Environmental Physiology

Managing Nitrogen Fertilization to Maximize Resource-Efficient Productivity in a Continuous Year-Round Vegetable Cropping Sequence

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Summary

Permanent high-bed cultivation systems are primarily used to overcome flood damage in vegetable crops cultivated in many lowland peri-urban production zones throughout Asia.

Overdoses of nitrogenous fertilizers in intensive tropical and subtropical vegetable production have created concern about their impacts on the environment and product quality, and have led to a demand for better N management practices. Within this context, we attempted to rationalize N fertilizer use.

The N_{min} method was tested in a 14-month continuous vegetable cropping sequence with five crops in two cultivation systems: flat planting beds and permanent high beds. Permanent high-bed cultivation and N_{min} method were compared with standard practices to test their potential for more resource-efficient productivity, particularly during the rainy summer off-season. Using plant petiole sap NO_3 testing, a promising new quick test procedure to detect N deficiencies, an integrated study of soil NO_3, plant sap NO_3, and crop yield was undertaken for a dry season crop of vegetable soybean and a rainy season crop of Chinese cabbage.

The influence of cultivation system (flat beds vs. high beds) on productivity was much more conspicuous than the effect of the fertilization method. Summer crops of Chinese cabbage and chili pepper in 1993 and Chinese cabbage in 1994 on high beds outyielded those on flat beds by 58, 240, and 161% for the standard N application rate. Winter crops of carrot and vegetable soybean were, however, slightly (8 and 14%) reduced.

Plant available N concentrations in soil (N_{min}) followed a seasonal pattern of fixation and/or immobilization of ammonium N fertilizer during the rainy summer, when water saturation inhibited nitrification most of the time. During winter, this bound nitrogen reappeared as soils dried out. This was particularly true for the more flood-prone flat beds.

The accelerated mineralization potential during the dry season led to N_{min} concentrations obviating the need for N fertilization for carrot and vegetable soybean crops in the N_{min} treatment. No yield reductions were observed compared to the standard N application rate. Although soil N supply was more limited during the rainy season, only yields of Chinese cabbage grown in summer 1994 on high beds were significantly reduced by the N_{min} method. This was attributed to heavy rain at head formation stage before the final harvest. A total of 360 kg N/ha (42%) was saved by the N_{min} method during 14 months for five vegetable crops.

The combination of hyperbolic relations of plant NO_3-N as a function of soil nitrate and yield as a function of plant NO_3 resulted in a good estimation of yield = f(soil NO_3) for vegetable soybean.

Small differences between measured sap NO_3 levels and calculated upper limits demonstrated that soil N was not a limiting growth factor for this dry season crop. Lower yields despite higher plant sap NO_3 contents on high beds were associated with excessive root growth which was favored by the physical soil environment on high beds.

A similar magnitude of soil nitrate absorption by summer Chinese cabbage, but limited efficiency of transformation into biomass in the former, resulted in significantly lower yields of the crop on flat planting beds. Large differences between measured sap NO_3 concentrations and regressed upper limits implied inadequate N supply from soil, for reasons stated earlier.

Permanent high-bed cultivation in combination with use of the N_{min} method was the most resource-efficient combination for out-of-season summer vegetable production. Plant sap NO_3 testing in combination with calculation of a mutual functional relationship — soil NO_3 - plant NO_3 - crop yield based on the Michaelis-Menten model of saturation kinetics (hyperbolic approach) — was a useful way to detect plant N deficiencies, and to explain crop performance in different cultural systems.

Introduction

Permanent high-bed cultivation is known to exist in many peri-urban lowland production zones in Asia ranging from China to India.

At present, heavy applications of N fertilizer are common practice in many of these and other intensive vegetable production areas in the tropics and subtropics. Increasing concern for the negative consequences of over-fertilization, particularly regarding nitrate contamination of groundwater and potentially harmful high nitrate contents in vegetables, has led to a demand for the development of innovative N management strategies to improve fertilizer use efficiency. One approach to improve N management is to fine-tune the amount of N fertilizer to better synchronize soil N availability with plant requirements.

Widely introduced in Central Europe is the N_{min} method that essentially depends on the measurement of soil N and takes into account crop needs only in so far that standardized critical values for plant available soil nitrogen are taken from extensive tables. Exclusively for basal N fertilizer application or more sophisticated for additional side-dressings, N fertilizer need for an individual dressing is calculated as follows:

N fertilizer need = crop demand for soil N (critical soil NO_3-N) - N_{min} (mineralized soil N; NO_3-N)

The limited use of N_{min} in commercial farms is attributed more to the immense requirement for time and labor to sample and analyze the soil than to the doubt that the soil analysis data would not reliably represent plant nutritional status. The first part of this study deals with the experience of the N_{min} method in a 14-month, five-crop continuous year-round vegetable cropping sequence in the subtropical environment of Southern Taiwan, where crops were either grown on traditional flat beds or on permanent high beds.

A suitable substitute to the slow and expensive N_{min} method is the sap nitrate test (SN-test) to improve N fertilizer management. This new and promising analytical procedure measures NO_3-N concentration in fresh petiole sap and has proved to be highly correlated with dry tissue NO_3-N concentrations in several vegetable species. Since nutrient concentrations decline most quickly in rapidly expanding new tissues, and the petiole acts as a storage and transport organ for nitrate-N, the petiole of recently matured leaves is a sensitive indicator of plant N status and N nutrition. The goal is to determine the minimum level of petiole sap NO_3-N associated with maximum yield, a "critical petiole NO_3-level" above which a crop would be adequately supplied with N and no additional N fertilizer would be needed, and below which the crop would be deficient in N nutrition and would require additional N fertilizer to ensure maximum yields.

At present, the calibration of the method poses the most significant hindrance to practical application since diagnostic standards for critical NO_3-N concentrations in plant sap are still lacking. Vegetable extension institutions in Europe and the U.S. are, however, beginning to use this technology and are providing the commercial grower with guidelines. New, portable nitrate-selective electrodes and quantitative reflectometric analysis procedures for test strips make it much easier to achieve reliable results.

The objective of the second part of this study is to describe a model that integrates (l) soil N status (soil NO_3-N), (2) crop N status (petiole sap NO_3-N), and (3) crop yield response to provide a theoretical background for further studies of its kind, and to apply this model to two field-grown vegetable crops, vegetable soybean and Chinese cabbage, cultivated either on flat beds or on permanent high beds.

Materials and Methods

N_{min} study

In spring 1993, an integrated permanent high-bed deep-furrow system was laid out and constructed in a randomized three-factor, split-split block design with four replications. Factors included: (1) high bed width, (2) with legume green manure living mulch or none, and (3) N fertilization method. The first two experimental factors will not be discussed here. The N fertilization method consisted of two levels, (l) traditional (standard) N fertilizer input, and (2) N_{min} method. The two levels of this factor were additionally randomized in four replications on 1.5-m-wide flat beds adjacent to the main experiment to represent a control to the permanent high beds.

In a 14-month continuous year-round vegetable cropping sequence, summer rainy season crops used were Chinese cabbage [*Brassica pekinensis* (Lour.) Rupr. variety ASVEG No. 1, AVRDC] and chili (*Capsicum annuum* L. variety Hot Beauty, Known You Seed Co.). Carrot [*Daucus carom* L. ssp. *sativus* (Hoffm.) Arcang. Red Judy, Known You Seed Co.] and vegetable soybean [*Glycine max (L.)* Men. variety AGS 292, AVRDC] were grown during the dry winter. Aquatic crops cultivated in the continuously flooded furrows were taro [*Coloasia esculenta* (L.) Schott] and rice (*Oryza sativa* L.).

Carrot was sown in paired rows in place of single rows for direct sown vegetable soybean and transplanted Chinese cabbage and chili crops. Dimensions of cultivation systems and plant rectangularity are presented in fig. 1; other details are summarized in table 1.

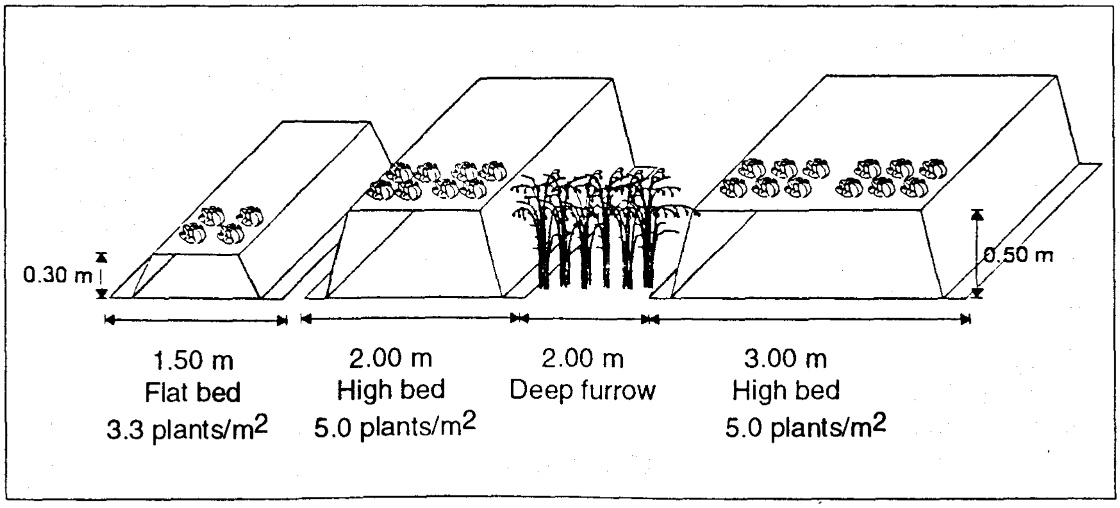

Fig. 1. Dimensions of cultivation systems and plant rectangularity

Table 1. Summary of cultural details

Crop	Chinese cabbage	Chili	Carrot	Vegetable soybean	Chinese cabbage
Cultivation period	May-Jun 93	Jun-Nov 93	Dec-Feb 93-94	Mar-May 94	Jun-Jul 94
Plant distance (cm x cm)	50×60	50×60	25×05	50×05	50×40
Plant density (plants/m^2)					
flat bed system	3.3	3.3	80.0	40.0	3.3
high bed system	3.3	3.3	80.0	40.0	5.0

[a]N_{min} method only for basal fertilizer application

All nitrogen was applied as ammonium sulphate [$(NH_4)_2SO_4$], the less costly and most readily available N fertilizer source.

Soil N_{min} was measured before each N fertilizer application by sampling 30-cm-deep soil in every N_{min} treatment plot (no legume green manure living mulch). Extracted 1:2 by volume in 0.8 % KCl water solution, samples were analyzed for NO_3 using Merck' s RQflex reflectometer and Reflectoquant nitrate analytical test strips. N application rate for the N_{min} treatment was calculated by subtracting the average N_{min} value from the traditional N application rate. All other cultural practices used were standard.

Statistical comparisons between main factors "N fertilization method" and "cultivation system" (means of two bed widths), and their interactions were performed using orthogonal contrasts on data from plots without green manure.

Integrated study of soil N, plant N, and crop yield

During the 1994 cropping of vegetable soybean and Chinese cabbage, soil NO_3 and plant nitrate data were also collected weekly. Soil was sampled from 0-30 cm and 30-60 cm layers in 4 flat-bed plots and 12 high-bed plots. Petioles were collected from about eight newly expanded leaves per plot for vegetable soybean, and five midribs of recently matured leaves per plot for Chinese cabbage. Petiole sap was expressed using a garlic press, diluted with deionized water to fit the range of the Reflectoquant test strips (5-225 ppm), and analyzed for NO_3-N with the RQflex.

To integrate soil N status, crop N status, and crop yield response, a functional relationship model was chosen based on theoretical and biological considerations and which was sufficiently well correlated with our data. The most widely used model in scientific publications is the polynomial approach ($V = a+b \times S+c \times S^2$ where V = crop yield, S = soil or plant N status). In contrast, the Michaelis-Menten model of saturation kinetics describes the velocity of an enzyme-mediated reaction as a function of substrate concentration. Analogous to the Michaelis-Menten model, the relationships (1) plant sap nitrate = f(soil nitrate), (2) crop yield = f(plant sap nitrate), and (3) crop yield = f(soil nitrate) were fitted to the hyperbolic model:

$$V = (V_{max} \times S) / (K_m + S)$$

where: V = plant sap nitrate concentration or crop yield, V_{max} = (constant) upper limit for V, S = soil nitrate concentration or plant sap nitrate concentration, and K_m = (Michaelis constant) affinity for S.

In an earlier study, the relationship plant sap nitrate = f(soil nitrate) has been well established for potato and peppermint. The same functional dependency may also be true for the two remaining models. For this analysis, however, since field experiments were not specially laid out for this purpose (N fertilizer rates were not systematically varied), it was expected that the regression equations would not provide very accurate predictions.

Yield as a function of soil N is usually poorly correlated. Substitution of (l) plant NO_3-N = [(a × soil NO_3-N)/(b + soil NO)] into (2) yield = [(A × plant NO_3-N)/(B + plant NO_3-N)] results in: yield = {[(Aa/B+a) × soil NO_3-N]/[(Bb/B+a) + soil NO_3-N]}. Comparison of this latter estimated function with the field-derived regression equation of yield = f(soil NO_3-N) can function as a control to govern whether the mutual relationship of hyperbole dependencies is sufficiently determined. Using the polynomial approach instead would result in a fourth-order polynomial function, implausible and unsuitable from a theoretical and practical standpoint.

Results and Discussion

N_{min} study

The cultivation system was much more influential on productivity than N fertilization regime throughout the 14-month cropping sequence (table 2). This tendency was at the same time much more pronounced for marketable yields than for total biomass production. Yields of the standard fertilization treatment on high beds surpassed those on flat beds by 58, 240, and 161% for the summer crops of Chinese cabbage and chili in 1993, and Chinese cabbage in 1994. Winter season crop yields of carrot and vegetable soybean were, however, slightly (8 and 14%) reduced compared to flat-bed cultivation.

Soil N_{min} contents were very similar in flat-bed and high-bed systems during the rainy season summer (table 2). In the dry season, however, high soil nitrification rates in both cultivation systems resulted in N_{min} concentrations that in the most part largely exceeded requirements of both crops of carrot and vegetable soybean. Very obvious is the accelerated mineralization potential on the flat beds during that season. Consequently, no additional N fertilizer was applied in the N_{min} treatment. No significant yield differences were finally recorded between N fertilization regimes for these cool season vegetables.

The tendency for reduced N fertilization to become a significant factor in crop production when yields reach higher levels can be summarized from summer crops of chili (1993) and Chinese cabbage (1994): with chili yields of around 0.2 kg/m^2 on flat beds the orthogonal comparison between fertilizer treatments is far from significant (P = 0.88). At higher yields of 0.7 kg/m^2 on high beds it comes close to significant (P = 0.16). For Chinese cabbage, low yields of 0.8 and 0.2 kg/m^2 did not differ on flat beds (P = 0.10), but it did on high beds (2.0 and 1.2 kg/m^2; $P < 0.01$). Higher N fertilizer application did not overcome the disadvantageous crop environment of the commonly used flat planting beds in summer vegetable production.

To summarize, N fertilization for individual crops was reduced by up to 100% and a total of 360 kg N (42% of the traditional rate) was saved in a 14-month continuous vegetable cropping sequence by use of the N_{min} method. Significant yield loss due to reduced N fertilization was only observed in the 1994 Chinese cabbage crop grown on high beds. The yield reduction occurred in the second harvest, after a first harvest that showed no yield differences between traditional N fertilization and N_{min} method (P = 0.79). Heavy typhoon rain between harvests may have denitrified or leached out plant available nitrogen essential for head formation. This thesis is supported by less pronounced differences in total biomass at the second harvest (P = 0.08).

Table 2. Influence of N_{min} fertilization method and cultivation system on vegetable yields

	Chinese cabbage			Chili				Carrot		Vegetable soybean			Chinese cabbage		
Cultivation period	May-June 1993			June-November 1993				December-February 1993/94		March-May 1994			June-July 1994		
N_{min} content (kg N/ha)															
WAS/WAT	0	2	4	0	4	8	12	0	7	0	2	4	0	2	4
Flat bed system	43[a]	-	-	30[a]	-	-	-	132	213	43	120	51	22	32	21
High bed system	60[a]	-	-	34[a]	-	-	-	139	37	16	101	20	19	39	13
Fertilization (kg N/ha)															
WAS/WAT	0	2	4	0	4	8	12	0	7	0	2	4	0	2	4
Traditional fertilization	60	30	30	50	50	50	50	60	60	20	20	20	60	30	30
N_{min} method	0	30	30	20	50	50	50	0	0	0	0	0	20	0	0
Fresh biomass (kg/m^2)	Flat bed	High bed	P level	Flat bed	High bed	P level	Flat bed	High bed	P level	Flat bed	High bed	P level	Flat bed	High bed	P level
Traditional fertilization	2.97	3.37	0.07	0.98	1.62	<0.01	2.41	2.31	0.83	2.16	1.80	0.01	2.76	4.46	<0.01
N_{min} method	3.06	3.42	0.10	0.80	1.46	<0.01	2.52	2.18	0.41	1.96	1.69	0.04	1.80	3.86	<0.01
P level	0.72	0.77		0.27	0.19		0.81	0.70		0.15	0.29		0.04	0.08	
P level fertilization	0.66			0.09			0.86			0.09			0.01		
P level cultivation	0.02			<0.01			0.46			<0.01			<0.01		
Marketable yield (kg/m^2)	Flat bed	High bed	P level	Flat bed	High bed	F^f level	Flat bed	High bed	P level	Flat bed	High bed	P level	Flat bed	High bed	P level
Traditional fertilization	1.37	2.16	<0.01	0.22	0.75	<0.01	1.29	1.20	0.70	1.26	1.11	0.09	0.75	1.96	<0.01
N_{min} method	1.49	2.22	<0.01	0.20	0.63	<0.01	1.40	1.17	0.33	1.20	1.06	0.12	0.19	1.22	<0.01
P level	0.44	0.57		0.88	0.16		0.68	0.88		0.47	0.42		0.10	<0.01	
P level fertilization	0.36			0.22			0.91			0.28			<0.01		
P level cultivation	<0.01			<0.01			0.33			0.02			<0.01		

[a] N_{min} method only for basal fertilizer application

Level of soil N_{min} concentration depended largely on season. High nitrification potential was evident particularly for the flat-bed system during the dry winter season. Much less plant biomass was produced on flat beds compared to high beds during the preceding rainy season. Thus, since N fertilizer application rates were the same, much less N was removed from the soil system during that season when the soil was wet and partially anaerobic most of the time. Under anaerobic conditions, nitrification of ammonium fertilizer is largely inhibited and NH_4 is easily immobilized by soil microbes or fixed to clay minerals (Drury and Beauchamp 1991). Following drying of the soil in winter and intensive aeration through management (e.g., bed construction), this immobilized or fixed N obviously reappeared in the oxidized N form, leading to immense NO_3 accumulation. We may infer from this preliminary evidence that excessive leaching of nitrates during the rainy season is not as important as assumed.

Since soil water content in the topsoil averaged less in the high than low beds, plant available N was produced more readily, and less nitrogen for current plant biomass accumulation was lost through immobilization and fixation. Permanent high beds in combination with use of the N_{min} method was the most appropriate management option for rainy season summer vegetable production in this experiment.

Integrated study of soil N, plant N, and crop yield

Vegetable soybean. The most satisfactory fit of yield and nitrate data was obtained for 4 WAS when plants set flowers and the first side-dressing was applied. While the fit was good for the regression plant sap NO_3 = f(soil NO_3), crop yield was only poorly related to soil nitrate content (0-60 cm depth; table 3). Scatter plots in fig. 2 illustrate significant differences between cultural systems in the ability to take up available soil nitrate and to reduce this absorbed NO_3 efficiently to amino acids. Although plant sap nitrate accumulation was significantly higher for vegetable soybean grown on high beds, these higher concentrations resulted in relatively low yields compared to the crop grown on flat beds.

Table 3. Regression equations of the hyperbolic form $V = (V_{max} \times S)/(K_m + S)$ for soil NO_3 (0-60 cm), plant sap NO_3, and yield of vegetable soybean and Chinese cabbage grown on flat beds and permanent high beds

Function type	Flat bed system		High bed system	
	Equation[a]	r^2	Equation[b]	r^2
Vegetable soybean				
plant NO_3 = f (soil NO_3)	$V = (2751^{*} \times S)/(115^{ns} + S)$	0.89^{ns}	$V = (4142^{**} \times S)/(62^{**} + S)$	0.53^{**}
yield = f (plant NO_3)	$V = (1.46^{*} \times S)/(299^{ns} + S)$	0.50ns	$V = (2.12^{*} \times S)/(3667^{*} + S)$	0.45^{*}
yield = f (soil NO_3)	$V = (1.30^{*} \times S)/(115^{ns} + S)$	0.33^{ns}	$V = (1.10^{**} \times S)/24^{ns} + S)$	0.17^{ns}
Estimated function yield = f (soil NO_3)	$V = (1.32 \times S)/(11 + S)$		$V = (1.12 \times S)/(29 + S)$	
Chinese cabbage plant NO_3 = f (soil NO_3)	$V = (7910^{ns} \times S)$	0.85^{ns}	$V = (4584^{ns} \times S)/(70^{**} + S)$	0.54^{**}
yield = f (plant NO_3)	$V = (7.65^{ns} \times S)/(5978^{ns} + S)$	0.82^{ns}	$V = (9.89^{ns} \times S)/(2721^{**} + S)$	0.51^{**}
yield = f (soil NO_3)	$V = (5.51^{**} \times S)/(112^{**} + S)$	0.99^{**}	$V = (4.63^{**} \times S)/(8^{ns} + S)$	0.04^{ns}
Estimated function yield = f (soil NO_3)	$V = (4.36 \times S)/(75 + S)$		$V = (6.21 \times S)/(26 + S)$	

[a]3 df, [b]11 df
****significant at 1% level; *significant at 5% level; [ns]not significant**

[1] Drury, C.F. and Beauchamp, E.G. 1991. Ammonium fixation, release, nitrification, and immobilization in high- and low-fixing soils. Soil Sci. Soc. Am. J. 55:125-129.

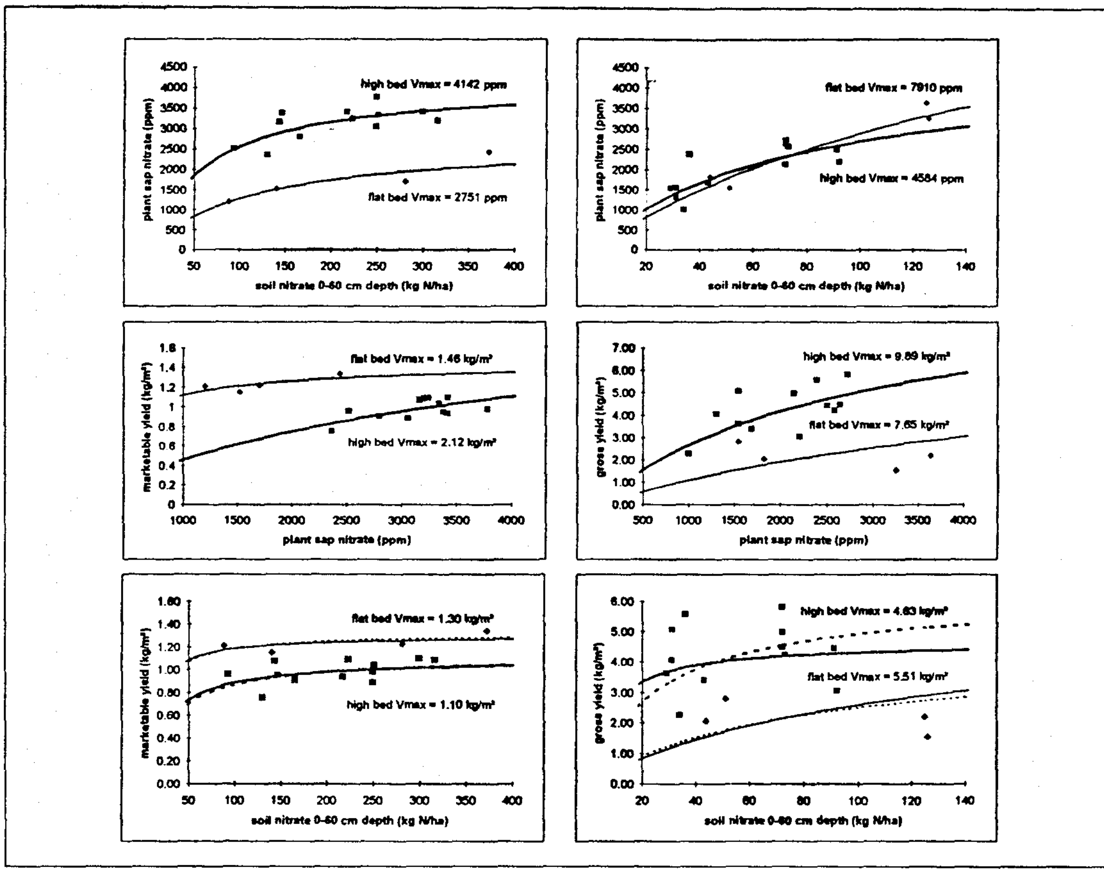

Fig. 2. Hyperbolic regression curves for functional relationships between soil NO_3, plant petiole sap NO_3, and crop yield

(left: vegetable soybean; right: Chinese cabbage; thick line: permanent high beds; thin line: flat beds; straight line: regressed function; dotted line: estimated function)

Regression equations for marketable yield as a function of plant NO_3-N overestimated yield potentials. Although low in r^2 and P, estimated functions of yield vs. soil NO_3 predicted upper limits of productivity that were almost precisely realized by the crop.

Small differences between yield and calculated yield potential suggest that soil N was not a factor limiting the growth of this crop, irrespective of cultivation system. This is confirmed by a lack of significant differences in yield between N_{min} and standard fertilization method (table 2). Excessive root growth particularly in the early growth stages at the expense of assimilatory leaf area (as indicated by crop cover and root distribution; data not shown), leading to a delay in crop maturity can explain these differences.

Chinese cabbage. Soil nitrate and plant sap nitrate fitted best to gross yield data when collected 4 WAT, before application of the second side-dressing. Marketable yields in Chinese cabbage during the rainy season are largely affected by soft rot *(Erwinia carotovora)* and poor head formation. Soil and plant analysis cannot account for these factors.

In contrast to the vegetable soybean crop, scatter plots of plant sap nitrate vs. soil nitrate (fig. 3) show that soil nitrate uptake of crops grown on either flat beds or high beds was not different, whereas efficiency of transformation of absorbed NO_3 to biomass [yield = f(plant NO_3)] was. With similar NO_3 concentrations in plant sap, Chinese cabbage yielded much better on high beds than on flat beds. The regressions for plant sap nitrate = f(soil NO_3) produced upper limits for plant sap nitrate concentrations that were distinctly higher than those measured in the crop. The same is true for the relationship yield = f(plant NO). Regressions indicate yield potentials that could have been reached if plant sap nitrate concentrations were much higher. Soil nitrate content at the end of the cultivation period resulted in suboptimum plant sap nitrate levels that were possibly too little to support maximum yields. If the higher plant sap nitrate concentrations as recorded 2 WAT (4473 ppm in high beds, 5293 ppm in flat beds) were maintained, it may have been possible to achieve much better yields.

For the summer crop of Chinese cabbage, the limited NO_3 supply from the soil system most likely restricted yields. Since reduced N fertilization in the N_{min} treatment did not significantly reduce gross yields compared to the traditional N application rate, both nitrogen application rates were too low given the reduced nitrification potential (= low fertilizer efficiency) of the soils under rainy season conditions.

The differences between cultural systems for reducing this absorbed NO_3 efficiently to amino acids for accumulation of biomass and yield can possibly be attributed to soil-plant water relations. This indicates higher water stress (reduced water intake through anaerobic conditions in the root zone) of Chinese cabbage on flat beds and other physiological disorders.

To sum up, under our experimental conditions the integrated analysis of soil N, plant sap N, and crop yield using the hyperbolic approach of the Michaelis-Menten model of saturation kinetics resulted in a sufficiently well-determined, mutual functional relationship for vegetable soybean. This was expressed by the similarities of parameters of regressed and estimated functions for yield = f(soil NO_3-N). Besides highlighting deficiencies in plant nutrition, the significance of petiole sap NO_3 analysis lies also in using the dependency of plant NO_3 = f(soil NO_3), which is usually highly determined, to estimate the relationship yield = f(soil NO_3), which is commonly poorly correlated.

For vegetable soybean, the analysis was able to show that no limitations in plant nutrition occurred and that other factors contributed to the somewhat poorer performance of the crop on permanent high beds. For Chinese cabbage, however, large differences between calculated upper limits for plant NO_3 and measured concentrations revealed suboptimum nitrogen nutrition of this high N-demanding leafy vegetable during the rainy summer. High soil water contents inhibited nitrification of ammonium fertilizer, even when applied in large doses.