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Consideration of the Soil N_{min} Content in N Fertilization of Vegetables in Intensive, Year Round Production in a Tropical, Rice Based Lowland

Berücksichtigung des N_{min}-Vorrats des Bodens bei der Stickstoffdüngung von Gemüse in intensiver, ganzjähriger Produktion in Reisfeldern im tropischen Tiefland

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Summary

From 1993 to 1995, reduction of traditional N application rates by soil N_{min} was evaluated in an intensive rotation of four vegetable species in the tropical, rice based lowland environment of southern Taiwan.

When crops were grown on traditional flat beds, no yield reductions due to this method were observed. This could be attributed to accumulation of soil nitrate in the dry season, and to overwet soil conditions in the rainy season. High soil moisture induced water stress and shallow root systems in vegetables, preventing them from effectively absorbing available nitrate. Consequently, more nitrate leached below the root zone.

Permanent high beds successfully alleviated water stress in vegetables during the rainy season and crops developed profound root systems. Soil nitrate was efficiently absorbed, and less nitrate was leached below the root zone when more N was applied. Better yields could not be sustained with the N_{min} method, and even the recommended fertilizer rates should presumably be adjusted to the greater vegetable biomass production potential on permanent high beds.

Zusammenfassung

Von 1993 bis 1995 wurde der Einfluß einer um N_{min} reduzierten Stickstoffdüngung in einer intensiven,

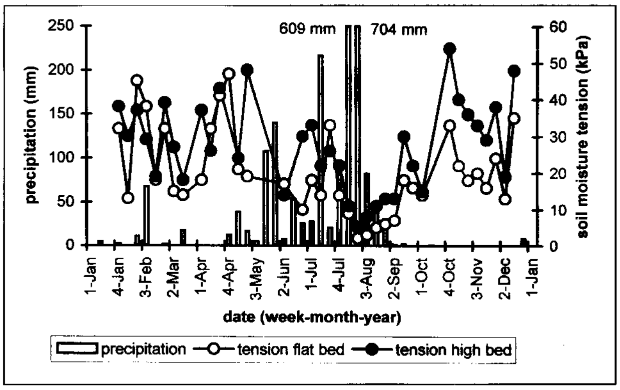

Fig. 1. Weekly precipitation and mean weekly soil moisture tension at 15-cm soil depth during 1994 in flat and high beds

Wöchentliche Niederschläge und durchschnittliche Saugspannung in 15 cm Bodentiefe 1994 in Flach- und Hochbeeten

ganzjährigen Fruchtfolge von vier Gemüsearten im tropischen, auf dem Reisanbau basierenden Tiefland von Südtaiwan getestet.

Auf gewöhnlichen Flachbeeten (20-25 cm hoch) führten die Düngereinsparungen durch diese Methode zu keinen Ertragseinbußen. Dies war während der winterlichen Trockenzeit darauf zurückzuführen, daß sich Bodennitrat ansammelte. Während der Regenzeit riefen überfeuchte Bodenwasserverhältnisse Wasserstreß in Gemüse hervor.

Gleichzeitig war das Wurzelwerk der Gemüsearten auf die oberste Bodenschicht beschränkt. Dies führte dazu, daß die größeren Stickstoffdüngemengen der „Standarddüngemenge" anstatt vom Gemüse aufgenommen, ausgewaschen wurden. Erträge blieben aus diesem Grunde gering.

Wirksame Abfuhr überschüssigen Bodenwassers durch dauerhaft angelegte Hochbeete (50 cm hoch) linderte Wasserstreß in Gemüse, welches ein dicht verzweigtes, tiefgründiges Wurzelwerk auch während der Regenzeit entwickelte. Verfügbarer Stickstoff wurde wirkungsvoll aufgenommen und damit einer Auswaschung vorgebeugt. Maximale Gemüseerträge konnten mit einer um den N-Gehalt des Bodens reduzierten N-Düngung nicht erzielt werden und wahrscheinlich war selbst die Standarddüngemenge zu niedrig. Diese sollte dem größeren Potential von Biomasseproduktion angepaßt werden.

Introduction

N fertilization of vegetables in many tropical regions is often oriented towards maximum productivity rather than optimum N-input. Some reasons are safeguarding of yields to reduce production risks (NIEDER 1983), or low N-fertilizer costs (BOOIJ et al. 1993). Over-use of fertilizers is consequently often associated with environmental pollution and degradation of agricultural soils (HUANG et al. 1989).

In tropical Asia, vegetables are intensively produced year-round, particularly in the peri-urban peripheries of the big cities (MIDMORE 1995). Crops are frequently cultivated in drained paddy rice fields in which soils are often alluvial and low in organic matter (LIAN 1986). Physical and chemical properties of these rice soils are not favorable for the growth of vegetable crops. Wet plowing (puddling) has formed a compact subsoil with plow pan beneath a degraded, single-grained surface soil with poor hydraulic properties (ISHII 1986). Under these conditions, root systems of upland crops are usually confined to the topmost soil, favoring leaching of nitrate (AVRDC 1995).

One main tool in integrated vegetable production to minimize N fertilizer consumption is the Nmin method (SCHARPF and WEHRMANN 1975, WEHRMANN and SCHARPF 1986). The major objective of this method is to prevent environmental pollution through excessive fertilizer use measuring the amount of plant available nitrogen in the soil at the time of fertilizer application. At the same time, maximum yields should be ensured and nitrogen fertilizer efficiency improved. N fertilizer rates are determined according to N_{min}, site, growth stage, and the demand of the crop. By applying the Nmin method, fertilizer can be saved and leaching of NO_3 minimized (WEHRMANN 1983).

Our objective was to evaluate a N_{min} reduced method to decrease traditional N application rates in intensive, continuous vegetable cultivation in the tropical lowland environment of southern Taiwan. The recommended ('standard') N fertilizer rates were used for application criteria and reduced by the soil N_{min} content. Nine crops were cultivated during a 29-month rotation of four vegetable species in two systems: traditional flat and permanent high beds. Preliminary results of this now completed study were reported in KLEINHENZ et al. (1996a).

Material and Methods

Site, systems, and crop management

From 1993 to 1995, validity of the Nmin reduced method for optimization of vegetable nitrogen nutrition in year-round production was studied at the experimental farm of the Asian Vegetable Research and Development Center (AVRDC), Shanhua in southern Taiwan (23° N latitude). Mean daily air and mean daily soil temperature for 1994 were 28.4 °C and 29.4 °C in the rainy season from May through September, and 22.3 °C and 24.3 °C during the rest of the year. Weekly sums of precipitation for 1994 are presented in Fig. 1. Soil at the experimental site is an alluvial sandy loam (18 % clay, 27 % silt, 55 % sand). Cultivation systems consisted of traditional flat beds (20-25 cm high), which were prepared before sowing or transplanting each crop, and permanent high beds (50 cm high) constructed at the beginning of the experiment. Flat beds and high beds were 40 m long, divided into 20 m-long flat bed plots and 4 m-long high bed plots. The experiment followed a randomized complete block design with four replications. Four vegetable crops, namely vegetable soybean (*Glycine max.* L. Merr; cv. 'AGS 292', AVRDC), Chinese cabbage (*Brassica pekinensis* Lour. Rupr.; cv. 'ASVEG No. 1', AVRDC), chili (*Capsicum annuum* L.; cv. 'Hot Beauty', Known You Seed Co.), and carrot (*Daucus carota* L. ssp. *sativus* Hoffm. Arcang.; cv. 'Parano', Nunhems) were cultivated with two N fertilizer rates: (1) the commonly used traditional (standard) N application rate and (2) the standard application rate reduced by the amount of

Table 1. Soil N_{min} contents in the N_{min}-reduced treatment (0-30-cm depth) and N-fertilizer schedules of vegetables cultivated with traditional rate and N_{min}-reduced rate in two cultivation systems 1993 to 1995 (N-application rates in the N_{min}-reduced treatment were lowered by the rounded mean of soil-NO_3 in flat and high beds)

Boden-N_{min}-Gehalte in der N_{min}-reduzierten Behandlung (0—30 cm Tiefe) und Zeitpunkt der Stickstoffdüngung von Gemüse mit Standard- und N_{min}-reduzierten Stickstoffdüngemenge auf Flach- und Hochbeeten 1993 bis 1995 (in der N_{min}-reduzierten Behandlung wurden N-Düngemengen um den gerundeten mittleren Bodennitratgehalt in Flach- und Hochbeeten verringert).

Crop	Chinese cabbage			Chili				Carrot	
Cultivation period (week-month)	1-May[1] to 3 -Jun '93			3 -Jun to 1-Nov '93				4-Nov to 4-Feb '94	
Date of application (week-month)	1-May	3-May	1-Jun	3 -Jun	3-Jul	2-Aug	4-Aug	4-Nov	3 -Jan
N_{min} content before fertilization									
Flat bed (kg NO_3-N/ha)	43	—[2]	—	30	—[2]	—	—	132	213
High bed (kg NO_3-N/ha)	60	—	—	34	—	—	—	139	37
Mean	52			32				136	125
Fertilizer application rate									
Traditional rate (kg N/ha)	60	30	30	50	50	50	50	60	60
Reduced N_{min}-rate (kg N/ha)	0[3]	30	30	20	50	50	50	0	0
Crop	Vegetable soybean			Chinese cabbage			Chili		
Cultivation period (week-month)	1-Mar to 4-May '94			4-May to 3 -Jul '94			3 -Jul to 4-Dec '94		
Date of application (week-month)	1-Mar	1-Apr	1-May	4-May	2-Jun	4-Jun	3-Jul	4-Aug	2-Nov
N_{min}-content before fertilization									
Flat bed (kg NO_3-N/ha)	43	120	51	22	32	21	16	52	23
High bed (kg NO_3-N/ha)	16	101	20	19	39	13	20	25	21
Mean	30	111	36	21	36	17	18	39	22
Fertilizer application rate									
Traditional rate (kg N/ha)	20	20	20	60	30	30	50	50	50
Reduced N_{min}-rate (kg N/ha)	0	0	0	20[4]	0	0[4]	30	10	30
Crop	Carrot		Vegetable soybean			Chinese cabbage			
Cultivation period (week-month)	2 -Jan to 1-Apr '95		1-May to 3-Jul '95			3-Jul to 3-Sep '95			
Date of application (week-month)	2-Jan	4-Mar	1-May	1-Jun	1-Jul	3-Jul	2-Aug	1-Sep	
N_{min}-content before fertilization									
Fat bed (kg NO_3-N/ha)	18	52	6	17	6	2	27	27	
High bed (kg NO_3-N/ha)	25	48	7	16	7	6	41	20	
Mean	22	50	7	17	7	4	34	24	
Fertilizer application rate									
Traditional rate (kg N/ha)	60	60	20	20	20	60	30	30	
Reduced N_{min}-rate (kg N/ha)	40	10	10	0	10	60	0	10	

[1] (week-month)
[2] N_{min}-reduced treatment only for basal fertilizer application
[3] N_{min}-calculation included expected N-release from crop residues of the preceding vegetable
[4] N_{min}-calculation included expected N-release from crop residues of the preceding vegetable

soil NO_3 content before application ('Nmin reduced treatment'). Soil NO_3 measurements for this calculation derived from the mean of flat and high beds in reduced N_{min} plots (0-30-cm soil depth). Fertilizer nitrogen was applied as ammonium sulfate. Details of N contents and N fertilization are presented in Table 1. Plant protection and other crop management practices followed standard AVRDC recommendations.

Root length density measurement

Root length was measured in one flat and one high bed before crop harvest using the 'gridline intersect method' (NEWMAN 1966). Soil was sampled to a depth of 60 cm in distances of 20 cm from the edge towards the center of the beds with two replications. The soil column was cut into 10-cm-long sections and roots separated by washing the soil through a 0.15-mm sieve. The roots were spread out uniformly in a petri dish and put upon a grid of lines with an interline distance of 1.27 cm. Root length in centimeter was determined by the number of counted root/gridline intersects (GIOVANETTI and MOSSE 1980). Three readings were made for each sample by rearranging the roots in the petri dish. Root length density (cm/cm^3) was calculated by dividing the mean of root length readings by the volume of the soil sample. Data from the topmost 10 cm of soil were excluded due to too many roots of weeds.

Measurement of soil moisture tension and calculation of water stress

Soil moisture tension was measured with vacuum gauge tensiometers installed at 15-cm soil depth within crop rows in one flat bed (one row), and one high bed (three rows with 40, 80, and 120-cm distance from the edge of the bed) with two replications. Readings were taken at

Table 2. Distribution of root length density of four vegetables cultivated on flat beds (FB) and high beds (HB) 1994/95
Verteilung der Wurzellängendichte von vier Gemüsearten auf Flachbeeten (FB) und Hochbeeten (HB) 1994/95

	Veg. soybean		Chinese cabbage		Chili		Carrot	
Depth (cm)	FB	HB	FB	HB	FB	HB	FB	HB
	root length density (cm/cm^3)							
10-20	3.32	2.45	2.32	1.88	2.31	2.11	4.57	2.53
20-30	0.76	1.93	0.67	1.42	1.24	1.82	0.11	0.84
30-40	0.09	0.79	0.48	1.06	0.69	1.17	0.76	0.89
40-50	0.24	0.48	0.57	0.47	0.47	0.33	0.48	0.54
50-60	0	0	0.03	0.01	0	0	0.01	0.02
Mean	0.86	1.13	0.81	0.97	0.94	1.09	1.18	0.96

approximately two-day intervals during the crop cultivation periods when field conditions allowed access.

Water stress was estimated by a modified calculation of Taylor's 'mean integrated soil moisture tension' (TAYLOR 1952). This method accounted for stress caused by overdry and overwet soil conditions according to the equation:

$$T_{pm} = \frac{\sum_{i=0}^{m} (d_{i+1} - d_i)\, ABS\, (T_i - T_{opt})}{\sum_{i=0}^{m} (d_{i+1} - d_i)}$$

where: T_{pm} is the mean integrated soil moisture tension, i represents a single time, m represents the total number of tensiometer readings, d represents the Julian day of the year when a reading was made, $(d_{i+1} - d_i)$ is the time interval in days between successive readings, T_i is the moisture tension at a single time, and T_{opt} is an 'optimum' soil moisture tension, which was approximated for both crops by an iteration procedure.

Soil nitrogen analysis

Soil mineralized nitrogen was measured by sampling soil 0 to 30-cm deep and 30 to 60-cm deep (three sam-

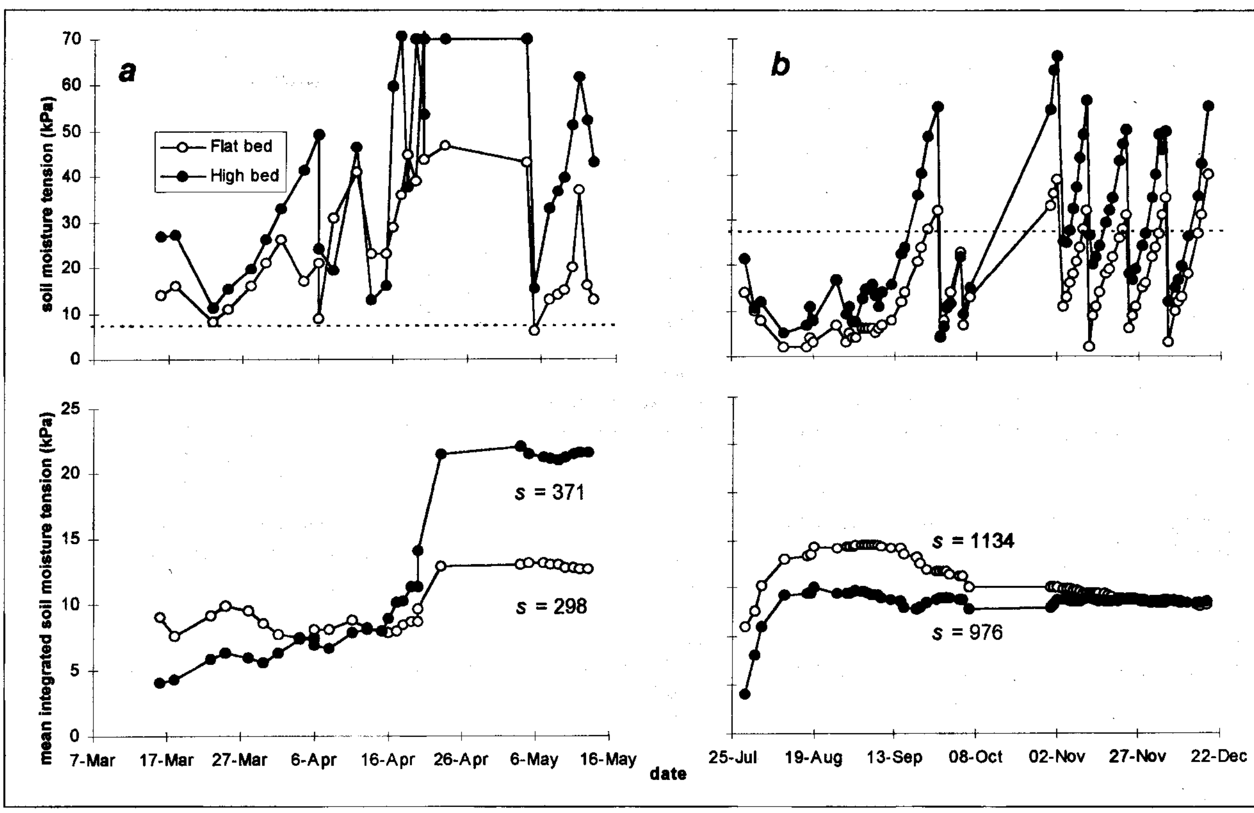

Fig. 2. Soil moisture tension at 15-cm soil depth (top) and mean integrated soil moisture tension (bottom) for (*a*) dry-season vegetable soybean and (*b*) rainy-season chili in flat and high beds. The dotted horizontal line (top) indicates an calculated 'optimum soil moisture tension' (T_{opt}= 9 kPa for vegetable soybean; T_{opt} = 27 kPa for chili). s (bottom) indicates the limit for mean integrated soil moisture tension in flat and high bed
Saugspannung in 15 cm Bodentiefe (oben) und „durchschnittliche integrierte Bodenwasserspannung" (unten) für (a) Gemüsesojabohne während der Trockenzeit und (b) Paprika während der Regenzeit auf Flach- und Hochbeeten. Die punktierte horizontale Linie (oben) kennzeichnet eine berechnete „optimale Bodenwasserspannung" (T_{opt} = 9 kPa für Gemüsesojabohne; T_{opt} = 27 kPa für Paprika). s (unten) kennzeichnet den Grenzwert für die durchschnittliche integrierte Bodenwasserspannung in Flach- und Hochbeeten

ples per plot) with a 2.0 cm-diameter punch tube before N fertilizer application until March 1994 and at weekly intervals thereafter until April 1995. Samples were taken in four flat and four high beds in the standard and N_{min} reduced treatment with two replications. Extracted 1:2 by volume in 0.8 % KCl water solution, samples were analyzed for NO_3 with Merck's RQflex reflectometer and Reflectoquant nitrate (5-225 ppm) analytical test strips (one reading). The technique was tested to be highly accurate by HOLDEN and SCHOLEFIELD (1995).

All readings were converted from concentrations (ppm) to contents (kg/ha). Soil ammonium was only measured occasionally and not considered for N_{min} calculations since nitrification proceeded rapidly thin 10 to 12 days after NH_4-fertilizer application (KLEINHENZ et al. 1996b).

Data analysis

Vegetable yield data were analyzed with a split-split-plot ANOVA, means were separated with the LSD-test, and significance between cultivation systems (flat beds vs. high beds) and fertilizer rates (N_{min} reduced vs. standard rate) were determined with orthogonal contrasts (SAS INSTITUTE INC. 1989).

Results

Root length density

Root distribution was restricted to the top 50-cm soil depth (Table 2). Mean root density throughout the profile was greater in high beds for all vegetables except carrot. Fewer roots were found above 20 cm depth in those beds, but roots elongated more profusely in the 20 to 40 cm soil layer.

Soil moisture tension and water stress

Seasonal differences in precipitation were reflected in soil water status with low weekly means of moisture tension during the peak rainy season particularly on flat beds (Fig. 1). In spring 1994 during the dry season, soil moisture tension values in vegetable soybean were less and amplitude smaller on the flat bed compared to the high bed (Fig. 2 *a*, top). When chili was grown in the summer rainy season, soil moisture approached low tensions from the end of July until the middle of September particularly on flat beds (Fig. 2 *b*, top). During autumn and winter 1994 this changed to a periodic pattern of drying and rewetting typical for fully irrigated field conditions. Soil moisture tension in flat beds averaged lower values with smaller amplitude than on high beds.

Vegetable soybean was particularly affected by overdry soil conditions on the high bed, hence water stress curves in Fig. 2 (*a*, bottom) show distinct differences between flat and high beds. Flooded soil conditions set in soon after transplanting chili in late July. Development of soil flooding was clearly reflected in the stress curves in Fig. 2 (*b*, bottom). In this phase, stress indices were highest for the flat bed. The influence of increasing soil moisture tension on moisture stress in the transition from rainy season to dry season was reflected in a steady decrease of mean integrated soil moisture tension in the flat bed.

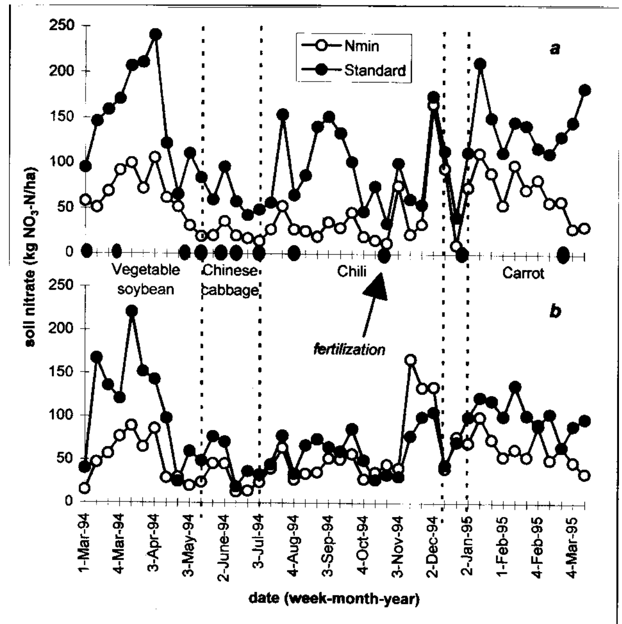

Fig. 3. Weekly soil contents of nitrate nitrogen at 0 to 30-cm soil depth with N_{min}-reduced method and standard N rate in: (*a*) flat beds and (*b*) high beds

Wöchentliche Gehalte an Nitratstickstoff in 0 bis 30 cm Bodentiefe mit N_{min} reduzierter Düngemenge und Standarddüngemenge in: (a) Flachbeeten und (b) Hochbeeten

Available soil nitrate in the root zone and leaching of nitrate

Since root density was low beneath 40 cm, soil nitrate content at 0 to 30 cm depth was plant available, and nitrate at 30 to 60 cm soil depth indicated nitrogen loss through leaching. Soil nitrate was high during the dry season and low during the rainy season. Compared to the N_{min} reduced rate, soil NO_3 content in flat beds was greater at 0 to 30 cm soil depth (Fig. 3 *a*) and at 30 to 60 cm soil depth (Fig. 4 *a*) when the standard N rate was applied. These differences were not distinct in high beds (Fig. 3 *b* and 4 *b*). The amounts of nitrate that were leached below the root zone were greater in flat than in high beds when the standard N rate was applied.

Influence of N fertilization on soil N content and vegetable yield

A total of 1,070 kg/ha nitrogen was applied to nine vegetable crops during the 29-month cropping sequence following standard fertilization. 470 kg/ha N or 56 % were saved by applying the N_{min} reduced method.

The relationship between nutrient application, soil nitrogen availability (indicated by the mean of soil NO_3 content at 0 to 30-cm depth over the cropping period), and crop yield is presented in 'double diagrams' (Fig. 5) which are closely related to VAN KEULENS' (1982) 'three-quadrant diagrams'. Slopes in the diagrams left indicate that N application resulted in higher soil nitrate contents on flat beds than on high beds, particularly during the rainy-season crop of chili (Fig. 5 c, left). Higher soil nitrate following standard fertilization

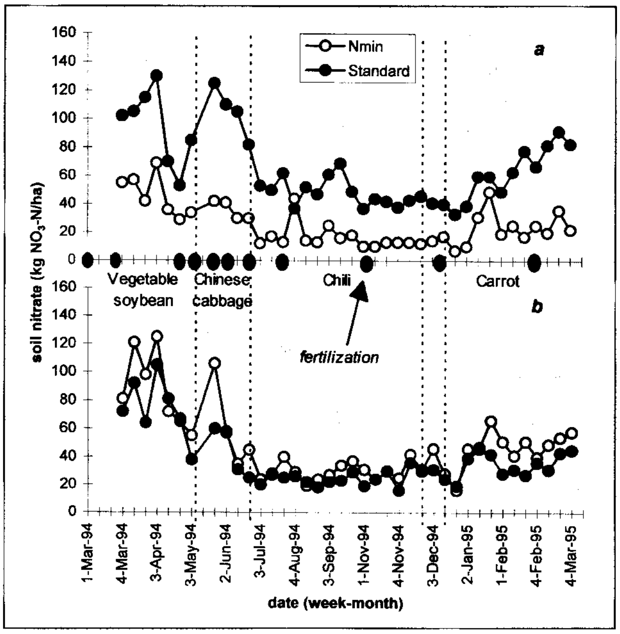

Fig. 4. Weekly soil contents of nitrate nitrogen at 30 to 60-cm soil depth with N_{min}-reduced rate and standard N-rate in: (*a*) flat beds and (*b*) high beds

Wöchentliche Gehalte an Nitratstickstoff in 30 bis 60 cm Bodentiefe mit N_{min}-reduzierter Düngemenge und Standarddüngemenge in: (a) Flachbeeten und (b) Hochbeeten

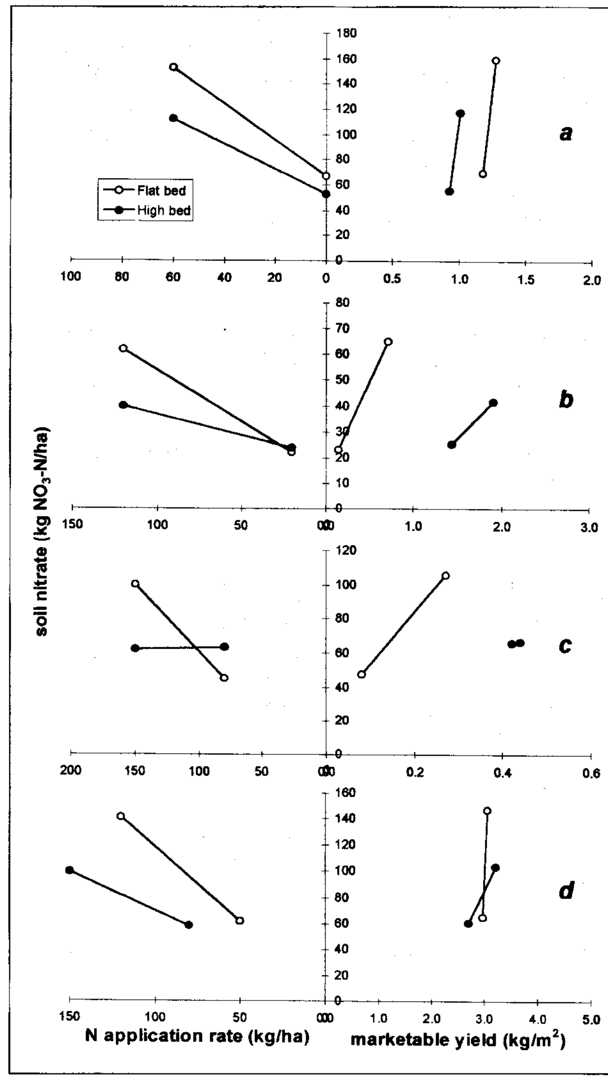

Fig. 5. Relationship of (left) N-fertilizer application and mean soil-nitrate content (0 to 30-cm soil depth), and (right) mean soil nitrate content and net yield of (*a*) vegetable soybean, (*b*) Chinese cabbage, (*c*) chili, and (*d*) carrot in flat and high beds

Zusammenhang zwischen (links) Stickstoffdüngemenge und durchschnittlichem Bodennitratgehalt (0 bis 30 cm Bodentiefe) und (rechts) durchschnittlichem Bodennitratgehalt und Marktertrag von (a) Gemüsesojabohne, (b) Chinakohl, (c) Paprika und (d) Möhre in Flach- und Hochbeeten

had only a small effect on yield in the dry season (Fig. 5 *a* and *d*, right). This influence was greater during the rainy season (Fig. 5 *b* and *c*, right), particularly on flat beds. However, yield differences were primarily due to the cultivation system. Yields on high beds were substantially greater than those on flat beds.

Flat bed yields surpassed high bed yields only in vegetable soybean 1994 (Table 3). No yield differences between cultivation systems were recorded for the carrot crops in the dry seasons of 1993/94 and 1995. High beds outyielded flat beds in all other crops. Except for Chinese cabbage, marketable yield of vegetables was not affected by fertilization regime on flat beds. However, on high beds, the N reduced treatment significantly decreased crop yields for all except three vegetable crops.

Discussion

The seasonal variation in precipitation with its marked influence on soil-water status in flat and high beds affected vegetable crop growth through: (1) causing seasonal variations in available soil nitrogen, (2) inducing different levels of water stress in vegetable crops, and (3) affecting the development of root systems of vegetables.

Seasonal variations in soil nitrate

Soil nitrate accumulated during the dry season, peaked just before the rainy season, and was low during the rainy season (Fig. 3 *a*). Nitrate accumulation in the dry season was observed in several seasonally wet dry climates in the tropics by GREENLAND (1958). Leaching is minimal in this season (REYNOLDS-VARGAS et al. 1994) and organic matter is microbially decomposed under drained conditions (TERRY and TATE 1980). Continued high soil temperatures favor mineralization (STANFORD et al. 1973), and nitrate can move upward from sub-soils when evaporation exceeds precipitation. This plant available nitrogen quickly declined with onset of wet season rainfall.

Water stress in vegetables

Overcoming flood stress in vegetables by high bed cultivation is based on quick removal of excessive soil moisture as a result of better drainage. This is indicated by higher water infiltration rates (KLEINHENZ et al.

Table 3. Marketable yield of vegetables as influenced by different bed heights (flat bed, high bed) and fertilizer rate (N_{min}-reduced rate, traditional rate)

Einfluß von Kulturbeeten (Flachbeete, Hochbeete) und Stickstoffdüngemenge (N_{min}-reduzierte Rate, Standarddüngemenge) auf den Gemüsemarktertrag

Year	1993			1994			1995		
Vegetable	Chinese cabbage	Chili	Carrot	Vegetable soybean	Chinese cabbage	Chili	Carrot	Vegetable soybean	Chinese cabbage
	Marketable yield (kg/m^2)								
Analysis of variance									
Flat bed									
Traditional rate	1.37a	0.220a	1.29a	1.26a	0.75a	0.172a	3.06a	0.89a	2.43a
Reduced N_{min}-rate	1.49a	0.202a	1.40a	1.19a	0.19a	0.070a	3.00a	0.88a	1.80b
High bed									
Traditional rate	2.10a	0.616a	1.10a	1.10a	1.99a	0.364a	3.24a	1.31a	3.07a
Reduced N_{min}-rate	2.14a	0.533b	1.16a	1.05b	1.32b	0.292b	2.99b	1.28a	2.32b
Orthogonal contrast									
Flat bed vs. high bed	< 0.01	< 0.01	0.13	< 0.01	< 0.01	< 0.01	0.43	< 0.01	< 0.01
Traditional vs. N_{min}	0.31	0.04	0.39	0.06	< 0.01	< 0.01	< 0.01	0.23	< 0.01

1995). However, higher water intake rates make high beds more drought prone in the dry season. During that season, water stress was primarily related to stresses caused by overdry soil conditions. Therefore, water stress was greater on high beds (Fig. *2* a, bottom). During the summer rainy season, stresses occurred through overwet soil conditions, and water stress was consequently greater on flat beds (Fig. *2* b, bottom).

Effect of the N_{min} reduced method

Adherence to the N_{min} reduced fertilization method considerably lowered the amounts of N applied. Accumulation of soil nitrate largely obviated the need for N fertilization of vegetable crops during the dry season. No yield reductions were observed, except for carrot on high beds in 1995.

During the rainy season, water stress developed more readily on flood prone flat beds than on high beds. Chinese cabbage and chili were tested as representatives of vegetables particularly sensitive to flooding under high temperature conditions. In chili, overwet soil conditions induced decline in photosynthesis, resulting in reduction in leaf area, plant weight, and dry matter accumulation (AVRDC 1993). Flooding in Chinese cabbage can cause a reduction in plant growth by impeding the active processes of the root system. This may also lead to a complete destruction of the root system (AVRDC 1980). Soil water plays an important role in the recovery of soil nutrients through its effect on soil oxygen. Anaerobic conditions inhibit uptake and transport of nutrients by roots of upland species (JACKSON and DREW 1984). Through the direct effect of excessive soil moisture, N absorption of vegetables on flat beds was ineffective in the rainy season. This process was accelerated by the shallow root depth and the small root density which prevented depletion of the soil nitrate nitrogen (SØRENSEN 1993). This caused poor biomass production and low yields. Consequently, higher rates of N fertilizer that were not absorbed were leached below the root zone (Fig. 4 a).

Due to the high contents of soil nitrate during the dry season and the limited ability of vegetables on flat beds to absorb available nitrogen during the rainy season, the N rates reduced by N_{min} lowered nitrate leaching without affecting crop yields on those beds. Similar findings with the N_{min} method for vegetable farming in Germany (CLAUS 1983, WEHRMANN and SCHARPF 1989, HÄNDEL and ISEMANN 1993) confirm these results.

High beds successfully alleviated the negative impact of overwet soil conditions in the rainy season. Roots were rich in long, slender and soft mainroots with many branches and roothairs, thus resulting in huge root mass. The deeper rooted plants could exploit a large soil volume. Available soil nitrogen was efficiently absorbed by vegetables and productivity was kept high throughout the season. Therefore, the higher application rate of fertilizer N did not result in greater leaching losses. The N_{min} reduced method decreased yields in all but three vegetable crops. It can, however, be argued, that even the recommended (standard) N rate may not have been sufficient for maximum vegetable yields since N application rates were tailored to the specific production conditions of flat beds. Under improved field conditions of high beds, these N fertilizer recommendations should be adjusted to the greater potential of biomass production and yield.

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