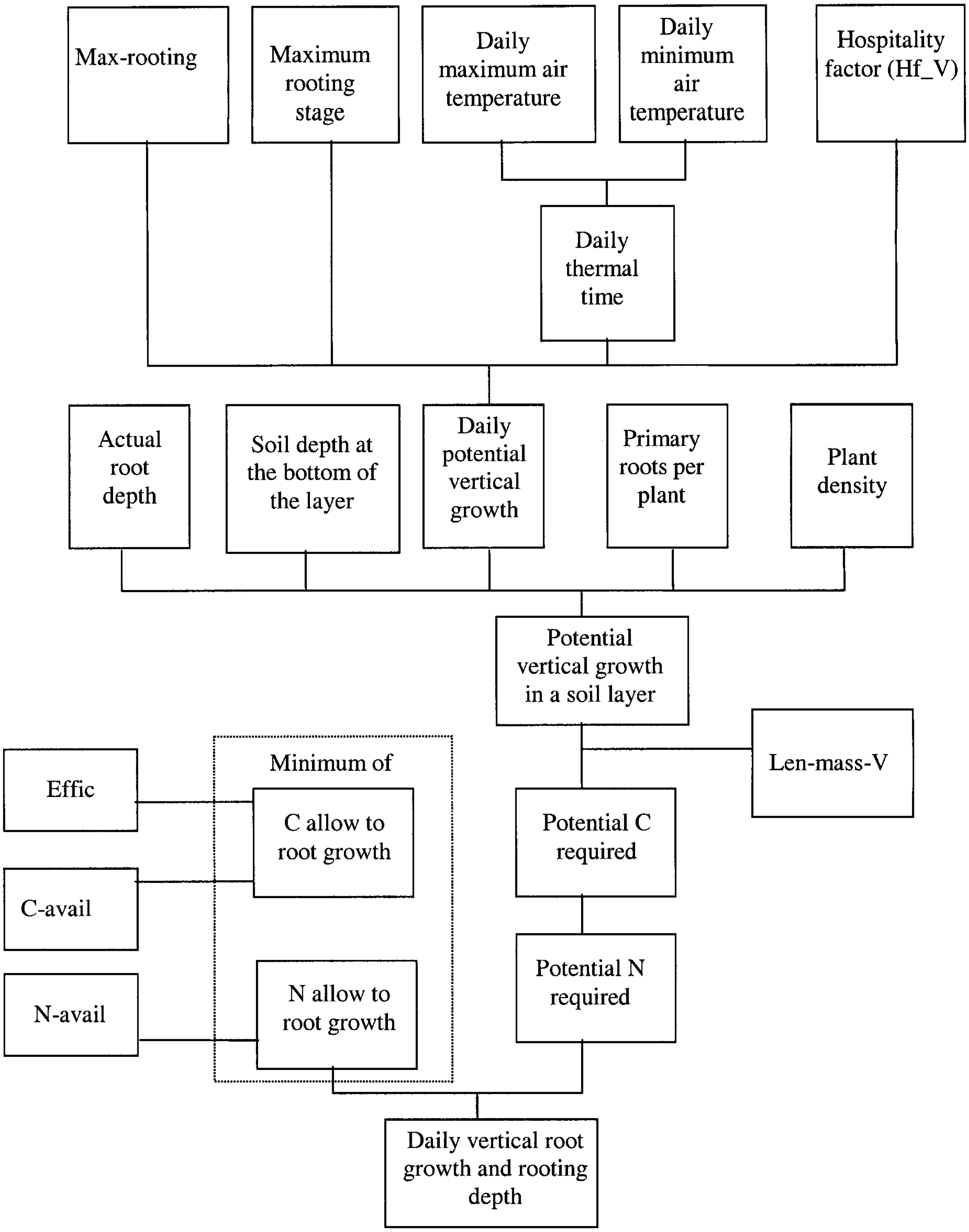


Figure 1. Factors controlling the vertical root growth

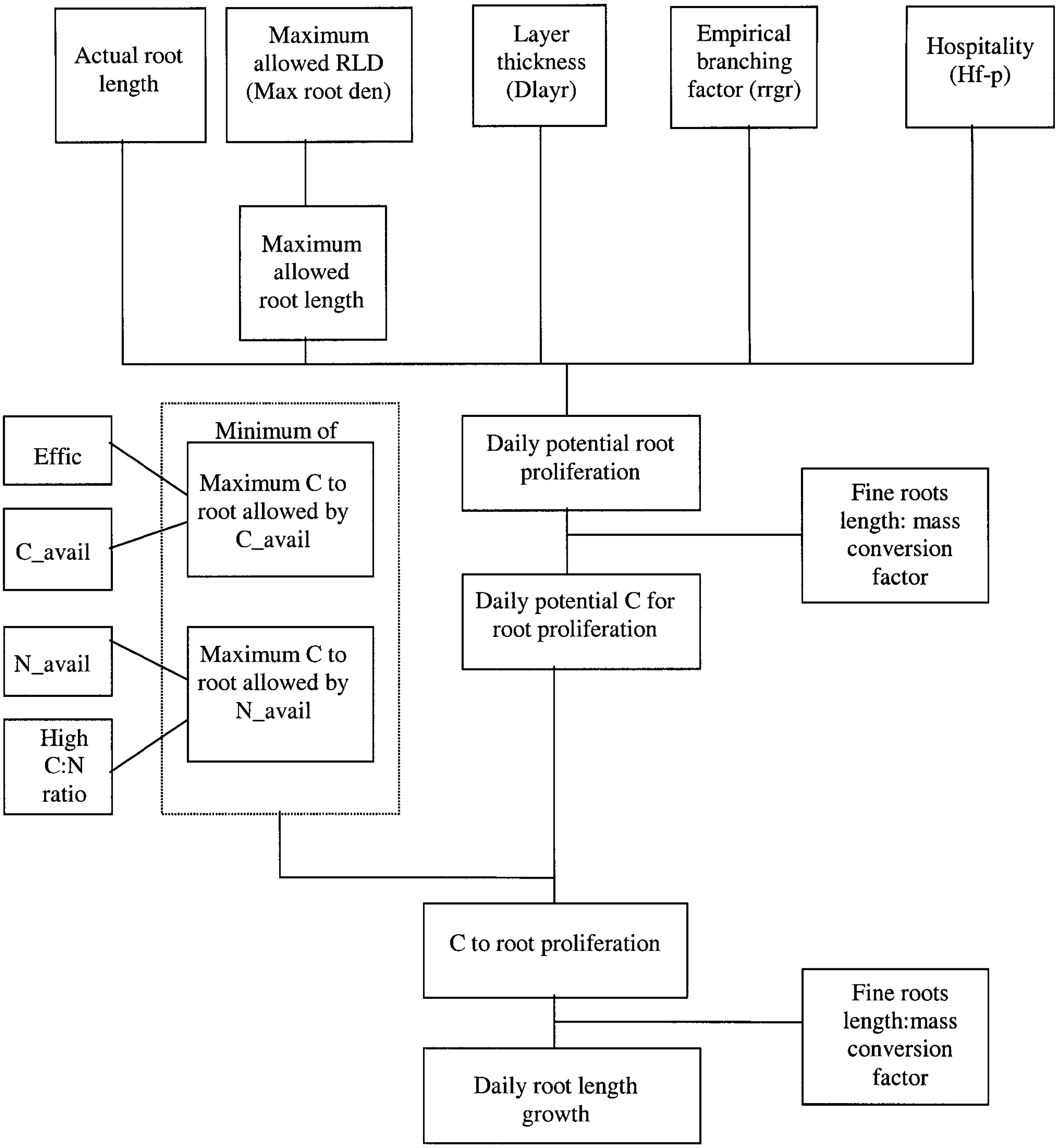
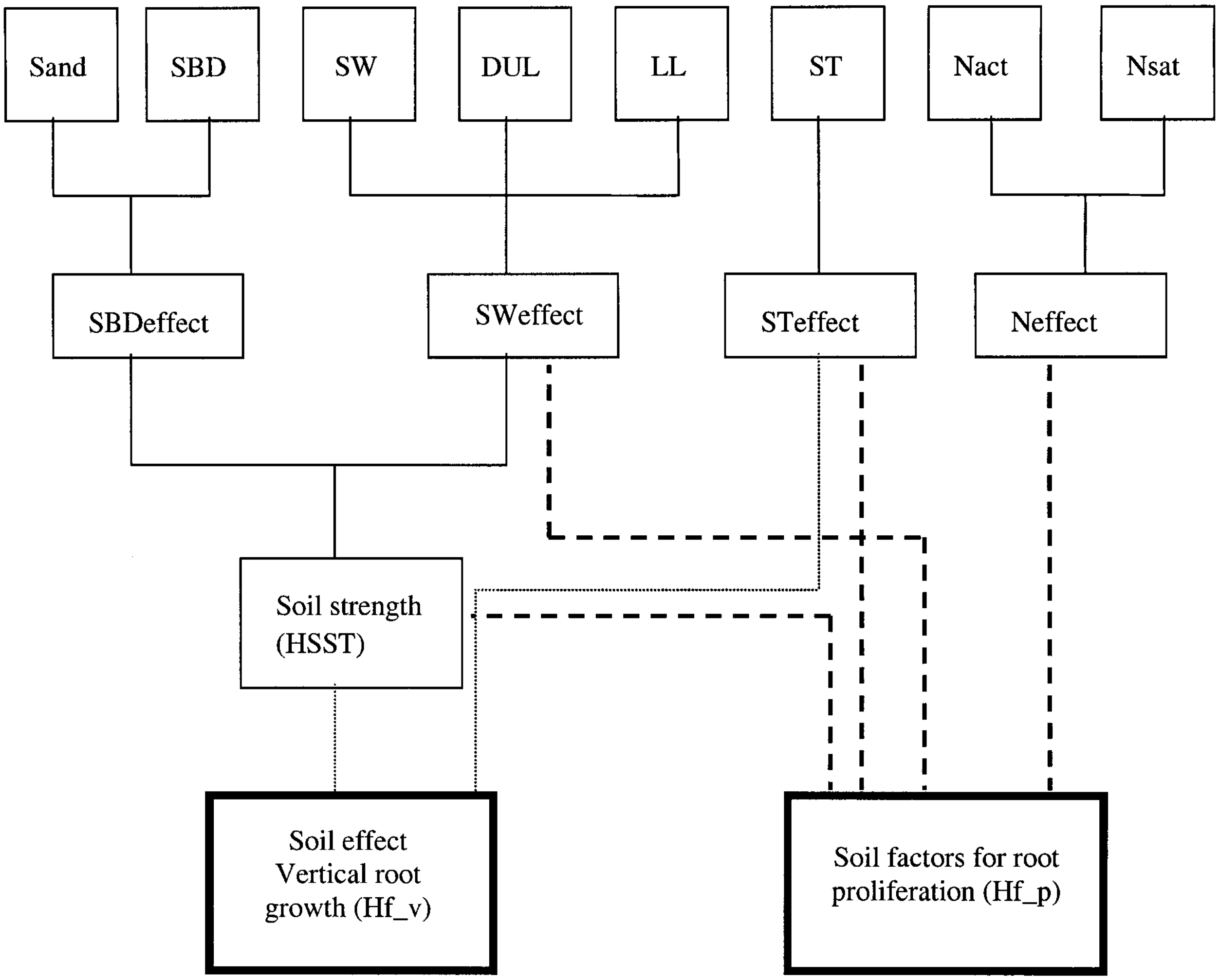


Figure 2. Factors controlling the root proliferation



Sand, SW, DUL, LL, Nact, as indicated in Table 2

SBDeffect, Sweffect, Steffect, Neffect, and Soil strength are the simple or combined effects of soil properties on root growth.

Lines: ········ - - - - - Indicate soil factors regulating vertical root growth and root proliferation, respectively.

Figure 3. Soil properties considered in soil hospitality factor for vertical root growth and root proliferation.

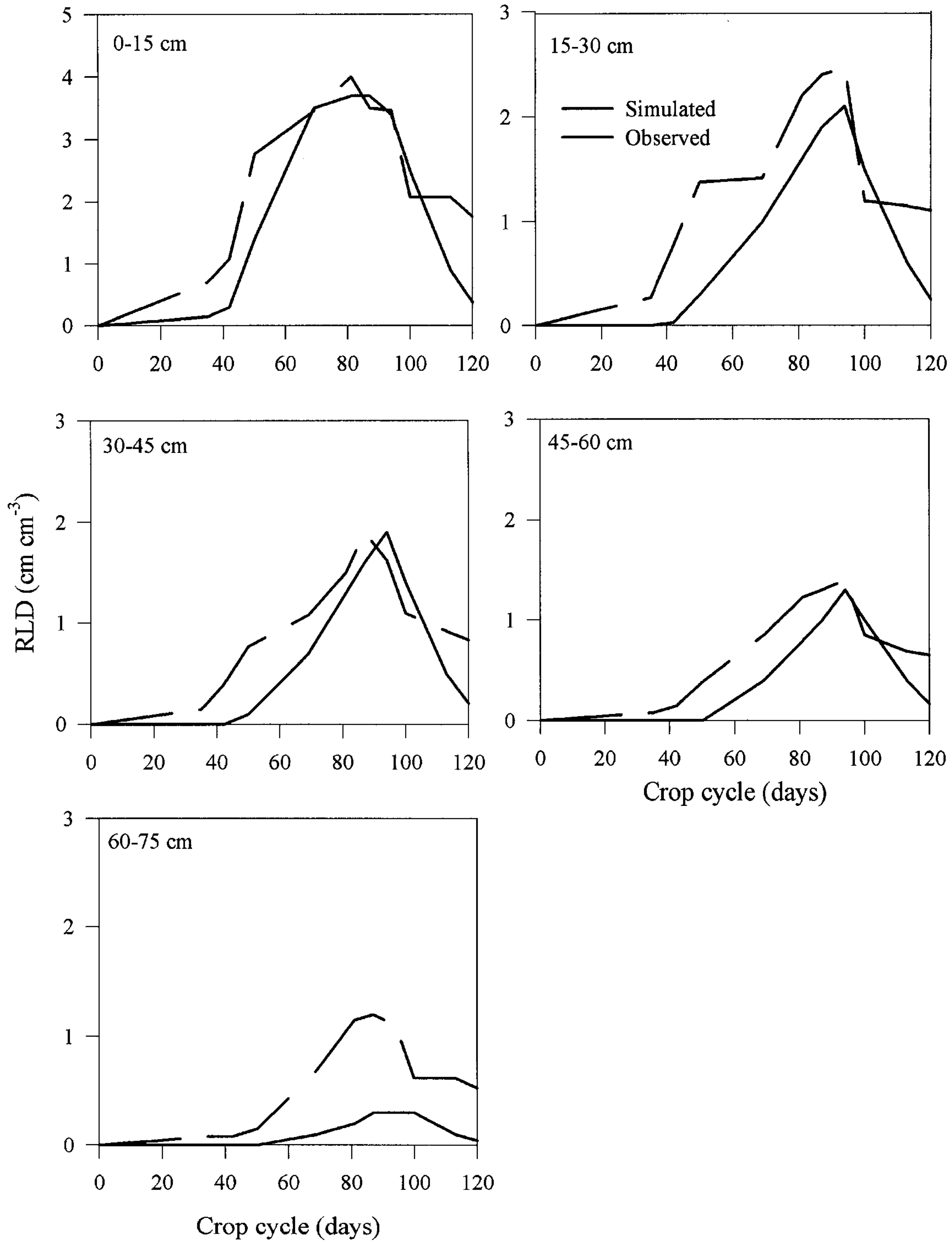


Figure 4. Simulated and observed root length density in different soil layers in corn sown in a Chalmers soil of Indiana.

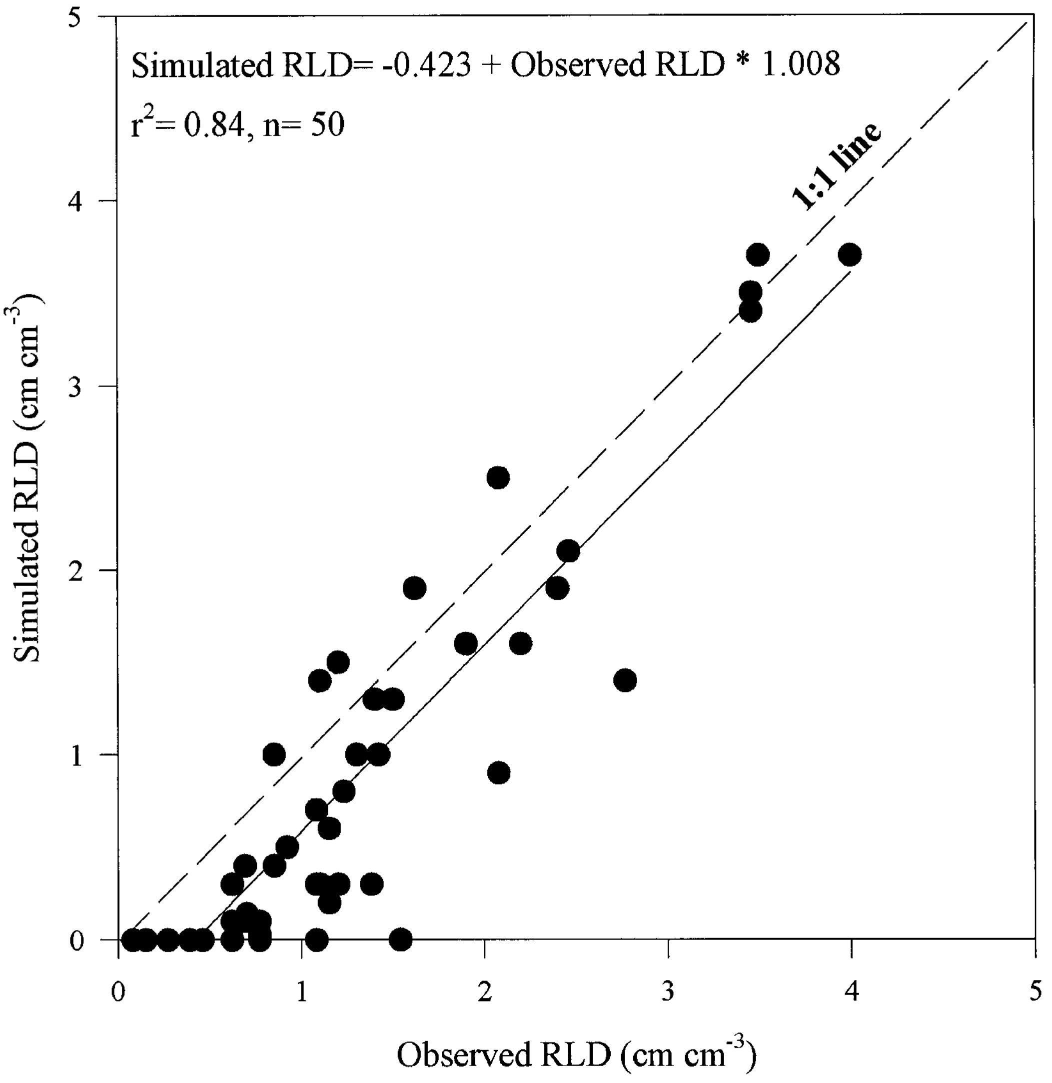


Figure 5. Relationships between observed and simulated root length density for the soil layers.

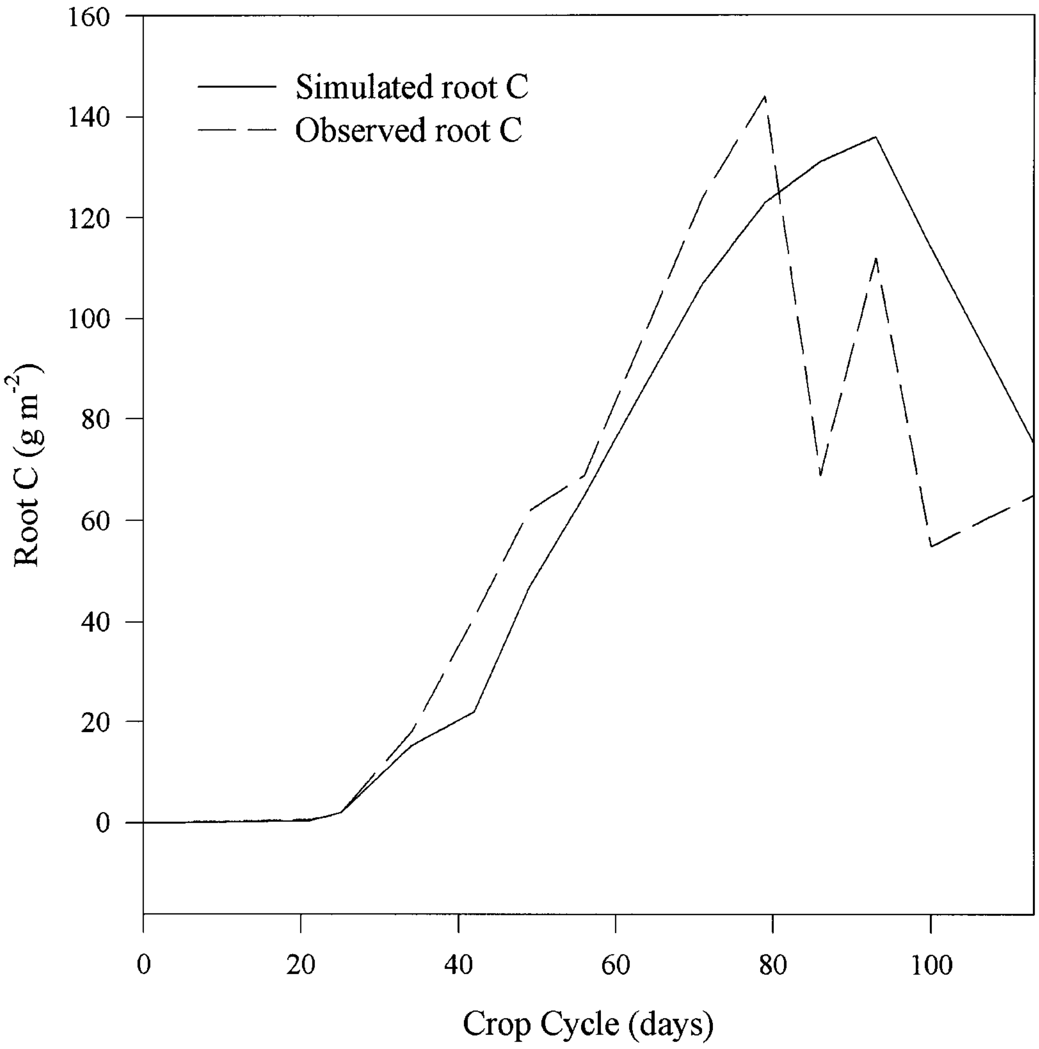


Figure 6. Simulated and observed total root carbon at different stages of the corn cycle.

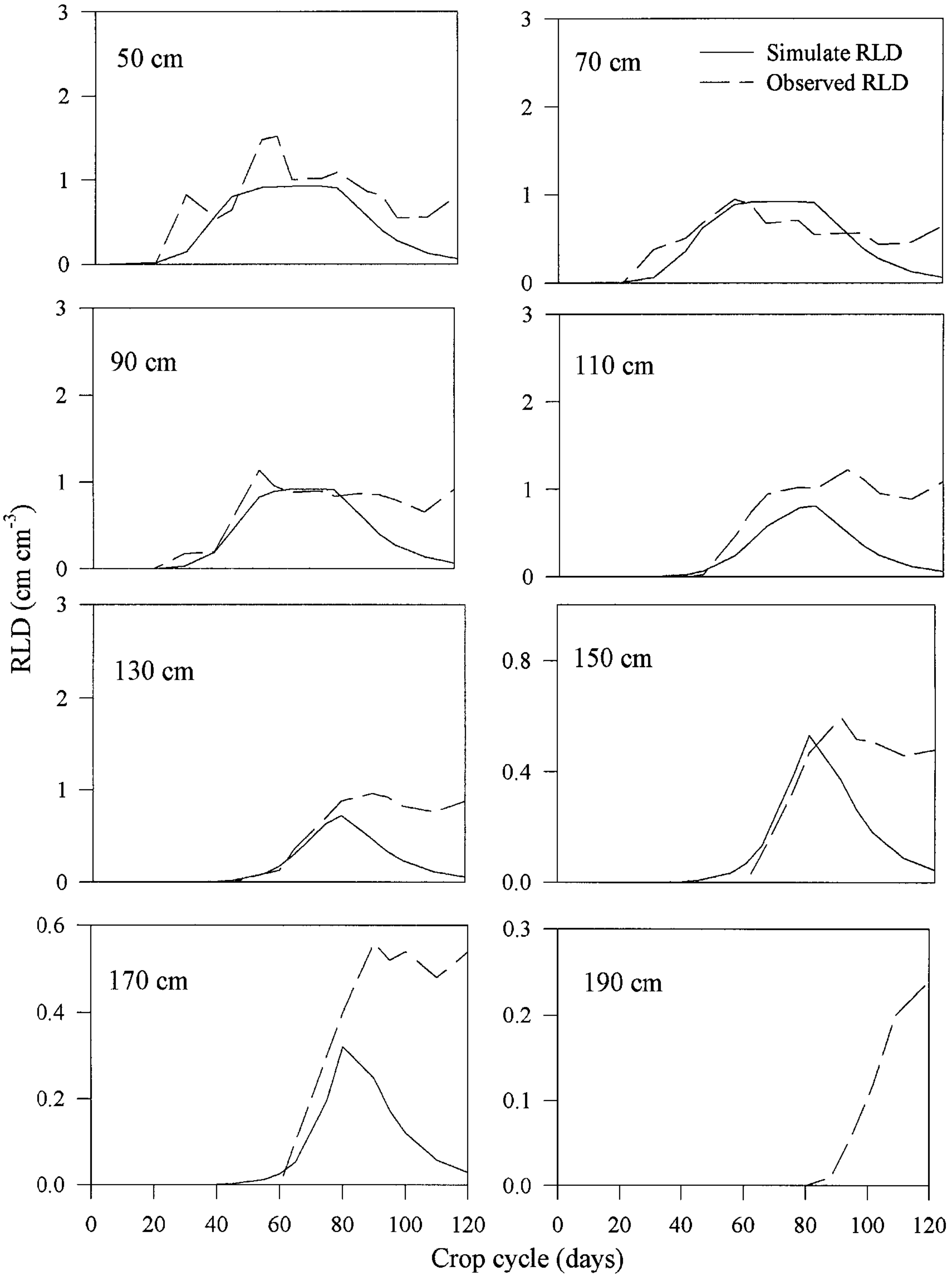


Figure 7. Observed and simulated root length density for cotton in a Frio soil series of Texas.

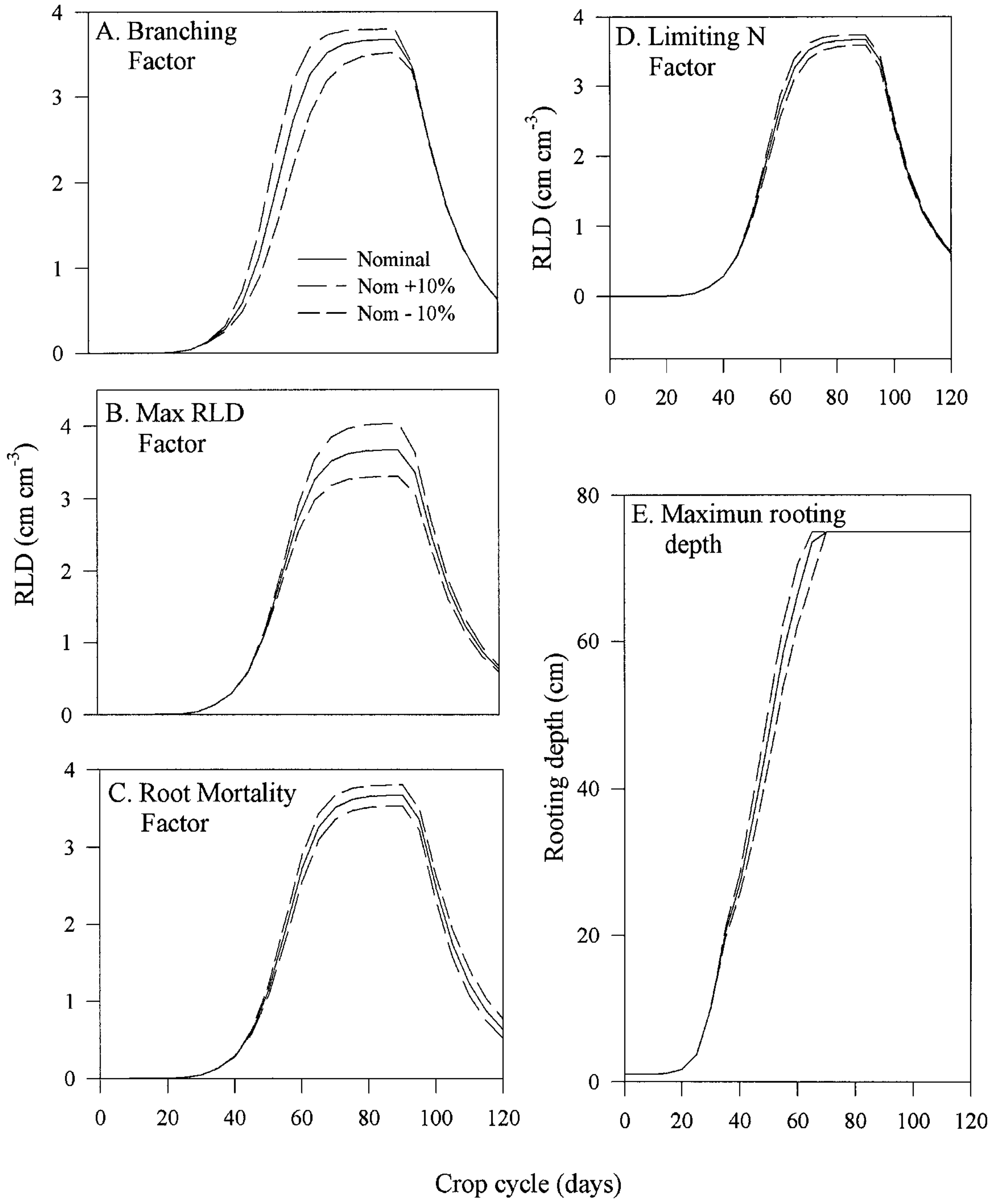


Figure 8. Sensitivity analysis of different parameters included in the root model.

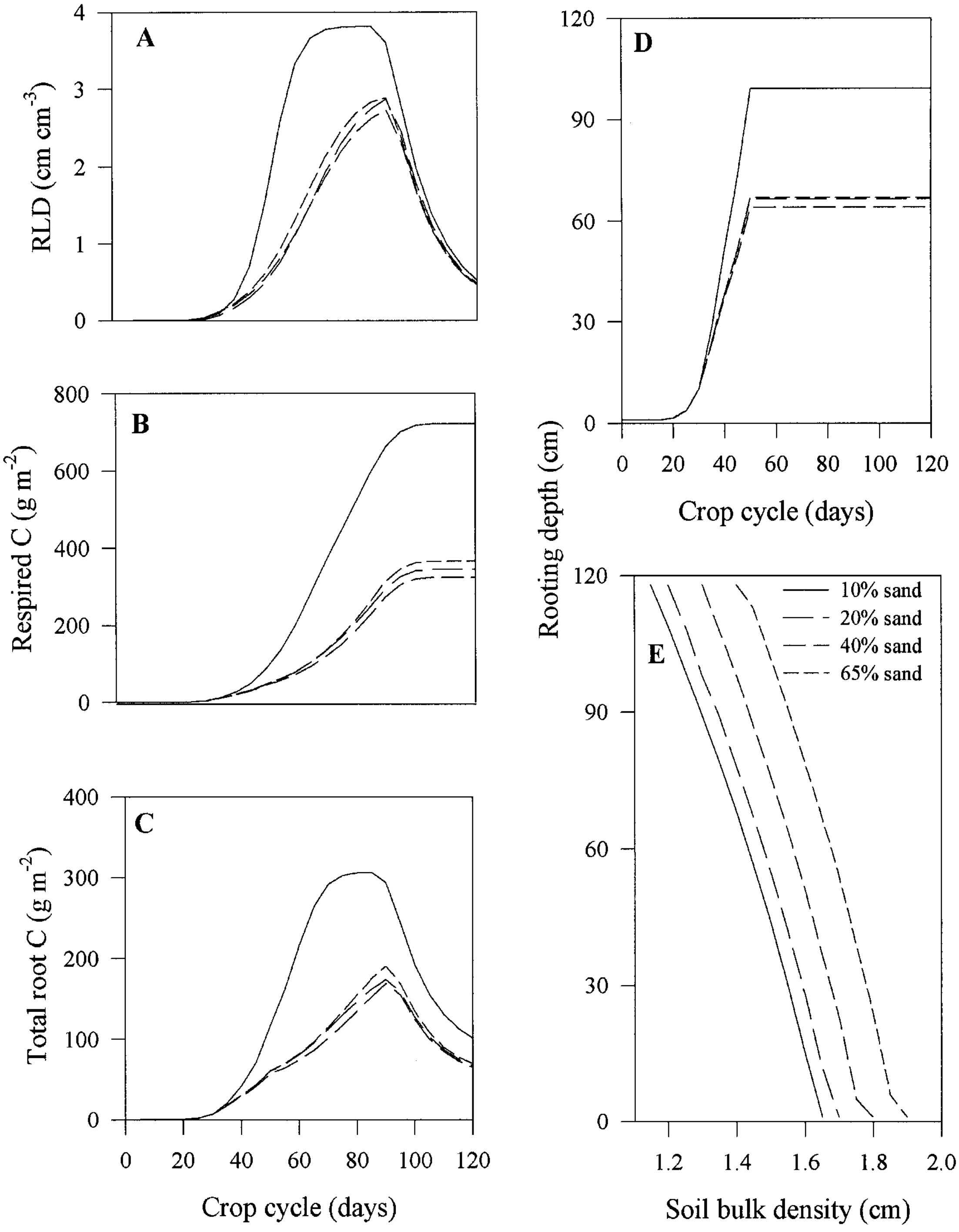


Figure 9. Effects of variable soil sand content and soil bulk density on root growth.

APPENDIX TO CHAPTER I

EFFECT OF DIFFERENT MANAGEMENT PRACTICES ON SOIL N AVAILABILITY

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Tillage Systems	Brown sandy loam or loamy-sand (Humic Gleysol; Typic Endoaquent)	Fertilized corn (*Zea mays L.*) (180 kg N/ha) under NT, RT, CT, with and without removal of plant residues.	Plots with removed residues had more NO_3-N, but it was not consistent in all the years. Also, less NO_3-N was available in the upper soil layer under RT. Removal of plant residues probably allowed losses of N by leaching and denitrification	Burges et al., 1999
Tillage system / Fertilizer location	Weswood silt loam. (Texas A&M University research farm, Burleson, Texas)	Sorghum (*Sorghum bicolor L.*) fertilized (150 kg N/ha) under CT, and NT. N fertilizer was broadcast, or subsurface banded	Under NT immobilization and slow N mineralization probably promoted more use of N fertilizer, but total N uptake was not different by tillage systems. CT probably allowed more N mineralization and initial uptake by sorghum. NT system delayed crop growth. CT allowed more N availability during the crop season.	Locke and Hons, 1988
Tillage systems / cover crop	Maury silt loam (Typic Paleudalf).	Corn under NT, and CT and under application of Vetch (*Vicia villosa Roth*), and corn residues.	Early season N uptake was increased due to incorporation of residues (CT), but NT made more N available during grain filling. In NT total N uptake is more dependent on season precipitation than in CT: probably drying of surface layer affected mineralization and root uptake of N.	Varco et al., 1989

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Tillage system	Wentworth silty clay loam. (UdicHaplustoll) Nicollet loam or clay loam. (Aquic Hapludoll)	Corn sowed under 1) Fall Moldboard plow-spring disk (FP). 2) Fall Chisel-spring disk (FC), and 3) NT. N fertilizer was applied at 13 or 31 kg N/ha	In Nicollet soil NT delayed growth, and N accumulation. Without N fertilizer application, tillage enhanced N accumulation. In Wentworth soil, fertilized NT and FC reduced levels of N-NO_3 in the 0-30 cm soil layer, when compared against FP.	Olness, 1984
Tillage management / plant residues / N fertilizers	Black Chernozenic loam. (Udic Boroll) Gray Luvisol loam. (Boralf)	Barley (*Hordeum vulgare* L.), grown under ZT, CT, with straw residues on or off, and N fertilizers 0, 33, 67, and 100 kg N/ha banded.	Uptake of N in grain or whole plant at low N rate was lower under ZT than CT, and lower with straw-on that with straw-off at both sites. Greater yields under straw-off than straw-on at low N rates probably are due to N immobilization by residues. These effects are overcome at 100 kg N/ha where yields were higher under straw-on.	Malhi and Nyborg, 1990
Previous crops	Harlinger clay. (Vertisol soil, Southern Texas)	Mustard (*Brassica juncea*) grown in winter after the spring grown Cotton (*Gossypium hirsutum L.*) or sorghum which had been fertilized with 0, 67, and 134 kg N ha^{-1}.	Very little N-NO_3 accumulated in the root zone after sorghum, but a substantial amount after cotton. Mustard response to N application was affected by N-NO_3 levels when sowed after cotton.	Hipp and Gerard, 1973

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Cover crops and N fertilizers	Cecil gravelly sandy loam. (Typic Kanhapludults)	CT with ^{15}N-Crimson clover (*Trifolium incarnatum L.*), and NT with 70 kg N/ha as NH_4NO_3.	Forty four percent of applied N-clover was detectable as inorganic N at 18 days following incorporation. More residual clover could contribute to the potentially mineralizable N pool, compared against N fertilizer treatment.	Crozier et al., 1998
Tillage systems / nitrogen sources	Murril silt loam. (Typic Hapludult)	Corn grown under NT, and CT with red clover (*Trifolium pratense L.*) or hairy vetch (*Vicia villosa)* double cropped with winter wheat.	Incorporation of legume green manure under CT allowed more N-NO_3 than under NT. Under NT with 0 kg N/ha, low levels of N-NO_3 probably were insufficient and corn yields were increased due to N fertilizer application. Soil disturbance due to plowing in the treatment fallow with 0 kg N/ha enhanced net N mineralization and relative mineralization rate in the CT compared with NT.	Dou et al., 1995

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Tree fallow / fertilization	Sandy clay loam. (Ustic Rhodustalf)	Effect of different fallow options (fixing and no-fixing N_2 trees, or uncultivated fallow), and fertilized and unfertilized corn on soil fertility was evaluated.	Total soil C, N, and P were not affected by different management practices. Light macroorganic matter (150-2000 μm, <1.13 Mg m^{-3}), which account for only 2.4 and 2.3% of the total soil C and N, normally is reportedly correlated with N mineralization in the whole soil, and is sensitive to management practices. Legume allowed N in light macroorganic matter fraction, mineral N, and increased aerobic mineralization. N fertilization allowed increases of N in the light and medium macroorganic matter, and N mineralization.	Barrios et al., 1997

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Tillage systems / crop rotations	Palouse silt loam. (Ulti Haploxerolls)	Effects of MP, CP, and NT, fertilization, and crop rotation on potential soil N mineralization.	MP resulted in higher mineral N, lower organic C, and narrower C/N ratio than NT. Soils receiving more N fertilizer were higher in mineral N than those with low N fertilizer, showing residual effects. Crop rotations affect organic C probably due to the amount and quality of the residues. Cumulative mineralized N in the top 5 cm of soil, averaged over the fall and spring samples, was higher for NT than MP but not CP. NT had the highest potentially mineralizeable N (N_o) in the top 15 cm, and MP the lowest, but the reverse was true for the 10-15 cm.	El-Haris et al., 1983
Cover crops / Fertilization / Tillage systems.	Maury silt loam. (Typic Paleudalf)	Corn cultivated after hairy vetch (*Vicia villosa Roth*), Rye (*Secale cereale*), and corn residues, under MP and NT and fertilizer N rates (0 and 170 kg N/ha).	Previous N fertilizer and cover crops (Vetch) increased N uptake by Corn on 20.4 and 28 kg N/ha respectively. Although NT increased total soil C and N, N uptake by corn was similar than MP. Practices such as fertilization and cover cropping will affect more the organic matter quality or lability than quantity.	McCracken et al., 1989

Management practice	Soil type	Experiment characteristics	Effects on soil N availability	Author(s)
Cropping systems	Misteguay. (Aeric Endoaquents)	Effects of different amount of corn, Oat (*Avena sativa L.*), and alfalfa (*Medicago sativa L.*) on production of Navy bean (*Phaseolus vulgaris L.*) and sugar beet (*Beta vulgaris L*).	The active fraction of organic matter, which is the ratio between N_o: total N, reflected the amount of crop residues returned to the soil due to the different management practices. Mineralization was directly related to the amount of crop residues returned.	Christenson and Butt, 1997

NT, RT, CT, ZT, MP, CP are no-tillage, reduced tillage, conventional tillage, zero tillage, Moldboard plowing, and chisel plowing.