AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY

1. SUBJECT CLASSIFICATION

A. PRIMARY: Food production and nutrition AF25-0000-GG50

B. SECONDARY: Soil fertility, fertilizers, and plant nutrition--Tropics

2. TITLE AND SUBTITLE

Nitrogen fertility in oxisols and ultisols of the humid tropics

3. AUTHOR(S)

Grove, T. L.

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1979	29p.	ARC 631.42.G883

7. REFERENCE ORGANIZATION NAME AND ADDRESS

Cornell

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

(Study prepared by Cornell Univ. [contracts AID/csd-2490, AID/ta-C-1104, and AID/ta-C-1441] and North Carolina State UNiv. [contracts AID/csd-2806 and AID/ta-C-1236]) (In Cornell Int. agriculture bulletin 36)

9. ABSTRACT

10. CONTROL NUMBER

PN-AAG-620

11. PRICE OF DOCUMENT

12. DESCRIPTORS

Soil fertility
Nitrogen
Fertilizers
Acid soil
Yield
Tropics

13. PROJECT NUMBER

931050500; 931052500

14. CONTRACT NUMBER

AID/ta-C-1104 Res.

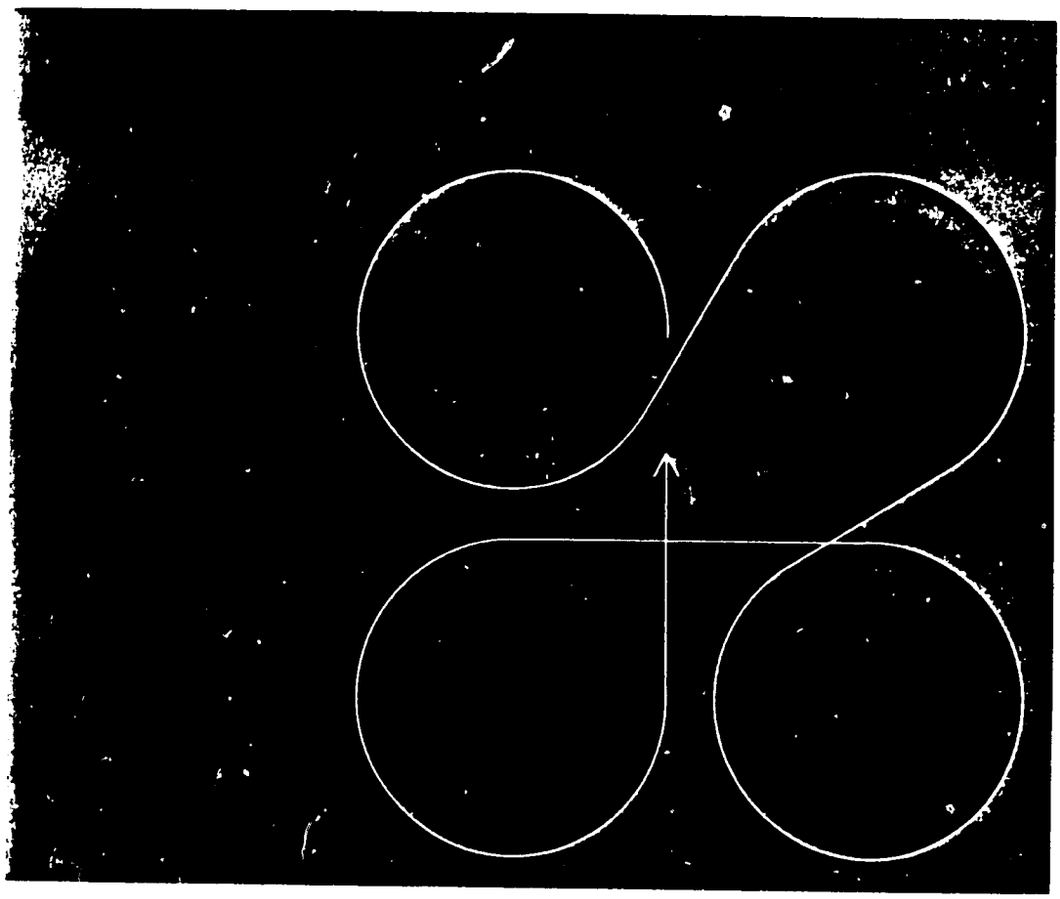
15. TYPE OF DOCUMENT

AID 590-1 (4-74)

PN-AAG-620

CORNELL INTERNATIONAL AGRICULTURE BULLETIN 36

631.42
G783



NITROGEN FERTILITY IN OXISOLS AND ULTISOLS OF THE HUMID TROPICS

A summary of cooperative projects carried out by
Centro de Pesquisa Agropecuaria dos Cerrados, Planaltina, Brazil
University of Puerto Rico, Rio Piedras, Puerto Rico
Soil Research Institute, Kumasi, Ghana
Yurimaguas Experiment Station, Ministerio de Agricultura, Yurimaguas, Peru
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NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
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AT CORNELL UNIVERSITY, ITHACA, NEW YORK

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January 1979

Nitrogen Fertility in Oxisols and Ultisols of the Humid Tropics*

Edited by Thurman L. Grove†

SUMMARY

Field experiments were performed in Puerto Rico, Brazil, and Ghana on highly weathered acid soils (Oxisols and Ultisols) to assess the capacity of these soils to supply nitrogen to nonleguminous crops and to determine crop response to fertilizer nitrogen. Results were consistent with expectations that were based on temperate-region experience. Soils typically supplied from 60 to 80 kg/ha N to crops. Yield responses were qualitatively similar at all locations, and maximum maize yields in excess of 5 tons/ha were common on well-managed field plots. Application of 80 to 120 kg/ha fertilizer N resulted in a 95 percent maximum yield. When fertilizer was properly applied, the increase in N content of above-ground dry matter was 0.56 per unit of applied N through the application range of 0 to 100 kg N/ha. The identical value is commonly obtained in temperate regions with similar methods of application. To attain this value, most of the fertilizer N must be applied just before the period of most rapid plant uptake; and such fertilizers as urea must be incorporated into the soil to prevent ammonia volatilization. Residual effects from fertilizer N in inorganic forms are unlikely, although returning crop residues to the soil may have beneficial effects on nitrogen economy.

No simple, reliable, and general methods are available for estimating fertilizer N requirements. A first approximation procedure, proposed by Stanford, is based on estimates of the relationship between yield and N content of above-ground dry matter, estimates of yield without fertilizer N, and desired yield.

*This study was supported in part by the United States Agency for International Development (AID) under research contracts with North Carolina State University, csd-2806 and ta-c-1236 and with Cornell University, csd-2490, ta-c-1104, and ta-c-1441.

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INTRODUCTION

The purpose of this publication is to summarize selected aspects of soil nitrogen research in temperate and tropical regions and to identify nitrogen management practices for crop production on highly weathered acid soils in the wet–dry humid tropics.

The tropics have several hundred million hectares of highly weathered, well-drained soils of low base status. They are mainly classified as Oxisols and Ultisols, and they cover approximately 51 percent of the tropics (President's Science Advisory Committee, 1967) in vast areas of South America and Africa and lesser areas of Central America and Southeast Asia. These soils are not extensively used for producing crops, primarily because of their low native fertility and high acidity. However, many of these soils are located in terrain and climatic regimes that are favorable for crop production. Furthermore, their physical properties, especially of the Oxisols, facilitate tillage. Similar soils — mainly Ultisols — , found in temperate regions of the southeastern United States and southeastern China, are intensively cropped after their low fertility is corrected (Sanchez and Buol, 1975). Consequently, increased crop production on the highly weathered, well-drained, acid soils of the humid tropics seems probable with proper soil amendments and crop management practices.

In the humid tropics, as in temperate areas, sustained production of high yields of nonleguminous crops requires adding nitrogen to the soil. Whether mineralization of organic nitrogen in the soil is sufficient for maximum crop production depends on crop yield potential and nitrogen requirements, soil moisture content, soil organic-matter content, and rate of mineralization. The rate of mineralization depends on soil moisture, aeration, temperature, pH, mineralogy, nature of organic matter, and the previous moisture and temperature histories of the soil (Fox, 1972). When soils are initially brought into cultivation, mineralization of soil organic nitrogen is usually sufficient for modest yields of nonleguminous crops, but as organic matter levels decline, the ability of the soil to supply nitrogen for crop production decreases. The natural processes of rainfall and nonsymbiotic biological fixation also add nitrogen to the soil under nonleguminous cropping. Kass and Drosdoff (1970) estimated annual nitrogen gains of 4 to as much as 89 kg/ha in tropical grasslands and sugar cane fields, but they concluded that gains from these sources are inadequate for sustained high yields of nonleguminous crops.

NITROGEN TRANSFORMATIONS AND MOVEMENT IN TROPICAL SOILS

Research on nitrogen in soils of the tropics has been limited. Tropical agriculture has relied upon research in temperate regions for fundamental information on soil nitrogen. This transfer of information seems

reasonable, as fundamental principles should apply in all situations if proper consideration is given to environmental factors (Bartholomew, 1972, 1973). However, some differences in nitrogen transformation and movement processes are attributable to climatic factors, primarily rainfall and temperature. These differences require consideration when transferring temperate soil-management practices to tropical agricultural systems.

Organic matter and mineralization of organic nitrogen

Although amounts of organic matter and organic nitrogen have been measured and reported in numerous instances, a lack of agreement exists concerning the comparative amounts of organic matter in tropical and temperate soils. Bartholomew (1973) stated that organic nitrogen content is low in tropical soils, while Buol (1973), in the same volume, reported that many well-drained tropical soils have greater organic matter content than do comparable humid temperate soils. He further reported that C/N ratios are usually 10 to 15; thus, a great deal of N is potentially available. Wade and Sanchez (Sanchez, 1976; Sanchez and Buol, 1976) randomly selected 16 soil profiles in the United States, Brazil, and Zaire and found no difference in organic matter concentrations among four major soil orders. Organic nitrogen content of Oxisols and Ultisols in Brazil, Puerto Rico, and Zaire range from 0.07 to 0.3 percent in the plow layer (Sanchez, 1976). Stevenson (1965) and Bremner (1965) stated that organic nitrogen in the plow layer of temperate soils ranges from 0.08 to 0.4 percent. While the controversy over relative organic-matter concentration remains unresolved, a substantial amount of organic N is present in some tropical Oxisols and Ultisols.

Several factors peculiar to the tropics influence mineralization of soil organic nitrogen. Buol (1973) stated that the only parameter common to all tropical soils is a relatively uniform temperate regime. Soil temperatures are always above freezing in arable areas. Consequently, if sufficient water is available, mineralization can occur throughout the year at annual rates that are potentially larger than in temperate regimes (Jenny, 1949).

In an undisturbed system, soil organic nitrogen remains at a steady-state level characteristic of the system. In such a system, the amount of organic nitrogen added annually equals the amount of organic nitrogen mineralized. This equilibrium is disturbed upon cultivation. A new steady state will evolve, at a level characteristic of the cultivated system and generally lower than in the undisturbed system. New steady-state levels are established much more rapidly in some tropical systems under favorable year-long temperature and moisture regimes (Laudelout, undated).

Soil moisture has a marked effect upon nitrogen mineralization. Semb and Robinson (1969) have shown that mineralization occurs even in very dry soils, which means that nitrate accumulates during the dry season. At the onset of the rainy season, however, a large flush of mineralization occurs, and inorganic nitrogen increases dramatically (Wild, 1972; Semb and Robinson, 1969). Birch (1958, 1959) explained that these flushes are

primarily a consequence of active microbial populations which build up rapidly when moisture becomes available. Birch (1958) further reported that mineralization is greater under alternate wetting and drying conditions than when moisture is steady, so that minor droughts within the rainy season further enhance mineralization.

Nitrogen Losses

Conditions in well-drained tropical soils are conducive to nitrogen loss through leaching, which occurs most rapidly in soils of coarse, sandy texture (Englestad and Russell, 1975) and during the rainy season, when rainfall often exceeds evapotranspiration. Nitrate-nitrogen is highly mobile and thus very susceptible to leaching losses. Allison (1966) concluded that leaching is the primary mechanism of nitrogen loss in temperate regions. Wetselaar (1962) reported high correlations between rainfall and nitrogen movement in tropical soils of Australia, and Charreau (1972) showed progressive loss of nitrogen with increased rainfall in West African Ultisols. Gamboa, Paez, and Blasco (1971) reported leaching losses of 65 percent of applied nitrogen in Costa Rican alluvial soils planted in maize.

The significance of denitrification losses in tropical soils is insufficiently documented. Denitrification is primarily affected by oxygen, quantity and type of organic matter, and soil pH (Bremner and Shaw, 1958; Cady and Bartholomew, 1961; Ekpete and Cornfield, 1965; Greenland, 1962; and Stefanson and Greenland, 1970). Greenland (1962) studied denitrification losses from cultivated, grassland, and forest soils in Ghana and reported insignificant nitrogen losses at field capacity. Significant losses occurred only in waterlogged conditions. Dubey and Fox (1974) found significant denitrification losses only from waterlogged surface soils from Puerto Rico. Furthermore, denitrification required an adequate energy supply which they obtained by adding glucose. They found insignificant losses from samples of surface and subsurface soils at field capacity and concluded that surface soils are seldom waterlogged, because they are nearly always well drained. Consequently, large denitrification loss in humid tropical soils is not likely to occur under field conditions.

CROP RESPONSE TO APPLIED N

Yield Response

Field experiments were conducted in Puerto Rico, Brazil, and Ghana on representative Oxisols and Ultisols with the following objectives:

- to estimate the capacity of the soil to supply nitrogen to successive nonleguminous crops,
- to define fertilizer nitrogen response curves,
- to estimate the increase in nitrogen content of above-ground dry matter for each unit of fertilizer nitrogen applied,
- to determine the effects of timing of fertilizer nitrogen application,

• and to compare conventional urea and sulfur-coated area.

In Puerto Rico, five sites were selected for representative soil series, including two Ultisols — Humatas and Torres clays — and three Oxisols — Catalina and Coto clays and Bayamon sandy loam. The experiments in Brazil were conducted on the Oxisol, Latossolo Vermelho Escuro (LVE). In Ghana an Ultisol, Asuansi series, and an Oxisol, Basachia series, were selected. Chemical properties available for six of these soils are presented in table 1. Previous site histories and the number of crops grown at each site are briefly described in table 2.

The details of the experimental procedures are published elsewhere (Fox, Talleyrand, and Bouldin, 1974; Cornell University, 1973, 1974, 1975; NCSU 1973). A brief summary of the salient features of the experiments follows:

— the primary test crop was maize;
— the nitrogen source was urea;
— in most treatments, the bulk of the fertilizer nitrogen was applied as a sidedress approximately 4 weeks after planting, although timing of application was a variable in some experiments;
— nitrogen applications were incorporated into the soil.

All crops responded to applied N with the exception of six crops in Puerto Rico, of which three suffered severe drought and three were affected with a relatively uncommon disease, tar spot (*Phylachora maydis*). The results of these experiments are discussed elsewhere (Fox, Talleyrand, and Bouldin, 1974).

Average yield response curves for maize are presented in figure 1 for Puerto Rico (Fox, Talleyrand, and Bouldin, 1974), Brazil, and Ghana. For purposes of comparison with temperate region results, response curves from New York (Lathwell, Free, and Bouldin, 1966) and Nebraska (Olsen et al., 1964) are included. Yield varied considerably among areas. However, relatively high yields (5 tons/ha) were obtained with fertilization in all locations other than Ghana. The reasons for low yields in Ghana were not completely understood, but the varieties available were not specifically adapted for local conditions. Furthermore, Ghanian crops were routinely heavily infested with pests, particularly with the stem borer (*Eldana saccharina*), during the minor growing season.

Despite the quantitative differences in yield among the various areas, the response curves were qualitatively similar. All showed an initially rapid yield increase at low nitrogen application rates and a typical diminishing response at higher levels. The inflection points occurred in the range 80 – 120 kg/ha applied N. Relative-yield response curves were generally parallel (fig. 2), further emphasizing this similarity. In all areas except New York, 95 percent of maximum yield was obtained in the range 80 – 120 kg/ha applied N. In these same areas, nitrogen fertilization increased yield by 60 to 82 percent, a relatively narrow range. Yield response in New York was limited to a 12-percent increase because of the high yields without fertilizer nitrogen resulting from previous manure applications and legume residues.

Table 1. Chemical properties of highly weathered soils in Brazil, Puerto Rico, and Ghana

Soil designation and location	*Depth of sample*	*Sand*	*Silt*	*Clay*	*C*	*N*	*Exchangeable cations*				*pH*	
							Ca+Mg	*K*	*Al*	*Σ*	*H_2O*	*KCl*
	cm	*percent*					*me/100 g*					
Latossolo Vermelho* Escuro; Planaltina, D. F., Brasil	0–10	36	19	45	1.8	0.21	0.4	0.10	1.9	2.4	4.9	4.2
	10–35	33	19	48	1.2	0.08	0.2	0.05	2.0	2.2	4.8	4.3
	35–70	35	18	47	0.9	0.05	0.2	0.03	1.6	1.8	4.9	4.2
	70–150	35	18	47	0.7	0.05	0.2	0.01	1.5	1.7	5.0	4.4
Catalina clay† Torrecillas, Puerto Rico (S59PR-10-7)	0–15	6	18	76	3.8	0.32	6.8	0.3	0.3	7.4	5.1	4.3
	15–35	5	13	82	1.2	0.14	1.9	0.1	0.7	2.7	4.8	4.2
	35–55	4	14	82	0.9	0.11	1.6	0.1	0.7	2.4	4.9	4.2
	55–80	5	20	76	0.6	0.08	1.0	–	1.3	2.3	5.0	4.0
Humatas clay† Oeste SCD, Puerto Rico (S61PR-8-1)	0–10	6	29	65	4.9	0.43	3.9	0.4	4.0	8.3	4.6	3.9
	10–22	2	28	69	2.0	0.21	3.5	0.1	5.4	9.0	4.7	3.7
	22–38	3	34	63	1.2	0.12	3.7	0.1	4.5	8.3	4.9	3.8
	38–62	6	46	48	0.6	0.07	1.6	0.1	7.0	8.7	5.0	3.8
	62–80	11	50	39	0.4	0.05	1.0	0.2	9.1	10.3	4.9	3.8
Coto clay† Noroeste SCD, Puerto Rico (S63PR-6-1)	0–13	22	7	71	2.4	0.25	4.5	0.4	0.6	5.5	4.1	4.8
	13–25	22	7	71	1.7	0.20	2.6	0.1	1.4	4.1	3.9	4.5
	25–43	19	5	76	1.0	0.14	1.6	0.1	1.6	3.3	3.9	4.5
	43–64	14	6	80	0.6	0.13	4.3	0.1	0.9	5.3	4.1	4.6
	64–91	11	7	82	0.5	0.11	4.3	0.1	—	—	5.5	5.9
Pina†, Norte SCD Puerto Rico (S63PR-7-1)	0–20	19	8	73	2.7	0.23	10.2	0.6	—	—	4.9	5.6
	20–46	12	6	81	0.9	0.14	5.8	0.6	0.3	6.7	4.7	5.4
	46–69	9	5	86	0.6	0.11	6.5	0.4	—	—	5.4	5.9
	69–99	6	5	90	0.4	—	7.8	0.1	—	—	5.2	5.6
Kumasi series‡ Kwadaso Central Station, Ghana	0–7	60	13	27	4.6	.29	5.8	0.2	—	—	4.4	—
	7–11	76	9	15	1.1	.07	1.1	0.1	—	—	4.6	—
	11–18	64	11	25	0.6	.05	.7	0.04	—	—	4.5	—
	23–46	43	12	45	0.6	.06	.7	0.05	—	—	4.7	—
	87–114	36	18	44	0.4	.02	.8	0.01	—	—	5.1	—

Sources:
* Equipe de Pedologia e Fertilidade do Solo, 1966.
† Soil Conservation Service, 1967.
‡ Soil Research Institute, unpublished data.

Table 2. Number of crops and previous land use at experimental sites

Soil series	*Number of maize crops*	*Previous land use*
Puerto Rico		
Humatas clay	2	Improved, fertilized pasture, several years
Catalina clay	1	Continuous food crop cultivation, 30 years
Coto clay	1	Exposed subsoil, 10 years fallow
Bayamon sandy loam	1	Previous pineapple research field, 2 years fallow
Brazil		
Latossolo Vermelho Escuro	6	Virgin cerrado
Ghana		
Asuansi series	3	Continuous food crop cultivation, several years
Basachia	2	Second growth tropical forest, 10 years

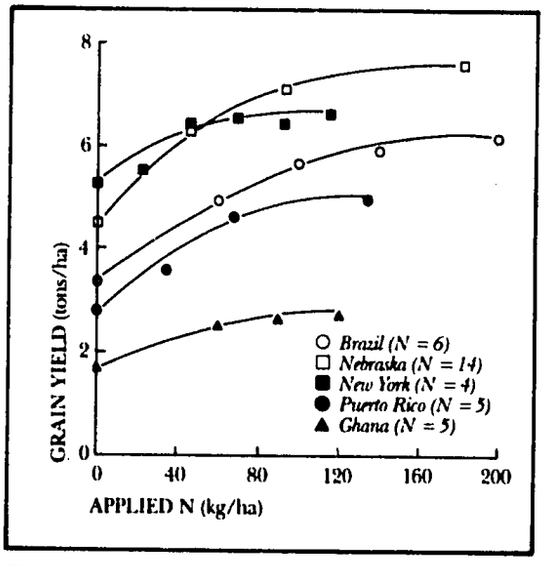

Figure 1. Average effect of fertilizer N on maize yield.

In Puerto Rico, the yield responses of sorghum and maize were similar. The response curve (fig. 3) shows 95 percent maximum yield at approximately 100 kg/ha applied N.

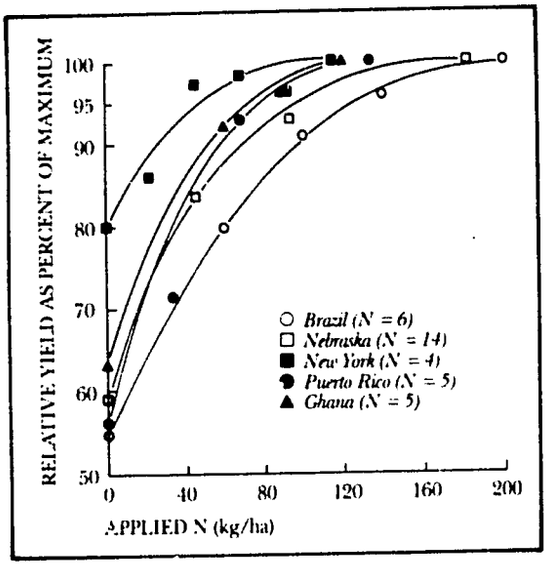

Figure 2. Average effect of fertilizer N on relative maize yield.

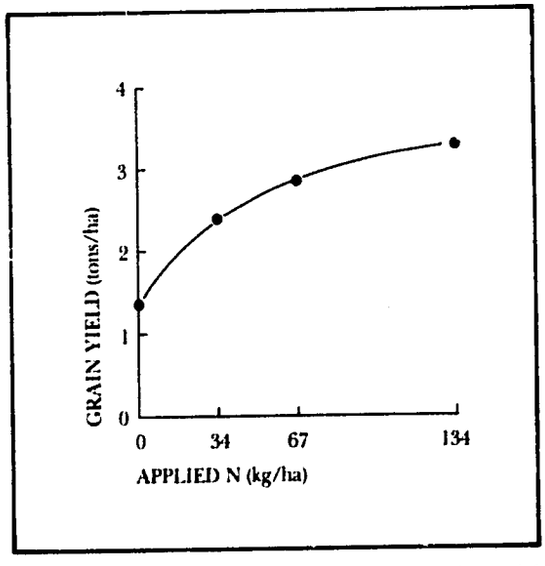

Figure 3. Average effect of fertilizer N on sorghum yield in Puerto Rico (N = 2).

Root crops appeared to be more variable than grain crops in response to nitrogen fertilization. Cassava grown in Puerto Rico (Fox, Talleyrand, and Scott, 1975) and Chana showed a yield response much like that of grain (fig. 4). Irish potatoes (fig. 5) and sweet potatoes (fig. 6) responded sharply to lower levels of applied N: 95 percent maximum yield occurred at 50 kg/ha applied N with Irish potatoes and 35 kg/ha with sweet potatoes.

Yield response to applied nitrogen did not differ significantly between temperate and tropical areas. Quantitative differences did occur in check-plot yield and absolute magnitude of response, but relative responses were similar among all locations.

Nitrogen Recovery

Nitrogen contents of above-ground dry matter in maize for Puerto Rico (Fox, Talleyrand, and Bouldin, 1974), Brazil, New York (Lathwell et al., 1966), and Nebraska (Olson et al., 1964) are presented in figure 7. As with yield, nitrogen content increased with fertilization similarly at all locations. Despite quantitative differences, the N-content curves increased in parallel. Mean nitrogen content in check plots ranged from 64 kg/ha in Puerto Rico and Brazil to 117 kg/ha in New York.

Apparent N recovery (fig. 8) was defined as nitrogen in above-ground dry matter in excess of that in the check plots. The relationship between apparent N recovery and applied N appeared identical for all locations, both temperate and tropical. Mean recovery rate of fertilizer N for the

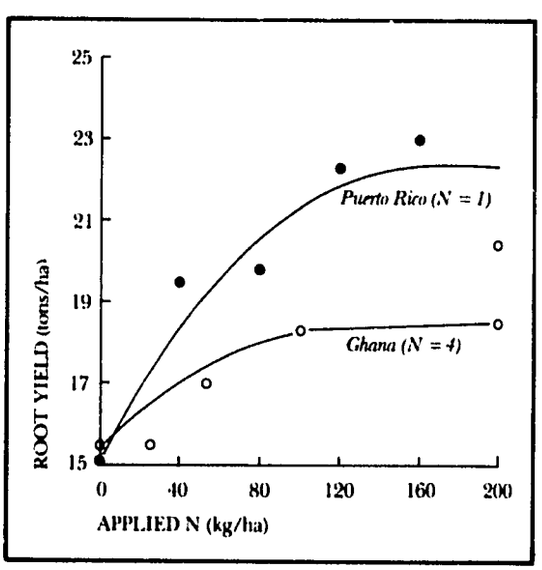

Figure 4. Average effect of fertilizer N on Cassava yield.

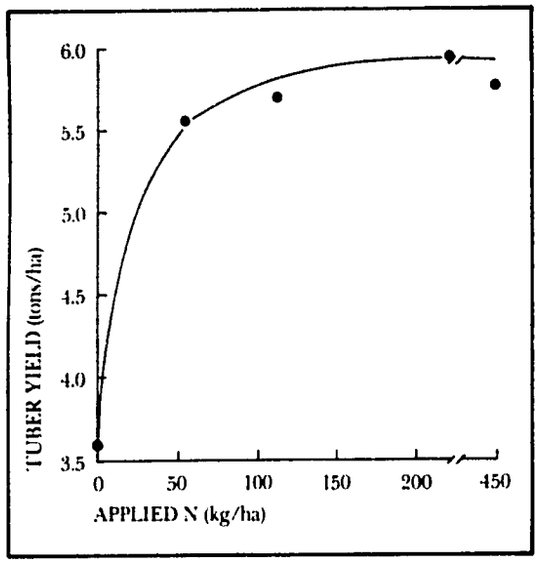

Figure 5. Average effect of fertilizer N on Irish potato yield in Puerto Rico (N = 2).

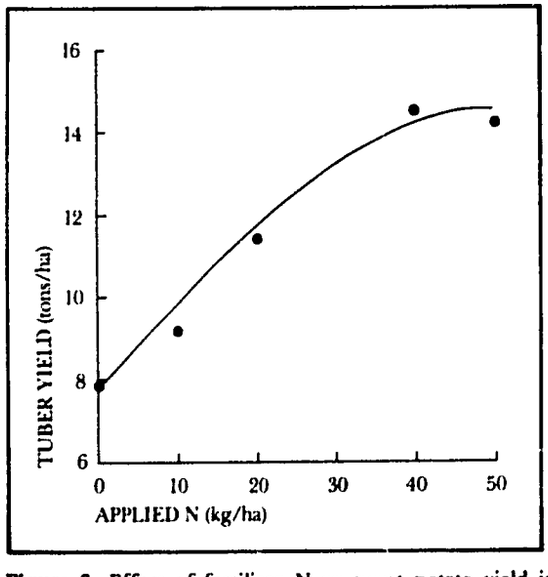

Figure 6. Effect of fertilizer N on sweet potato yield in Puerto Rico (Talleyrand and Lugo-Lopez, 1976).

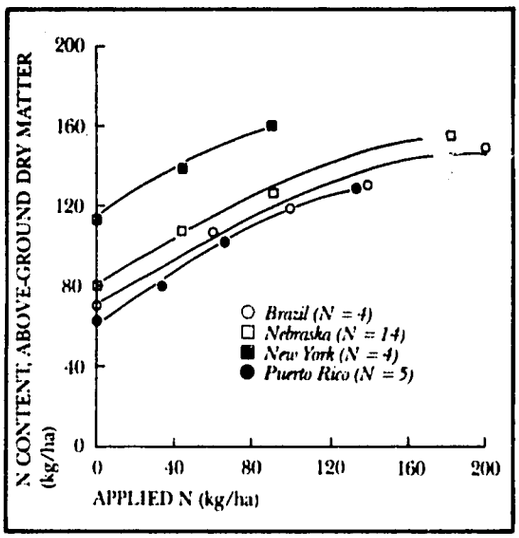

Figure 7. Average effect of fertilizer N on the N content of above-ground dry matter in maize.

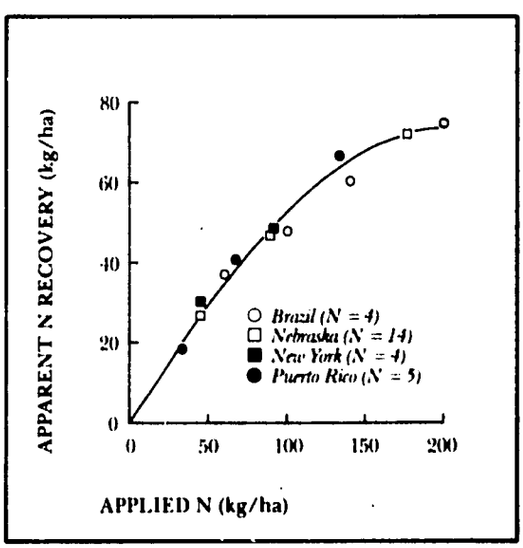

Figure 8. Effect of fertilizer N on apparent N recovery in maize.

range 60–120 kg/ha was 56 percent. Maximal recovery of 60 percent occurred at about 60 kg/ha applied N. Recovery percentages diminished at higher levels of application and fell below 50 percent at application rates in excess of 120 kg/ha.

The concentration of soil organic nitrogen in unfertilized plots did not change significantly during the experiment (fig. 9) even though 384 kg N were removed in above-ground dry matter. Apparently, the amount of organic nitrogen mineralized was sufficiently small, relative to experimental error, that changes were undetectable. Mean concentration of soil organic nitrogen (0.124 percent N) in fertilized treatments (sampled in 1975 and 1976) was similar to that in check plots.

TREATMENT METHODS

Timing and Placement

Temperate-region research has demonstrated (Olson et al., 1964; Lathwell et al., 1966) that greater nitrogen recovery and increased yields result when fertilizer nitrogen is applied to corn as a sidedressing than when it is broadcast before planting. Fox et al. (1974) reported similar results in Puerto Rico (fig. 10 and 11). To obtain 90 percent maximum yield (4.5 tons/ha), 120 kg/ha of applied N were required in broadcast applications, whereas only 60 kg/ha were needed in sidedressings applied about 4 weeks after planting (see fig. 10).

Proper timing of application holds the most promise for influencing the recovery efficiency of fertilizer N (Lathwell, Bouldin, and Reid, 1970; Bouldin and Selleck, 1977). The longer fertilizer N remains in the soil, the

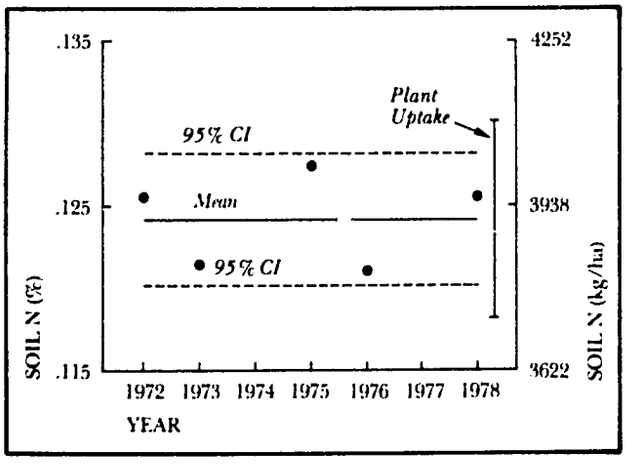

Figure 9. Content of soil nitrogen in check plots for 6 crop years in Brazil. Range of total plant uptake is indicated for reference.

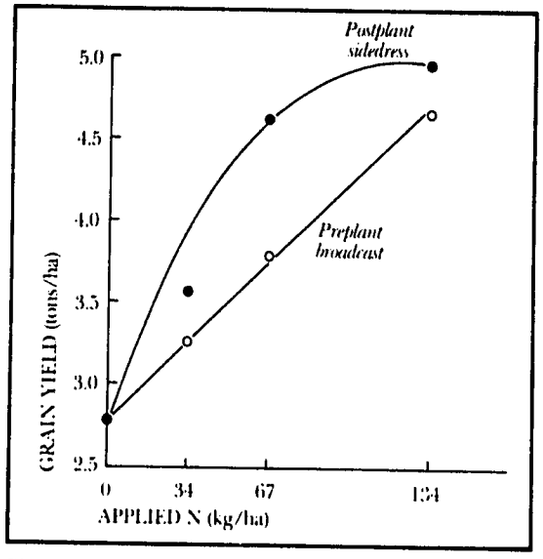

Figure 10. Average effect of fertilizer N on maize yield in Puerto Rico, postplant sidedress vs. preplant broadcast application.

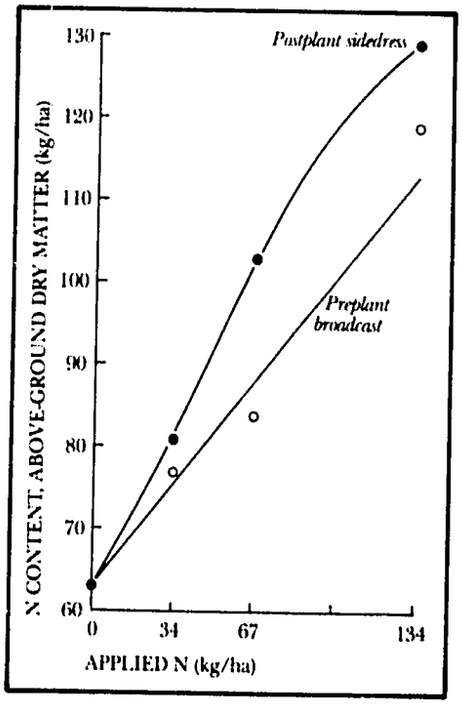

Figure 11. Average effect of fertilizer N on N content of above-ground dry matter of maize in Puerto Rico, postplant sidedress vs. preplant broadcast application.

greater the probability of loss; less N, therefore, will be lost if it is applied at the time of maximum uptake by the crops. With proper timing of application, the amount of N required for any given yield is reduced.

This reduction is not only economically desirable, but it alleviates a potential source of environmental pollution. Because of its high solubility, soil nitrate is almost completely dissolved in the soil water. Consequently, nitrate will move wherever the soil water moves, so that when leaching occurs, nitrate enters the ground and stream water. The potential for perturbation of watersheds from nitrate addition is particularly significant in the tropics. Deevey (1957) noted that N/P ratios in Central American lakes were lower than in temperate zones by a factor as great as 5. He suggested that nitrogen deficiency may be general in the tropics and that eutrophication may result from increased nitrogen addition. Thus, proper timing and level of fertilization reduce potential environmental damage.

Source Material

Leaching appears to be the most probable mechanism of nitrogen loss in well-drained tropical soils. One might expect that a slow-release fertilizer, such as sulfur-coated urea, would reduce leaching losses and result in greater fertilizer-nitrogen recovery in crops. Experiments with maize conducted in Puerto Rico (Fox, Talleyrand, and Bouldin, 1974) and Brazil, however, demonstrated that urea produced superior yield and greater nitrogen recovery than either sulfur-coated urea or lime-coated ammonium nitrate (table 3).

Table 3. Grain yield and nitrogen recovery of maize with various sources of fertilizer N

Location and source	*Application rate*	*Mean grain yield*	*Mean nitrogen content of above-ground dry matter*	*Number of crops*
	kg/ha	*tons/ha*	*kg/ha*	
Puerto Rico				
Urea	67	4.6	103	5
SCU*	67	3.8	86	5
Brazil				
Urea	140	6.0	99	3
SCU	140	5.4	90	3
Lime-NH_4NO_3†	140	5.6	90	3

Source: Fox, Talleyrand, and Bouldin, 1974.
* Sulfur-coated urea.
† Lime-coated ammonium nitrate.

Residual Effects

Maize experiments in Puerto Rico reported by Fox et al. (1974) showed that previous N applications had little residual effect on crop yield or N uptake. In Brazil, results were ambiguous (table 4). The 1975–76 crop showed little residual effect. Yield and nitrogen uptake were similar in the check plots and in the plots that had previously received 520 kg/ha N. Significant effects were observed in the 1976–77 crop. The plots to which nitrogen had previously been applied produced greater yield and N uptake than the check plot. However, the mean check-plot yields were significantly lower than those of the preceding four crop years of the experiment. The fertilized plots, however, produced yields comparable to those of previous years at all levels of fertilization. In general, significant residual effects from inorganic nitrogen are not likely, because excess N from previous treatments is apt to have leached beyond the root zone. Higher rates of fertilization increased the organic nitrogen content in the returned residues, which may explain results of the 1975–76 crop year shown in table 4.

Crop Residue Effects

Talleyrand, Perez-Escolar, Lugo-Lopez, and Scott (1977) have reported on crop rotation experiments designed to evaluate the N supplied by crop residues to succeeding crops. Field experiments were conducted on three Puerto Rican soils. Three rotations were used in main plots: soybeans, corn, corn; fallow, corn, corn; and continuous corn. Substantially higher yields were obtained in the Bayamon and Humatas soils from the corn crop that followed soybeans or corn than one that followed fallow, but no statistical relationship was evident between the total N returned to the soils from the residues and yields of subsequent crops.

Table 4. Residual N effects measured according to grain yield and nitrogen recovery in maize

Year	*Previous N application*	*Grain yield*	*Nitrogen in above-ground dry matter*
	kg/ha	*t/ha*	*kg/ha*
1975–76	0	3.9	74
	520*	4.2	81
1976–77	0	1.9	39
	560†	4.4	94

* Applied over 3 years and 3 crops before current crop. Current crop received no N fertilization.

† Applied over 4 years and 4 crops before current crop. Current crop received no N fertilization.

MANAGEMENT RECOMMENDATIONS

Estimating Fertilizer Nitrogen Needs

The practical value of a method for estimating soil nitrogen availability and the consequent ability to predict fertilizer N requirements has long been recognized. Bremner (1965) has reviewed the extensive literature on nitrogen availability indices. Incubation and chemical extraction procedures continue to appear in the literature (Keeney and Bremner, 1966a, 1966b; Ryan, Sims, and Peaslie, 1971; Smith and Stanford, 1971; Stanford, 1968; Stanford and Legg, 1968; and Lathwell, Dubey, and Fox, 1972). Several of these methods have been related to plant N uptake in the greenhouse. However, calibration of laboratory indices with field production of crops has been unsatisfactory. Consequently, no simple reliable method is available for predicting nitrogen fertilizer needs from laboratory analyses of soil samples.

Stanford (1973) proposed a technique for estimating the fertilizer nitrogen requirements of field crops using the following equation:

$N_f = (N_y - N_s)/E_f$, where

N_f = fertilizer N required,

N_y = the quantity of nitrogen that must be accumulated in above-ground dry matter to attain desired yield,

N_s = N supplied from the soil, and

E_f = the increase in nitrogen content of above-ground dry matter per unit of fertilizer N applied.

The above equation contains several approximations, but the utility of the concept has been demonstrated in several situations. This equation will be used as a basis for the following discussions, and its application will be illustrated with maize data.

The parameter N_y is estimated from the empirical relationship between yield and nitrogen content of the plant. This relationship has been determined for a number of crops including sugar cane (Stanford and Ayres, 1964), maize (Stanford, 1973), paddy rice (Sanchez, Ramiriz, and de Calderon, 1973), wheat (Stanford and Hunter, 1973), sugar beets (Carter, Jensen, and Bosma, 1974), and white potatoes (Meisinger, 1976). Figure 12 illustrates the relationship between grain yield and N content of the above-ground dry matter in maize. This figure was derived from more than 300 data points, and the three correlation coefficients ranged from 0.81 to 0.89. For practical purposes, the relationship between the data from Puerto Rico and Brazil was the same as that of the data from the southeastern United States, New York, and CIMMYT. The relationship from Nebraska and California, however, differed substantially. This difference demonstrates the necessity to assure that available data is appropriate to the varieties and environmental conditions under consideration when estimating N_y. The conclusion drawn from these data is that one can use field data to estimate the nitrogen required (N_y) to produce a specific yield. The value of N_y (used to predict fertilizer requirements) is primar-

ily fixed by expected yield potential. However, it can be adjusted for economic factors and for the effects of variety, management practices, and soil or climatic variables.

The parameter N_s is estimated in one of two ways. First, the mean N content of the above-ground dry matter of crops grown on field plots that receive no nitrogen fertilizer provides a direct estimate of N_s. Second, if the N-content – yield relationship is known, then N_s can be extrapolated from grain yields on field plots that received no nitrogen fertilizer.

The use of N_y and N_s to predict fertilizer N requirements is illustrated in figure 13. Nitrogen content of the above-ground dry matter is plotted against grain yield. The relationship between N content and yield for maize is represented by the regression line. As illustrated by the dotted line, expected yield of 6.5 tons/ha maize grain requires 150 kg/ha N content in the plants = N_y. Similarly, without fertilizer nitrogen, yield of 1.8 tons/ha maize grain requires 50 kg/ha N content in the plants = N_s. The difference, $N_y - N_s$, of 100 kg/ha N must be supplied to the plants by fertilizer.

The parameter E_f is often termed "the fertilizer efficiency factor" and is equal to the increase in nitrogen content in the above-ground dry matter

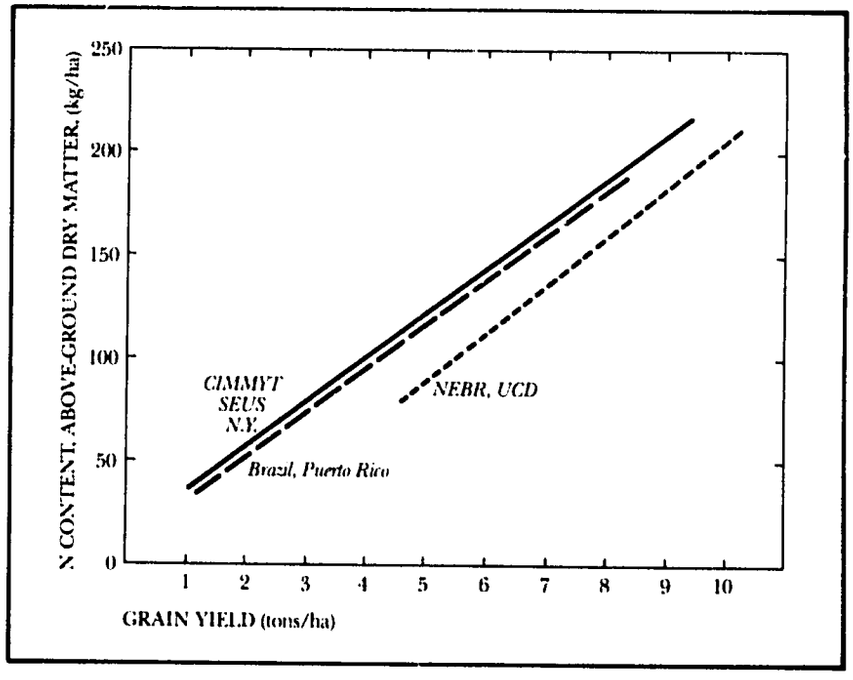

Figure 12. Relationships between maize grain yield and nitrogen content of above-ground dry matter in several geographic areas.

per unit of applied fertilizer. Mean E_f was estimated (fig. 8) as 0.56. When this efficiency value is entered in the example, the following solution results:

$$N_f = (N_y - N_s)/E_f$$
$$N_y = 150 \text{ kg/ha N}$$
$$N_s = 50 \text{ kg/ha N}$$
$$E_f = 0.56 \text{ kg/ha N.}$$

Therefore,

$$N_f = (150 - 50)/0.56 \text{ kg/ha N}$$
$$= 178 \text{ kg/ha N.}$$

Consequently, applying 178 kg/ha of fertilizer N is required to obtain a yield of 6.5 tons/ha maize grain.

Expected yield is a primary variable in estimating fertilizer N requirements. The yield potentials of many crops are well known. The genetic yield potentials of several varieties of maize were well documented in Puerto Rico, Brazil, and the United States with mean yields in excess of 5 tons/ha. The variety must be matched to the local edaphic and climatic conditions to attain the yield potential. The percentage of yield potential that can be obtained depends in part on the level of fertilizer applied.

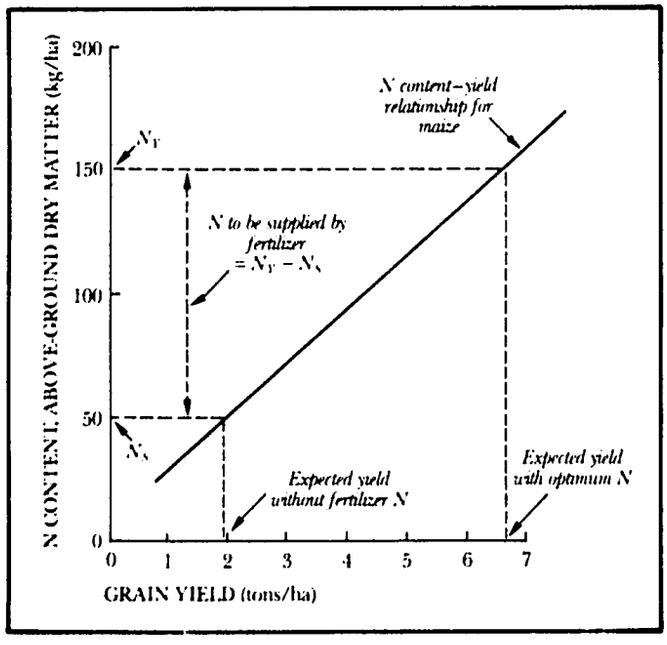

Figure 15. Illustrative example for determination of fertilizer N requirements.

Yield response diminishes as optimum yield is approached. The economic value of both unit yield (output) and unit fertilizer additions is fixed. The economic optimum, therefore, may occur at lower levels and is a direct function of the economic input–output ratio.

If, in a given circumstance, estimates of N-content–yield relationships or soil nitrogen supplies are unavailable, then initial fertilizer applications can be based upon results such as those presented in this paper. N applications of 80 to 120 kg/ha at several diverse locations resulted in 95 percent maximum yield. Maximum N recovery was obtained within the same range. Applying fertilizer nitrogen within this range would probably assure high yields while appropriate data are being collected to provide more precise estimates of fertilizer requirements.

Yield Variability

In this discussion, we have identified the need for collecting field data to estimate fertilizer nitrogen requirements. The variability in this data must be considered when making such estimates. Check-plot yields varied among locations in Puerto Rico by a factor of 3. Consequently, field experiments may be required at several locations. Uncontrolled and often unidentified variables cause substantial variation in results from field experiments. Fox et al. (1974) reported no response in six of eleven crops grown in Puerto Rico. Check yields from a single location in Brazil varied by a factor of 2.2.

Figure 14 illustrates the variability of the Brazilian field experiments. In general, parallel changes were observed in maximum yields, yields at the application rate of 60 kg/ha, and check yields. However, yields at all

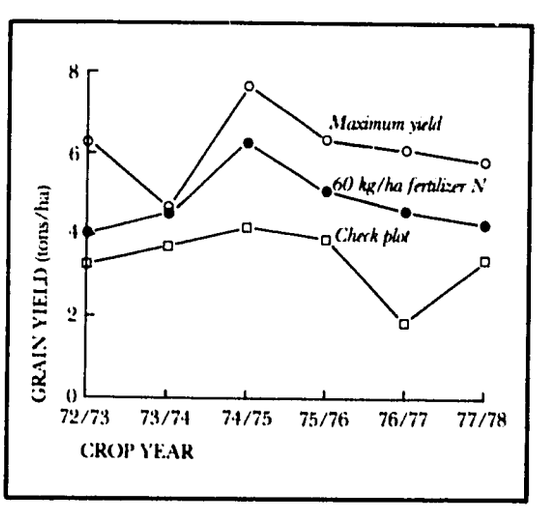

Figure 14. Maize grain yields at three treatment levels for 6 crop years in Brazil.

fertilization levels showed a nearly twofold variation. The results from the 1973–74 or 1976–77 crops, if considered singly, would lead to different estimates of fertilizer requirements. In 1973–74, no additional yield response was observed at fertilization levels in excess of 60 kg/ha. Yield potential and N_y would be grossly underestimated, if only that year's data were considered. During 1976–77, the check yields were depressed, whereas yields on fertilized plots were maintained. N_s would also be underestimated, if only that year's data were considered. The solution to the variability problem is to gather several crop years of data, thereby allowing more precise estimates of variance.

Several strategies are possible for choosing fertilizer application rates that take into account the variable response to fertilizer nitrogen. Using an average response curve is one possible technique. Table 5 compares yields of maize in Brazil in each of 6 crop years and total yields over 6 years. The comparison is between the expected yields at two fertilizer application rates: the amount of fertilizer N required to produce 95 percent of average maximum yield, and the amount needed to produce 95 percent of the maximum yield for that year. In effect, prior knowledge of the response curve each year would reduce fertilizer use by 80 kg over 6 years, an average of 13 kg per year. In addition, a 10-percent increase in fertilizer "efficiency" (i.e., kg grain per kg fertilizer N) would occur. Thus the "cost" of using averages is not excessive in the long term. In fact, it may be the only reasonable alternative, since predictions of climate and other uncontrollable variables cannot be made with any degree of success.

Table 5. Comparison of maize grain yields in Brazil when fertilizer N application rates are estimated from individual crop response curves and when they are estimated from mean response curve

Year	*95% maximum yield*	*Fertilizer N required to attain 95% maximum yield*	*Predicted yield at 112 kg/ha fertilizer N**
	kg/ha		
1972–73	5,944	118	5,800
1973–74	4,406	36	4,600
1974–75	7,315	116	7,200
1975–76	6,032	80	6,000
1976–77	5,804	122	5,800
1977–78	5,250	120	5,300
Total	34,578	592	34,700

*112 kg/ha N is mean fertilizer nitrogen level required to produce 95% mean maximum yield when based on mean response curve. 6 crops × 112 kg/ha/crop = 672 kg N total fertilizer application.

Treatment Methods

The advantages of postplant sidedressing of fertilizer N are well documented. This method increases yield, nitrogen uptake, and recovery efficiency (E_f). In general, the effects of sidedressing will be maximal if the bulk of the fertilizer is applied just before the period of maximum plant uptake; application at other times is considerably less efficient. Increased fertilizer efficiency is also improved by incorporating ammonium sources to prevent ammonia volatilization. These losses are likely to be most serious with urea on all soils and with other ammonium sources on high pH soils. The simple expedient of covering urea with soil during application will increase fertilizer efficiency.

Slow-release fertilizers appear to offer no advantage in well-drained soils. The choice of N fertilizers should not be based upon release rate.

ACKNOWLEDGEMENTS

Several of the active researchers are identified in the literature citations. However, among the many additional persons instrumental in planning, initiating, and executing these studies, we especially thank Elmar Wagner, Wenceslau Goedert, and Edson Lobato of Centro de Pesquisa Agropecuaria dos Cerrados; Henry Obeng, Charles Ofori, and Peter Kwakye of the Soil Research Institute; Jose Vicente-Chandler and Mario Perez-Escolar of the University of Puerto Rico; Carlos Valverde of the Ministerio de Agricultura de Peru; John Malcolm of USAID; Charles McCants, Pedro Sanchez, and John Nicholaides of North Carolina State University; and Matthew Drosdoff and Marlin Cline of Cornell University. The interests of Cornell and North Carolina State Universities were ably represented by the field project leaders, Richard Fox in Puerto Rico, George Naderman and Dale Ritchey in Brazil, Amos Ngongi in Ghana, and Dale Bandy in Peru.

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