

**Objective 2:** Improve the diagnosis and recommendations for acidity and nutrient problems by identifying and resolving knowledge gaps through extensive literature reviews and, when necessary, developmental research.

*Output 1* Enhancing the knowledge base for the acidity decision support system - collecting, developing and synthesizing soil, plant and management information to improve the diagnosis and recommendations of location-specific problems related to the soil acidity syndrome.

The current knowledge base on acidity in NuMaSS does not predict the rate of movement of basic cations into acid subsoils from surface-applied liming materials. This limits our ability to recommend management strategies for alleviating acidity constraints below the depth of lime incorporation, or properly accounting for the economic value of improved crop rooting depth as lime reaction products move into the subsoil. The introduction and movement of Ca and Mg into subsoils is a major consideration for sustained productive use of the acid, sandy soils in the African Sahel. The acidity knowledge base needs to be expanded to evaluate soil conditions with limited Ca and/or excess Mn. The consequences of using lime materials low in Mg on soil Mg availability also need to be added to the acidity module knowledge base.

Funding for all activities for improving the acidity module knowledge base is provided through the end of the year 3, but completion dates extend through year 4. Investigations related to basic cation (lime) movement were funded during years 1 and 2, but information continues to be collected in subsequent years. Investigations related to Ca and Mg deficiencies and/or Mn toxicity continue through year 3 in the Sahel and year 4 elsewhere.

#### Lead Investigators and Contributors

Jot Smyth (N.C. State) provides overall coordination to activities related to the acidity module. Investigations on basic cation movement prediction parameters are under the direction of David Bouldin (Cornell) and Anthony Juo (Texas A&M) directs field and lab work on this task in the Sahel. Nguyen Hue (Hawaii) and Smyth provide direction to lab, greenhouse and field investigations in Costa Rica and the Philippines related to diagnosis of Ca and Mg deficiencies, Mn toxicity, and lime equivalence of organic inputs. All team members are involved in efforts to review and assemble pertinent knowledge in the published and “grey” literature. Additional contributors to this output during year 3 are listed according to their respective institutions: University of Costa Rica/Costa Rica - Alfredo Alvarado, Rafael Salas, Lidieth Uribe and Eloy Molina

Institut d’Economie Rurale/Mali - Mamdou Doumbia (Sotuba Station); Zoumana Kouyate and Adama Coulibaly (Cinzana Station)

Texas A&M University - Yuji Nino graduate student

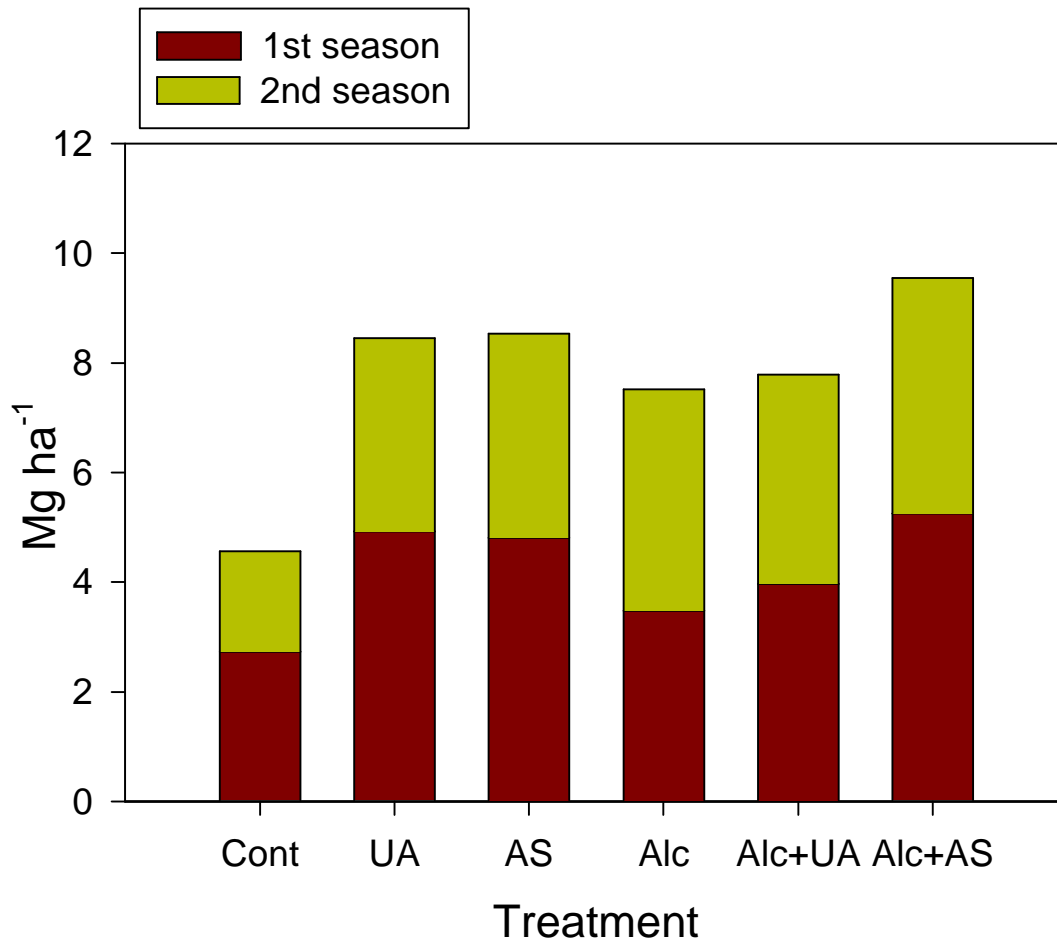
IITA/Nigeria - G. Tiau

#### Progress

1. *Movement of Ca and Mg in a Kaolinitic Alfisol under maize in the humid tropics* - (conducted by Yuji Nino of Texas A&M and G. Tian of IITA with support from A. Juo and Frank Hons from Texas A&M) This study was conducted in Ibadan, Nigeria to determine the extent of acidification due to N fertilization and movement of cations (Ca and Mg) displaced from the surface layers of an Oxic Paleustalf (Egbeda series). The N sources included two inorganic N fertilizers, urea (UA) and ammonium sulfate (AS), and one green manure, *Alchornea cordofolia* (Alc). The decline in surface soil pH after one year of cropping (2 seasons) followed the order of AS>(AS+Alc)>UA. (UA+Alc)>Alc>Control. The pH (H<sub>2</sub>O)

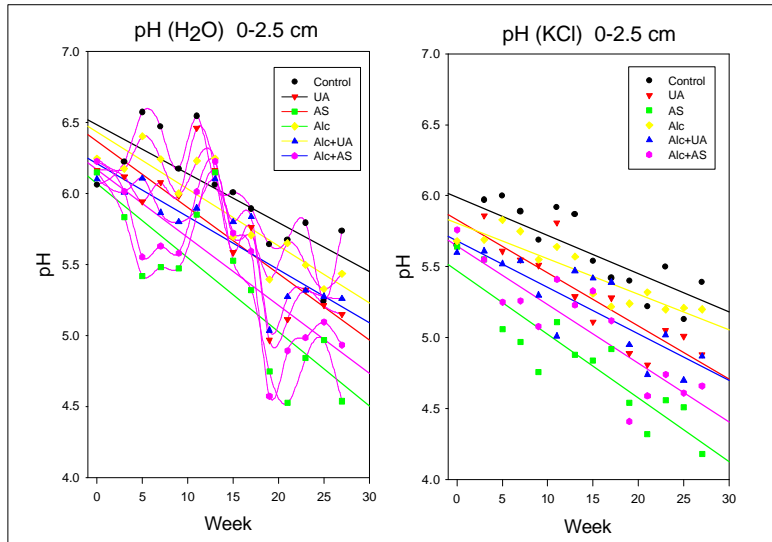
of the AS treatment decreased from 6.2 to 4.5. Acidity induced by inorganic fertilizers decreased exchangeable Ca and Mg in the surface soils. Magnesium leached more rapidly than Ca. Addition of organic input retarded the leaching of Ca, Mg, and NO<sub>3</sub>-N.

**Results** - Maize grain yield is shown in Fig. 1. Both organic and inorganic N inputs gave significantly higher grain yields than the control for both seasons. The combination of AS+Alc treatment gave the highest grain yield. The yield response due to the three N sources were not statistically significant. The second season maize yield from the AS treatment was not affected even though soil pH was lowered to 4.5.



**Figure 1.** Maize grain yields during the main and minor seasons in 1999

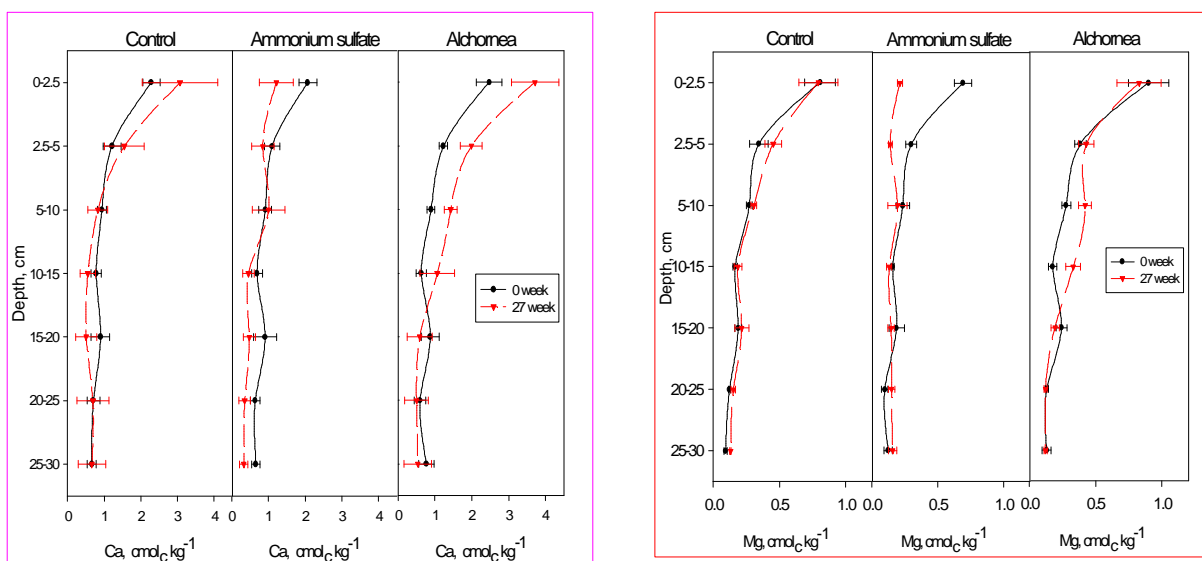
Changes in surface soil pH (0-2.5 cm) after application of different N sources are shown in Fig. 2. The pH (H<sub>2</sub>O) of the AS treatment decreased from 6.2 before planting to 4.5 after two cropping seasons. Soil acidification among the different treatments followed the order of AS>Alc+AS>UA. Alc+UA>Alc>Control. In the subsequent depths up to 30 cm, the treatment effects were significant in each depth. Control and Alc plots showed the least decrease in pH. Changes in pH due to AS was significantly different from other treatments in 0-20 cm (p=.05).



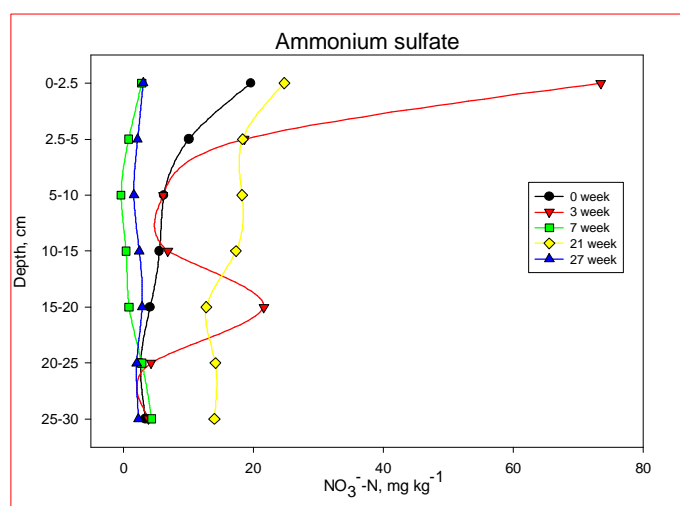
**Figure 2.** Changes in surface soil pH (0-2.5 cm) after application of different N sources.

The amounts of exchangeable Ca and Mg at different depth at the beginning and the end of the cropping season are shown in Fig. 3. Acidity induced by inorganic fertilizers significantly decreased exchangeable Ca concentration, especially in the 0-2.5 cm and 2.5-5 cm depths. The Alc treatment increased exchangeable Ca in the surface 5 cm layer. Changes in exchangeable Mg showed a similar trend as that of Ca. Vertical distribution of exchangeable Ca and Mg data from soil samples taken at 3 and 5 WAP (not shown), indicating more rapid leaching of Mg than Ca. Nitrate N movement (Fig. 4) corresponded with Ca and Mg movement. Increase of exchangeable Ca in the surface layer in the control treatment may be due to P fertilizer (TSP) application and organic matter decomposition.

Conclusions - This study showed that rapid acidification occurred in kaolinitic Alfisols as a result of N fertilizer applications. Incorporation of Alchornea residue retarded the rate of acidification and helped prevent rapid leaching of Ca, Mg, and  $\text{NO}_3^-$ -N during cropping.



**Figure 3.** Amounts of exchangeable Ca and Mg at different depths at the beginning (week 0) and the end of the cropping seasons (week 27).



**Figure 4.** Nitrate N movement with time and depth.

- Calcium and Magnesium Movement in Sandy and Clayey Millet Soils of the Sudano-Sahelian Region** - (supervised by Adama Coulibaly, M.D. Doumbia, Aminata Sidibi, A. Bagayokol, M.A. Diarra, and J. Keita of IER, Mali with support from Lloyd Hossner and Frank Hons) An increase in the acidity of soils in pearl millet (*Pennisetum glaucum* (L. Br.) growing areas of the Sudano-Sahelian Zone of Mali is a major threat to the sustainability of agricultural production and subsequently to the food security of the entire region. Potential sources of soil acidification include continuous cropping of dryland cereal (in most cases millet and commonly over 35 years), return of little or no crop residue, an extreme decline in soil organic matter content, eolian and water erosion of soil, and the lack of appropriate management techniques. Pearl millet ranks as the staple cereal in Mali with an average

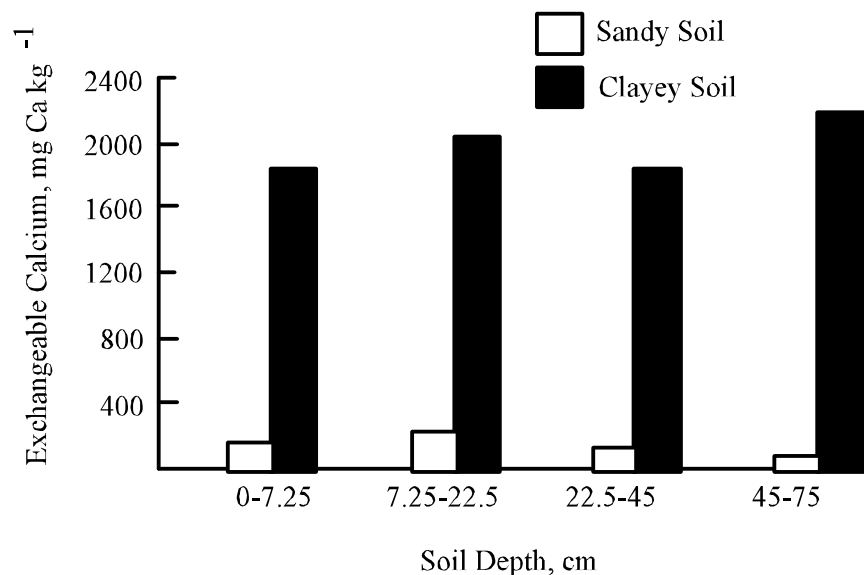
consumption rate of 86 kg per capita per year. Approximately 1.7 million hectares are devoted to millet production with low yields in the range of 450 to 735 kg ha<sup>-1</sup>. Low crop yield performance in the Sudano-Sahelian region are usually associated with soils that are chemically characterized by limited organic matter content, low pH, low buffer capacity, and low effective cation exchange capacity (ECEC). Management techniques to alleviate aluminum (Al), manganese (Mn), and iron (Fe) toxicities in acid soils and increase exchangeable calcium (Ca) and magnesium (Mg) for millet farmers are not commonly practiced. Local materials (sources of Ca and Mg) with some liming potential are available in Mali. This study focused on evaluating selected physical and chemical properties of different sources of locally available potential lime materials and their effect on soil properties and subsequent grain and stover yields.

Locally available materials included in the study were ash from millet stover, poultry manure, farm manure (cow and small ruminants), profeba (a locally manufactured organic manure mixed with an imported active ingredient), gypsum, Diamou lime, Telemsi natural rock phosphate, and guala. Selected physical characteristics of the local Ca source materials are in Table 1. Among all sources, Diamou lime had the highest percentage of CaCO<sub>3</sub>. The lowest CaCO<sub>3</sub> equivalent was associated with the ash, gypsum, poultry and farm manure, profeba, and the TPR. Although the guala has 27.7% Ca, the Ca is not present as CaCO<sub>3</sub>. Materials such as lime, Telemsi rock phosphate, and ash had pH values greater than 9.0. The pH of lime, poultry manure, and farm manure was not affected by particle size, however, high pH values were associated with the finest particle fractions of the profeba, ash, and Telemsi rock phosphate. The highest P contents were associated with the Telemsi rock phosphate and the poultry and farm manures and the least from the ash, guala, lime, and the gypsum.

Table 1. Some chemical characteristics of locally available calcium sources in Mali.

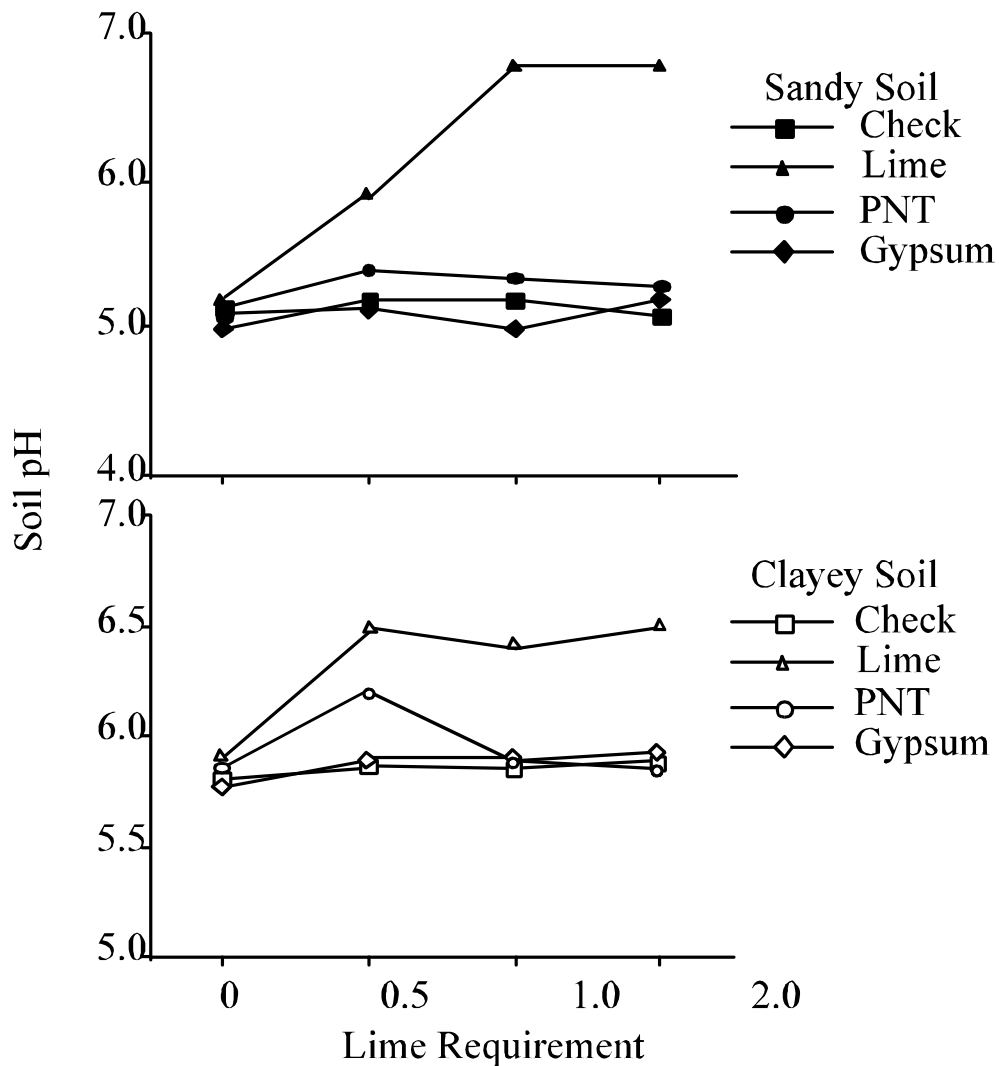
Material	pH	N	P <sub>2</sub> O <sub>5</sub>	Ca	Mg	K	CaCO <sub>3</sub>
		----- % -----					
Ash	10.6	0.26	0.53	0.25	0.93	1.54	1.8
Poultry Manure	7.2	3.76	4.74	1.93	0.40	1.16	1.4
Farm Manure	7.7	1.97	2.24	0.44	0.94	1.93	0.1
Profeba	7.4	1.63	2.36	0.16	0.31	0.52	0.0
Gypsum	8.2	0.00	0.03	26.70	0.36	0.08	2.0
Lime	13.0	0.00	0.05	45.80	5.65	0.00	60.4
Tilemsi PR	9.6	0.03	23.20	50.00	2.62	0.02	1.0
Guala	8.2	0.00	0.06	27.70	0.83	4.00	0.0

A field experiment was conducted during the 1998 and 1999 growing seasons on two millet soil types (sandy and clayey) located at the Cinzana Agronomic Research Station in the Sudano-Sahelian Region of Mali. The sandy soil is located on the summit of the toposequence and the clayey soil is located on the toeslope. These soils are representative of soils encountered in the region. Calcium bearing materials (lime, Telemsi rock phosphate (PNT), and gypsum) were applied at liming rates (Lr) of 0Lr, 0.5Lr, 1.0Lr, and 2.0Lr. PNT and gypsum were applied to provide equal amounts of Ca as with lime. The cropping system was a continuous monoculture of millet on both soils. The materials were mixed with the surface soil at application. The cumulative rainfall for the 1998 growing season (841.7 mm) and the 1999 season (999.3 mm) exceeded the 10 year average rainfall of 697.8 mm. The available soil Ca level of the two soils as a function of depth is presented in Figure 5. The clayey soil has a higher Ca concentration in the deeper horizons while the sandy soil tends to have decreasing Ca with depth. The clayey soil contains more exchangeable soil Ca than the sandy soil at any depth. The difference between the two soils is probably related to their origin and cropping history. The clayey soil is formed from alluvial deposits of the Bani River and contains calcareous nodules. This soil has a moderate clay content (40%), higher pH (5.98), and very low acid saturation. The sandy soil has low clay content, a low pH (4.91), and higher exchangeable acidity. There is no evidence of Ca movement below the 7.5 cm depth for either soil.



**Figure 5.** Soil Ca as influenced by soil type and depth at Cinzana, Mali (1997-1999)

Soil pH in the 0-7.5 cm portion of the profile due to lime and Telemsi rock phosphate application increased significantly (Figure 6). There was no significant change in pH due to gypsum application compared to the control. Similar trends in pH due to application of materials were apparent in the sandy and clayey soils.



**Figure 6.** Sandy and clayey soil pH (0-7.5 cm depth) as influenced by lime source and rate at Cinzana, Mali.

The higher grain yield in 1998 was on the sandy soil compared to the clayey soil. In 1999, grain yield on the clayey soil was greater than on the sandy soil but the difference was not statistically significant (Table 2). This crop performance pattern appears to be the result of an interaction between cumulative rainfall by soil type. Higher millet yields in years with low rainfall are usually associated with sandy soil. Sandy soils have higher water infiltration, less runoff, and retain more available moisture than clayey soil during the growing season. The cumulative rainfall for the 1998 growing season (841 mm) and the 1999 growing season (900 mm) exceeded the 10 year average rainfall of 677 mm. There was not an increase in grain yield due to Ca application, however, the highest yields were associated with Telemisi rock phosphate applications. This was apparently a response to applied P.

Table 2. Millet yield in 1998 and 1999 as influenced by soil and source and rate of Ca applied in 1998.

Treatment	Millet Grain Yield	
	1998	1999
	----- kg ha <sup>-1</sup> -----	
	<i>Soil Means</i>	
Sandy	2132 a	4408 a
Clayey	1590 b	4837 a
	<i>Ca Source Means</i>	
Check	1735 ab	4916 ab
Diamou Lime	1675 ab	4225 b
Telemsi PR	2153 a	4991 a
Gypsum	1862 ab	4358 b
	<i>Calcium Rate Means</i>	
0 x Lime requirement (LR)	1635 b	4589 a
0.5 x LR	1823 ab	4636 a
1 x LR	1871 ab	4760 a
2 x LR	2104 a	4505 a
	<u>Analysis of Variance</u>	
Soil x Source	NS	NS
Soil x Rate	S	NS
Source x Rate	NS	NS
Coeff. Variation (%)	39	26

3. *H/Al rhizotoxicity and Ca/Mg requirements for peach palm root growth* - (supervised by Rafael Salas at UCR with support from Nguyen Hue and Jot Smyth) due to problems in applying some of the lime treatments to soil, the desired neutralization of acidity was not achieved. The experiment is being repeated and results will be provided during the coming year.

Through our extensive evaluation network we learned of and gained access to a similar investigation conducted at the University of Viçosa in Brazil (Pachêco, R.G. 1997. Growth of peach palm seedlings (*Bactris gasipaes* H.B.K.) in response to liming and soil Ca:Mg ratios, and nitrate:ammonium ratios in nutrient solutions with Al. Ph.D. Thesis, Federal University of Viçosa, Minas Gerais, Brazil. 102 p.). In studies with peach palm seedling in ¼ Hoagland nutrient solutions plant top and root growth inhibition with increasing Al

concentrations from 0 to 30 mg L<sup>-1</sup> were considerably less than responses observed for row crops. Peach palm seedling response to lime was also evaluated in pots with subsoil material from an Oxisol initially containing 0.2 cmol L<sup>-1</sup> of Ca, traces of Mg and 72% Al saturation. Shoot dry weight increased by 10% relative to the unlimed treatment with the lowest lime rate which reduced % Al saturation to 37 and raised soil pH to 4.5. At higher rates of lime, shoot dry weight was less than that for the control regardless of the Ca:Mg ratios in the lime material which ranged 0.5:1 to 8:1. These results lend support to our hypotheses that peach palm tolerance to acidity is high and requirements for Ca and Mg are less than for most row crops.

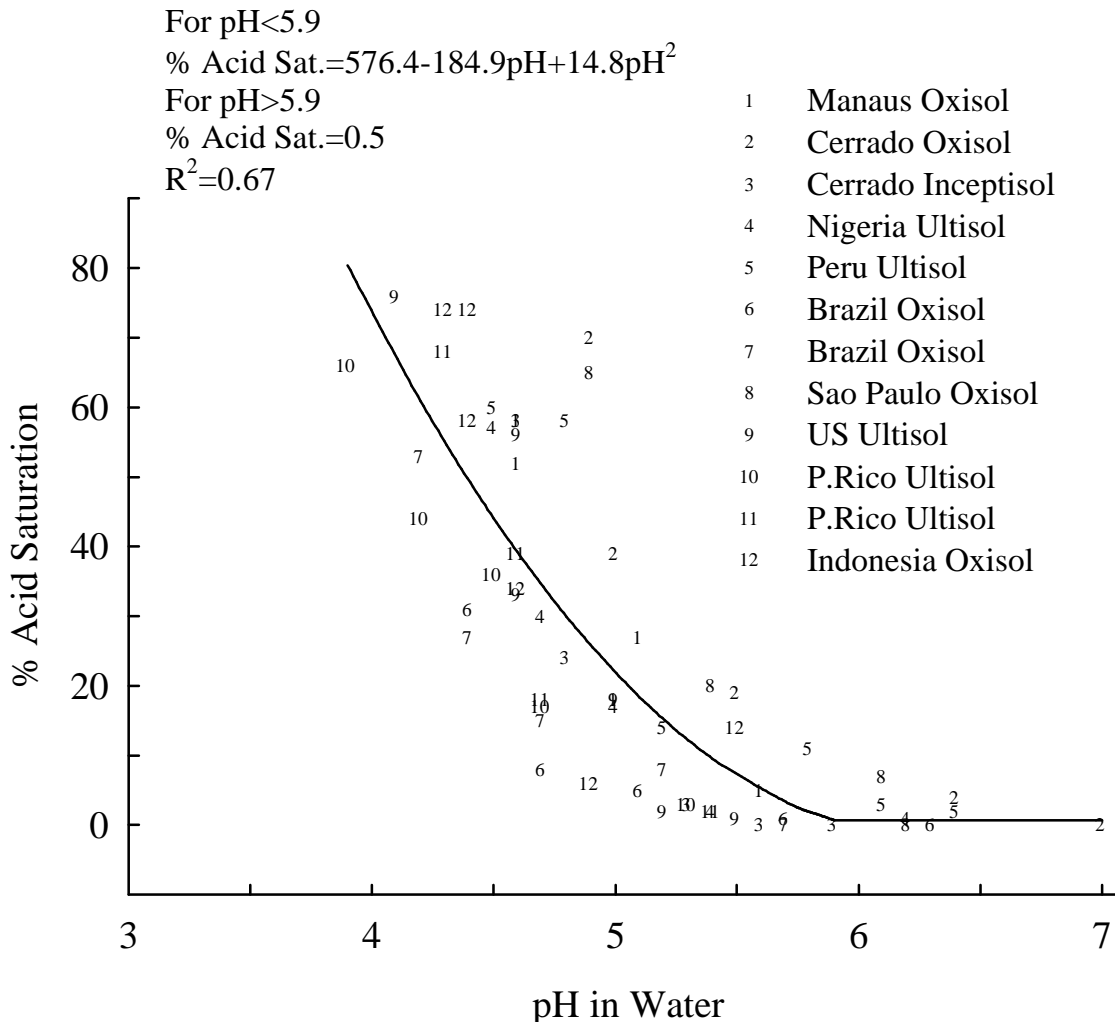
4. *NuMaSS acidity diagnosis: prediction of acid saturation % from soil pH* - the diagnosis component of NuMaSS uses information about field location, land use history, previous crop yields, indicator plants and visual plant symptoms to predict whether there will be a nutrient constraint for the targeted crop. Soil chemical data is not required for a diagnosis, but will be considered and contribute to the assessment of constraints when provided. Users evaluating NuMaSS prototypes have suggested consideration of soil pH as a substitute for soil data on acid saturation % in the diagnosis of acidity constraints. Calculation of % acid saturation requires soil analytical data for exchangeable cations, namely Ca, Mg, K and either Al or Al+H. In many cases user may have soil pH data, but not the exchangeable cation data. Data from field trails with multiple rates of lime in Inceptisols, Oxisols and Ultisols were investigated for relations between soil pH and acid saturation %. Only data for the first crop cycle in each lime trial was considered. A segmented quadratic-plateau model provided a reasonable fit to the data across all soils (Figure 7). The model predicts that acid saturation % drops to essentially zero (0.5%) at pH 5.9, whereas various studies indicate that this break point occurs around pH 5.5. This relation will be included in NuMaSS 2.0 to enable use of soil pH data in acidity diagnosis. If an acidity constraint is identified for the targeted crop, however, a lime recommendation will only be provided by the prediction module upon user input of acid saturation % data for the soil under consideration.

#### External Funding and Support

Collaborators at intensive sites are conducting laboratory, greenhouse and field trials on various aspects of soil acidity management. Estimates of their funding contributions to this output are contained in values provided for Objective 1, Output 2.

#### Travel and Meetings Attended

- Loyd Hossner - travel to Mali to assist IER collaborators to organize data collected in 1998-1999 and discuss plans for the 2000 crop year. May 22-June 3.
- Jocelyn Bajita - travel to Philippines to conduct field research on diagnosis and alleviation of Mn toxicity in acid upland soils as part of Ph.D. program at the Univ. of Hawaii. May 15-August 22.
- Frank Hons - travel to Mali to assist IER collaborators in planting experiments for the 2000 crop year and collect pending data from the 1998-1999 crop seasons. August 12-19.



**Figure 7.** Relation between soil acid saturation % and pH in water for lime trials in Inceptisols, Oxisols and Ultisols.

Relevant Publications, Reports and Presentations at Meetings

Hossner, L. 2000. Report on trip to Mali. Decision Aids for Integrated Soil Nutrient Management Project. 2p. ([http://intdss.soil.ncsu.edu/sm-crsp/Download/Trip\\_Reports/Hossner\\_Mali\\_0500.pdf](http://intdss.soil.ncsu.edu/sm-crsp/Download/Trip_Reports/Hossner_Mali_0500.pdf)).

Hons, F. 2000. Report on trip to Mali. Decision Aids for Integrated Soil Nutrient Management Project. 3p. ([http://intdss.soil.ncsu.edu/sm-crsp/Download/Trip\\_Reports/Hossner\\_Mali\\_0500.pdf](http://intdss.soil.ncsu.edu/sm-crsp/Download/Trip_Reports/Hossner_Mali_0500.pdf)).

Nino, Y., G. Tian, F.M. Hons and A.S. Juo. Movement of Ca and Mg in a kaolinitic Alfisol under maize in the humid tropics. Agron. Abstr. p. 57.

Oliveira, F.H., R.F. Novais, T.J. Smyth and J.C. Neves. 2000. Aluminum diffusion in Oxisols as influenced by soil water matric potential, pH, lime, gypsum, potassium chloride and calcium phosphate. Commun. Soil Sci. Plant Anal. 31:2523-2533.

*Output 2* Enhancing the knowledge base for the N decision support system - collecting, developing and synthesizing soil, plant and management information to improve the diagnosis and recommendations of location-specific N problems.

Diagnosis and recommendations for N are based on N content of total above ground dry matter production for the targeted crop yield. Fertilizer N requirements are based on the differences between total above ground N needs and the N supplied by soil, manures and atmosphere. Unlike acidity and P, there is no single measure of soil N that allows an evaluation of N source efficiencies and mineralization transfer coefficients among different soils and climates. Coefficients must, therefore, be derived for a variety of soil, crop and climate conditions using prior experimentation whenever possible. Given the size of this task, acquisition and refinement of coefficients will be an ongoing process throughout the entire project. Transfer coefficients for contributions of biologically fixed N need to be categorized in terms of a variety of factors: the legume source and its nutrient requirements, inoculant availability, C constituents, plant age, soil conditions, and timing and method of incorporation. Nitrogen losses need to be either incorporated into transfer coefficients or predicted.

Milestone events for this output, during the 5-year plan are as follows:

- # annual improvement of the database on N transfer and mineralization coefficients to encompass a broader combination of soil, crop and climate conditions;
- # prediction of N losses - year 3; and
- # guidance for legume management and prediction of BNF contributions - year 5.

#### Lead Investigators and Contributors

Shaw Reid provides overall coordination to activities related to the N module. During the past year investigators at Cornell and N.C. State University received funding to continue the collection and calibration of N transfer and mineralization coefficients. Funding was also provided to all universities to work on legume management. N.C. State, Cornell and Hawaii also received funding to work on prediction of N losses. However, all other U.S. members of the N group and testing site collaborators have begun to share via correspondence their findings upon searches of the existing literature as well as core experiment activities related to N management. Overseas collaborators contributing to this output during year 3 are listed according to their respective institutions:

Center for Agricultural Research/University of Costa Rica - Alfredo Alvarado, Gabriela Soto and Raphael Salas

Institute d'Economie Rurale/Mali - Mamadou Doumbia and Aminata Sidibe (Sotuba Station); Adama Coulibaly and Zoumana Kouyate (Cinzana Station)

International Rice Research Institute - Thomas George

Philippine Rice Research Institute - Teodula Corton

#### Progress

1. *Calibrating N coefficients* (Pedro Luna with assistance from Shaw Reid, Dan Israel, Deanna Osmond, Jot Smyth and Michael Waggoner) nitrogen recommendations by NuMaSS are based on the following modified version of the Stanford equation:

$$N_f = (Y * N_c) - [N_s + (N_{gm} * C_{gm}) + (N_m * C_m)] / E_f$$

where

$N_f$  = fertilizer N to obtain a target dry matter yield,  $Y$  = dry matter yield, vegetative and/or reproductive,  $N_c$  = N concentration in dry matter,  $N_s$  = soil N taken up by the crop,  $N_{gm}$  = N applied in green manure,  $C_{gm}$  = fraction of N from green manure taken by the crop,  $N_m$  = N

applied in manure,  $C_m$  = fraction of N from manure taken by the crop, and  $E_f$  = fraction of fertilizer N recovered by the crop. This report concentrates on summarization of data for  $Y$ ,  $N_c$ ,  $N_s$  and  $E_f$ . Analysis of published N fertilization field trials and assembly of N coefficients on corn, millet and sorghum for Africa, Asia and Latin America continued throughout the year, using a procedure developed with corn data from South America. The procedure entails use of the Mixed Model in SAS to evaluate relations between crop variables and determine whether field trial observations for each commodity can be grouped within or across agro-climatic regions, crop cultivars, and countries. Certain specific relations between crop variables (Table 3) are investigated to determine coefficients for the N recommendations by NuMaSS. Apparent N recovery (ANR) is defined as the difference in total aboveground crop N accumulation between either a fertilizer or green manure treatment and the zero-N treatment. Only treatments within the linear response range were considered for ANR, to avoid unrealistic values with fertilizer N rates that exceeded the optimum level.

Table 3. Relations between crop variables and the corresponding coefficients for NuMaSS N recommendations.

<b>Crop Variable Relations</b>	<b>Corresponding NuMaSS N Coefficients</b>
Aboveground N accumulation vs. grain yield	$Y*N_c$ for targeted yields
Apparent N recovery vs. applied fertilizer N	$E_f$
Green manure N accumulation vs. green manure dry matter yield	$N_{gm}$
Apparent N recovery vs. applied green manure N	$C_{gm}$

Most of the experiments investigated contained several fertilizer N treatments, including a zero N, and many encompassed several crop cycles. Both local or improved varieties and hybrids were included among the field trials for each commodity. Crop yield response to fertilizer N was also characterized by linear-plateau functions and grouped among experiments using options provided by non-linear regression procedures in SAS. Thus far, only the green manure data for South America has been summarized and very little animal manure data has been found which contains the desirable measurements for this analysis. Many of the experiments did not contain sufficient information to estimate all of the coefficients. Each experiment, with the exception of those in Puerto Rico, was grouped into one of three general agro-climatic regimes: semiarid, wet/dry and humid tropical. Experiments in Puerto Rico were grouped as either “northern coastal plain” (similar to wet/dry) and “interior highlands”. The number of experiments investigated for each commodity are shown in Table 4 by commodity, continental and agro-climatic region along with the countries and soil orders represented.

Table 4. Distribution of experiments investigated by commodity, continental and agro-climatic region, and the countries and soil orders represented.

Commodity	Continental Region	Countries	Soil Orders	Climatic Regime <sup>a</sup>
				(# of experiments)
Corn	East Africa	Kenya, Malawi, Sudan, Tanzania, Uganda, Zambia, Zimbabwe	Alfisols, Entisols, Mollisols, Oxisols, Vertisols	W/D (17) HT (3)
	West Africa	Burkina Faso, Cameroon, Congo, Ghana, Gambia, Nigeria, Mali, Senegal, Togo	Alfisols, Entisols, Inceptisols, Oxisols, Ultisols	W/D (15) HT (8)
	Caribbean	Puerto Rico	Oxisols, Ultisols	Coastal (6) Highlands (6)
	South America	Bolivia, Brazil, Peru	Entisols, Inceptisols, Oxisols, Ultisols	W/D (12) HT (9)
Millet	West Africa	Niger, Nigeria, Mali, Senegal	Alfisols, Aridisols, Inceptisols	W/D (4) Semi-arid (4)
	Asia	India	Alfisols, Aridisols, Inceptisols, Mollisols, Vertisols	W/D (9) Semi-arid (12)
Sorghum	West Africa	Burkina Faso, Cameroon, Nigeria, Mali	Alfisols, Inceptisols	W/D (5)
	Asia	India	Alfisols, Aridisols, Inceptisols, Ultisols, Vertisols	W/D (15) Semi-arid (13)

<sup>a</sup> W/D=wet-dry; HT=humid tropical

### Corn

a. *Aboveground N accumulation* - regression slopes in Table 5 show that aboveground N accumulation among the regions and climatic regimes vary from 0.017 to 0.027 kg N/kg of grain yield. Differences in N accumulation are attributed to a combination of factors, namely hybrids and cultivars, harvest indices and N concentrations in both grain and stover. In South America, for example, predicted N accumulation per unit grain yield was similar for all experiments in the ‘Cerrados’ (wet-dry) region, but different from all experiments in the Amazon region (humid tropical). A distinction between experiments in these two regions, in addition to climatic regime, was the use of hybrids in the ‘Cerrados’ and improved varieties in the Amazon.

Table 5. Prediction equations for aboveground N accumulation as a function of grain yield, and range or mean values for agronomic properties used in estimating crop N uptake.

Region	Equation <sup>a</sup>	Country/ Climate	Harvest	N Concentration			
			Index <sup>b</sup> Range	Grain		Stover	
				Mean	Range	Mean	Range
				----- g kg <sup>-1</sup> -----			
East Africa	Y=9.6+0.024X	Sudan/(W/D)	0.4-0.8	15.8	14.6-19.3	5.9	5.4-7.8
		Zimbabwe/(W/D)	0.5-0.7				
West Africa	Y=5.3+0.017X	Ghana/(W/D)					
Africa	Y=1.4+0.017X	Ghana/(HT)	0.5-0.9	10.6	8.0-12.9	3.0	2.8-3.5
	Y=7.8+0.017X	Nigeria/(W/D)	0.5-1.4	12.0	11.0-13.0	5.4	3.3-6.2
	Y=1.4+0.026X	Nigeria/(HT)	0.3-0.8	14.5	13.5-17.2	11.4	9.2-14.6
		Mali/(W/D)	0.7-0.9				
		Senegal/(W/D)	0.4-0.9				
Puerto Rico	Y=9.2+0.022X	Coastal	0.4-0.5	15.5	13.9-16.5	8.3	6.0-9.8
	Y=9.2+0.027X	Highlands	0.4-0.7	15.8	11.1-17.6	8.9	3.8-13.6
S. America	Y=11.6+0.023X	Brazil/(W/D)	0.7-1.4	13.4	9.0-16.3	5.7	4.1-7.6
		Brazil/(HT uplands)	0.4-0.8	15.6	14.5-16.9	8.2	6.1-12.9
	Y=6.8+0.023X	Brazil/(HT lowlands)	0.5-1.0	16.5	14.4-20.6	6.1	5.1-8.6
		Peru/(HT uplands)	0.7-0.9	16.9		2.3	2.2-2.4

<sup>a</sup> Y=Total aboveground N accumulation in kg ha<sup>-1</sup>; X=grain yield in kg ha<sup>-1</sup>

<sup>b</sup> Grain:stover ratio

b. *Yield response to fertilizer N* - yield responses (in % relative yield) to fertilizer N in several regions were similar for experiments conducted in various countries within the same climatic regime (Table 6). Fertilizer N requirements to achieve optimum yields ranged from 36 to 107 kg ha<sup>-1</sup>, but were not related to the maximum grain yields which ranged from 3.7 to 7.0 t ha<sup>-1</sup>.

c. *Apparent N recovery and soil N supply* - only a limited number of experiments with corn contained sufficient data to determine apparent fertilizer N recovery (Table 7). Fertilizer N efficiency (Ef), estimated from the slopes of the relations between apparent N recovery and applied N, were similar among experiments and ranged from 41 to 47%. In regions such as Puerto Rico and South America, there was no difference in Ef between climatic regimes; this may be due to distribution of applied N in a greater number of split-applications in high rainfall regions (HT), thus minimizing losses from leaching.

Table 6. Linear-plateau yield response functions, critical fertilizer N levels, and grain yield plateaus, mean and range values for corn in various regions.

Region	Country/Climate	Equation <sup>a</sup>	Critical	Yield	Grain Yield	
			Fertilizer N	Plateau	Mean	Range
			kg ha <sup>-1</sup>	%	----- t ha <sup>-1</sup> -----	
East Africa	Sudan/(W/D)	Y=33+0.79N	81	97	2.6	0.8-5.1
	Kenya-Tanzania/(W/D)	Y=65+0.59N	60	96	3.5	2.1-7.0
	Malawi-Zimbabwe/(W/D)	Y=53+0.74N	51	94	3.5	1.4-7.0
	Zambia/ (W/D)	Y=35+0.61N	107	100	3.1	1.4-6.8
	Uganda (Bukwa)/(H/T)	Y=67+0.91N	36	100	4.3	3.7-5.3
	Uganda (N. Bugisu)/(H/T)	Y=65+0.75N	44	98	4.1	3.0-6.2
West Africa	Burkina Faso, Gambia/(W/D)	Y=45+1.28N	64	93	2.8	1.8-3.8
	Nigeria, Senegal, Mali/(W/D)	Y=33+0.83N	72	92	2.5	0.8-6.4
	Cameroon, Ghana, Nigeria/(HT)	Y=52+0.60N	71	94	3.0	0.7-5.7
	Togo/(HT)	Y=80+0.39N	53	100	3.1	1.6-3.7
Puerto Rico	Coastal	Y=38+0.58N	107	100	3.3	2.2-4.3
	Highlands	Y=70+0.34N	80	97	3.3	1.4-6.4
S. America	Brazil/(W/D)	Y=57+0.50N	72	93	5.0	3.1-6.8
	Brazil-Peru uplands/(HT)	Y=32+0.82N	74	92	3.1	0.8-5.3
	Brazil alluvial/(HT)	Y=57+0.68N	57	96	3.4	2.6-4.3

<sup>a</sup> Y=% of maximum relative yield; N=fertilizer N in kg ha<sup>-1</sup>

Considerable variation was observed in the means and range of values for soil N supply, both within and across regions, countries and climatic regimes. Estimates of soil N supply can be influenced by previous land-use history; although a general trend towards decreasing soil N supply was observed with successive crop cycles, there were not sufficient crop cycles in the experiments to quantify this time effect.

Table 7. Relations between apparent N recovery (ANR) and fertilizer N, and mean and range of values for soil N supply to corn among experiments in various regions and climatic regimes.

Region	Equation <sup>a</sup>	Country/Climate	Soil N Supply	
			Mean	Range
			----- kg ha <sup>-1</sup> -----	
East Africa	ANR=0.44N	Sudan/(W/D)	28	6-49
West Africa	ANR=0.47N	Ghana/(HT)	26	21-33
		Nigeria/(HT)	48	28-89
	ANR=0.51N	Nigeria (W/D)	48	28-89
Puerto Rico	ANR=0.41N	Coastal Plain	47	43-94
		Highlands	71	54-104
S. America	ANR=0.42N	Brazil/(W/D)	65	39-110
		Brazil-upland/(HT)	31	15-45
		Brazil-alluvial/(HT)	55	23-86
		Peru-upland/(HT)	39	33-46

<sup>a</sup> ANR=apparent N recovery in kg ha<sup>-1</sup>; N=fertilizer N in kg ha<sup>-1</sup>

d. *Green manure N accumulation and apparent recovery in South America* - investigations of 13 separate experiments in the wet-dry and humid tropical regions that included 17 leguminous species used as green manures indicated that N accumulation in the green manure (Y in kg N ha<sup>-1</sup>) could be estimated for all species by the equation

$$Y = 7.7 + 0.0222DM$$

where DM = green manure dry matter in kg ha<sup>-1</sup>. Likewise, apparent recovery of green manure N (ANR) by corn could be estimated by separate expressions for wet-dry and humid tropical climatic regimes:

$$\text{Wet-dry} \quad \text{ANR} = 0.41N$$

$$\text{Humid tropical} \quad \text{ANR} = 0.08N$$

where N = accumulated N in the green manure material. The lower N use efficiency factor for green manure in humid tropical regions (8%) as opposed to wet-dry regions (41%) is probably related to higher N losses by leaching and lower maximum corn yields (and, thus, crop N accumulation) in the high rainfall regions.

#### Millet

a. *Aboveground N accumulation* - experiments conducted in India, Niger and Nigeria contained sufficient data to estimate most of the coefficients. With few exceptions as noted in the tables, however, there were no differences within or among countries between hybrids and improved cultivars. Thus, data for hybrids and cultivars were pooled for many of the coefficient estimates.

Total N accumulation functions represented three distinct groups (Table 8): (i) Niger, North India (New Dehli, Haryana, Hisar, Ludhiana, Jaipur and Agra) and Senegal; (ii) Nigeria and West India (Bombay and Pune); and (iii) East India (Vizianagaram). Harvest indices were noticeably different between hybrids and non-hybrids in North India.

Table 8. Prediction equations for aboveground N accumulation as a function of millet grain yield, and range or mean values for agronomic properties used in estimating crop N uptake.

Region	Equation <sup>a</sup>	Harvest	N Concentration			
		Index <sup>b</sup>	Grain		Stover	
		Range	Mean	Range	Mean	Range
----- g kg <sup>-1</sup> -----						
Niger/(SA)		0.2-0.5	17.8	13.2-27.6	10.1	4.3-18.0
N. India-hybrid/(SA)	Y=-5.2+0.044X	0.1-1.9	18.4	17.2-19.8	7.3	6.8-7.8
N.India-variety/(SA)		0.1-0.4	18.5	18.4-19.5	5.8	5.6-6.1
Senegal/(SA)						
-----						
Nigeria/(SA&WD)	Y=1.8+0.028X					
W. India/(SA)		0.1-0.3	21.5	16.4-22.7	4.5	3.7-6.8
-----						
E. India/(SA&WD)	Y=-58.4+0.032X					

<sup>a</sup> Y=Total aboveground N accumulation in kg ha<sup>-1</sup>; X=grain yield in kg ha<sup>-1</sup>

<sup>b</sup> Grain:stover ratio

b. Yield response to fertilizer N - without applied N approximately half of the maximum millet yield was obtained in most regions (Table 9). Data for hybrid and improved varieties were pooled because there was no difference in fertilizer response for any region.

Table 9. Linear-plateau yield response functions, critical fertilizer N levels, and grain yield plateaus, mean and range values for millet in India and West Africa.

Country or Region	Climate	Equation <sup>a</sup>	Critical	Yield	Grain Yield	
			Fertilizer N	Plateau	Mean	Range
			kg ha <sup>-1</sup>	%	----- t ha <sup>-1</sup> -----	
East India	Wet-dry	Y=47+0.62N	83	98	1.6	0.9-2.1
Central India	Semi-arid	Y=55+0.71N	56	94	2.0	1.0-3.6
South India	Wet-dry	Y=55+1.07N	42	100	1.7	0.6-2.4
West India	Semi-arid	Y=52+1.30N	37	100	1.0	0.5-2.2
-----						
North India	Semi-arid				1.9	0.8-3.7
NW India	Semi-arid	Y=58+0.60N	58	93	2.7	1.7-3.9
Mali	Semi-arid				1.5	1.1-2.0
-----						
Niger	Semi-arid	Y=63+0.69N	47	95	1.3	0.6-2.8
Nigeria	SA & WD	Y=50+0.79N	56	94	2.0	0.9-2.7

<sup>a</sup> Y=% of maximum relative yield; N=fertilizer N in kg ha<sup>-1</sup>

c. *Apparent N recovery and soil N supply* - fertilizer N efficiencies (Ef) were in a similar range as for corn, with the exception of the 70% value for the North India data (Table 10). Soil N supply for trials in North India also was considerable higher than for other regions.

Table 10. Relations between apparent N recovery and fertilizer N, and mean and range of values for soil N supply to millet among experiments in Niger, Nigeria and India.

Country or Region	Climate	Equation <sup>a</sup>	Soil N Supply	
			Mean	Range
			----- kg ha <sup>-1</sup> -----	
North India	Semi-arid	ANR=0.68N	67	47-90
West India	Semi-arid	ANR=0.41N	20	11-34
Niger	Semi-arid	ANR=0.43N	34	19-52
Nigeria	SA & WD	ANR=0.47N	35	31-38

<sup>a</sup> ANR=apparent N recovery in kg ha<sup>-1</sup>; N=fertilizer N in kg ha<sup>-1</sup>

### Sorghum

a. *Aboveground N accumulation* - experimental data for sorghum came from arid and semi-arid regions in India and West Africa (Burkina Faso, Cameroon, Nigeria and Mali), although the latter trials lacked sufficient data for estimating most of the coefficients. In several instances, prediction equations differed between improved varieties (non-hybrids) and hybrids.

Total N accumulation by sorghum in the Central region of India differed between improved varieties and hybrids (Table 11). The improved varieties had higher N concentrations in the grain than the hybrids.

Table 11. Prediction equations for aboveground N accumulation as a function of sorghum grain yield, and range or mean values for agronomic properties used in estimating crop N uptake.

Region	Equation <sup>a</sup>	Harvest		N Concentration			
		Index <sup>b</sup>	Range	Grain		Stover	
				Mean	Range	Mean	Range
				----- g kg <sup>-1</sup> -----			
N. India/(SA&WD)	Y=18.2+0.025X	0.2-0.7					
C. India-hybrid/(SA&WD)	Y=-2.1+0.019X	0.2-0.8	12.0	9.0-18.0	3.9	3.2-4.3	
C. India-variety/(SA&WD)	Y=-2.1+0.079X	0.1-0.6	14.7	13.0-16.6	5.3	3.8-6.0	

<sup>a</sup> Y=Total aboveground N accumulation in kg ha<sup>-1</sup>; X=grain yield in kg ha<sup>-1</sup>

<sup>b</sup> Grain:stover ratio

b. *Yield response to fertilizer N* - yield response functions to fertilizer N differed between varieties and hybrids for all regions of India, except the South (Table 12). However, there was no consistent difference between varieties and hybrids in terms of fertilizer N requirements for optimum yield.

Table 12. Linear-plateau yield response functions, critical fertilizer N levels, and grain yield plateaus, mean and range values for sorghum in India and West Africa.

Country or Region	Climate	Equation <sup>a</sup>	Critical Fertilizer N	Yield Plateau	Grain Yield	
					Mean	Range
			kg ha <sup>-1</sup>	%	----- t ha <sup>-1</sup> -----	
Central India-varieties	SA&WD	Y=58+0.63N	54	92	2.5	0.7-5.1
Central India-hybrids	SA&WD	Y=44+0.60N	89	97	3.7	0.5-5.2
South India	SA&WD	Y=50+0.59N	73	92	3.2	0.7-5.9
West India-hybrids	Wet-dry	Y=52+0.50N	86	96	3.9	3.3-4.5
North India-hybrids	SA&WD	Y=56+0.71N	48	90	2.7	1.1-5.5
North India-varieties	SA&WD	Y=63+0.45N	68	93	2.5	1.0-5.2
Mali	Wet-dry	Y=64+0.33N	100	98	2.7	2.0-3.7
Nigeria	SA & WD	Y=55+0.48N	94	100	1.8	1.2-2.4

<sup>a</sup> Y=% of maximum relative yield; N=fertilizer N in kg ha<sup>-1</sup>

c. *Apparent N recovery and soil N supply* - data for these estimates were only available for trials in India (Table 13). There was no difference in relations between apparent N recovery and applied N for hybrids in North and Central India, whereas relations for improved varieties differed between the same regions. Fertilizer N efficiency values (Ef) varied considerably between hybrids, varieties and regions within India.

Table 13. Relations between apparent N recovery and fertilizer N, and mean and range of values for soil N supply to sorghum among experiments in North and Central India.

Country or Region	Climate	Equation <sup>a</sup>	Soil N Supply	
			Mean	Range
			----- kg ha <sup>-1</sup> -----	
North&Central India, hybrids	SA & WD	ANR=0.44N	65	43-95
North India, varieties	SA & WD	ANR=0.28N		
Central India, varieties	SA & WD	ANR=0.79N	76	32-135

<sup>a</sup> ANR=apparent N recovery in kg ha<sup>-1</sup>; N=fertilizer N in kg ha<sup>-1</sup>

2. *Predicting nitrogen gains from legume N<sub>2</sub>-fixation* - (Thomas George, Jonathan Quiton and Paul Singleton) - Despite the substantial contribution BNF can make to the N economy of legumes, there are limited efforts to develop decision aids to better manage legume BNF. Attempts are being made to incorporate a BNF sub-routine to NuMaSS. Several legume crops are included in NuMaSS. The NDSS component of NuMaSS presently predicts N fertilizer requirement for any crop from an algorithm that considers total crop N, total plant available N from soil and manure sources and fertilizer recovery efficiency. Applying the NDSS equation to legumes results in the prediction of N fertilizer required to produce a specified target yield. While the target yield for the legume may be achieved by applying fertilizer N, it would be at a much greater cost and with unnecessarily large wastage of N fertilizer compared to relying on legume's ability to acquire most of its N from BNF. The NDSS module is being programmed to not recommend fertilizer N for legumes, but such a solution misses the opportunity to better manage and benefit from legume BNF. To fully benefit from legume BNF, a subroutine specific to legumes could be incorporated in to the NDSS algorithm. In this paper, we make a preliminary attempt to develop an algorithm to predict potential BNF benefits.

Terminology used:

$N_{\text{Demand}}$  = total N that is potentially attainable

$N_{\text{Attained}}$  = total N that is actually attained

$N_{\text{Deficit}}$  = the deficit in N uptake from soil to meet the potentially attainable total N

$N_{\text{BnfDerived}}$  = N derived from biological nitrogen fixation (BNF)

$N_{\text{BnfCapacity}}$  = N that could be potentially derived from BNF

$N_{\text{BnfLost}}$  = Loss in total N that could have been potentially derived from BNF

$N_{\text{SoilSupply}}$  = Mineral N supply in soil

$N_{\text{SoilUptake}}$  = Mineral N uptake from soil

$N_{\text{FertSupply}}$  = Total fertilizer N supply in soil

$N_{\text{FertUptake}}$  = Fertilizer N uptake by plant

$N_{\text{SeedUptake}}$  = Seed N assimilated by the plant

*mat* = period from emergence to maturity

*lag* = period from emergence to beginning of nitrogen fixation

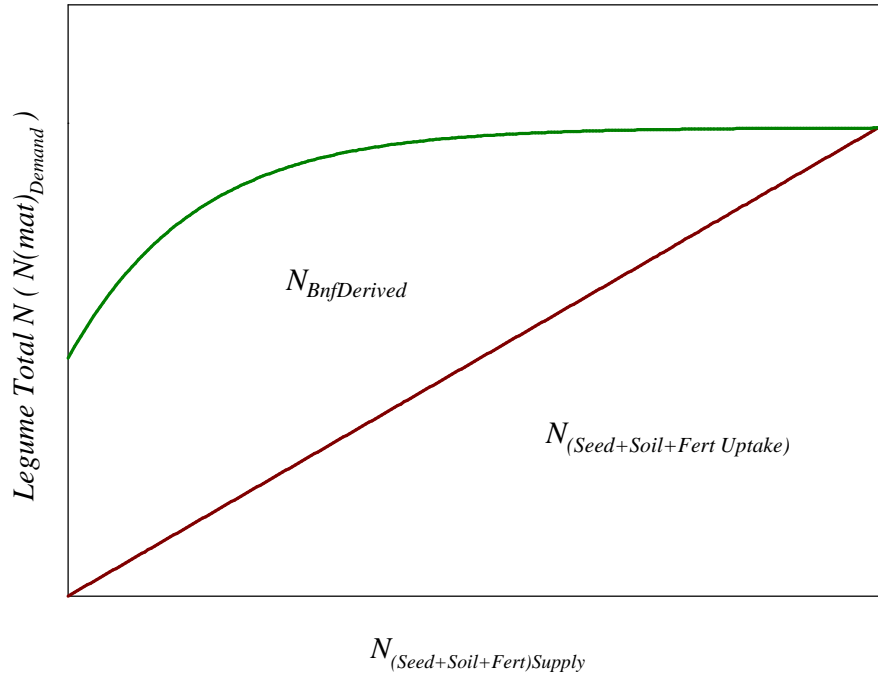
*BNF period* = period from end of lag phase to legume maturity

*nrf* = nitrogen recovery fraction, the fraction of total combined N supply in soil that is recovered by the plant

*yrf* = yield reduction factor, the reduction in final yield due to a deficit in N uptake during early growth of the legume

The relationships between legume N demand and N supply from combined N sources (soil and fertilizer) and *Rhizobium* symbiosis must be considered in order to predict the N derived from BNF ( $N_{\text{BnfDerived}}$ ) by a legume. In a schematic representation of this relationship in a nodulated legume by Marchner (1986), the total N increases asymptotically with increasing combined N supply and the  $N_{\text{BnfDerived}}$  increases by moderate levels of combined N, but decreases substantially at high levels. George *et al.* (1992) presented a similar scheme wherein there would be a moderate N accumulation by a nodulated legume even at the zero combined N level (Figure 8).

It may be seen from Figure 8 that legume total N ( $N_{Attained}$ ) would be the simplest approximation for  $N_{BnfDerived}$  since the *Rhizobium* symbiosis is a N source that supplies N to



**Figure 8.** Schematic representation of N demand ( $N(mat)_{Demand}$ ) and N supply to a nodulated legume. Adapted after Marschner, 1986 and George et al., 1992.

the legume in the absence of sufficient combined N. While the symbiosis as an N source may be replaced by a sufficient supply of combined N, it is nearly a non-limiting source with its capacity only limited by the  $N_{Attained}$ . Therefore, the theoretical upper limit for  $N_{BnfDerived}$ , i.e., the potential cumulative BNF capacity at maturity,  $N(mat)_{BnfCapacity}$ , would be the potential maximum cumulative legume N demand at maturity,  $N(mat)_{Demand}$ , in a given growing environment. The  $N(mat)_{BnfCapacity}$ , however, would be somewhat less than the  $N(mat)_{Demand}$  due to two reasons. First, the legume-*Rhizobium* symbiosis is not functional during both the initial lag phase of the symbiosis from rhizobial infection to the onset of  $N_2$ -fixation and during the late reproductive phase when the nodules senesce (Marschner, 1986). Second, the energy cost of assimilating  $N_{BnfDerived}$  is slightly higher than that of combined N (Pate et al., 1979; Ryle et al., 1979) resulting in lower photosynthate (biomass) accumulation. Thus, the  $N_{Attained}$  by plants solely dependent on BNF would always be somewhat lower than that of plants dependent on combined N as observed for several legumes by Thies et al. (1991a) and George and Singleton (1992).

Meeting the  $N(mat)_{Demand}$  would require a non-limiting supply of combined N, an economically and environmentally undesirable option especially for legumes given the high cost and the low recovery efficiency of N fertilizers. But, combined N supplied during the

early vegetative and late reproductive phases of a BNF-dependent legume can be complimentary in attaining an N yield approximating the maximum possible (George and Singleton, 1992; George *et al.*, 1992). In a practical N fertilization scheme, therefore, a well-nodulated legume is more likely to have a higher  $N_{Attained}$  compared to one that is not. Thus,  $N_{BnfCapacity}$  should increase in tandem with  $N_{Demand}$  and should approximate  $N(mat)_{Demand}$  expressed as,

$$N(mat)_{BnfCapacity} \cong N(mat)_{Demand} \quad (2)$$

where  $N(mat)_{BnfCapacity}$  is the cumulative BNF capacity from time=0 to maturity (mat), and  $N(mat)_{Demand}$  is the cumulative N Demand from time=0 to maturity. The lag phase in the legume-*Rhizobium* symbiosis is about 3 to 5 weeks (Marschner, 1986). The dysfunctional symbiosis at late reproductive phase would be about 2 to 3 weeks in an annual legume. Considering N uptake during the late reproductive phase as negligible for most annual legumes and disregarding the reduction in N yield from the higher energy costs, the  $N_{BnfCapacity}$  can be expressed as,

$$N(mat)_{BnfCapacity} = N(mat)_{Demand} - N(lag)_{Demand} \quad (3)$$

where  $N(lag)_{Demand}$  is the cumulative N demand from time=0 to the end of the lag phase as depicted in Figure 9.

It can be seen from Figures 8 and 9 that the  $N_{BnfCapacity}$  is reduced by the amount of N uptake from any or all of seed ( $N_{SeedUptake}$ ), soil ( $N_{SoilUptake}$ ) and fertilizer ( $N_{FertUptake}$ ) sources. In other words, the  $N_{BnfCapacity}$  is in fact the deficit in N demand that is not met by  $N_{(Seed+Soil+Fert)Uptake}$  during the period from the onset of N<sub>2</sub> fixation (end of lag phase) to legume maturity, here in after called the BNF period. Thus, the  $N_{BnfCapacity}$  would be equal to the aggregate N deficit ( $N_{Deficit}$ ) during the BNF period, which is the difference between the cumulative daily N demand and cumulative daily  $N_{(Seed+Soil+Fert)Uptake}$  from lag phase to maturity as described in Equation 4.

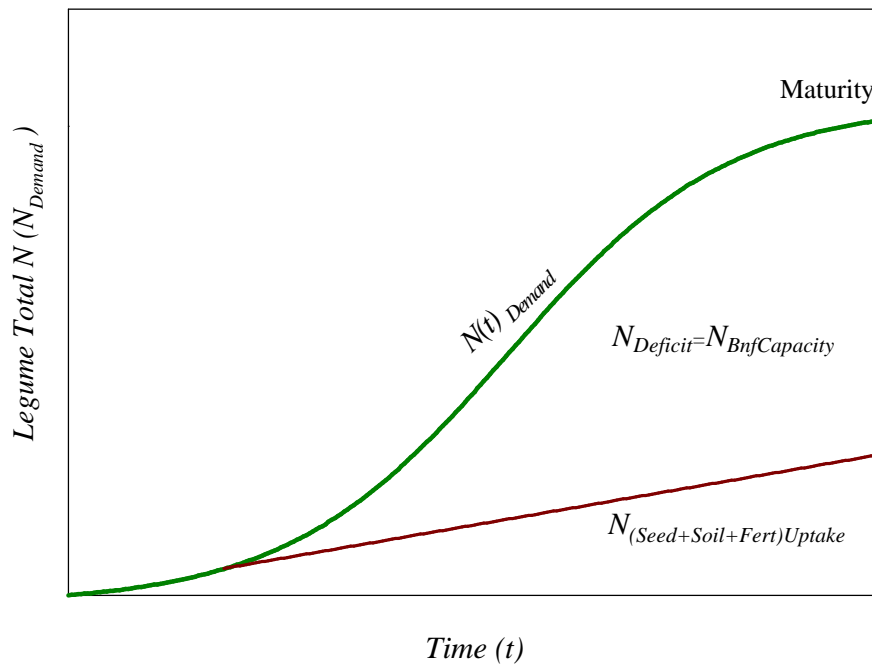
$$\begin{aligned} N(mat)_{BnfCapacity} &= \sum_{t=lag}^{mat} \Delta N(t)_{Deficit} \\ &= \sum_{t=lag}^{mat} [\Delta N(t)_{Demand} - \Delta N(t)_{(Seed+Soil+Fert)Uptake}] \\ &= \sum_{t=lag}^{mat} \Delta N(t)_{Demand} - \sum_{t=lag}^{mat} \Delta N(t)_{(Seed+Soil+Fert)Uptake} \end{aligned} \quad (4)$$

where  $DN(t)_{Deficit}$ =daily increment in  $N_{Deficit}$  at day=t,  $DN(t)_{Demand}$ =daily increment in  $N_{Demand}$  at day=t, and  $DN(t)_{(Seed+Soil+Fert)Uptake}$ =daily increment in  $N_{(Seed+Soil+Fert)Uptake}$  at day=t. Given that  $N_{SeedUptake}$  precedes the BNF period lasting only until the seed N reserve is utilized, any factor that decreases  $N_{(Soil+Fert)Uptake}$  during the BNF period or increases the  $N(mat)_{Demand}$  would invariably increase  $N_{BnfCapacity}$  (George *et al.* 1988 & 1992, George and Singleton 1992, Thies *et al.* 1991b).

Simplifying Equation 4 yields:

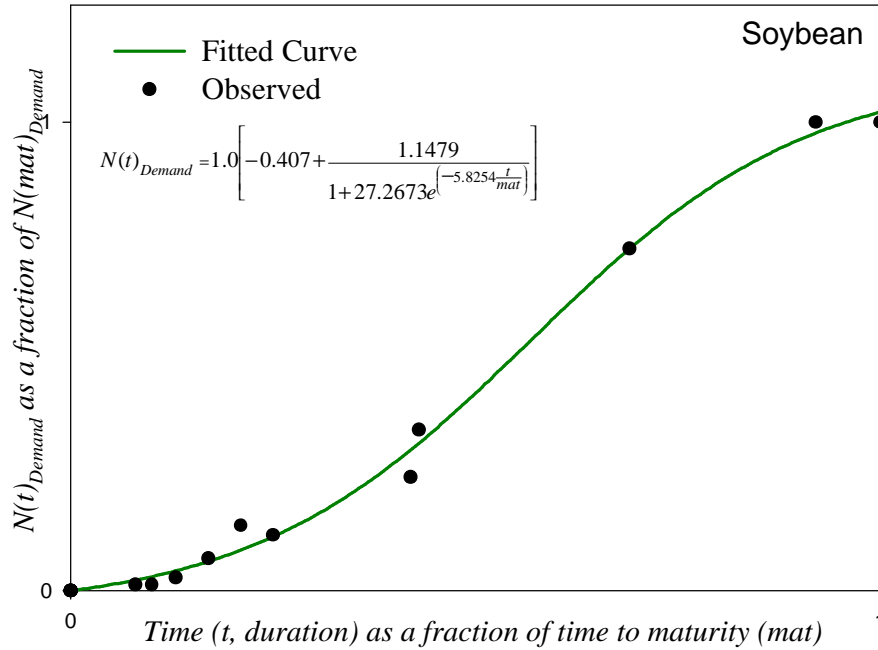
$$N(mat)_{BnfCapacity} = [N(mat)_{Demand} - N(lag)_{Demand}] - [N(mat)_{(Seed+Soil+Fert)Uptake} - N(lag)_{(Seed+Soil+Fert)Uptake}] \quad (5)$$

When  $N(lag)_{(Seed+Soil)Uptake}$  is inadequate to meet the  $N(lag)_{Demand}$ , the alleviation of N stress with supplementary fertilizer N increases the  $N_{BnfDerived}$ , in a phenomenon often referred to as the 'starter N' effect (Marschner, 1986; George *et al.* 1992). In other words, when there is a  $N(lag)_{Deficit}$ , i.e.,  $N(lag)_{(Seed+Soil)Uptake} < N(lag)_{Demand}$ , the  $N(mat)_{BnfDerived}$  is reduced because of a reduction in  $N(mat)_{Demand}$ . Meeting the  $N(lag)_{Deficit}$  by starter N fertilizer ensures that  $N(mat)_{Demand}$  is at its maximum and therefore,  $N(mat)_{BnfDerived}$  is also at its maximum. Therefore, if the reducing effect of  $N(lag)_{Deficit}$  on  $N(mat)_{Demand}$  can be predicted, the consequent loss in  $N(mat)_{BnfDerived}$  can also be estimated.



**Figure 9.** Conceptual time course of legume N demand indicating BNF capacity as the remainder of N uptake from seed, soil and fertilizer N. Adapted from George *et al.*, 1992.

By establishing the time course curves for cumulative  $N_{Demand}$  and  $N_{(Seed+Soil)Uptake}$ ,  $N_{Deficit}$  at any time point can be determined. From data on soybean from humid tropics (George and Singleton, 1992; George unpublished), it was found that the cumulative N demand followed a modified logistic equation as follows (Figure 10).



**Figure 10.** Cumulative N demand during the growth cycle of soybean in the humid tropics (data from George and Singleton, 1992 and George, unpublished).

$$N(t)_{Demand} = K \cdot \left[ a + \frac{b}{1 + c \cdot e^{\left(d \frac{t}{mat}\right)}} \right] \quad (6)$$

where  $K$  = N carrying capacity of the legume crop and  $a$ ,  $b$ ,  $c$ , and  $d$  are parameters specific to the crop controlling the shape of the curve based on flowering date and total crop duration.

The cumulative  $N_{SoilUptake}$ , on the other hand, found to follow a linear response for the growth period excluding the early seedling phase when the plant is dependent only on  $N_{SeedUptake}$  and the late maturity phase when the plant is no longer absorbing soil N. Assuming that  $N_{SoilUptake}$

is negligible for about 7 days each after seeding and before maturity, the  $N_{SoilUptake}$  can be expressed as,

$$N(t)_{SoilUptake} = \begin{cases} N_{Seed} & , \quad t \leq 7 \\ N_{Seed} + (t-7) \frac{N(mat)_{SoilUptake} - N_{Seed}}{mat-14} & , \quad 7 < t \leq (mat-7) \\ N(mat)_{SoilUptake} & , \quad t > (mat-7) \end{cases} \quad (7)$$

By determining the  $N(lag)_{Demand}$  and  $N(lag)_{(Seed+Soil)Uptake}$ , the  $N(lag)_{Deficit}$  can be calculated as follows,

$$N(t)_{Deficit} = N(t)_{Demand} - \left[ N(t)_{(Seed+Soil+Fert)Uptake} + N(t)_{BnfDerived} \right] \quad (8)$$

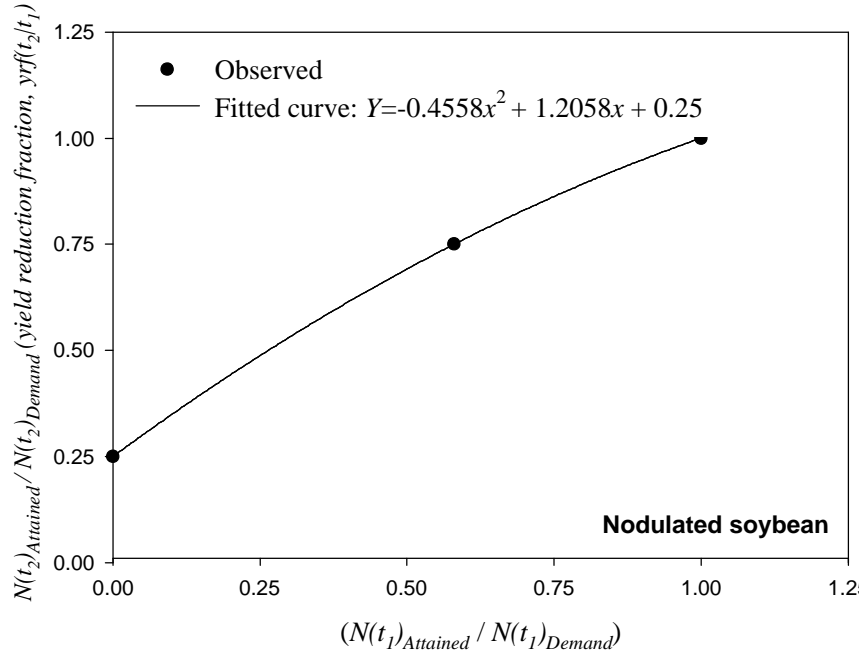
In order to predict the reducing effect of  $N(lag)_{Deficit}$  on  $N(mat)_{Attained}$ , a yield reduction fraction (*yrf*) must be first determined based on a relationship between expected incremental increases in  $N(mat)_{Demand}$  from unit increases in  $N(lag)_{(Seed+Soil+Fert)Uptake}$ . It was found that the relationship between  $N(mat)_{Attained}$  as a fraction of  $N(mat)_{Demand}$  and  $N(lag)_{Attained}$  as a fraction of  $N(lag)_{Demand}$  followed a quadratic response for soybean in the tropics based on data from George and Singleton (1992) (Figure 11) as represented in the generic equation 9.

$$yrf(t_2 | t_1) = a \left[ \frac{N(t_1)_{Attained} - N_{SeedUptake}}{N(t_1)_{Demand} - N_{SeedUptake}} \right]^2 + b \left[ \frac{N(t_1)_{Attained} - N_{SeedUptake}}{N(t_1)_{Demand} - N_{SeedUptake}} \right] + \frac{N^*(t_2)_{Attained}}{N(t_2)_{Demand}} \quad (9)$$

where  $yrf(t_2/t_1)$ = yield reduction fraction at time=  $t_2$  given  $N_{Attained}$  at time=  $t_1$  (where  $t_0 < t_1 < t_2$ );  $t_0=0$  (i.e, at seeding);  $t_1$ =any time from 0 to mat;  $t_2$ =any time from  $t_1$  to mat; a=quadratic coefficient; b=linear coefficient; and  $N^*(t_2)_{Attained}$  = minimum N attained at  $t_2$  when  $N_{Uptake}$  is only  $N_{SeedUptake} + N_{BnfDerived}$  (the latter applicable only to legumes).

The *yrf* would be crop, time and environment specific as its value is determined by the extent of  $N_{Demand}$  at time  $t_2$  that is potentially attainable at a given  $N_{Attained}$  or  $N_{Deficit}$  at a preceding time  $t_1$ . For nodulated soybean in the tropics,  $N^*(mat)_{Attained}$  is assumed to be 25% of  $N(mat)_{Demand}$ . With the *yrf*, the  $N(mat)_{Attained}$  can be calculated as follows,

$$N(mat)_{Attained} = yrf(mat | lag) \cdot N(mat)_{Demand} \quad (10)$$



**Figure 11.** The relationship between N attained at time  $t_2$  and time  $t_1$  by nodulated soybean. The  $(N(t_2)_{Attained} / N(t_2)_{Demand})$  is expressed as a yield reduction fraction ( $yrf(t_2/t_1)$ ). For nodulated soybean, the minimum N attained when N from seed is the only source of  $N_{uptake}$  is assumed to be 0.25. Data from George and Singleton, 1992.

In terms of actual  $N_{BnfDerived}$  and  $N_{Attained}$ , equation 5 can be rewritten as,

$$N(mat)_{BnfDerived} = [N(mat)_{Attained} - N(lag)_{Attained}] - [N(mat)_{(Seed+Soil+Fert)Uptake} - N(lag)_{(Seed+Soil+Fert)Uptake}] \quad (11)$$

Since,  $N(lag)_{Attained}$  would equal  $N(lag)_{(Seed+Soil+Fert)Uptake}$ , equation 11 simplifies to,

$$N(mat)_{BnfDerived} = N(mat)_{Attained} - N(mat)_{(Seed+Soil+Fert)Uptake} \quad (12)$$

When  $yrf(mat/lag) = 1$  (i.e., no yield reduction),  $N(mat)_{Attained}$  would equal  $N(mat)_{Demand}$  and  $N(mat)_{BnfDerived}$  would equal  $N(mat)_{BnfCapacity}$ . Therefore, when  $yrf(mat/lag)$  is less than 1, there would be a loss in  $N(mat)_{BnfDerived}$ . Thus,

$$N(mat)_{BnfLost} = N(mat)_{Demand} - N(mat)_{Attained} \quad (13)$$

where  $N_{BnfLost}$  is the cumulative potential loss in BNF if  $N(lag)_{Deficit}$  is not eliminated by the application of starter N fertilizer.

Maximizing the  $N_{BnfDerived}$  would require managing the starter N effect without a drawn out effect of applied fertilizer N replacing subsequent  $N_{BnfDerived}$ . Therefore, it is important that the right amount of starter N fertilizer is applied.

The amount of N fertilizer that must be applied to any crop to meet a given N demand depends on a nitrogen recovery fraction ( $nrf$ ), which is the fraction of total combined N supply in soil ( $N_{(Soil+Fert)Supply}$ ) that is recovered by the crop ( $N_{(Soil+Fert)Uptake}$ ). Thus,

$$N(mat)_{(Soil+Fert)Uptake} = nrf(mat) \cdot N(mat)_{(Soil+Fert)Supply} \quad (14)$$

It should be noted that the  $N_{SoilSupply}$  is likely to be relatively constant for a given soil and season unlike  $N_{FertSupply}$  which is dependent on the timing and amount of application. But regardless of N supply, George and Singleton (1992) found that legume species do differ in their  $nrf$  (George and Singleton, 1992). Thus, under same  $N_{(Soil+Fert)Supply}$ , legumes that are efficient in extracting soil N will have a greater  $N(t)_{(Soil+Fert)Uptake}$ , a lower  $N(t)_{Deficit}$ , and consequently a lower  $N(t)_{BnfDerived}$ , than those that are not. Using  $^{15}N$ , George and Singleton (1992) determined in the field that common bean scavenges N from soil much more efficiently than soybean, partly contributing to its lower  $N(mat)_{BnfDerived}$  compared to soybean. The  $NRF$  of soybean was less than half that of common bean and, consequently, KCl-extracted mineral N in the soil under soybean was almost twice as high as that under common bean. Further, the data indicated that the  $nrf$  as determined by  $^{15}N$  increases with time as indicated by the increasing linear coefficients for plots of  $N_{FertSupply}$  vs.  $N_{FertUptake}$  for periods of 35 days, 58 days and 84 days for soybean (Figure 12).

Rewriting, equation 12 will yield,

$$N(mat)_{BnfDerived} = N(mat)_{Attained} - [N_{SeedUptake} + nrf(mat) \cdot N(mat)_{(Soil+Fert)Supply}] \quad (15)$$

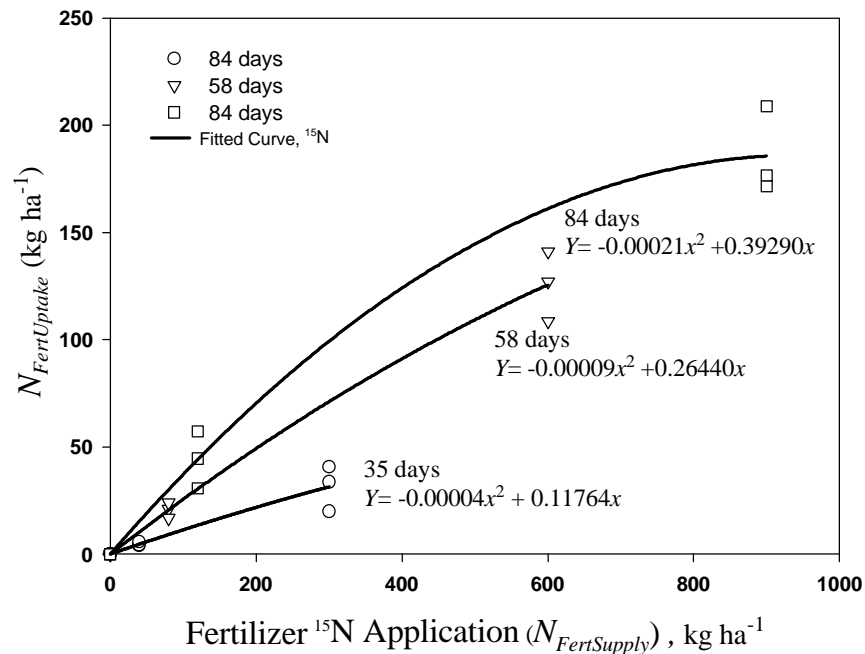
As pointed out earlier,  $N(mat)_{BnfDerived}$  would be the maximum when  $N(lag)_{Deficit}$  is eliminated by starter N fertilizer. To meet the  $N(lag)_{Deficit}$ , therefore, the amount of starter N fertilizer required could be calculated as,

$$\text{Starter N fertilizer} = \frac{N(lag)_{Deficit}}{nrf(lag)} \quad (16)$$

Any increase in  $N_{BnfDerived}$  from the starter N effect is further influenced by the pattern of N assimilation (George and Singleton, 1992). A legume that is able to meet its  $N(lag)_{Demand}$  from  $N(lag)_{(Seed+Soil)Supply}$  (no  $N(lag)_{Deficit}$ ), but has subsequent N requirement that substantially exceeds  $N(mat)_{(Seed+Soil)Uptake}$  would have high  $N(mat)_{BnfDerived}$  because of high  $N_{Deficit}$  during the BNF period. Consequently, in contrast to common bean, soybean that has a high N requirement from flowering to mid-podfill also has high BNF rates during the same period (George and Singleton 1992). Thus, the  $N(mat)_{BnfLost}$  would be much larger for a legume such

as soybean if the  $N(lag)_{Deficit}$ , which although is much smaller compared to common bean, is not met.

Summary - We were able to develop a preliminary model to predict N derived from BNF by legumes for possible improvement of the NDSS module of NuMaSS. Our concepts and model are based on limited data available particularly on N accumulation and biological N fixation during in early growth of a legume. The terminology and computations used in this paper are preliminary in nature. Next step would be to improve on the terminology and computations and test and improve the model with additional data from core as well as other experiments.



**Figure 12.** Relationship between fertilizer nitrogen uptake ( $N_{FertUptake}$ ) and fertilizer nitrogen supply ( $N_{FertSupply}$ ) in soybean estimated using  $^{15}\text{N}$  (Adapted from George and Singleton, 1992).

Literature Cited -

George T., J. K. Ladha, R. J. Buresh, and D. P. Garrity. 1992. Managing native and legume-fixed nitrogen in lowland rice-based cropping systems. *Plant Soil* 141:69-91.  
 George, T. and P.W. Singleton. 1992. Nitrogen assimilation traits and dinitrogen fixation in soybean and common bean. *Agron. J.* 84:1020-1028.  
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External Funding and Support

IRRI: Travel and time costs \$5, 000

Collaborators at intensive sites are conducting laboratory, greenhouse and field trials on various aspects of soil acidity management. Estimates of their funding contributions to this output are contained in values provided for Objective 1, Output 2.

Travel and Meetings Attended

Pedro Luna attended the ASA/CSA/SSSA Annual Meetings to present a poster describing the development of N coefficients for NuMaSS.

Relevant Publications, Reports and Presentations at Meetings

Luna-Orea, P, D.L. Osmond, T.J. Smyth, M.G. Waggoner and D.W. Israel. 2000. Methodology to generate NDSS-NuMaSS parameters and calculate N requirements: the case for maize in South America. Agron. Abstr. p.60.

*Output 3* Enhancing the knowledge base for the phosphorus decision support system - collecting, developing and synthesizing soil, plant and management information to improve the diagnosis and recommendations of location-specific P problems.

The P module in NuMaSS is at a younger stage of development than the modules for acidity and N. For many conditions, predicted P requirements are uncertain or undetermined; existing coefficients need to be improved and expanded over more soil and crop conditions; our current ability to diagnose and prescribe P requirements for tree species is limited. Rock phosphate exists in local deposits and, when of high quality and applied to acid soils or perennial crops, it can be as effective as soluble fertilizer P. To enable users to consider rock P options algorithms are needed that predict their performance based on data and information available to the intended users.

Milestone events for this output, during the 5-year plan are as follows:

- # Development of P diagnosis, prediction and fertilizer guidance for tree crops - beginning in year 1 and completed in year 3;
- # Refinement of soil P coefficients for improved P predictions - beginning in year 2 and completed in year 3;
- # Predicting effects of P fertilizer placement - year 3; and
- # Prediction and fertilizer guidance for rock P use - beginning in year 4 and completed in year 5.

#### Lead Investigators and Contributors

Russell Yost provides overall coordination to activities related to the P module. During the past year Yost received funding to continue P activities related to tree crops and predicting placement effects of fertilizer P. Cox continues to work on testing short-term methods for estimating P buffer coefficients using residual funds from years 1 and 2. Hossner continues testing diagnostic methods and P recommendations in on-station and on-farm trials in Mali. All U.S. members of the P group and testing site collaborators continued to share via correspondence their findings upon searches of the existing literature. Yost, Cox and Hossner are also contributing on P-related issues of the core experiments at the three intensive testing sites. Collaborators contributing to this output during year 2 are listed according to their respective institutions:

University of Hawaii - X. Wang, X. Shuai, Adrian Ares, and Richard Kablan.

University of Costa Rica - Alfredo Alvarado, Rafael Salas, Eloy Molina, Lidieth Uribe, Gabriela Soto and Jimmy Boniche.

Costa Rica Ministry of Agriculture, 'Los Diamantes' Experiment Station - Antonio Bogantes

Amazonia National Research Institute/Brazil - Charles Clement, Newton Falcão, Kukio

Yuyama.

University of the South, Sewanee, TN - Deborah MacGrath

Institute d'Economie Rurale/Mali - Mamadou Doumbia, Aminata Sidibe, M. Keita, O.B.

Coumare.

ICRISAT/Niger - A. Bationo

International Rice Research Institute - Thomas George and J. Quiton.

Philippines Rice Research Institute - Teodula Corton, Josephina Lasquite

Ilagan Research Station - Quirino Ascuncion and Danilo Tumamao.

EMBRAPA/Manaus - Manoel Cravo and Jeferson Macedo.

## Progress

1. *Greenhouse P fertilization trial with peach palm seedlings* - (supervised by Eloy Molina, Alfredo Alvarado and Jimmy Boniche, with support from Fred Cox) the purpose of this experiment is to evaluate P uptake and growth response by peach palm seedlings from Ultisols and Andisols in Costa Rica. In September, 2000 a greenhouse experiment was initiated in the La Leona area near Guapiles, Costa Rica to determine P uptake by palmito seedling from 10 soils, 5 Andisols and 5 Ultisols. It had taken considerable time to select and collect these soils from the region as they had to be low in P and represent the change in soil characteristics from Andisol to Ultisol. Six rates of P were applied to each soil based on a short-term P sorption assessment. The Los Diamantes Experiment Station provided palmito seedlings which were transplanted to each pot. There was considerable variability among the seedlings, so after planting the height of each was measured. After about 4 months, plant height will again be measured and soil and plant (a few leaflets) samples taken and P determined. After several more months, the same measurements plus plant weight will be taken and the data analyzed to determine P sorption by the soil and the ability of the plant to take up P from soils varying in characteristics from Andisols to Ultisols. This will assist in confirming the soil properties, especially of the Andisols, that should be considered in evaluating soil P and recommending P fertilization in the Decision Support System.

2. *Laboratory P incubations as estimates of soil P buffer coefficients* - (supervised by Eloy Molina and Alfredo Alvarado, with support from Fred Cox) the purpose of this study is to determine factors affecting P sorption in a variety of soils, primarily Andisols and Ultisols, as part of our effort to devise laboratory methods to estimate field P buffer coefficients for NuMaSS. The Soils Laboratory at the University of Costa Rica analyzed selected chemical and physical properties of 62 soils. After several reruns were conducted, these data were used to determine the relationship between P sorption and soil properties for soils which vary in clay type from crystalline to non-crystalline for use in PDSS. Countries of origin and number of soils were Costa Rica 45, Ecuador 8, Panama 3, Hawaii 3, Honduras 2, and Guatemala 1 (Table 14). Data included nutrients extracted by Modified Olsen and Mehlich 3, pH, organic matter, acidity, texture, amorphous Fe, amorphous Al (AmAl), and KOH-extractable Al (KOHAl).

The soils were also mixed with 0, 35, 70, and 140 ug P/cm<sup>3</sup>, allowed to dry, and extracted with both Modified Olsen and Mehlich 3 to determine the change (recovery) in soil test P per unit of P applied. Soil test P generally increased linearly with rate of P applied (Table 15). The slopes determined from these relationships were termed the Modified Olsen (MOPBC) and Mehlich 3 (M3PBC) P buffer coefficients. These slopes were markedly greater for soils with high initial soil test P, so soils with P greater than 20 ug/cm<sup>3</sup> in the check samples by either method or in the original samples by the Modified Olsen were deleted from further evaluation. Soils with high soil test P do not require diagnosis and interpretation by PDSS anyway. Thus, data from 21 soils were deleted, leaving a set of 41 with 18 Andisols, 21 Ultisols, and 2 Oxisols.

Table 14. General chemical and physical soil data from the analyses conducted in Costa Rica.

Soil		Country	Amorphous		KOH		Exchangeable				Org.				
No.	Order		Al	Fe	Al	pH	Ca	Mg	K	Acid.	CEC	Mat.	Sand	Silt	Clay
			----- % -----		----- cmol dm <sup>-3</sup> -----				----- % -----						
1	Ultisol	Costa Rica	1.65	0.54	0.33	5.0	4.54	1.41	0.23	1.20	7.38	7.71	48	17	35
3	Ultisol	Costa Rica	0.64	0.32	0.19	4.6	3.50	1.96	0.81	4.40	10.67	8.71	39	32	29
4	Ultisol	Costa Rica	0.71	1.24	0.36	4.9	1.17	0.36	0.10	1.80	3.43	3.89	28	19	53
5	Ultisol	Costa Rica	0.81	1.04	0.44	5.2	3.25	1.71	0.14	5.20	10.30	4.02	29	18	53
6	Ultisol	Costa Rica	2.88	0.3	0.48	5.2	1.08	0.16	0.08	0.60	1.92	1.94	29	26	45
7	Ultisol	Costa Rica	2.16	1.12	0.78	5.3	3.40	1.17	0.32	0.50	5.39	6.43	14	26	60
8	Ultisol	Costa Rica	2.66	0.83	0.81	5.5	0.72	0.36	0.18	0.70	1.96	7.89	44	23	33
9	Ultisol	Costa Rica	1.75	0.71	0.66	5.1	1.70	0.17	0.16	0.70	2.73	5.25	45	14	41
10	Ultisol	Costa Rica	3.20	0.54	0.72	5.1	1.60	0.20	0.05	0.70	2.55	4.29	29	16	55
11	Ultisol	Costa Rica	1.20	0.49	0.47	4.3	1.60	0.99	0.17	5.40	8.16	8.91	14	26	60
12	Ultisol	Costa Rica	0.57	1.55	0.37	5.4	5.12	2.27	0.23	0.90	8.52	3.22	34	15	51
13	Ultisol	Costa Rica	1.18	1.55	0.51	4.9	1.24	0.35	0.48	2.80	4.87	7.17	31	23	46
14	Ultisol	Costa Rica	1.48	1.55	0.44	5.3	0.84	0.33	0.12	1.40	2.69	3.95	29	21	50
15	Ultisol	Costa Rica	0.12	0.49	0.8	5.5	15.40	6.30	0.14	0.80	22.91	3.55	34	34	32
16	Ultisol	Costa Rica	4.49	1.11	0.19	5.6	2.92	0.70	0.10	0.90	4.62	9.31	19	34	47
17	Ultisol	Costa Rica	2.95	0.45	0.32	5.0	2.27	0.40	0.39	2.20	5.26	2.95	6	16	78
18	Ultisol	Costa Rica	0.94	1.93	0.39	4.8	1.29	0.52	0.53	1.80	4.14	5.43	46	32	22

Soil		Country	Amorphous		KOH		Exchangeable				Org.				
No.	Order		Al	Fe	Al	pH	Ca	Mg	K	Acid.	CEC	Mat.	Sand	Silt	Clay
			----- % -----		----- cmol dm <sup>-3</sup> -----				----- % -----						
19	Ultisol	Costa Rica	3.38	0.92	0.66	4.8	1.53	0.48	0.18	1.00	3.19	6.36	35	26	39
20	Ultisol	Costa Rica	0.62	1.07	0.42	5.3	6.03	1.80	0.15	1.50	9.48	7.44	28	17	55
22	Ultisol	Costa Rica	0.96	2.07	0.56	5.1	7.04	3.14	0.37	6.30	16.85	4.96	28	22	50
24	Ultisol	Costa Rica	0.52	0.68	0.31	5.3	6.25	1.81	0.09	0.60	8.75	3.48	49	11	40
76	Andisol	Costa Rica	2.83	1.86	1.27	6.0	3.79	1.36	0.45	0.50	6.10	8.20	64	31	5
77	Andisol	Costa Rica	3.67	2.59	2.42	5.5	0.63	0.27	0.29	0.40	1.59	24.00	73	19	8
78	Andisol	Costa Rica	2.25	2.64	1.02	5.8	5.71	1.67	0.44	0.40	8.22	10.80	56	30	14
79	Andisol	Costa Rica	5.10	2.12	3.41	5.9	1.73	0.40	0.13	0.70	2.96	13.30	68	30	2
80	Andisol	Costa Rica	4.05	1.19	2.71	6.0	10.10	2.10	0.72	0.30	13.22	20.40	60	25	15
81	Andisol	Costa Rica	0.95	1.39	0.54	6.3	11.10	2.17	2.05	0.30	15.62	5.20	46	22	32
82	Andisol	Costa Rica	4.72	1.05	2.81	6.0	7.17	0.75	0.31	0.40	8.63	13.90	50	34	16
83	Andisol	Costa Rica	1.12	1.16	0.47	5.9	4.98	1.32	1.00	0.40	7.70	4.76	12	30	58
84	Andisol	Costa Rica	0.92	0.71	0.32	5.5	3.64	1.57	0.49	0.40	6.10	5.01	78	20	2
85	Andisol	Costa Rica	2.25	0.75	0.85	6.0	5.20	0.47	0.40	0.30	6.37	5.65	60	27	13
86	Andisol	Costa Rica	5.07	1.92	5.07	6.3	4.80	0.68	0.80	0.20	6.48	10.60	63	29	8
87	Andisol	Costa Rica	4.82	1.55	2.71	5.4	0.73	0.32	0.35	1.20	2.60	18.80	71	19	10
88	Andisol	Costa Rica	4.75	1.34	2.57	5.8	1.25	0.23	0.30	0.40	2.18	22.50	81	14	5
89	Andisol	Costa Rica	0.72	1.29	0.30	5.9	10.50	3.23	0.87	0.50	15.10	6.55	71	24	5

Soil		Country	Amorphous		KOH		Exchangeable				Org.				
No.	Order		Al	Fe	Al	pH	Ca	Mg	K	Acid.	CEC	Mat.	Sand	Silt	Clay
			----- % -----		----- cmol dm <sup>-3</sup> -----				----- % -----						
90	Andisol	Costa Rica	1.87	0.79	0.88	6.3	8.87	0.78	0.29	0.20	10.14	7.57	45	49	6
92	Andisol	Costa Rica	1.77	1.10	0.59	4.6	3.88	1.35	2.50	0.90	8.63	7.11	70	10	20
93	Andisol	Costa Rica	2.87	0.92	2.21	5.8	7.59	2.50	0.66	0.30	11.05	8.84	60	30	10
94	Andisol	Costa Rica	2.47	0.73	0.94	5.7	3.94	1.35	1.22	0.20	6.71	14.10	55	41	4
95	Andisol	Costa Rica	4.15	0.54	2.79	5.8	4.12	0.94	0.23	0.20	5.49	5.32	70	23	7
96	Andisol	Costa Rica	3.97	0.55	2.79	5.8	3.34	0.56	0.21	0.20	4.31	12.19	60	26	14
97	Andisol	Costa Rica	4.35	1.39	3.38	5.7	2.93	0.24	0.18	0.20	3.55	12.05	52	42	6
98	Andisol	Costa Rica	4.55	0.95	3.07	5.4	2.40	0.30	0.22	0.30	3.22	9.23	60	28	12
99	Andisol	Costa Rica	0.25	1.29	0.22	6.2	29.70	6.60	1.01	0.20	37.51	4.09	36	37	27
100	Andisol	Costa Rica	2.67	1.50	0.79	4.8	3.05	1.36	0.24	7.60	12.25	8.44	55	34	11
101	Andisol	Ecuador	0.65	0.47	0.30	5.6	6.63	1.31	0.19	0.30	8.43	6.37	51	41	8
102	Andisol	Ecuador	0.50	0.41	0.25	5.6	9.63	1.76	0.19	0.35	11.93	7.29	45	46	9
103	Andisol	Ecuador	0.40	0.41	0.28	6.0	8.50	1.80	0.59	0.25	11.14	8.23	45	43	11
104	Andisol	Ecuador	0.55	0.46	0.32	6.3	6.60	1.89	0.41	0.20	9.10	5.64	61	30	9
105	Andisol	Ecuador	0.30	0.75	0.26	5.5	8.00	2.60	0.20	0.25	11.05	5.97	69	25	6
106	Andisol	Honduras	1.52	1.11	0.83	6.7	2.74	0.50	0.34	0.80	4.38	5.57	16	29	55
107	Andic	Honduras	0.95	1.02	0.98	6.2	9.16	3.44	0.52	0.20	13.32	4.38	62	24	14
108	Ultisol	Panama	0.92	0.29	0.26	5.4	1.55	0.36	0.10	1.65	3.66	4.64	23	22	55

Soil		Country	Amorphous		KOH	pH	Exchangeable				CEC	Org.			
No.	Order		Al	Fe	Al		Ca	Mg	K	Acid.		Mat.	Sand	Silt	Clay
			----- % -----		----- cmol dm <sup>-3</sup> -----				----- % -----						
109	Oxisol	Hawai	1.60	0.44	0.33	5.0	1.76	1.35	0.39	0.35	3.85	5.17	18	15	68
110	Oxisol	Hawai	1.67	0.89	0.68	5.0	2.40	0.78	0.15	0.40	3.73	7.10	74	16	11
111	Andisol	Hawai	4.55	7.64	3.45	5.2	3.98	0.72	0.18	0.95	5.83	6.51	53	31	16
112	Andisol	Panama	3.45	1.09	2.37	5.2	2.16	0.42	0.40	0.60	3.58	10.54	47	32	21
113	Andisol	Panama	3.62	1.03	2.51	5.5	1.65	0.31	0.30	0.60	2.86	8.29	42	40	18
114	Andisol	Ecuador	1.22	0.93	0.99	5.5	8.52	0.58	0.35	0.25	9.70	4.97	32	43	25
115	Andisol	Ecuador	1.10	0.90	0.87	5.7	8.28	0.62	0.44	0.25	9.59	5.11	36	44	20
116	Andisol	Ecuador	1.27	0.97	1.02	6.7	8.83	0.58	0.32	0.20	9.93	5.24	30	45	25
117	Andisol	Guatemala	2.75	0.88	2.19	7.0	8.53	1.64	0.42	0.20	10.79	10.15	48	35	18

Table 15. Modified Olsen and Mehlich 3 P after application of four rates of P to the soils from Costa Rica.

Soil ID	Modified Olsen Extractant				Buffer Coeff.	Mehlich 3 Extractant				Buffer Coeff.
	Applied P (mg dm <sup>-3</sup> )					Applied P (mg dm <sup>-3</sup> )				
	0	35	70	140		0	35	70	140	
	----- P recovery, mg dm <sup>-3</sup> -----					----- P recovery, mg dm <sup>-3</sup> -----				
1	6.8	8.0	10.6	19.8	0.096	5.2	6.8	10.3	18.0	0.094
3	12.9	25.4	32.4	41.0	0.192	5.4	12.7	20.6	41.3	0.258
4	5.0	9.5	19.1	40.2	0.259	4.6	8.2	15.9	29.4	0.183
5	4.2	5.3	10.3	21.5	0.129	6.1	8.5	13.7	26.4	0.149
6	3.2	3.5	6.0	16.0	0.096	5.2	5.3	6.7	10.3	0.038
7	7.3	8.0	13.7	23.3	0.121	7.0	11.0	14.6	23.2	0.115
8	5.6	10.5	18.6	35.5	0.218	4.8	11.6	18.0	23.6	0.132
9	4.2	5.3	11.1	27.6	0.175	4.5	7.0	12.1	18.8	0.105
10	5.2	5.4	9.5	22.2	0.128	2.8	5.8	12.4	17.9	0.112
11*	21.9	40.2	45.6	61.0	0.262	131.0	137.0	149.0	188.0	0.415
12	1.4	4.3	8.7	21.5	0.147	5.2	7.7	11.6	22.1	0.123
13	5.7	9.3	14.2	31.0	0.184	5.3	15.4	20.7	33.4	0.194
14	1.5	5.2	8.4	20.5	0.136	5.6	9.3	14.9	25.1	0.142
15	3.4	9.8	17.0	37.4	0.245	5.8	21.7	29.1	48.2	0.292
16	1.5	6.3	10.5	13.8	0.086	6.2	11.3	15.0	22.7	0.116
17	3.9	5.3	8.3	13.7	0.072	6.3	10.3	13.6	19.1	0.090
18	5.6	11.4	16.2	27.9	0.158	11.2	18.7	26.8	42.4	0.223
19	4.0	7.9	13.3	27.1	0.168	3.4	13.7	21.3	37.0	0.236
20	3.8	10.4	16.6	29.0	0.179	6.0	13.7	21.5	43.2	0.267
22	4.7	9.5	16.5	33.2	0.207	7.5	16.1	20.3	36.7	0.204
24	2.9	4.4	7.2	11.4	0.066	1.8	4.0	8.5	19.1	0.127
76	6.4	16.8	21.1	32.5	0.178	16.0	19.9	30.8	37.6	0.161
77	6.2	20.6	25.3	35.1	0.193	6.6	17.0	20.2	30.8	0.163
78	2.2	11.3	15.7	26.9	0.170	4.6	7.3	11.5	18.9	0.104
79	2.4	8.1	10.3	17.2	0.101	5.6	6.8	7.8	9.8	0.030

Soil ID	Modified Olsen Extractant				Buffer Coeff.	Mehlich 3 Extractant				Buffer Coeff.
	Applied P (mg dm <sup>-3</sup> )					Applied P (mg dm <sup>-3</sup> )				
	0	35	70	140		0	35	70	140	
	----- P recovery, mg dm <sup>-3</sup> -----					----- P recovery, mg dm <sup>-3</sup> -----				
80*	35.5	90.0	97.0	75.5	0.211	54.0	74.0	81.0	103.0	0.333
81*	39.5	89.5	106.0	101.0	0.383	57.0	63.5	75.5	94.5	0.275
82	5.0	12.1	14.9	20.6	0.105	6.1	7.3	8.4	9.5	0.024
83*	33.0	33.0	33.0	37.0	0.029	107.0	113.0	146.0	199.0	0.690
84*	54.1	170.0	232.0	234.0	1.180	200.0	200.0	223.0	264.0	0.485
85*	76.2	78.0	92.5	122.0	0.342	121.0	127.0	142.0	167.0	0.338
86	2.3	2.3	4.3	9.3	0.053	4.0	4.1	4.7	6.1	0.016
87	5.6	9.2	12.2	19.2	0.096	6.3	21.3	27.4	36.2	0.200
88	12.3	18.7	23.3	28.5	0.112	6.1	21.4	32.2	39.8	0.231
89*	3.3	5.1	8.0	16.2	0.094	5.6	35.8	44.6	57.2	0.337
90	7.1	11.9	22.4	44.7	0.276	4.9	5.9	10.3	25.1	0.150
92**	3.9	5.3	8.3	13.7	0.072	5.4	6.2	10.0	13.4	0.061
93*	33.6	44.7	46.3	73.5	0.276	58.7	59.7	61.9	64.8	0.045
94**	13.4	15.8	21.9	34.0	0.152	5.6	13.2	16.8	28.9	0.162
95*	26.6	33.7	41.3	65.0	0.277	39.1	41.2	54.5	68.7	0.225
96	3.9	2.8	5.3	11.2	0.057	5.2	5.4	8.4	11.8	0.051
97	2.9	4.7	7.0	12.0	0.066	0.6	0.8	1.6	2.9	0.017
98	2.2	3.8	5.8	10.3	0.059	0.6	0.9	7.0	11.8	0.085
99**	4.5	7.1	10.3	16.2	0.084	2.0	6.8	10.5	29.7	0.199
100*	32.6	40.8	68.0	83.5	0.383	49.1	62.6	74.6	77.0	0.192
101	13.2	24.0	37.3	67.0	0.388	3.0	11.2	28.8	93.9	0.699
102*	34.0	36.1	36.4	39.0	0.034	5.2	11.2	27.0	51.3	0.342
103*	19.9	40.9	56.2	89.0	0.486	80.0	93.5	105.0	144.0	0.457
104*	56.8	71.5	88.3	111.0	0.388	16.0	29.1	56.3	99.0	0.611
105*	23.1	36.6	54.1	92.5	0.502	66.0	88.0	106.0	148.0	0.579
106	18.6	19.9	23.2	39.6	0.155	13.4	24.4	42.1	57.5	0.320

Soil ID	Modified Olsen Extractant				Buffer Coeff.	Mehlich 3 Extractant				Buffer Coeff.
	Applied P (mg dm <sup>-3</sup> )					Applied P (mg dm <sup>-3</sup> )				
	0	35	70	140		0	35	70	140	
	----- P recovery, mg dm <sup>-3</sup> -----					----- P recovery, mg dm <sup>-3</sup> -----				
107	13.2	22.9	35.9	67.2	0.392	12.5	26.0	53.4	92.0	0.585
108	4.4	10.2	15.2	30.9	0.189	1.7	4.0	10.0	22.1	0.151
109	4.7	11.4	17.4	34.0	0.209	5.0	5.2	8.9	20.0	0.113
110	13.0	16.3	19.0	26.0	0.092	4.8	7.0	12.3	27.1	0.165
111	11.3	13.1	15.6	22.1	0.078	3.0	3.5	4.5	8.1	0.037
112	9.2	15.9	22.3	35.9	0.190	0.6	1.4	3.1	5.1	0.033
113	4.9	14.4	20.1	32.8	0.194	4.6	7.1	10.4	14.4	0.070
114*	32.0	50.5	67.0	105	0.520	4.8	7.6	10.7	15.2	0.074
115*	34.6	42.4	58.1	79.5	0.330	31.3	45.6	58.1	60.2	0.199
116*	12.9	20.9	32.2	59.4	0.338	35.9	49.8	60.3	59.5	0.159
117*	6.0	10.4	16.3	30.8	0.180	28.4	30.7	41.6	52.2	0.189

\* soils deleted because of high initial P in the check samples

\*\* soils deleted because of high initial P in the original samples

Modified Olsen and Mehlich 3 PBC were correlated with soil properties, first for all soils and then by soil order for the Andisols and Ultisols. The only factors showing a linear relationship were KOH-extractable Al (KOHAl) and Amorphous Al (AmAl) (Table 16). In prior work (Alvarado, 1984; Blakemore, 1983) KOHAl was found to be a quick, reliable estimate equaling about half that of the AmAl in Andisols. In the present set of data KOHAl is about two-thirds that of AmAl.

The relationships between the two forms of extractable Al and the change in soil test P were similar for the two extractants, Modified Olsen and Mehlich 3 (Table 16), and were much better for the Andisols than for the Ultisols. The highest r-value was 0.87 for the linear relationship between MOPBC and AmAl for the Andisols, so 76% of the variation was being explained. However, Alvarado and Buol (1985) found an exponential relationship between MOPBC and Amorphous Al with Andisols which was suggested for use in PDSS in March 1999. With an exponential model, the relationship between MOPBC and AmAl had an R<sup>2</sup>-value of 0.78 (Figure 13), that between M3PBC and AmAl had an R<sup>2</sup>-value of 0.82 (Figure 14), that between MOPBC and KOHAl had an R<sup>2</sup>-value of 0.67 (Figure 15), and that between M3PBC and KOHAl had an R<sup>2</sup>-value of 0.64 (Figure 16). Thus the relationships with AmAl were slightly better than those with KOHAl, and those with Modified Olsen were slightly better than those with Mehlich 3.

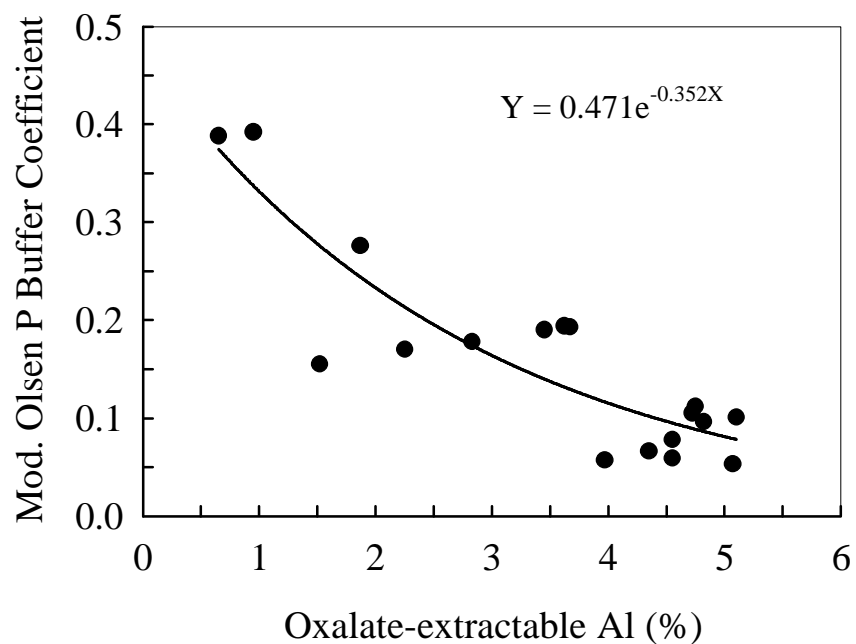
Table 16. Correlation of soil Al and clay content with the change in Modified Olsen P and Mehlich 3 P in soils analyzed in Costa Rica.

Soils	N	Variable	MOPBC	M3PBC
----- r -----				
All	41	AmAl	-0.55**	-0.52**
		KOHA1	-0.40*	-0.40**
		Clay	-0.03	-0.04
Andisols	18	AmAl	-0.87**	-0.77**
		KOHA1	-0.78**	-0.70**
		Clay	0.02	0.14
Ultisols	21	AmAl	-0.45*	-0.50*
		KOHA1	0.34	0.08
		Clay	-0.29	-0.38

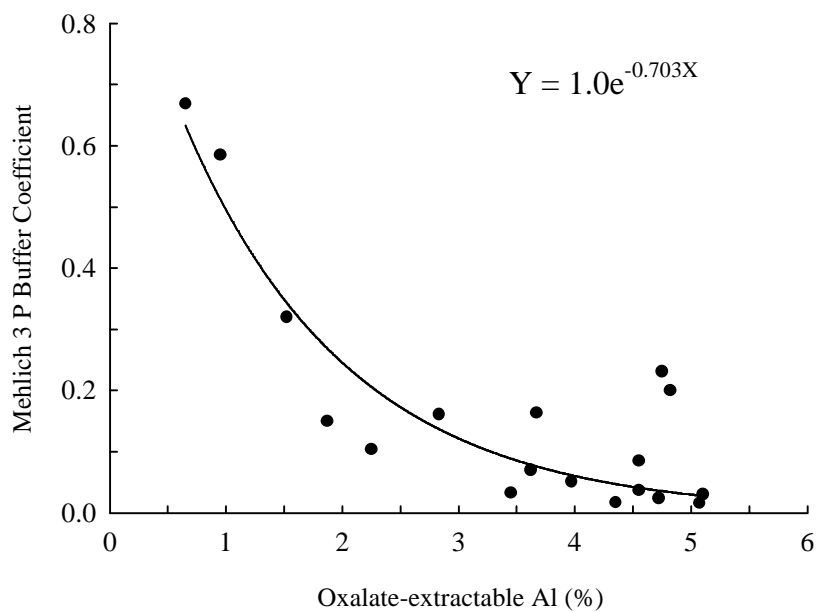
The current observations sent by Eloy Molina were compared with those by Alvarado and Buol data (1985) and the relationship was similar for the two sets of data (Figure 17). There are a number of outliers, more in the Alvarado and Buol data than in the current data by Molina and especially at low levels of AmAl; these seem to cause a reduction in the expected intercept. Nevertheless, this relationship between Modified Olsen P buffer coefficient and the oxalate-extractable Al is the best for determining P fertilizer recommendations for Andisols. Other relationships are also available for Mehlich 3 P buffer coefficient and oxalate-extractable Al, as well as for these two coefficients and KOH-extractable Al. These may be used to make P recommendations on Andisols just as clay content is used to make P recommendations on Ultisols and Oxisols.

Clay content was not related to the change in soil test level per unit of P applied in this set of soils. Although there was such a tendency with clay on the Ultisols, the range in clay content may not have been sufficient to show the effect.

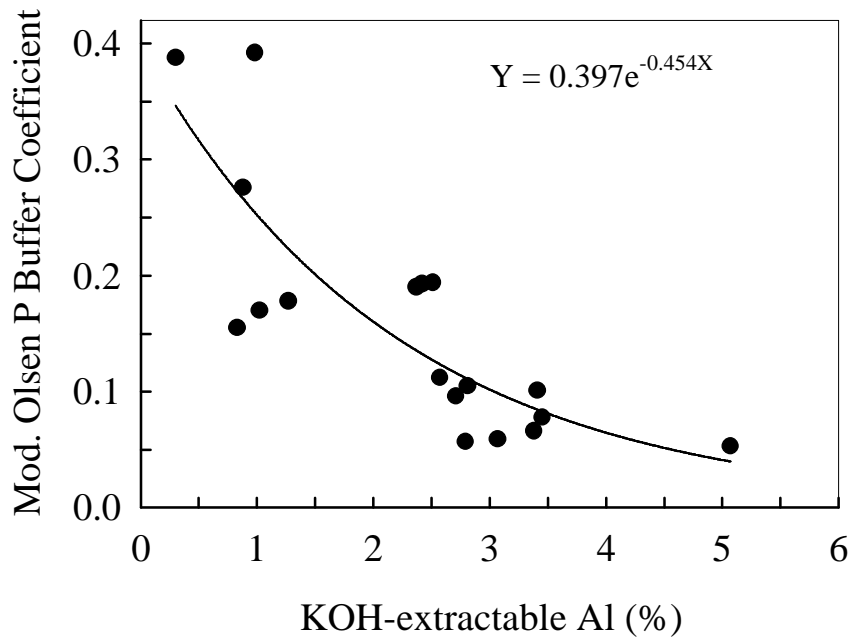
The relationship between M3PBC and clay content from the Costa Rica data also was compared with previous data for the Ultisols which serves as one of the foundations of PDSS. Mehlich 3 P buffer coefficient was similarly related to clay content for the two sets of data (Figure 18). Again, there are some outliers in the relationship, but this may be due to a mixture of clay types, as in some of the Ultisols from Costa Rica there may be both kaolinite and allophane.



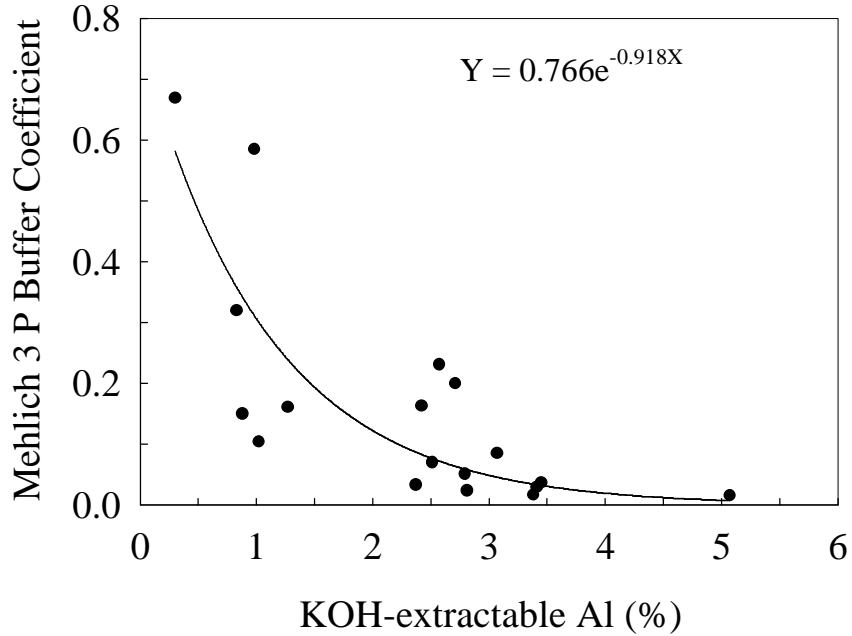
**Figure 13.** Relation between P buffer coefficients determined by the Modified Olsen extractant and oxalate extractable Al in Andisols



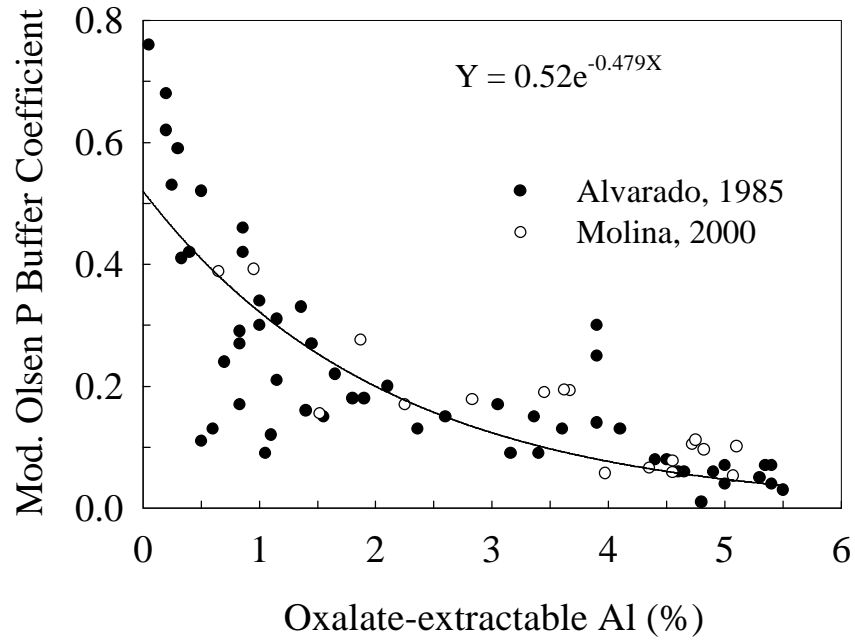
**Figure 14.** Relation between P buffer coefficients determined by the Mehlich 3 extractant and oxalate extractable Al in Andisols



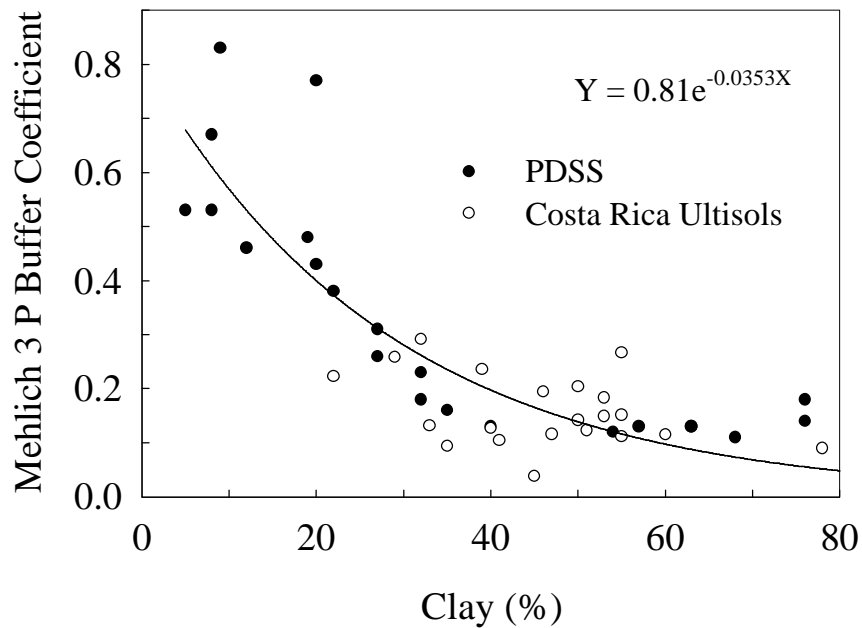
**Figure 15.** Relation between P buffer coefficients determined by the Modified Olsen extractant and KOH-extractable Al in Andisols.



**Figure 16.** Relation between P buffer coefficients determined with the Mehlich 3 extractant and KOH-extractable Al in Andisols



**Figure 17.** Relation between P buffer coefficients determined with the Modified Olsen extractant and oxalate-extractable Al in Andisols for data reported by Alvarado (1985) and the current data set by Eloy Molina.



**Figure 18.** Relation between Mehlich 3 soil P buffer coefficient and clay content for field observations in PDSS and for Ultisols in Costa Rica.

Another observation from the current set of data is that the concentration of P extracted by Mehlich 3 and Modified Olsen are very similar. Sobral and Cox (1998) reviewed concentrations of soil P obtained from various extractants and found Mehlich 3 P very close to Bray 1 P, but that from Modified Olsen was only about 53% of the two former extractants. It is unusual, therefore, to find Mehlich 3 and Modified Olsen to be as close as in the Costa Rica data. It would be valuable to know the cause of this effect.

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3. *Determining critical soil phosphorus levels for upland crops* - (Thomas George, Jonathan Quito, Roger Magbanua, Russell Yost) The yield response to P is considered close to its maximum at a critical soil P level. At higher soil test P levels than considered critical, it is expected that there would be no response to P fertilizer. The intent of P fertilization is then to increase the soil test P to or above this critical level. Several approaches are employed to determine the critical P levels for crops.

We examined critical soil P levels for upland rice and soybean for several seasons in a long term P experiment (part of IRRI Long Term Experiment (LTPE) network) in an acid upland soil at Siniloan, Laguna, Philippines. Since 1995, five crops each of upland rice and soybean were grown in a upland rice-soybean annual rotation with an initial application in 1995 of 0, 62.5, 125, and 250 and a subsequent application in 1999 of 0, 50, 100 and 200 kg P ha<sup>-1</sup>.

Nutrient amendments other than P were aimed to achieve sufficiency in the crop of all nutrients by liming and applying N, K, Zn for rice and K, Mo and B for inoculated soybean.

Soil extractable P was measured by Mehlich 1 (M1P) extractant for each crop at 30 days after P fertilizer application or at seeding of the crop in seasons when no P fertilizer was applied. Critical P levels were estimated by the Cate and Nelson graphical approach or by fitting the linear response and plateau function to yield vs. Mehlich 1 P values.

The critical soil P levels determined for upland rice and soybean by Cate-Nelson graphical and LRP procedures and the plateau and intercept yields obtained in the different seasons are presented in Tables 17 and 18.

Table 17. Mehlich 1 P critical P levels for rice grown in aerobic soil, Siniloan, Laguna, Philippines

Year	Upland rice variety/line	Critical P level			Intercept yield
		Cate-Nelson graphical	Linear response and plateau	Plateau yield	
					t ha <sup>-1</sup>
1995	IRAT 216	4.0	3.4	1.6	0
1996	UPLRi 5	Scatter	Scatter	2.4	-
1997	IR55423-01	8.7	11.3	3.8	2.8
1998	IR55423-01	4.8	4.7	3.2	2.3
1999	Panay hybrid	2.0	2.1	2.2	1.1
1999	Mestizo hybrid	2.9	2.8	2.6	0.5

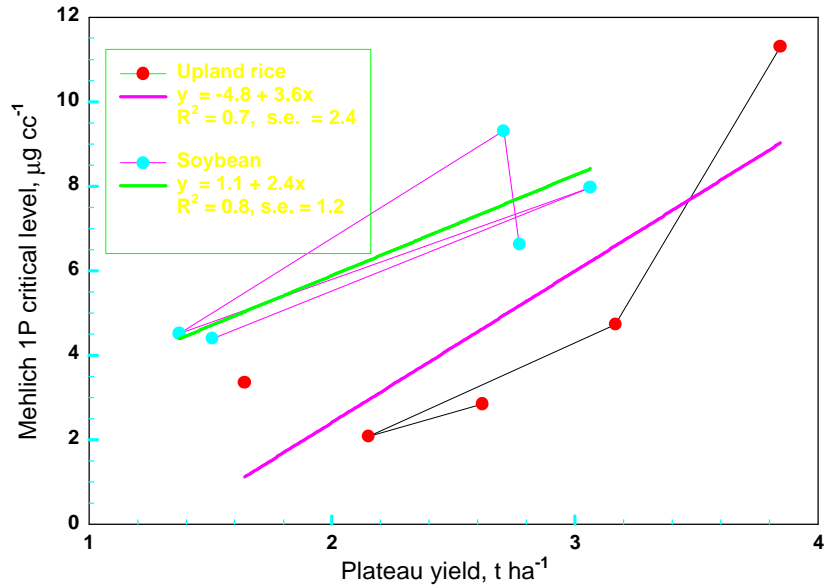
Table 18. Mehlich 1 P critical P levels for soybean, Siniloan, Laguna, Philippines.

Year	Soybean variety	Critical P level			Intercept yield
		Cate-Nelson graphical	Linear response and plateau	Plateau yield	
					t ha <sup>-1</sup>
1996	UPSY 2	4.3	4.4	1.5	0.04
1997	UPSY 2	8.0	7.8	3.1	1.60
1998	UPSY 2	4.5	4.5	1.4	0.02
1999	UPSY 2	7.4	9.3	2.7	0.12
2000	UPSY 2	6.6	6.6	2.8	0.22

The Cate-Nelson and the LRP critical levels were comparable with any given season but both varied across seasons. For upland rice, the Cate and Nelson values ranged from 2 to 8.7 while LRP values ranged from 2.1 to 11.3 ug M1P cc<sup>-1</sup> soil. It should be noted that in the 1996 season, no critical value could be determined for upland rice as no response was observed. For soybean, Cate and Nelson values ranged from 4.3 to 8.0 while LRP values ranged from 4.4 to 9.3 ug M1P cc<sup>-1</sup> soil. The variability in critical values among seasons appeared not to be related to the build-up or decline of soil P levels or the length of time from applied P. The critical M1P levels, however, tended to be associated with the yield levels; the higher the LRP plateau yield, the higher the critical M1P value (Figure 19) for both upland rice and soybean. It seems, therefore, that at least in the case of soybean, the yield levels attained seem to influence the critical P levels estimated.

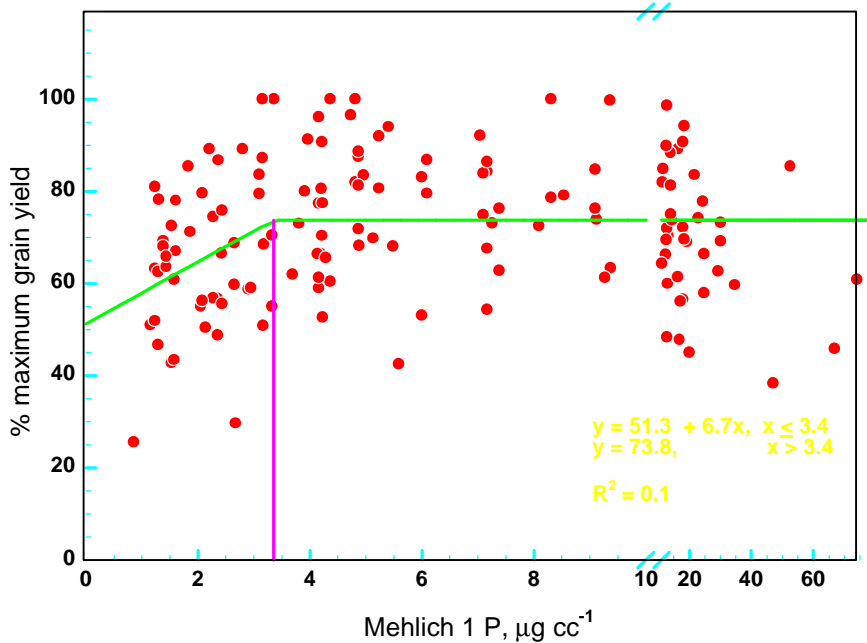
The variability in critical P values across seasons would be masked if LRP functions were plotted across seasons with yields relative to the maximum yield in each season (Figures 20 and 21). Thus, the critical M1 P across seasons for upland rice would be 3.4 and for soybean 8.2 ug M1P cc<sup>-1</sup> soil.

Both Cate and Nelson graphical and the linear response and plateau approaches provide critical levels in a comparable range. Even at the same site, critical P levels varied across seasons and this variability was masked only when relative yields were plotted instead of absolute yields. In the present study, the seasonal variation in critical P level estimates

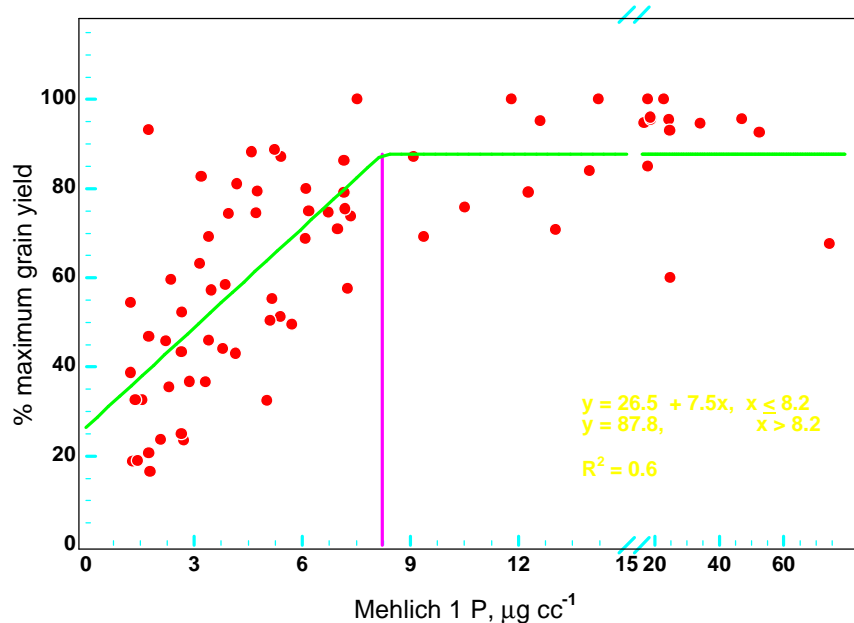


**Figure 19.** Relationship between the LRP plateau yield and critical Mehlich 1 P value for 5 crops each of upland rice and soybean, Siniloan, Laguna, Philippines.

appeared to be related to yield levels attained. This association with yield level was more obvious in the case of soybean where high plateau yields were achieved in some seasons with relatively unchanged intercept yield. Further studies are needed to confirm whether



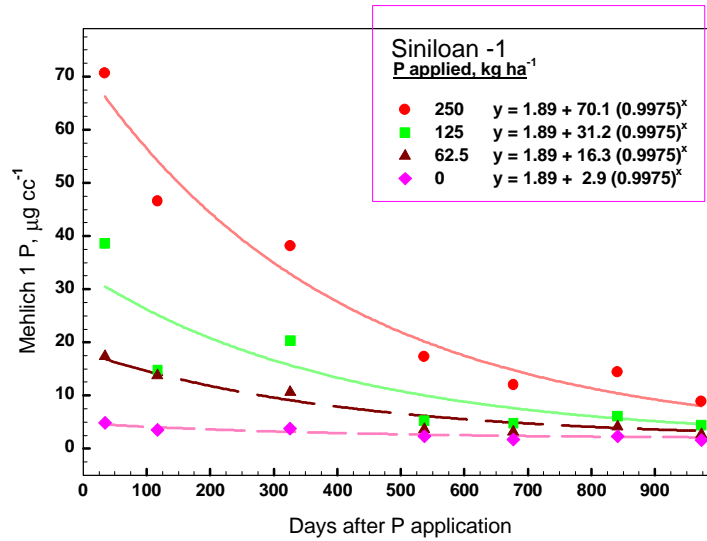
**Figure 20.** Linear response plateau plot of relative grain yield (expressed as a % of the maximum) against soil Mehlich 1 P for five crops of upland rice, Siniloan, Laguna, Philippines.



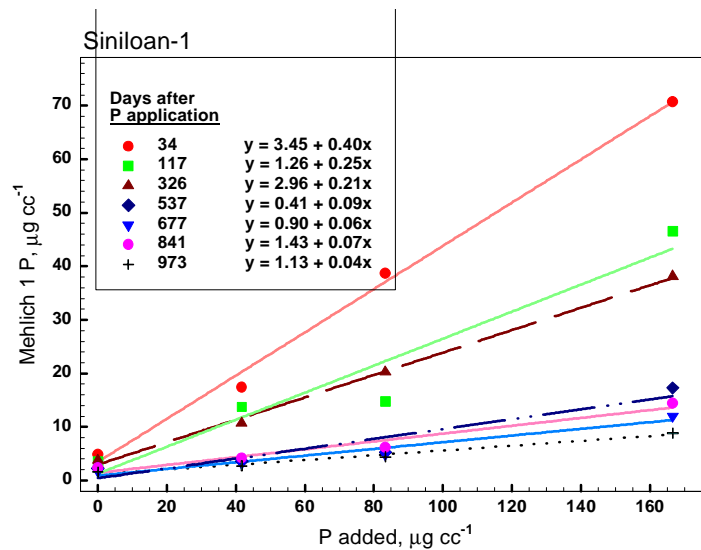
**Figure 21.** Linear response plateau plot of relative grain yield (expressed as a % of the maximum)

critical level estimations are biased by the range of plateau and intercept yield levels achieved in experiments.

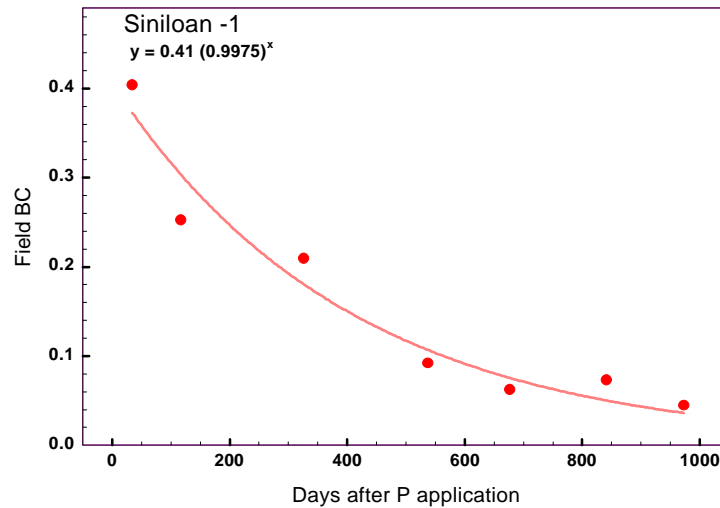
4. *Determining P slow reaction coefficient in the field* - (Thomas George, Jonathan Quiton, Roger Magbanua, Russell Yost) We analyzed the decline in Mehlich 1 extractable P at one of IRRI's LTPE site, Siniloan, Laguna, Philippines. Mehlich 1 extractable P over a period of 973 days for 7 crops of upland rice or soybean grown in a rotation was plotted against P applied at the beginning (Figure 22). The slope of the curve, termed the buffer coefficient was then plotted against time (Figures 23 & 24). The slow reaction coefficient (b) is determined from the equation:  $y = a b^x$ . The estimated slow reaction coefficient (b) per day for Siniloan is 0.9975. In PDSS, a slow reaction coefficient for four months termed Fslow (120 days) ( $=b^{120}$ ) currently has a default value of 0.97. But, the slow reaction coefficient calculated for a 4-month period at Siniloan would be 0.74, substantially lower than the PDSS default indicating a much more rapid decline of extractable P through slow reaction. Crop P uptake is not accounted for in the decline, but its effect on buffer coefficient or extractable Mehlich 1 P seems to be insignificant compared to that of slow reaction. The next step is to determine whether the slow reaction coefficient should also be used to update PDSS predictions of after harvest extractable P.



**Figure 22.** Predicted vs observed decline in Mehlich 1 P using a slow reaction coefficient,  $b=0.9975$ .



**Figure 23.** Field determined buffer coefficients (BC) for seven crops of upland rice or soybean grown in rotation starting with upland rice in 1995, Siniloan, Laguna, Philippines.



**Figure 24.** The effect of time on buffer coefficient over seven crops of upland rice or soybean grown in rotation starting with upland rice 1995, Siniloan, Laguna, Philippines.

5. *Improving parameter estimates of LRP using a nonlinear approach* - (Jonathan Quiton, Thomas George, Graham McLaren, Russell Yost) The application of the LRP could be applied theoretically to nutrient response studies where the law of the minimum holds. However, there are cases where the x-variable is a continuous random variable as opposed to the assumptions of the Anderson-Nelson procedure for x to be composed of 'n' levels and 'p' replications. For example, in P response studies, the effect of soil extractable P on yield is studied. Such a variable is continuous and while the Anderson and Nelson procedure may still be feasible, there is a need for a modification of the procedure that removes the restriction on the x-variable.

We postulate an alternative procedure that combines nonlinear regression approach with the ordinary least squares approach in finding the best parameter estimates for the LRP. The nonlinear regression component is used to find the best estimate of the optimum rate ( $X_0$ ) of the linear response plateau model while the ordinary least squares approach is used to estimate the linear parameters:  $b_0$  and  $b_1$  for the intercept and slope, respectively.

*The modified nonlinear regression procedure* - The mathematical derivation of the modified nonlinear regression procedure starts with the adaptation of the Anderson and Nelson's definition of the LRP Model IIIj (Anderson-Nelson, 1975 & 1987).

$$Y(LRP) = \begin{cases} b_0 + b_1x, & x \leq x_0 \\ b_0 + b_1x_0, & x > x_0 \end{cases} \quad (1)$$

where  $b_0$  and  $b_1$  are the intercept and slope linear phase, respectively and  $X_0$  is the optimal rate, (otherwise known as the critical level). Suppose that the optimum rate,  $X_0$ , is known or

is an assigned value anywhere in the domain, then the model can be transformed to a simple linear equation (Equation 2) and therefore,  $b_0$  and  $b_1$  can be solved using the ordinary least squares.

$$Y(LRP | x_0 = c) = b_0 + b_1 x^* \quad (2)$$

where

$$x^* = \begin{cases} x, & \text{if } x \leq c \\ c, & \text{if } x > c \end{cases} \quad (3)$$

To illustrate, Figure 25 shows a hypothetical linear response plateau of an experiment with 10 treatment levels as values of the independent variable ( $x$ ). If the optimum level is 5.0, then Equation 3 compresses all the data points to the right of 5.0 by forcing the value of 5.0 as their  $x$ -coordinates. The result is the scatter plot in Figure 26 and therefore, the ordinary least squares estimate will result to similar values for  $b_0$  and  $b_1$ .

In the case of a continuous  $x$ -variable, the location of  $X_0$  is difficult to point to. Therefore, a nonlinear regression is employed to search for the value of  $X_0$ , and then use the ordinary least squares to find  $b_0$  and  $b_1$ . This is the basic principle of the modified nonlinear regression procedure.

The nonlinear regression component implements two sets of iterations. The first one is the search for the best initial value for  $X_0$  at given increments, and the second set is the actual search for the value of  $X_0$ , once the initial value is determined. Only after the last iteration of the second step that the final values for  $b_0$  and  $b_1$  are determined. The two steps are discussed in detail as follows:

Step 1: Identifying the best initial value for  $X_0$ . The first step is implemented by assigning a series of values for  $X_0$ , and calculating the parameters  $b_0$ ,  $b_1$  and ESS for each  $X_0$  value using Equation 2. The best  $X_0$  value in this series is such that ESS is the minimum. This series of  $X_0$  values starts with the 2<sup>nd</sup>  $X$  observation,  $X_{(2)}$ , up to the last observation,  $X_{(n)}$  sorted in ascending order. This analysis can be summarized by plotting  $X_0$  versus ESS, which shows the response of ESS to changes in  $X_0$ .

Equations 4 and 5 shows that the series of  $X_0$  values is according to constant intervals ( $Dx$ ), which is a function of the desired number of divisions ( $f$ ). Hence, from  $X_{(2)}$  to  $X_{(n)}$ , the total number of iterations is equal to  $f + 1$ .

$$X_0 = X_{(2)} + \sum_{i=1}^k \Delta x, \quad k=0,1,2,\dots,f \quad (4)$$

where

$$\Delta x = \frac{1}{f} (X_{(n)} - X_{(2)}) \quad (5)$$

Step 2: The Nonlinear regression procedure. The second iterative process is the actual search for the best value of  $X_0$ , using the nonlinear regression procedure. Let  $X_0=c$  where  $c$  is identified to be the best initial value from step 1. Therefore, the solution region for  $X_0$  is identified to be at  $c \pm Dx$ . The nonlinear regression procedure can be set up for parameter  $X_0$ ,

using Equation 2 as the model and ESS as the objective function. Any search algorithm may be applied. As in step 1,  $b_0$  and  $b_1$  is determined through OLS.

It should be noted that this procedure is different from a purely nonlinear regression method. In such case, all the parameters  $b_0$ ,  $b_1$ , and  $X_0$  have initial parameter values and are simultaneously adjusted to get at a minimum level. Results may or may not arrive at the best solution, since the parameters are related and that the initial parameters may converge to a local minimum rather than the universal minimum. It may also be difficult to show graphically the ESS surface since the ESS, together with  $b_0$ ,  $b_1$ , and  $X_0$  constitutes a 4-dimensional space.

*Implementation of the Anderson and Nelson procedure for continuous variable data* - The scope of the study involves only LRP Models IIIj and IVj, where both are two-line LRP models comprising of an increasing linear trend and a plateau at a given optimum point, which may fall at a design point (Model IIIj) or between two design points (Model IVj). An attempt was made to expand the applicability of the procedure to a continuous x-variable. Model determination. Anderson and Nelson utilized the modified isotonic regression procedure in the determination of the LRP Model wherein successive moving averages are computed starting at the last observation (i.e, x-values are arranged in increasing order), and the plateau terminates just before MA begins to decrease monotonically (Anderson and Nelson, 1987). Equation 6 was used as the operational definition for the moving average, which is shown in Table 20.

$$MA(Y_j) = \frac{\sum_{i=j}^n Y_i}{n - j} \quad (6)$$

*Using hypothetical data as benchmark for the modified nonlinear regression procedure* - A hypothetical data set (Table 19, Figure 25) is used as a benchmark to verify whether the modified nonlinear regression method is producing the right solution. For this hypothetical data set, the parameters  $b_0$ ,  $b_1$ , and  $X_0$  are predetermined to be 1.0, 1.0, and 5.0, respectively. A series of  $X_0$  values was determined by dividing the  $X_{(2)}$  to  $X_{(n)}$  into 1000 increments, as shown in equation (4). The increment ( $Dx$ ) is determined be 0.008 such the  $X_0$  series consists of 1001 values as follows:  $X_0 \hat{=} \{2.000, 2.008, 2.016, \dots, 10.000\}$ . With such number of iterations, a computing software is necessary to calculate the ESS with  $X_0$  assuming each value in the series. The result is shown in Figure 27 where the ESS decreased as  $X_0$  moves to the right, and increased after passing the value of 5.0.

At the start of step 2,  $X_0$  is initialized with a value of 5.0, which is the 626<sup>th</sup> iteration in step 1. Hence, prior to step 2, the solution region of  $X_0$  is identified to be somewhere within  $5.0 \pm 0.008$ . The objective function is to minimize ESS by changing  $X_0$ . The nonlinear regression procedure was applied resulting to an optimum value still at 5.0 and consequently,  $b_0$  and  $b_1$  computed were similar to the predetermined parameter values.

*Application of the Anderson-Nelson procedure and the modified nonlinear procedure on P experiments* - Table 20 presents two data sets from long term P experiments in Kalayaan and Siniloan, Laguna, Philippines, both on an upland rice-based cropping system on a P-infertile upland. These studies aim to understand P dynamics under a range of soils, soil P supply characteristics, production potentials and phosphate additions in the tropical uplands.

Specifically, these studies are concerned about the effect of available P (Mehlich-1 P,  $\text{ug g}^{-1}$  soil) on yield. The x-variable is a continuous random variable and Figure 28 shows a LRP behavior for both data sets such that the linear relationship exists up to a certain threshold level after which there is no response.

The parameters of the LRP will be determined both by the Anderson-Nelson approach and the modified nonlinear regression approach. The moving average columns  $\text{MA}(Y_j)$  beside the response variable (Y) is calculated using Equation 4 and are used for model determination for the Anderson-Nelson approach.

Case1: Upland rice data, Kalayaan, Laguna. Results in Table 21 indicated that the modified nonlinear method computed the optimum level to be at 7.19  $\text{ug/g}$  with an ESS value of 6.83. It should be noted that 7.19 appears to be one of the data points for 1994 Kalayaan data. For the Anderson-Nelson procedure, Model IV was first selected since the scatterplot is not clear enough to choose a Model III. By using the moving average information, the cutoff point  $X_{(j)}$  is determined by observing the trend of MA starting from the last observation down to the first observation such that “the plateau terminates just before MA begins to decrease monotonically”(Anderson and Nelson, 1987) . In this case, Table 20 shows that MA monotonically decreases from  $j=3$  down to  $j=0$  and hence,  $X_0, X_1, X_2, X_3$  comprises the linear phase and  $X_4, X_5, \dots, X_{15}$  is the plateau phase. The LRP model is finally identified as Model  $\text{IV}_3$ , where 3 is the index of the last observation prior to the intersection point or plateau.

Results show that Model  $\text{IV}_3$  failed to give the correct parameter values since the condition  $b_1 > b_2 > b_3 > 0$  was violated (Anderson and Nelson, 1987). Other Model  $\text{IV}_j$ 's were tried (Model  $\text{IV}_4, \text{IV}_5, \text{IV}_6$ ), resulting to a solution in Model  $\text{IV}_6$  with an ESS of 7.505, but is inferior to the modified nonlinear regression estimates.

However, since it was known from the nonlinear regression results that  $X_0=7.19$  gave the minimum ESS and is one of the observed values, Model  $\text{III}_4$  was used. As expected, the results matched with the nonlinear regression estimates.

Case2: Soybean data, Siniloan, Laguna. The modified nonlinear regression procedure resulted with  $X_0=6.8$   $\text{ug/g}$  with  $\text{ESS}=2.2$ . On the other hand, the Anderson-Nelson recommends Model  $\text{IV}_6$  based on the moving average result, but didn't produce valid LRP coefficients since the restriction  $b_1 > b_2 > b_3 > 0$  is violated. Other cutoff points were explored resulting to a solution in Model  $\text{IV}_8$ , which produced similar results with the modified nonlinear regression procedure.

*Implications and limitations of the modified nonlinear regression procedure* - Based on the results of the two cases, the following implications are observed. First, the modified nonlinear regression procedure estimates produces similar results to the Anderson-Nelson procedure; however, the former has an advantage because the choice of the model (i.e., if it is Model III or IV) and the cutoff point are analytically determined through the nonlinear regression component. Second, the test data and the hypothetical data indicate that the modified nonlinear regression procedure can be applied to continuous and even to fixed independent variable (x).

In spite of its desirable properties, the modified nonlinear procedure also has limitations. The procedure requires at least two values to the left of the optimum value ( $X_0$ ). From the same data set, it can be shown that the ESS given  $X_0$  with a value between  $X_{(1)}$  and  $X_{(2)}$  will yield

similar results and the solution sets produced is not unique. As a general rule, one must have sufficient data before or after the optimum value to achieve reliable results.

Finally, as inherent in any nonlinear regression, there is a possibility of not arriving at the best solution if the ESS curve does not have a universal minimum. However, as long as the scatter plot of the response shows a strong of a linear and a plateau response, the procedure will arrive at the best solution.

*Testing the fitness of the LRP model* - The “fitness” of the LRP model can be quantified using the analysis of variance (ANOVA). Tables 22 and 23 show the total variation broken into a) variation due to the LRP model (Model SS) and b) variation due to error (ESS) for the two data sets, respectively. Furthermore, the Model SS can be partitioned to the individual contributions for the linear ( $b_1$ ) and the optimum rate ( $X_0$ ) parameters.

Both data sets show that the LRP fits the data sets at 5% level of significance. Furthermore, to isolate the effect of each parameter, Model SS was partitioned into extra sum of squares (Draper and Smith, 1981) due to  $b_1$  and due to  $X_0$ . For 1994 Kalayaan data, the effect due to the linear term ( $b_1$ ) was not significant at 5% because of the two high values present in the data set, whereas it was significant for the 2000 Siniloan data. The effect due to  $X_0$  was calculated by removing the effects of  $b_0$  and  $b_1$  from the Model SS. Results show that both 1994 Kalayaan and 2000 Siniloan data sets show significant effect due to  $X_0$ .

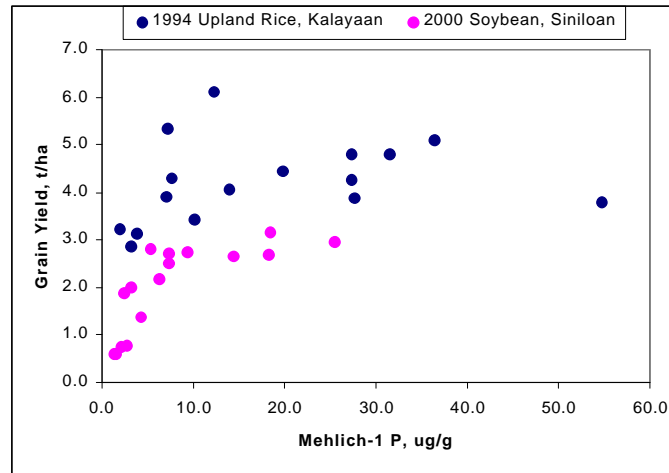
*Conclusions* - The modified nonlinear regression procedure was developed to extend the applicability of the linear response plateau to cases where the x-variable is a continuous random variable, as compared to the Anderson and Nelson procedure, which was developed for experiments in p replications and n treatment levels as x-values. Both methods were tested and compared based on two P experiments in a Philippine acid upland.

Results indicate that the two methods gave similar outcomes; however, the modified nonlinear regression method was more systematic in model detection and parameter estimation since the process is automatically determined in the iteration. On the other hand, the modified isotonic regression used by the Anderson and Nelson procedure on model determination were not able to detect the right cutoff points in the case of 1994 Kalayaan and 2000 Siniloan data. Only after an exhaustive search that the appropriate model was found which matched with the modified nonlinear regression result.

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**Figure 28.** Grain yields versus Mehlich 1 extractable P, Siniloan, Philippines.

Table 19. A hypothetical data showing a linear response plateau

<b>Independent variable(X)</b>	<b>Response(Y)</b>
1	2.0
2	3.0
3	4.0
4	5.0
5	6.0
6	5.7
7	6.3
8	5.7
9	6.3
10	6.0

Table 20. Upland rice data from Kalayaan and Siniloan, Laguna, Philippines.

Index (j)	Upland Rice, Kalayaan, Laguna, Philippines			Soybean, Siniloan, Laguna, Philippines		
	Mehlich-1 P, ug/g (X <sub>j</sub> )	Grain yield, t/ha (Y <sub>j</sub> )	Moving Average MA(Y <sub>j</sub> )	Mehlich-1 P, ug/g (X <sub>j</sub> )	Grain yield, t/ha (Y <sub>j</sub> )	Moving Average MA(Y <sub>j</sub> )
0	2.034	3.216	4.209	1.328	0.592	2.020
1	3.230	2.871	4.275	1.476	0.597	2.115
2	3.817	3.122	4.375	2.141	0.746	2.223
3	7.047	3.891	4.472	2.436	1.880	2.337
4	7.190	5.341	4.520	2.731	0.786	2.375
5	7.670	4.290	4.446	3.248	1.993	2.519
6	10.176	3.411	4.461	4.282	1.356	2.572
7	12.339	6.099	4.578	5.389	2.801	2.707
8	13.936	4.055	4.388	6.275	2.170	2.695
9	19.865	4.439	4.435	7.383	2.721	2.816
10	27.356	4.793	4.435	7.383	2.494	2.770
11	27.399	4.274	4.363	9.376	2.752	2.835
12	27.721	3.875	4.385	14.397	2.650	2.856
13	31.574	4.800	4.555	18.383	2.682	2.925
14	36.444	5.087	4.433	18.457	3.156	3.047
15	54.748	3.779	3.779	25.471	2.937	2.937

Table 21. Linear response plateau parameters for modified nonlinear regression and the Anderson-Nelson procedure for upland rice, Kalayaan data and Soybean, Siniloan data.

	LRP Parameters			Error sum of squares
	$b_0$	$b_1$	$X_0$	
A. Upland rice, Kalayaan				
Modified Non-linear Regression	2.139	0.323	7.190	6.825
Anderson-Nelson	IV <sub>3</sub>	2.592	0.169	0
	IV <sub>4</sub>	2.069	0.347	0
	IV <sub>5</sub>	2.191	0.309	0
	IV <sub>6</sub>	2.874	0.146	11.641
	III <sub>4</sub>	2.139	0.323	7.190
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B. Soybean, Siniloan				
Modified Non-linear Regression	0.217	0.374	6.821	2.173
Anderson-Nelson	IV <sub>6</sub>	0.248	0.352	0
	IV <sub>7</sub>	-0.020	0.474	5.732
	IV <sub>8</sub>	0.217	0.374	6.821

$X_0$  cannot be computed and ESS is not applicable since the condition  $b_1 > b_2 > b_3 \neq 0$  (Anderson and Nelson, 1987) is violated.

Table 22. Analysis of variance, upland rice data, Kalayaan, Laguna, Philippines

Source of variation	df	SS	MS	F	Prob>F
Model $SS(X_0, b_1/b_0)$	2	4.57	2.28	4.35	0.0357
$SS(b_1/b_0)$	1	0.74	0.74	1.41	0.2559
$SS(X_0/b_1, b_0)$	1	3.8278	3.83	7.29	0.0182
Residual	13	6.825	0.524993		
Total, corrected	15	11.39			

Table 23. Analysis of variance, soybean data, Siniloan, Laguna, Philippines

Source of variation	df	SS	MS	F	Prob>F
Model $SS(X_0, b/a)$	2	10.35	5.17	30.95	0.0000
$SS(b/a)$	1	6.72	6.72	40.18	0.0000
$SS(X_0/b, a)$	1	3.6307	3.63	21.72	0.0004
Residual	13	2.173	0.167187		
Total, corrected	15	12.52			

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Travel and Meetings Attended

- Thomas George - participation in Annual ASA/CSA/SSSA Annual Meetings, Minneapolis, MN.
- Fred Cox -

Relevant Publications, Reports and Presentation at Meetings

Doumbia, M.D., A. Sidibé, A. Bagayoko, A. Bationo, R. A. Kablan, R.S. Yost, L.R. Hossner et F.M. Hons. 2001. Recommandations Spécifiques d'engrais: Calibration et Validation du Module Phosphore de Numass. African Crop Science (in review)

George, T., J. Quito and R. Yost. 2000. Determining Critical Soil Phosphorus Levels for Upland Crops. Poster presented at the ASA-CSA-SSSA Annual Meetings, 5 Nov.- 10 Nov., Minneapolis

Oliveira, F.H., R.F. Novais, T.J. Smyth and J.C. Neves. 2000. Comparisons of phosphorus availability between anion exchange resin and Mehlich-1 extractions among Oxisols with different capacity factors. Commun. Soil Sci. Plant Anal. 31:615-630.