

NITROGEN REQUIREMENTS OF RICE WITH SPECIAL REFERENCE TO JAVA

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ABSTRACT

A unifying concept for the behaviour of small grains under conditions of nitrogen shortage is presented. The main emphasis is on the effect of nitrogen fertilizer application to lowland rice. It is concluded that for proper understanding of yield responses yield data should be accompanied by chemical analysis of the plant material. When all these data are available, they are most conveniently summarized in a graphical presentation, which allows discrimination between various processes playing a role in the reaction of rice to nitrogen fertilizer application.

It is shown, that the unifying concept presented, allows the construction of such graphical displays even when not all data are available. Interpretation of fertilizer experiments is therefore facilitated and generally applicable rules can be formulated. These rules in turn can be applied to arrive at nitrogen fertilizer recommendations for specific situations.

1. INTRODUCTION

Rice is the most important food crop, grown in the tropics. It accounts for the bulk of the caloric intake of the people in Asia and for a considerable portion of the diets in tropical Africa and the Americas. The introduction of improved rice varieties in the last decade, to a large extent brought about after pioneering work at IRRI, has increased the average yield per hectare over a considerable area. These high-yielding varieties should however not be considered as "miracle crops", as their production potential is realized only when optimum growing conditions are provided. Among these an adequate supply of nitrogen at all growth stages is of primary importance. As the inherent nitrogen supply of most tropical soils is low, additional nitrogen has to be applied. In most rice producing countries therefore production and consumption of nitrogen fertilizers has increased over the last decade. The associated increase

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in production falls however far short of what would be expected at that fertility level. A detailed analysis of the response of rice to nitrogen fertilizer partly explains this discrepancy. The recovery of the applied nitrogen in the plant tissue is very low and the recovery factors vary greatly between sites, seasons and fertilizer materials (3). It is therefore worthwhile to examine the fate of nitrogen in rice soils and crops. Understanding of the relevant processes in plants and soil might lead to the adaptation of improved management practices, which would result in an increased response of rice to nitrogen fertilizers. Such a study might furthermore lead to fertilizer recommendations, which take into account specific conditions in any given area and season. Implementation of such site-specific fertilizer recommendations (rather than a general one, based on a non-existing average situation) would undoubtedly result in a more efficient fertilizer use and save money and energy, both on the farmers and the national level.

In this paper nitrogen transformations in the soil are discussed on a qualitative basis, while the uptake and distribution of nitrogen in the plant are interpreted from a quantitative point of view. In the last chapter this analysis is used to give an outline for nitrogen fertilizer recommendations and their application.

2. DYNAMICS OF NITROGEN IN THE SAWAH-RICE SYSTEM

2.1. In rice soils

Most of the world's rice is produced on flooded soils of banded land, either under irrigated or rainfed conditions. Rice can grow under these circumstances because of its ability to oxidize its rhizosphere through the intake of atmospheric oxygen that diffuses from the leaves through intercellular channels (1). Flooding however brings about a series of physical, chemical and biological changes in the soil, quite different from those under upland conditions. These changes are of great practical importance for the behaviour of nitrogenous compounds in rice soils. A sudden flooding of an originally dry soil results in saturation of the structural aggregates of the soil matrix, while the pressure, built up by air entrapped within the soil, causes desintegration of many of the aggregates.

Subsequent puddling of the soil during land preparation and transplanting of the rice seedlings, transforms the surface layer into a uniform mud, with a conductivity for water flow several orders of magnitude lower than that of the original soil. Aerobic microorganisms present in the soil consume oxygen in respiratory processes. After flooding, oxygen in the soil is quickly depleted as the rate of diffusion of oxygen through water is a factor 10^4 slower than in the absence of water. At the then prevailing low oxygen pressures anaerobic microorganisms multiply, using decomposable organic material as energy source and oxidized soil components as electron acceptors. These compounds are reduced, following a thermodynamically determined sequence: nitrates, manganic oxides, ferric oxides, and hydroxides, sulphates, CO_2 and sometimes phosphates (38). The organic substrate itself may also serve as terminal electron acceptor. Depending on the nature of the organic material present and on the relative concentration of the different oxidized components, the redox potential drops, more or less sharply, reaching values of ∞ -200 to -400 mV after several weeks.

This complex of processes governs the dynamics of nitrogen in the soil. Nitrates originally present are used immediately after oxygen depletion, as electron acceptors and the nitrogen escapes to the atmosphere in gaseous forms, either N_2 or N_2O . Ammoniacal nitrogen, either released by the decomposition of organic material, or as fertilizer applied directly in the reduced soil layer, remains unchanged. It may be partially adsorbed on the surface of the clay particles and can leave the system only through uptake by the roots. In soils containing certain clay minerals, part of the ammonium may be fixed in the lattice and rendered unavailable in that way, but in most tropical soils this process is quantitatively not important. When ammonium fertilizers are broadcast, part of the nitrogen is lost by direct volatilization to the atmosphere (7). In the water layer on the rice field part or all of the remaining NH_4^+ -ions may be converted to nitrates as a result of the activity of nitrifying bacteria. When these nitrates reach, through leaching or diffusion, the reduced zone, they become a substrate for the denitrifying organisms and within a short time the nitrogen is lost in gaseous forms (23). Generally speaking, the efficiency of

nitrogen fertilizers, applied through broadcasting, is therefore rather low. This is equally true for fertilizers from which ammonium is formed after hydrolysis, like different forms of urea, as the rate of hydrolysis is high compared to the residence time of nitrogen in the soil (50), especially in the beginning of the growing season. The situation is even worse, when alternate drying and wetting of the soil occurs. Such conditions may prevail especially in the drier parts of the growing period, in areas where no irrigation facilities exist. In drying-wetting cycles oxidation and reduction take place alternately. Under oxidative conditions nitrogen is converted to nitrate, which is subsequently lost in the next flooded period.

2.2. In the rice plant

Uptake of nitrogen by the rice plants is determined by their demand or by the availability of the element in the soil. As rice plants take up NO_3^- and NH_4^+ -ions indiscriminately (46, 21), the growth determining factor is the concentration in either form in the soil solution.

When nitrogen is abundantly available, its concentration in the plant tissue is the highest, at, or shortly after transplanting (4.5%) and gradually decreases towards maturity (\approx 0.7% in the straw). Adequate supply of nitrogen at all growth stages ensures proper development of the rice plant, characterized by prolific tillering, satisfactory panicle formation, good seed setting and proper filling of those grains (30). It also leads to the formation and maintenance of a green leaf surface throughout plant life, providing optimum conditions for canopy photosynthesis and dry matter production.

Deficiency of nitrogen at early growth stages shows up first in reduced tillering ability, at nitrogen contents that are only slightly below the optimum. As a consequence leaf area development is hampered and the rate of dry matter production decreases. Inadequacies in nitrogen supply at later stages, notably during the grain filling period, causes increased translocation of this element from the vegetative parts to the developing seeds. As a result the nitrogen content of the leaves decreases, which leads to a lower photosynthetic capacity (55) and accelerated senescence and dying. Sufficient availability of nitrogen in the soil at that time counteracts this

phenomenon and may therefore result in ripening of the seeds on a still green rice plant.

It should be recognized of course, that nitrogen application to traditional indica varieties is not without danger. These plants are in general tall and have weak stems. Abundant supply of nitrogen may lead to excessive vegetative growth, followed by severe lodging at the time of grain filling. This lodging results in a heavy yield depression, so that the nitrogen response in terms of grain yield may become negative as is often observed (18).

3. THE INTERPRETATION OF FERTILIZER EXPERIMENTS

3.1. Introduction

When fertilizers are applied to a crop it is expected that this application will result in an increase in yield. To achieve that, the applied fertilizer must first be taken up by the plants and secondly be utilized by the plants to produce economically useful material. When the expected yield increase is not observed it may be due to either of two causes: 1) The fertilizer has *not been taken up* by the plants because it was applied at the wrong time or in the wrong place, or biological or chemical transformations in the soil render it unavailable. 2) Although being taken up it is *not used* in a profitable way. This may be inhibited by other growth limiting factors, such as water shortage or lack of mineral elements other than the one applied.

When the results are presented in the usual way, i.e., yield increase per amount of fertilizer applied, it is difficult if not impossible to distinguish between these two causes. Fertilizer experiments have to be combined therefore with chemical analysis of the different plant parts, thus enabling the calculation of the uptake of the element by the plant, and its subsequent distribution.

3.2. Presentation of data

When in fertilizer experiments yield and chemical composition of the material have been determined, graphical presentation of the data, as suggested by de Wit (1953), greatly facilitates their interpretation. An example of this approach is given in Figure 1, which

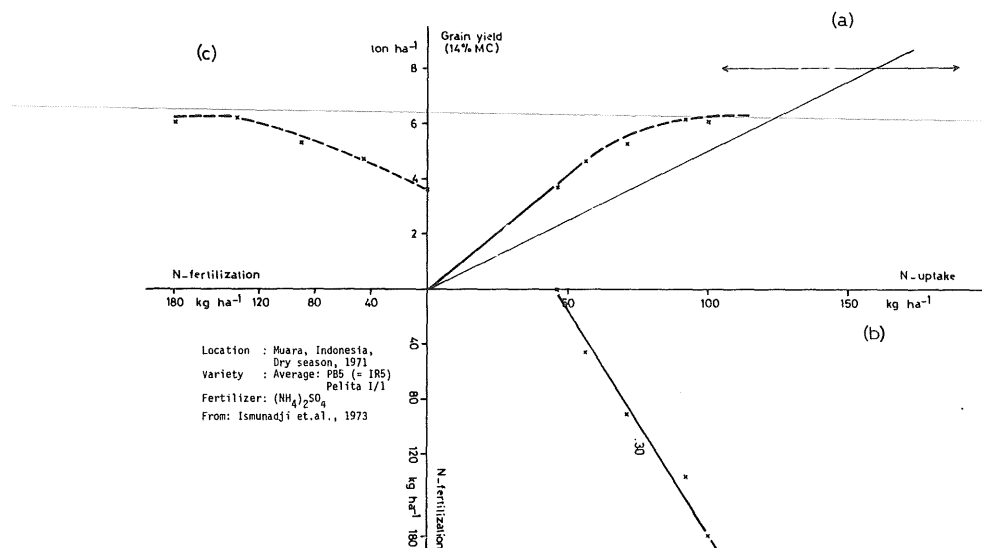
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Figure 1. The relation between total nitrogen uptake and grain yield at 14% moisture content (a), between rate of nitrogen application and total nitrogen uptake (b) and between rate of nitrogen application and grain yield (c).

Gambar 1. Hubungan antara absorpsi nitrogen total dan hasil gabah berkadar air 14% (a), antara tingkat pemupukan nitrogen dan absorpsi nitrogen total (b), serta antara tingkat pemupukan nitrogen dan hasil gabah (c).

is based on data of Ismunadji et al. (1973). It is composed of three graphs: in the first graph (a) the relationship between yield and the total amount of the mineral element taken up by the canopy is given. The latter value is calculated by multiplying the amounts of grain and straw harvested by their respective nitrogen contents. The horizontal axis of graph (b) shows again the total uptake while on the vertical the amount of fertilizer applied is given. In the third graph the relation between fertilizer application and yield is given. It is obvious that the three graphs are not independent, the third one always being constructed from the two others, through elimination of one variable.

When considering first graph (a) attention is drawn to the following features:

The lower end of the curve passes through the origin, indicating that at zero uptake, no yield can be expected. This point of the graph is easily obtained but is often disregarded in the presentation of results. It should be kept in mind that the uptake, referred to

here, is the total uptake of the mineral concerned in above ground plant parts and not only the amount present in the economically important plant parts, e.g. the grain. Strictly speaking only vegetative plant parts could have been formed, in which case the curve given here does not pass through the origin. For all practical purposes however, that can be disregarded. It is important to consider the total amount taken up, because at later growth stages, minerals may be translocated quickly from one plant part to another (9, 42). The extent and rate of this translocation may differ between treatments, which would lead to distortions in the observed yield uptake curve when only certain plant parts are considered.

At low N-uptake the relation between yield and uptake is linear. This indicates, that under conditions of limited supply, nitrogen in the tissue may be diluted to a minimum level, thus enabling the plant to make optimum use of the amount available.

With increasing uptake the curve starts levelling off, reflecting an increase in the nitrogen concentration of the harvested material. The efficiency of utilization of nitrogen, expressed in grain yield per unit of nitrogen taken up thus decreases. This does not necessarily have to be detrimental as at this stage the protein yield does increase, which is often as important for the diet as the caloric value.

Finally the curve reaches a plateau. At that stage increased uptake is not reflected anymore in higher grain yields. The level of this plateau is determined by the growth factor being in short supply, according to Liebig's "law of the minimum". Under optimum supply of water and nutrients and in the absence of pests and diseases, the level is dependent on the available radiant energy during the growth period (53, 41, 24).

The curve will extend to the point, where the plant has taken up so much nitrogen that the maximum content in the tissue is reached. In this latter part there may still be increased protein yields.

An extensive analysis of yield-uptake curves of various crops and for different mineral elements showed that this relationship is in general independent of the kind of fertilizer and the method of application (52) This holds, provided that the fertilizer does not

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change other growing conditions than the one governed by its main acting mineral. (Thus it may be expected to find different relations for ammoniumsulphate and urea on a sulfur-deficient soil). Another prerequisite is that the fertilizer should not be applied so late, that the plant cannot utilize it properly, or that an extended period of shortage hampers early development of the plants.

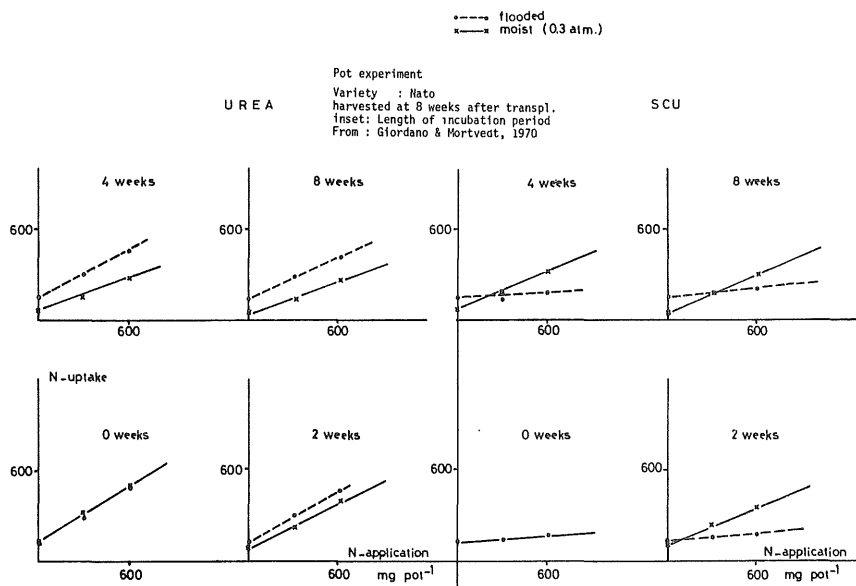


Figure 2. The relation between rate of N-application and N-uptake for eight week old rice plants. [SCU = sulfur coated urea; incubation period is time between fertilizer application/flooding and transplanting].

Gambar 2. Hubungan antara tingkat pemupukan nitrogen dan absorpsi nitrogen pada tanaman padi berumur delapan minggu (SCU = sulfur coated urea; masa inkubasi adalah antara saat pemberian pupuk/penggenangan dan saat tanam).

The first phenomenon drawing attention in graph (b) is that it is linear over the complete range presented here. This indicates, that in this situation a constant proportion of the fertilizer is taken up by the plant, irrespective of the amount being applied. It seems most likely that both the uptake by the plants and the losses due to denitrification and leaching are proportional to the concentration of the element in the soil solution. This means that in any given

situation the uptake is proportional to the amount applied. This also holds for the early stages of growth, as illustrated in Figure 2, where the fertilizer rate-uptake curves are given for eight-week old rice plants. The slope of the line with respect to the vertical expressed in kg N taken up/kg N applied represents the fraction of the fertilizer recovered in the above ground plant parts.

The other characteristic of graph (b) is the intercept with the horizontal axis. This value represents the inherent soil fertility with respect to the element concerned. This nitrogen is partly mineralized from the organic matter in the soil and partly originates from non-symbiotic nitrogen fixation mainly by blue-green algae. As such, it is to some extent a soil characteristic depending on the organic matter content of the soil and its composition. For another part it is determined by environmental conditions, like temperature, and nutrient content of the flood water, which govern the rate of decomposition of the organic matter and the efficiency of nitrogen fixation. Furthermore, the history of the field, more particularly the previous crop, fertilizer application and management practices (removal or burning of straw), influences the nitrogen availability at the zero fertilizer level.

It is obvious from the foregoing discussion that the relationship presented in graph (c), being a combination of graphs (a) and (b), may vary widely under different circumstances. The two most important parameters are undoubtedly the yield level at zero fertilization and the slope of graph (b), which determines the proportion of the fertilizer taken up by the plant. When only graph (c) is given, as is often the case, many of the underlying causes remain unclear. The combination of these three graphs permits a full analysis of fertilizer experiments and directly pinpoints the reason for a particular type of response curve.

3.3. Quantitative analysis of the uptake-yield function

To investigate whether a presentation as suggested in the previous section can result in the formulation of rules with a general validity, suitable literature data were analyzed. They cover a wide range of rice varieties, environmental conditions, fertilizer treat-

ments and management practices. The results are presented in Figure 3. In this section the graphs of type (a) of Figure 1 will be discussed.

3.3.1. Initial slope

3.3.1.1. *Field experiments*

Examination of the various curves shows that the initial slope of the uptake-yield function, the values of which are given in table 1a expressed as kg N/1000 kg grain at 14% moisture content, is virtually constant under all conditions. As explained before, this value reflects the minimum level, to which the nitrogen in the various plant parts may be diluted. It appears that the grain weight does not increase any more, when its nitrogen content drops below approximately 1% (calculated on basis of 14% moisture content). Similarly the nitrogen present in the straw below $\cong 0.4\%$ is irreversibly incorporated in the structural plant material and cannot be remobilized and translocated. When furthermore it is assumed that the grain/straw ratio of the rice crop does not deviate substantially from unity, the slope will be 14 kg N/1000 kg grain (14% moisture content). Fluctuations around this value may be explained by variations in each of the three numerical values used above. The minimum level to which nitrogen in the tissue may be diluted depends on the physiological age of the plant at the onset of nitrogen shortage (9). The largest variation however is likely to occur in the grain/straw ratio. When rice is grown under conditions where the vegetative period is very long, due to for instance photoperiodic influences, the grain/straw ratio may reach very low values. This is for instance the case in the experiments carried out in Burma (Figure 3i), where the vegetative growth period extends throughout

Gambar 3. Hubungan antara absorpsi nitrogen total dan hasil gabah, antara tingkat pemupukan nitrogen dan absorpsi nitrogen total, serta antara tingkat pemupukan nitrogen dan hasil gabah, untuk berbagai varietas padi yang tumbuh di bermacam-macam lokasi. Keterangan yang terperinci terdapat pada grafik dan publikasi asli. Garis horisontal berbentuk panah menunjukkan potensi hasil (24). Angka-angka sebelah garis menunjukkan hubungan antara tingkat pemberian dan absorpsi dan merupakan fraksi yang diketemukan kembali.

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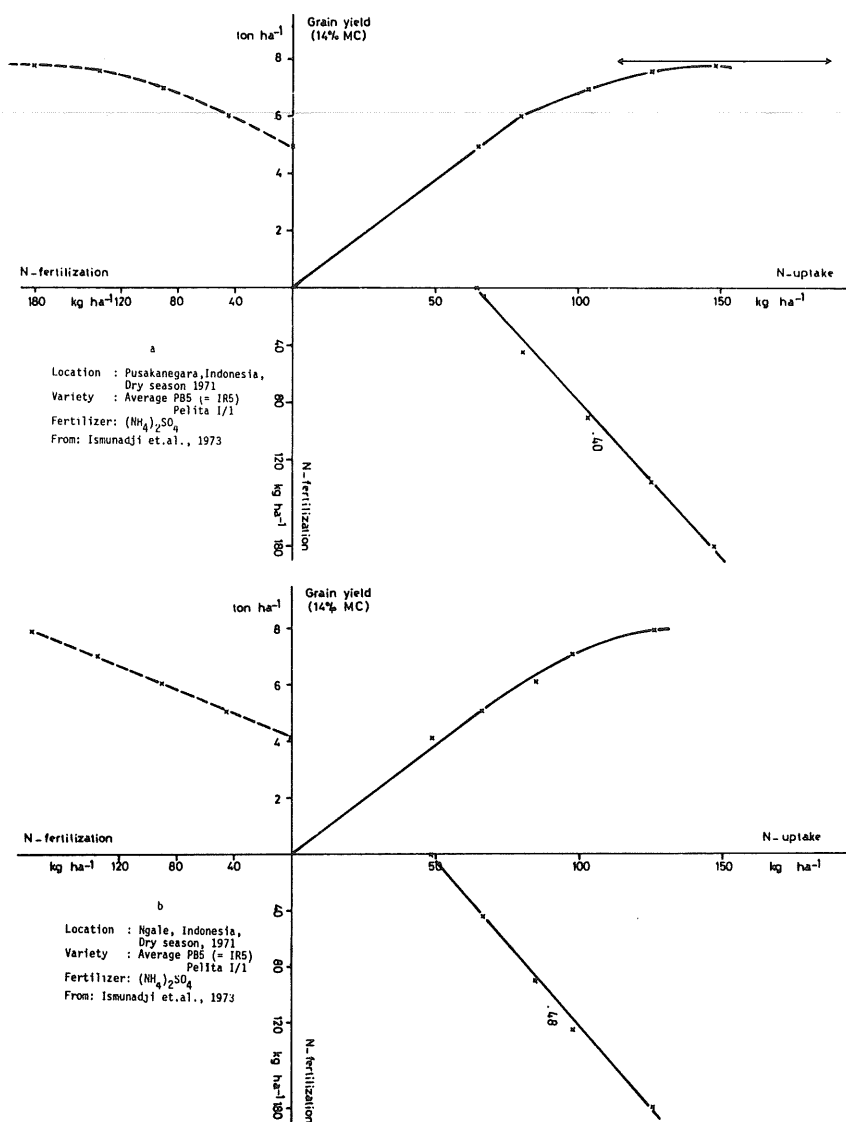


Figure 3. The relation between total nitrogen uptake and grain yield, between rate of nitrogen application and total nitrogen uptake and between rate of nitrogen application and grain yield, for various rice varieties grown in the field at different locations. Details in the graphs and in original publications. The horizontal arrowed lines indicate potential grain yield (24). Numbers next to lines giving the relation between rate of application and uptake indicate recovery fractions. (cont. on page 10).

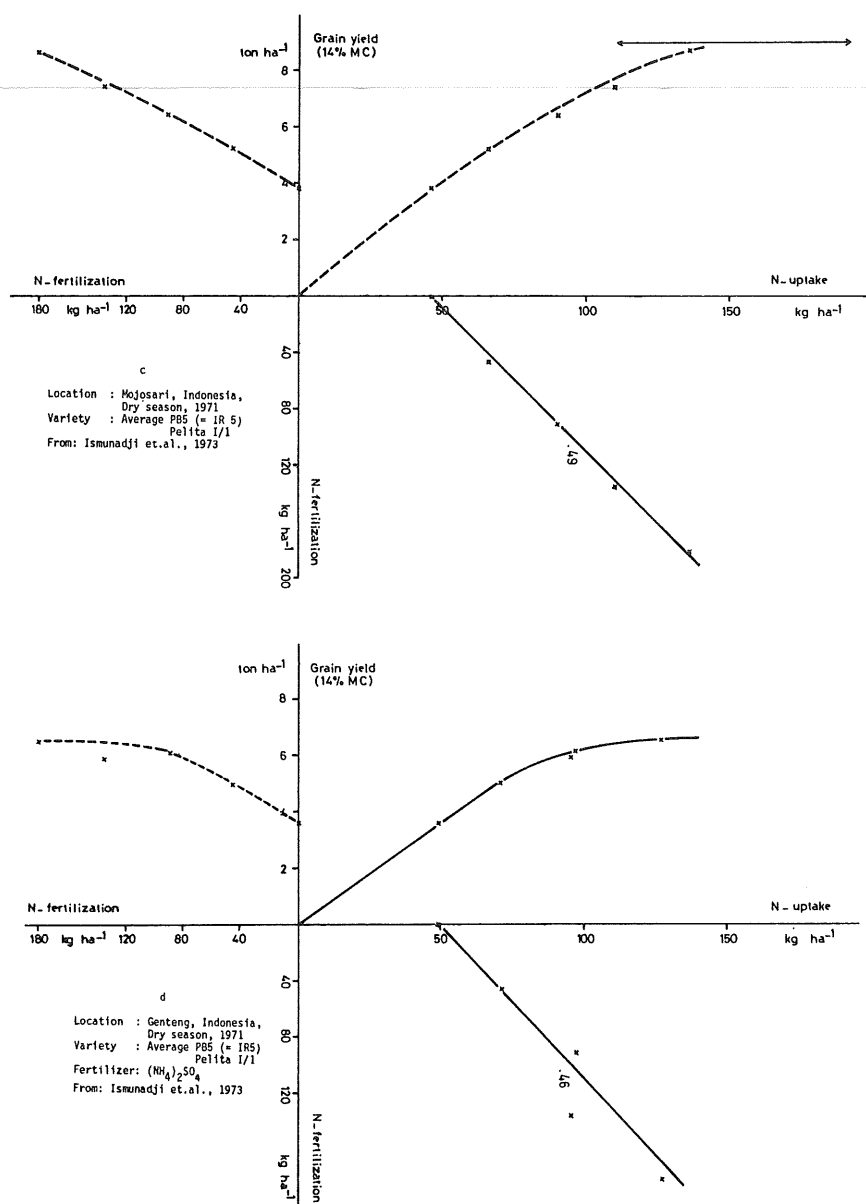
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Figure 3 (Cont.)

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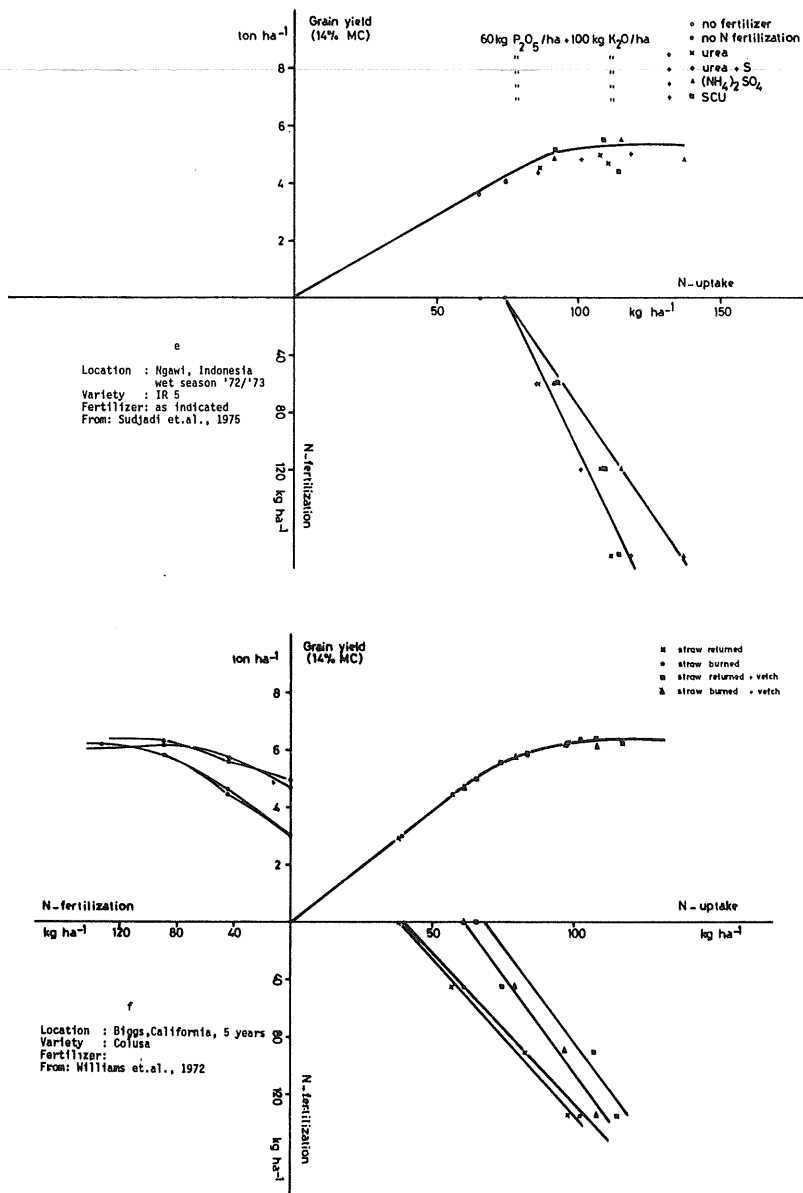


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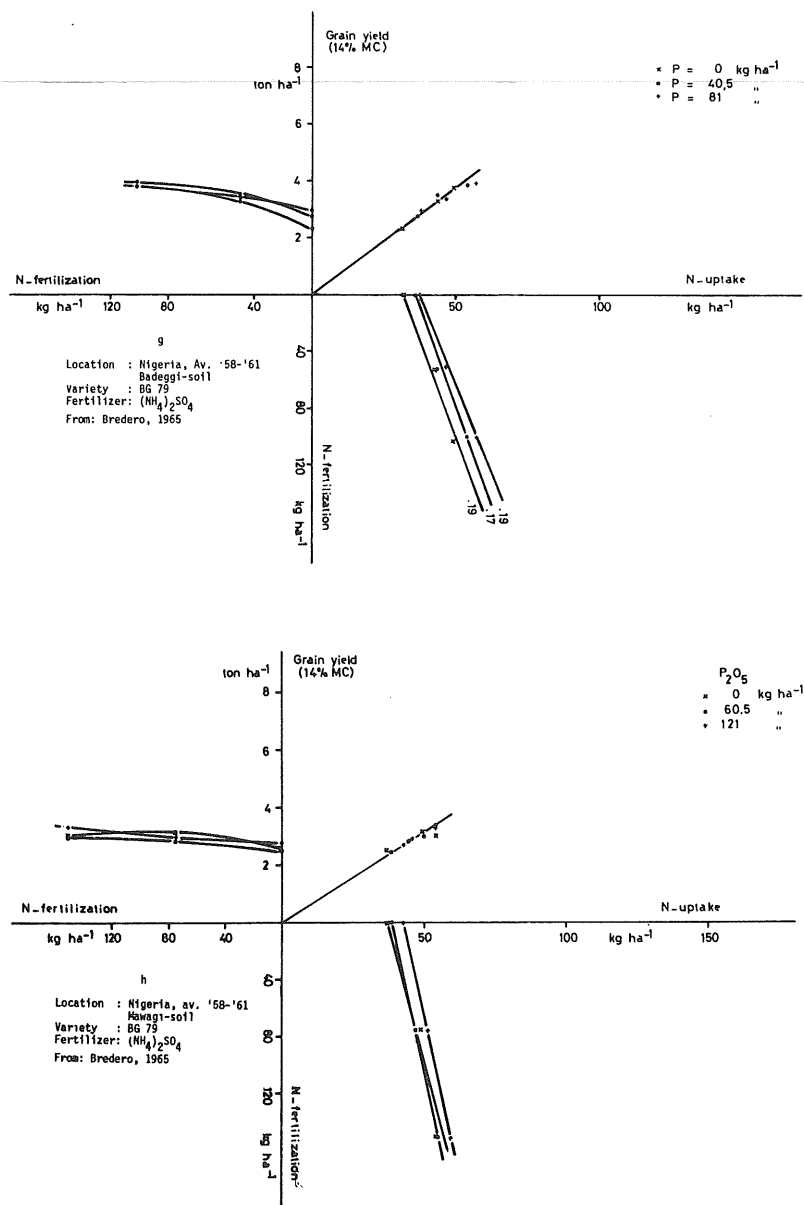
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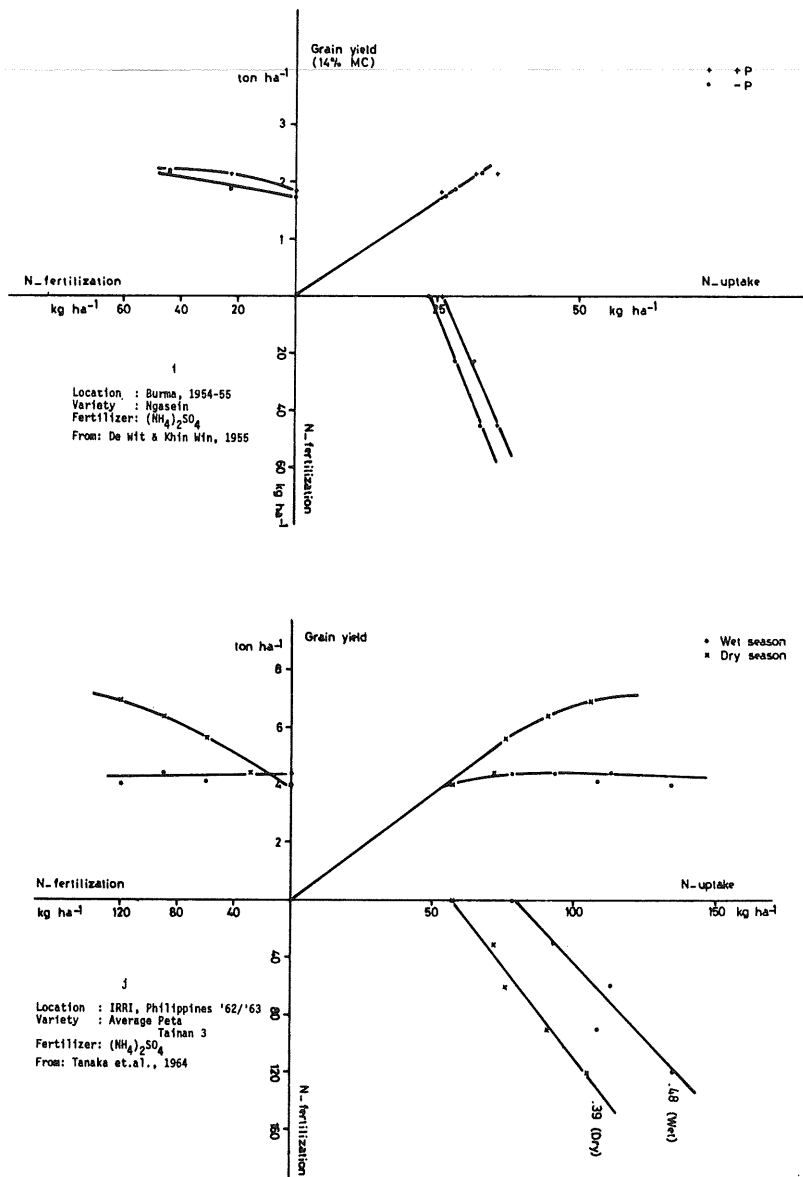


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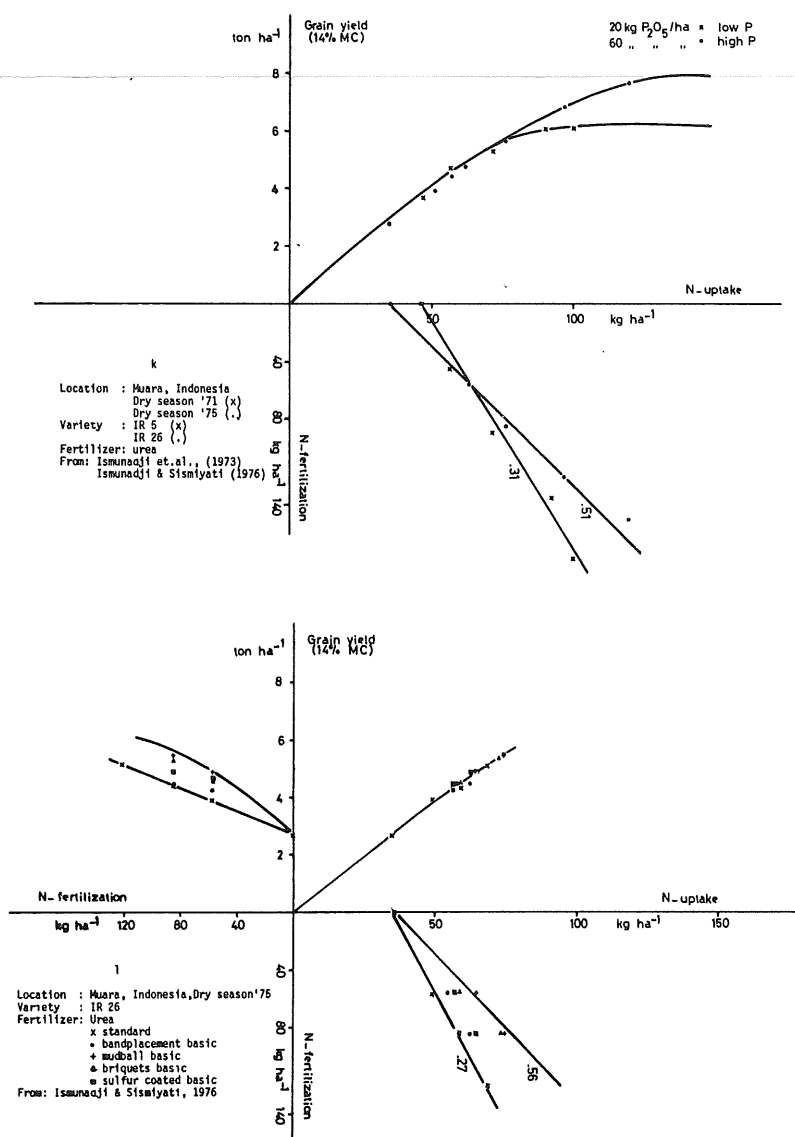
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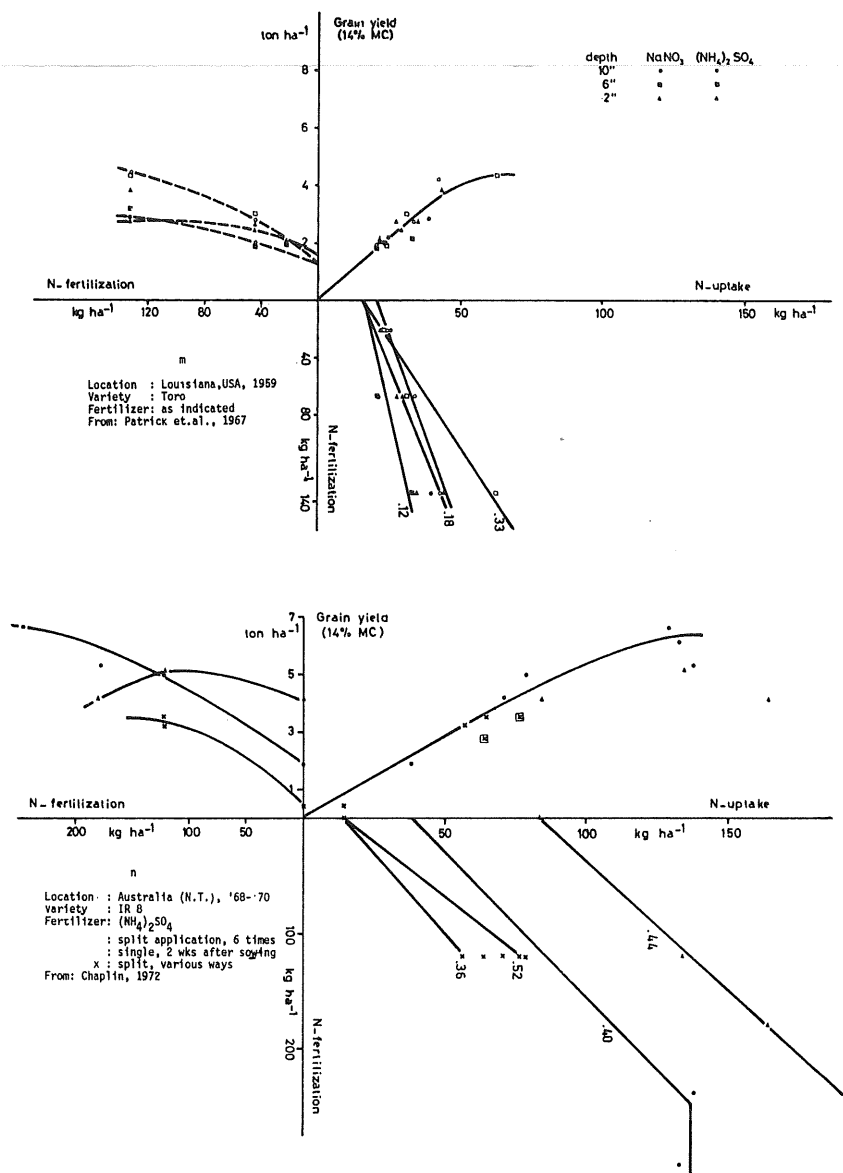


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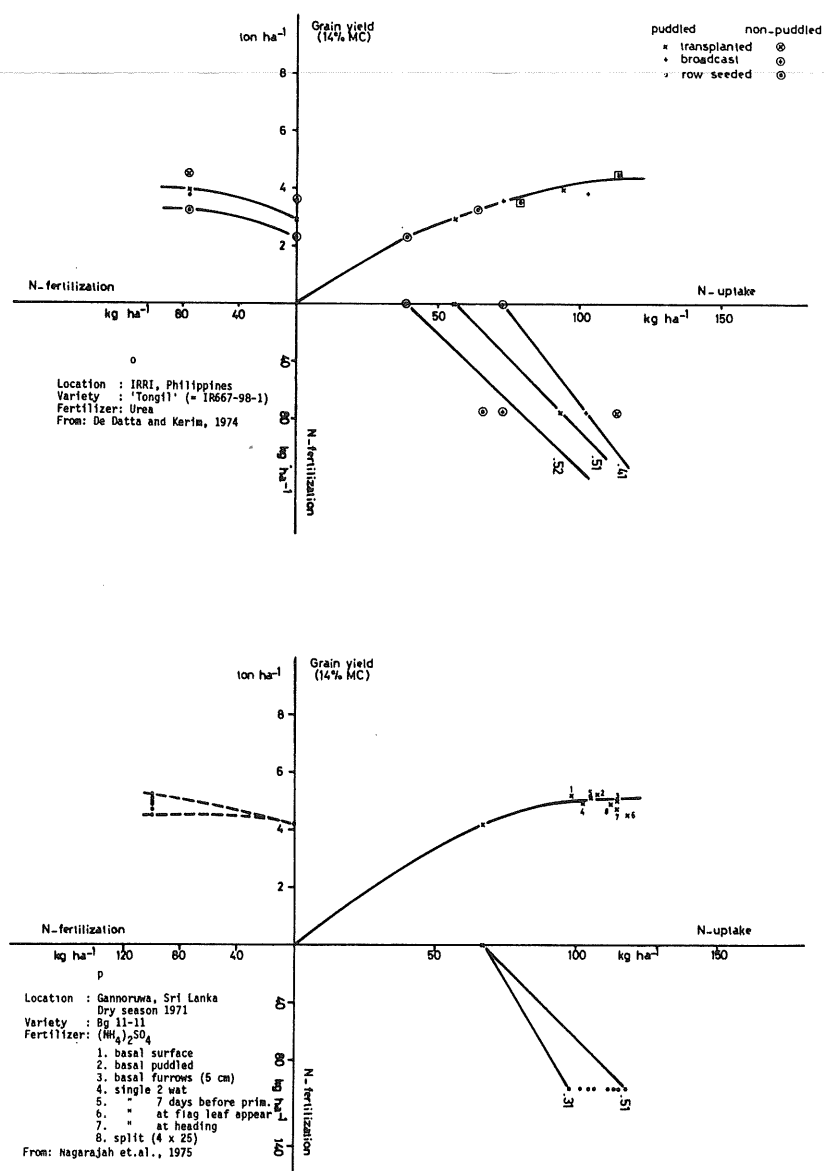
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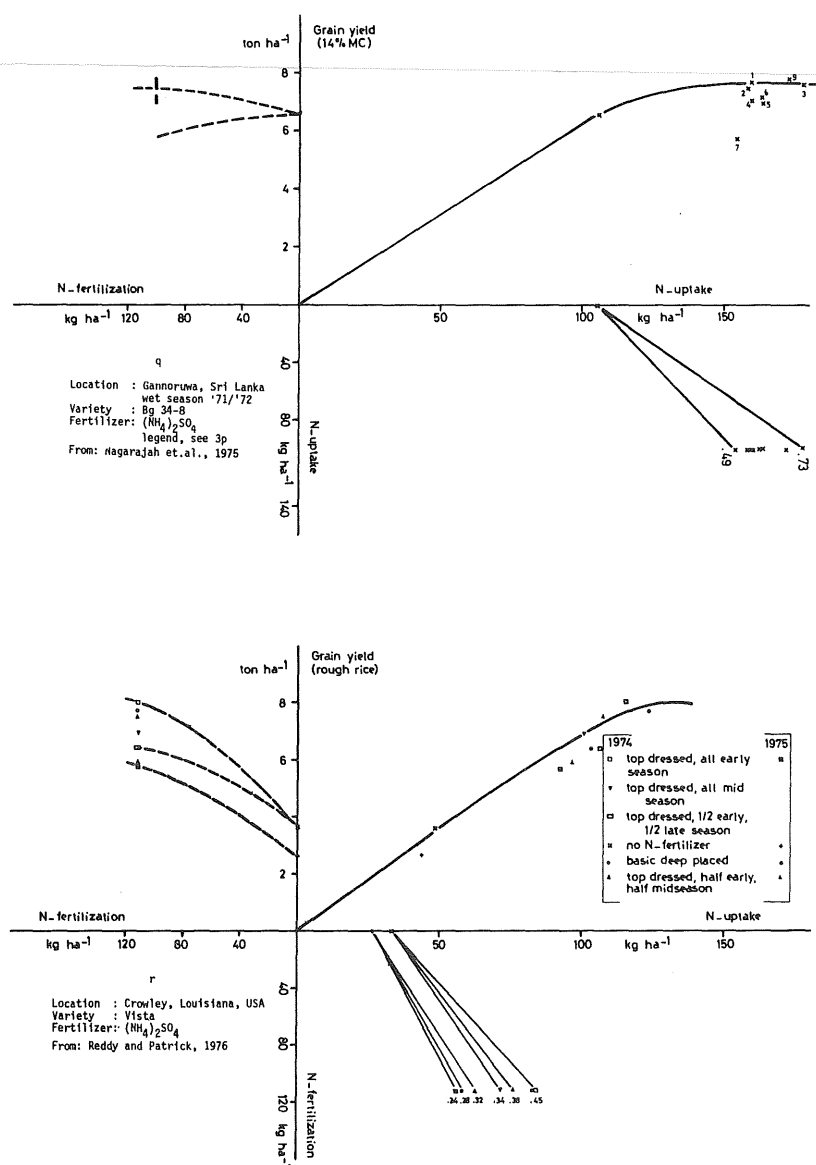


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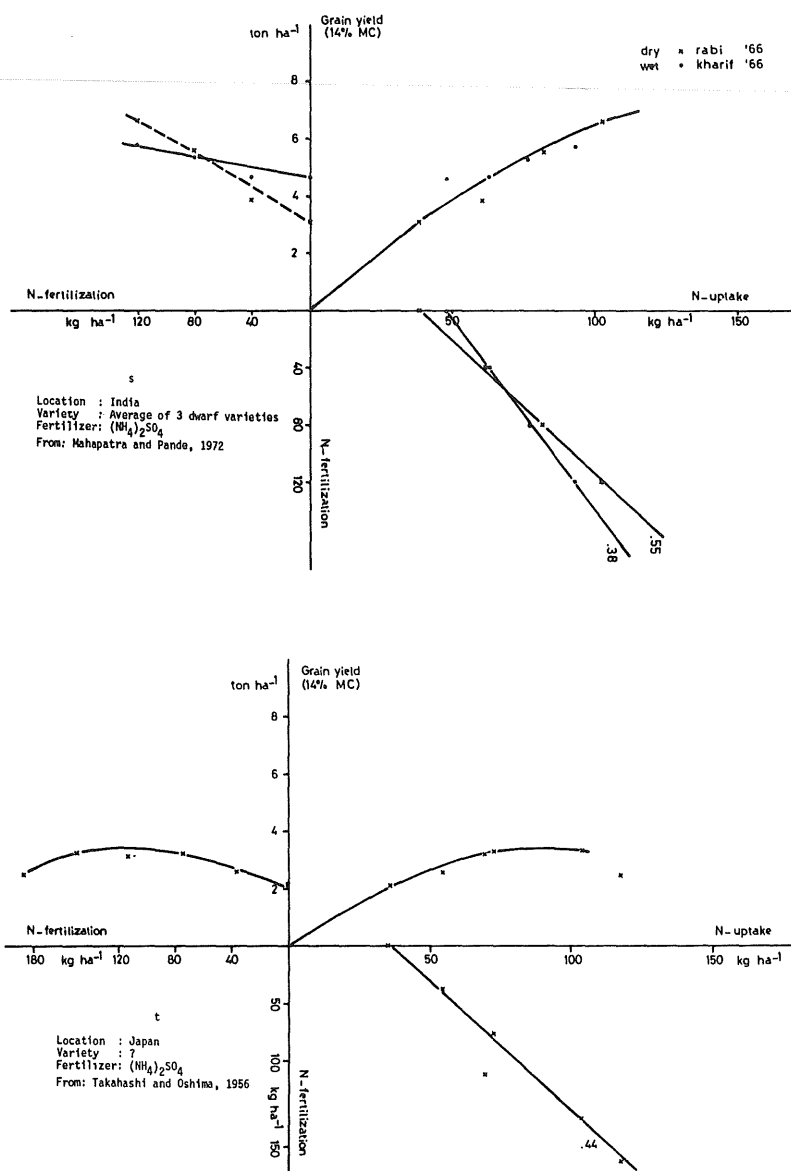
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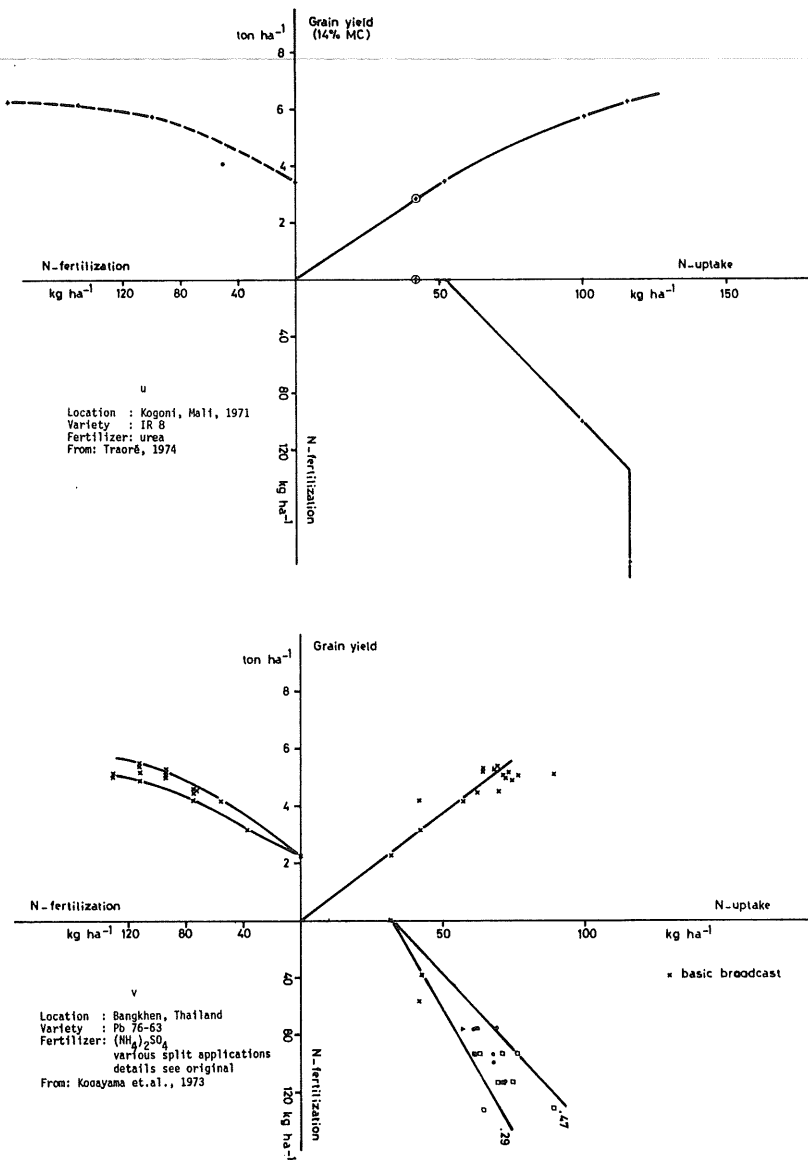


Figure 3 (Cont.)

the long rainy season (5 months), so that the grains ripen after cessation of the wet monsoon. This results in a grain/straw ratio of about 0.6 and an initial slope of ≈ 15.5 kg N/1000 kg grain. The same holds for a Nigerian experiment (Figure 3h) with a grain/straw ratio of 0.75 and an initial slope of 15.5 kg N/1000 kg grain and for the Japanese data (Figure 3t) where the value of 17 kg N/1000 kg of grain is accompanied by a grain/straw ratio of 0.55. Overall comparison of the curves however leads to the conclusion, that the slope seldom deviates more than 10% from the estimated value of 14 kg/1000 kg. This value may therefore be considered a plant characteristic applicable under most growing conditions.

3.3.1.2. *Pot experiments*

Often fertilizer experiments are carried out in pots, to facilitate handling and to ensure controlled environmental conditions. To investigate, whether the results obtained in that way, are applicable to the field situation, the behaviour of rice plants grown in containers was also analyzed. The results are presented in Figure 4. With respect to the initial slope of the uptake – yield curve, whose numerical values are given in table 1 the results fully agree with the field experiments. In this case ≈ 10 g of grain is produced at an uptake of 0.14 g nitrogen. This gives the same ratio as in the field experiments, illustrating that the processes taking place under limited nitrogen supply do not essentially differ under field or pot conditions.

3.3.1.3. *Other small grains*

To examine how the rice crop compares to other small grains with respect to the efficiency of nitrogen utilization, a number of experiments with other crops was analyzed. The initial slope of the uptake-yield curve of modern wheat varieties, grown in the Nether-

Gambar 4. Hubungan antara absorpsi nitrogen total dan hasil gabah, antara tingkat pemupukan nitrogen dan absorpsi nitrogen total, serta antara tingkat pemupukan nitrogen dan hasil untuk berbagai varietas padi yang tumbuh dalam pot di bermacam-macam lokasi. Keterangan terperinci terdapat pada grafik dan publikasi asli. Angka-angka dekat garis menunjukkan hubungan antara tingkat pemberian dan absorpsi dan merupakan fraksi yang diketemukan kembali.

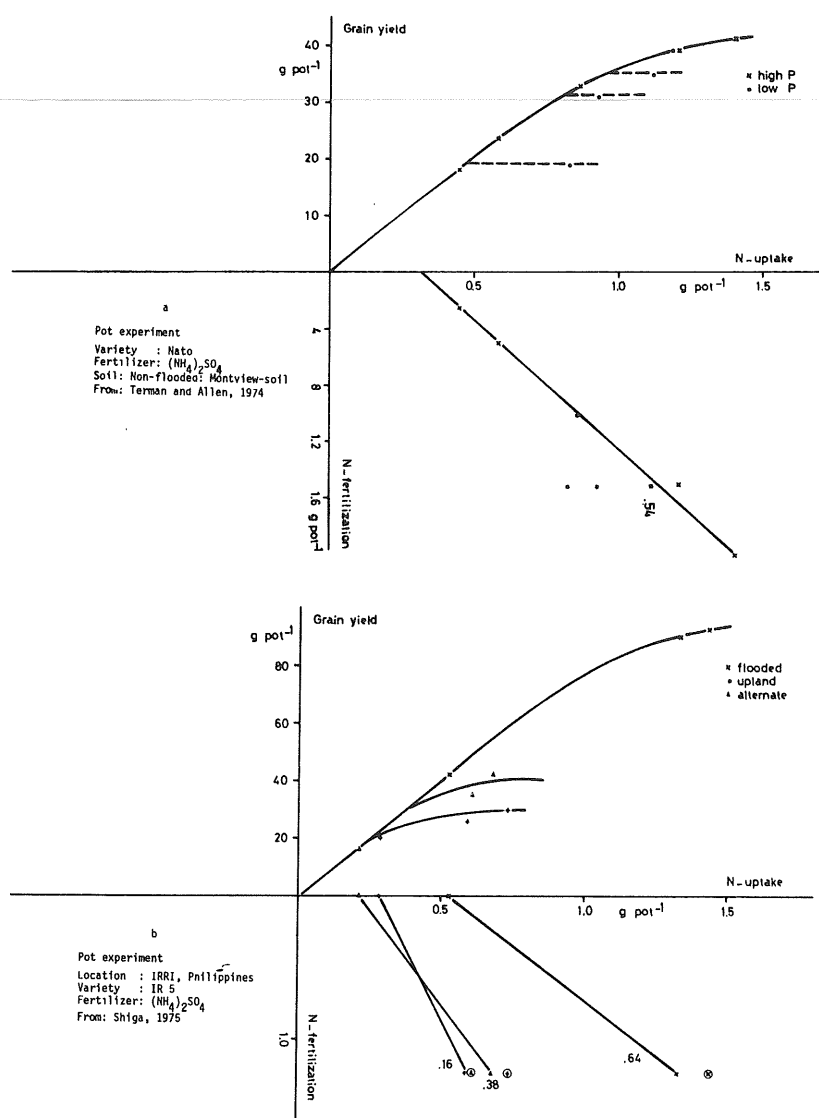


Figure 4. The relation between total nitrogen uptake and grain yield, between rate of nitrogen application and total nitrogen uptake and between rate of nitrogen application and grain yield for various rice varieties grown in pots at different locations. Details in the graphs and in original publications. Numbers next to lines giving the relation between rate of application and uptake, indicate recovery fractions. (Cont. on page 22).

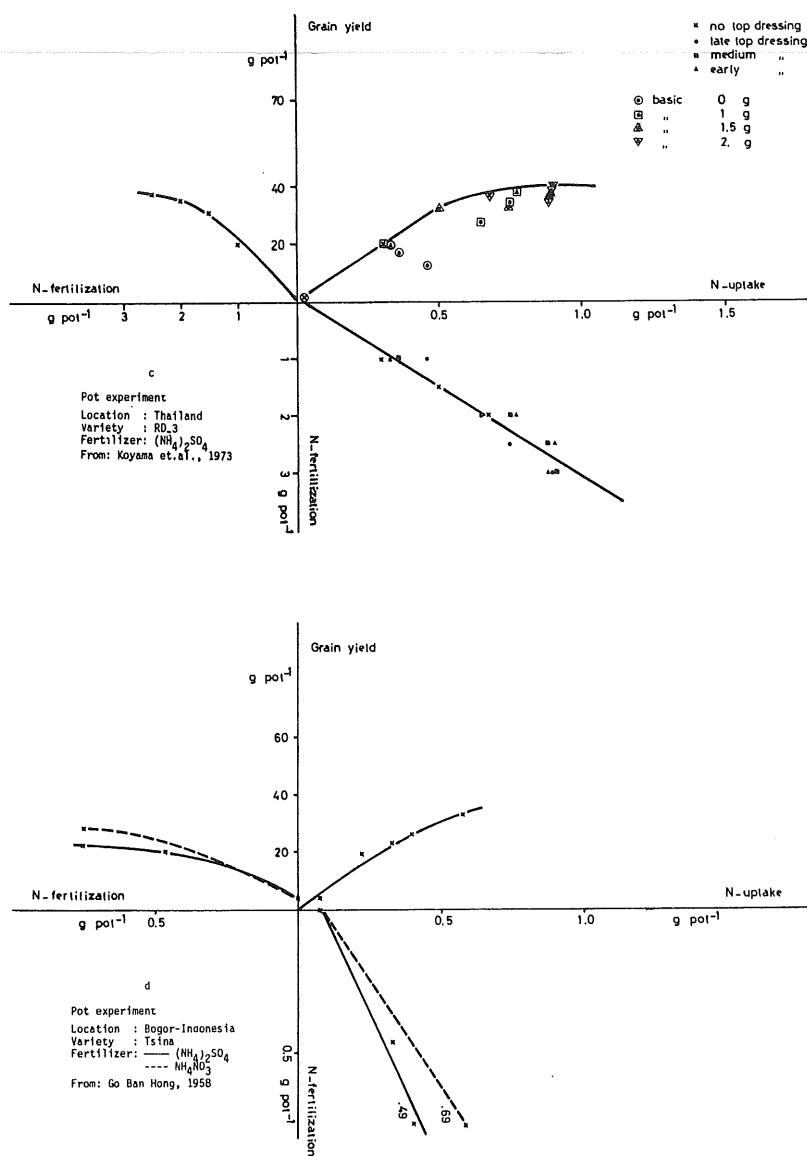
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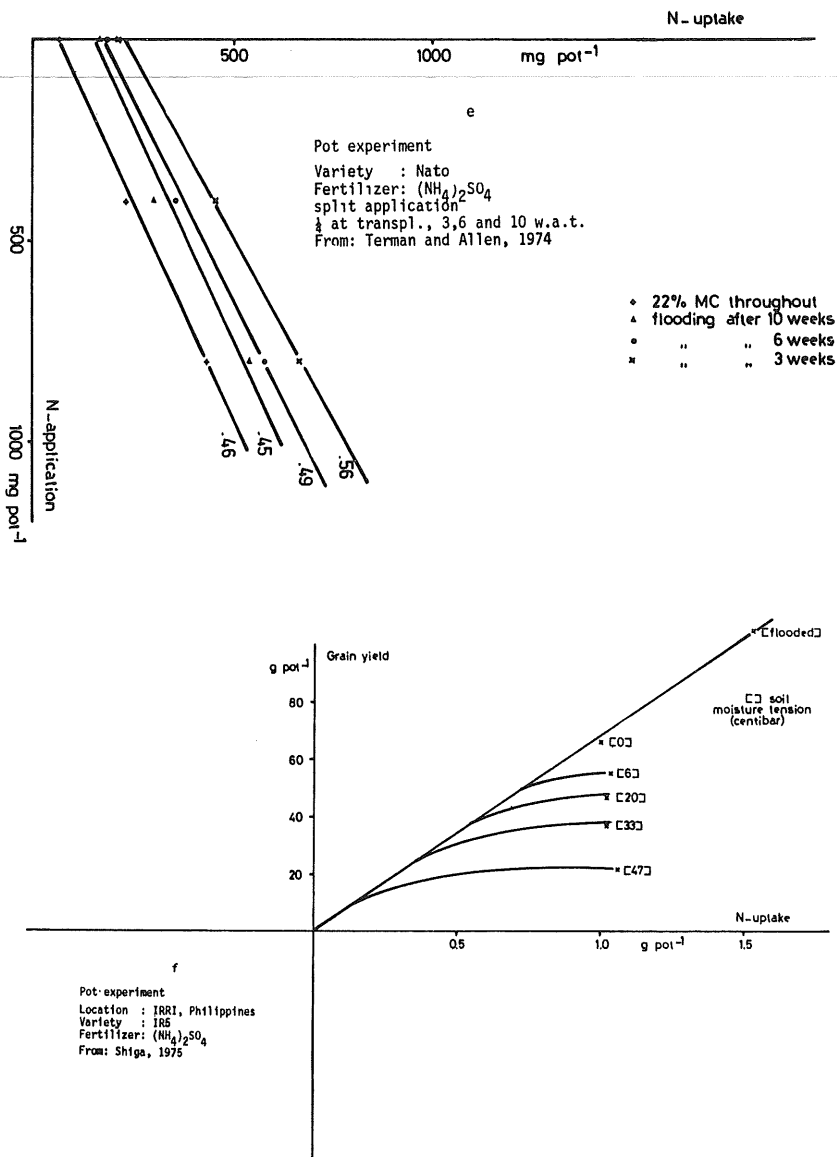


Figure 4 (Cont.)

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lands, varies between 12.5 and 16 kg N per 1000 kg of grain (Figures 5 a, d, e and f). A dwarf Mexi-Pak wheat, grown in Pakistan, yielded 1000 kg of grain at an uptake of 15.5 kg N (Figure 5g). Oats and summer barley in the Netherlands give values of ≈ 12 kg N/1000 kg grain (Figures 5b and 5c). In a pot experiment with oats, the initial slope turned out to be 0.14 g N/10 g grain (Figure 5h). All these examples show, that although rice is generally considered to be a less protein-rich crop than for instance wheat, all small grains behave approximately the same under *low* nitrogen fertility conditions. The minimum level to which nitrogen in the tissue can be diluted, both in the vegetative material and in the grains, must be almost identical.

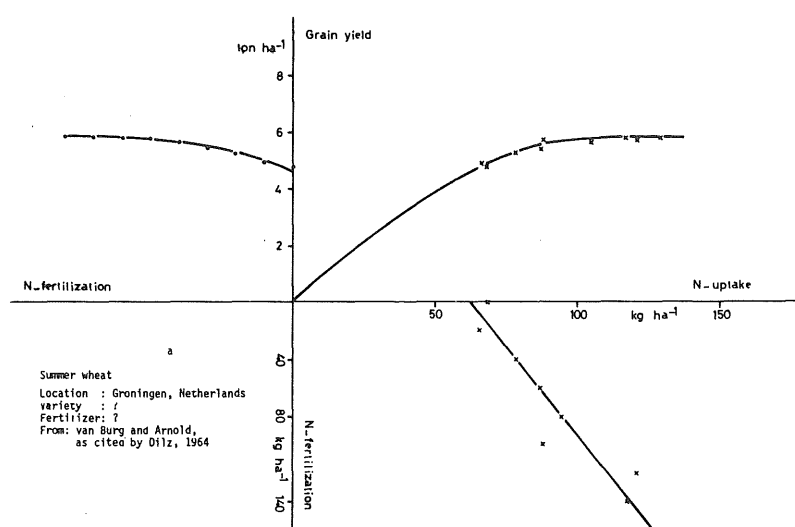


Figure 5. The relation between total nitrogen uptake and grain yield, between rate of nitrogen application and total uptake and between rate of nitrogen application and grain yield for various species of small grains grown at different locations. Numbers next to lines giving the relation between rate of application and uptake indicate recovery fractions.

Gambar 5. Hubungan antara absorpsi nitrogen total dan hasil gabah, antara tingkat pemupukan nitrogen dan absorpsi total, serta antara tingkat pemupukan nitrogen dan hasil gabah untuk berbagai padi-padian yang tumbuh di bermacam-macam lokasi. Angka-angka dekat garis menunjukkan hubungan antara tingkat pemberian dan absorpsi dan merupakan fraksi yang diketemukan kembali.

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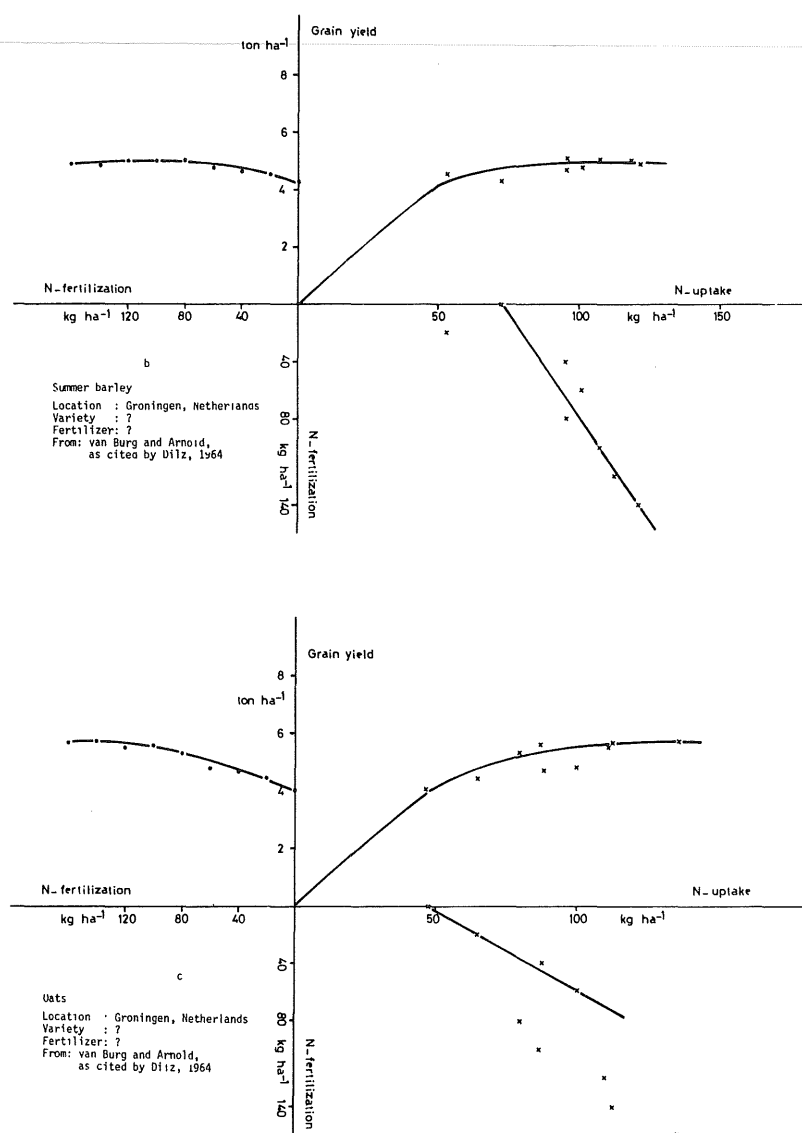


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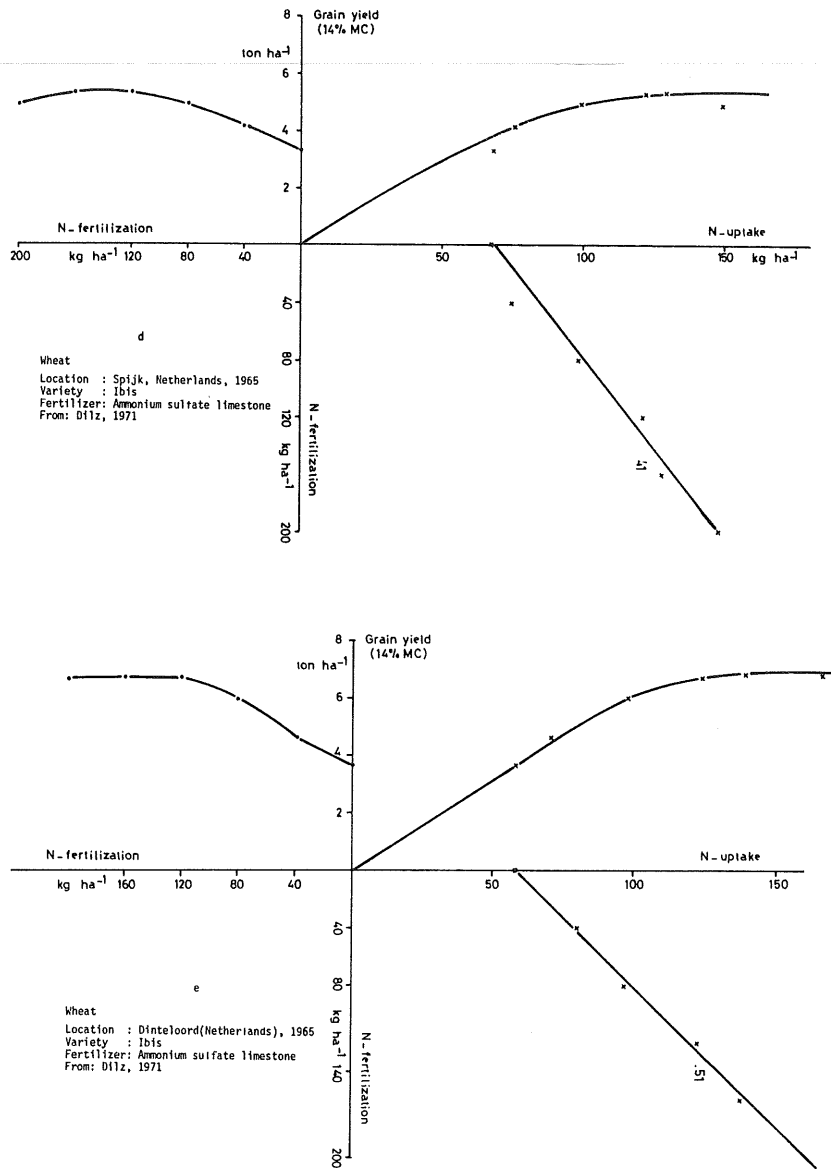
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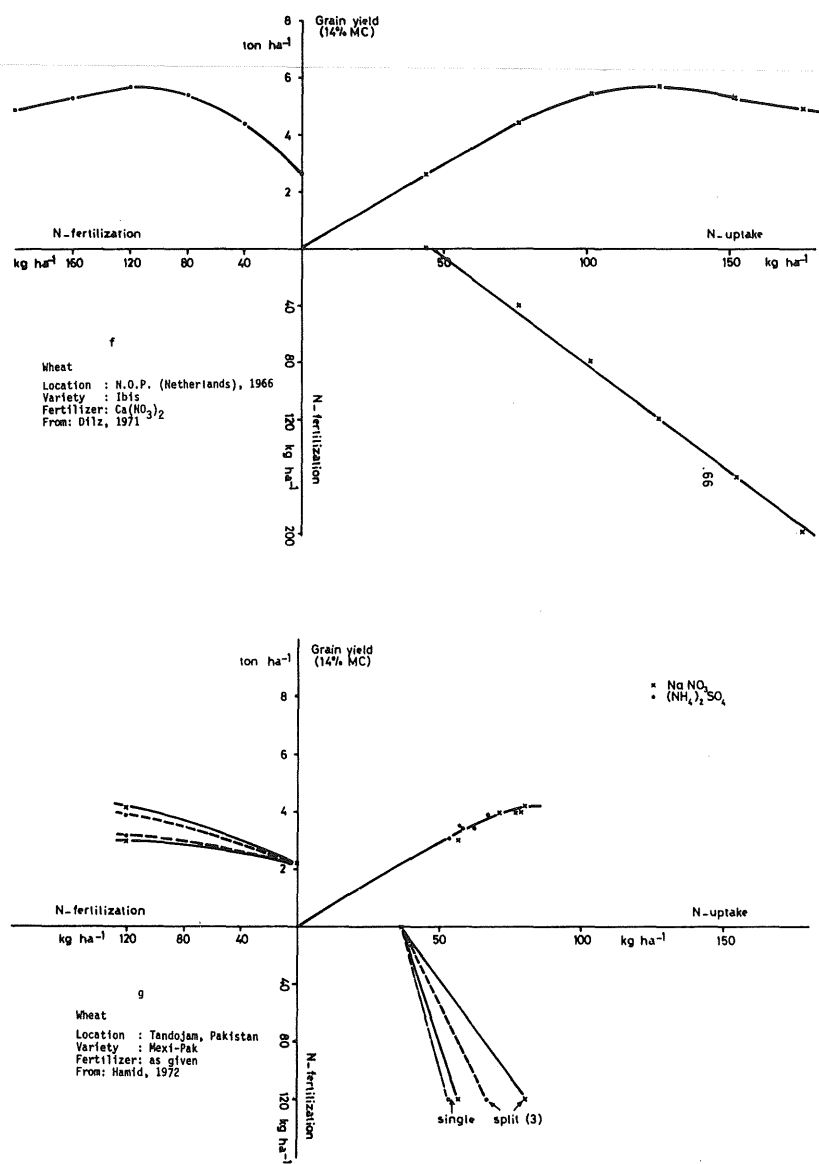


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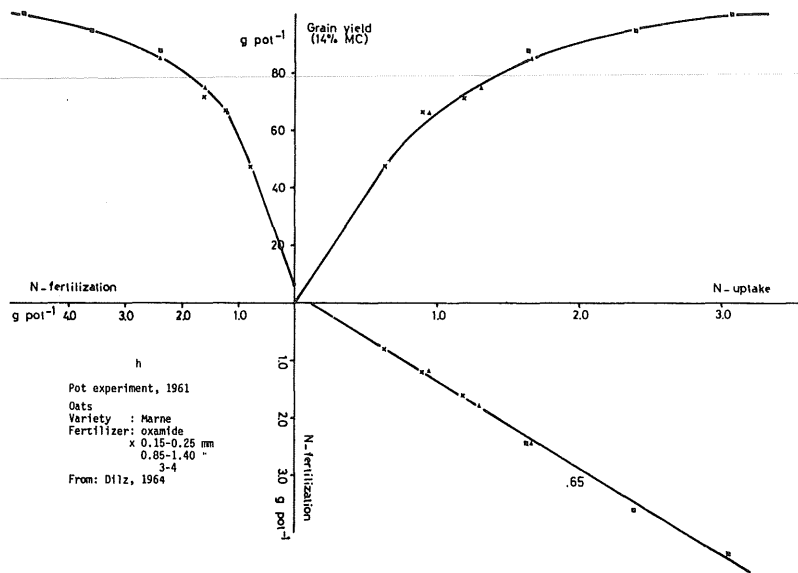
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Figure 5 (Cont.)

3.3.1.4. *Exceptions to the rule*

In the course of the study on the nitrogen nutrition of small grains, a number of examples were encountered which did not follow the rule arrived at in the previous sections.

Figure 6a, referring to an experiment with upland rice in India, shows an initial slope of about 36 kg N per 1000 kg of grain produced. Figure 6b, referring to wheat grown in Australia, yields a value of 23 kg N per 1000 kg of grain. Although in both cases the grain/straw ratio is very low (0.5 and 0.35 respectively) this cannot explain the very low efficiency of the incorporated nitrogen. It is

Gambar 6. Hubungan antara absorpsi nitrogen total dan hasil gabah, antara tingkat pemupukan nitrogen dan absorpsi total, serta antara tingkat pemupukan nitrogen dan hasil gabah pada padi gogo yang tumbuh di India (a) dan pada gandum yang tumbuh di Australia (b). Keterangan terperinci terdapat pada publikasi asli. Angka-angka dekat garis menunjukkan hubungan antara tingkat pemberian dan absorpsi dan merupakan fraksi yang diketemukan kembali.

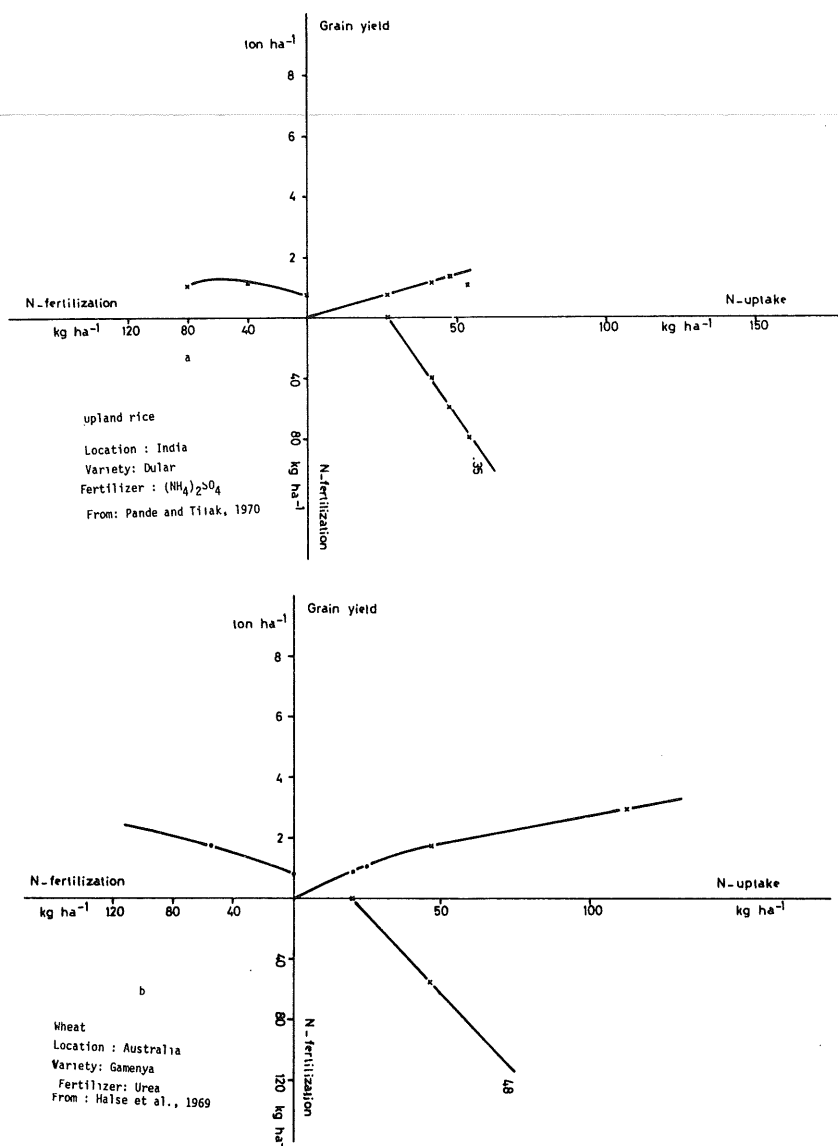


Figure 6. The relation between total nitrogen uptake and grain yield, between rate of nitrogen application and total uptake and between rate of nitrogen application and grain yield for upland rice grown in India (a) and for wheat grown in Australia (b). Details in original publications. Numbers next to lines giving the relation between rate of application and uptake indicate recovery fraction. (Cont. on page 30).

obvious, that in both experiments the nitrogen content of the plant tissue must have been high, i.e., much higher than the ≈ 1 and 0.4% normally found in grain and straw respectively under conditions of limited nitrogen supply.

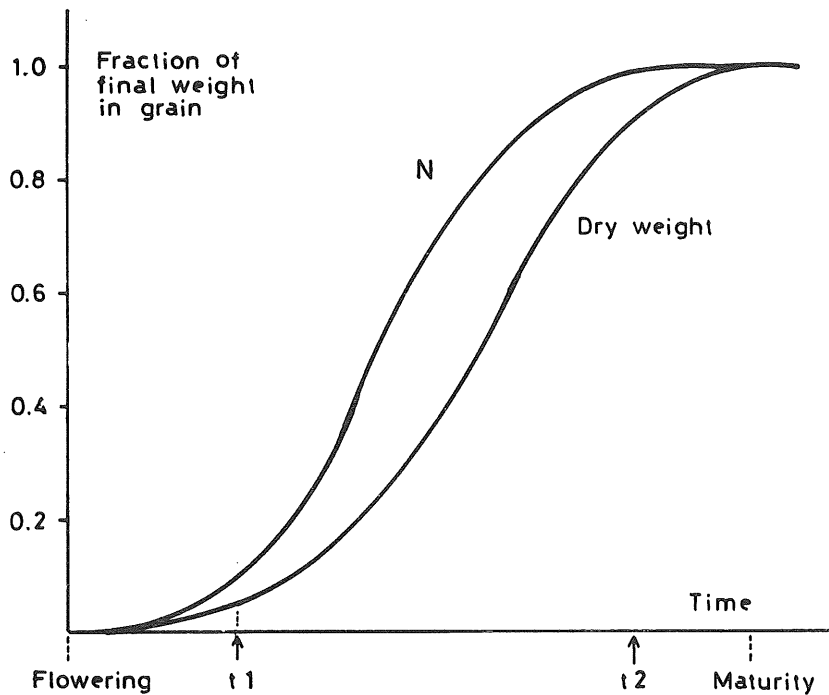


Figure 7. Hypothetical course of increase in dry weight and nitrogen content of rice grains.

Gambar 7. Peningkatan bobot kering hipotetis dan kadar nitrogen gabah.

A possible explanation for this is illustrated in Figure 7, giving the relative increase in both nitrogen uptake and dry weight of the grain as a function of time. It shows that at the beginning of the grain filling period, nitrogen-rich components (i.e. proteins) are formed in the grain. Subsequent formation of compounds, containing less nitrogen (a process similar to that occurring in the vegetative phase (10)), results in the dilution of the nitrogen. Any process

which causes a disruption of normal maturing between t_1 and t_2 (Figure 7) will result in grains with a high percentage of nitrogen and a low 1000-grain weight. The effect will be even more pronounced in the uptake-yield curve as under such conditions the final N-percentage in the vegetative material will also be higher, as a result of hampered translocation (9). Experimental evidence in support of this hypothesis is provided by Go Ban Hong (1958, Figure 8) and by data of Tanaka (1961), which show that the nitrogen concentration in the rice grains decreases towards maturity.

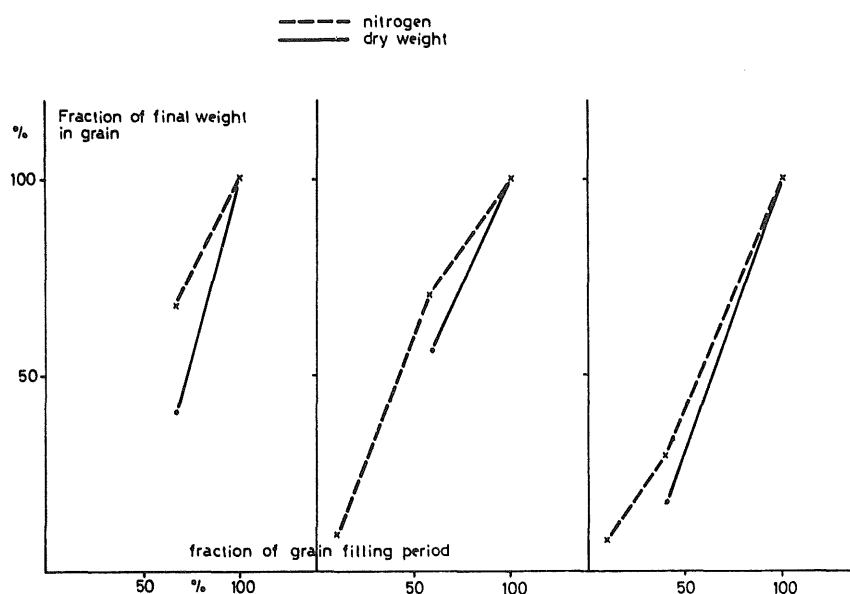


Figure 8. Time course of increase in dry weight and nitrogen content of rice grains. Variety: Tsina (13).

Gambar 8. Peningkatan bobot kering yang berhubungan dengan waktu dan kadar nitrogen gabah varietas Tsina (13).

Further evidence for other small grains may be derived from the fact, that in 1976, which was unusually hot and dry in Western Europe, wheat in the Netherlands showed "emergency ripening", i.e., accelerated senescence of the vegetative plant parts. This

resulted in relatively low grain yields, with a high protein content (Dilz, pers. comm.) In upland rice this process could be associated with water shortage in the later part of the growing season. Moisture stress at that stage leads to increased senescence of the leaves and hence to unfavourable conditions for photosynthesis. A similar situation would arise, with the occurrence of serious ripening diseases, having adverse effects on the green leaf area (e.g. *Helminthosporium*). In lowland rice one would also observe this phenomenon in case of late stem-borer attacks which would block the transport system to the panicle, thus preventing the translocation of carbohydrates to the filling grain.

Table 1. Slope (kg N/1000 kg grain or g N/10 g grain) of the eyefitted lines through the data points in Figure 3, 4, 5 and 6.

Sudut (kg N/1000 kg gabah atau g N/10 g gabah) dari garis-garis yang ditarik melalui titik-titik data pada Gambar 3, 4, 5 dan 6.

Figure 3.

desig.	slope	desig.	slope	desig.	slope	desig.	slope
a	13.5	g	13.5	m	12	s	13
b	13	h	15.5	n	17	t	17
c	13	i	15.5	o	16	u	15
d	14	j	14	p	13	v	14
e	16.5	k	12.5	q	15.5		
f	13	l	13	r	14		

desig.	slope	desig.	slope	desig.	slope	desig.	slope
4a	0.13	4e	—	5a	12.5	5f	16
4b	0.13	4f	0.14	5b	13	5g	15.5
4c	0.15			5c	12	5h	0.14
4d	0.15			5d	15		
				5e	15.5	6a	36
						6b	23

3.3.2. The level of the plateau

3.3.2.1. *Field experiments*

The level of the plateau gives the maximum amount of dry matter accumulated in the grain. It is the result of the balance between photosynthesis and respiration, modified by the partitioning of the material between roots, vegetative and generative plant parts. As stated before, this maximum is determined by the available radiant energy during the growing period, provided that the plants are growing under optimum conditions of moisture and nutrients (24). This is clearly illustrated in Figure 3j, where the yield-uptake curves, determined at IRRI, are given, for both the wet and the dry season. The levels of the plateau, 4400 kg ha^{-1} and $\approx 7500 \text{ kg ha}^{-1}$ respectively, are in very good agreement with the calculated potential yields for those conditions, the incoming energy being much higher in the dry season. (This graph also illustrates the fact, that increased nitrogen uptake does not necessarily lead to higher grain yields, but results in increased N-content in both the grain and the straw).

When other growing conditions are not optimal, the maximum yield is determined by the factor being in the minimum. This is shown in Figure 3k, which gives yield-uptake curves for two different levels of phosphate application. The curves are determined in different growing seasons and with different rice varieties, but, as stated before, this does not influence the basic shape of the curve. At the high phosphate level, the plateau approaches again the yield potential, set by the climatic conditions. At low P however, the supply of this element is limiting and the highest yield obtained is lower. The effect is not very spectacular here, because the soil in Muara being rather rich in phosphorous naturally is not very responsive to phosphorous application. Similar results are obtained when other mineral elements or moisture are in short supply, as is also illustrated by de Wit (1953) for other crops. It is therefore important to realize that although nitrogen may be the most important single element in the mineral nutrition of the rice plant, its effectiveness in increasing yield may be limited by the influence

of other elements. This is of particular importance when experiments are carried out to study the effect of nitrogen application. To facilitate the interpretation of the results, such experiments should preferably be done under optimum conditions for other growth factors.

A situation which has qualitatively the same effect on the level of the plateau occurs, when all the nitrogen is given so late, that normal development of the plants is inhibited. When during the vegetative phase nitrogen shortage occurs, the tillering ability of the plants is seriously affected. This has a twofold effect:

- leaf area growth is hampered, so that the yield potential is not determined anymore by the available radiation but by the absorbed energy.
- only a limited number of panicles can be formed and consequently a limited number of grains. The potential size of rice grains is limited by the hull size and this also sets a limit to the grain yield.

A subsequent abundant supply of nitrogen during the generative stage may result in continuing uptake, but this does not change anymore the yield potential, which is already fixed. The effect of such late applications is shown in Figures 3n and 3q: The results of treatments which received nitrogen fertilizer only in the later part of the growing period show a subnormal yield-uptake curve. In these cases the nitrogen has been taken up, but is *not utilized* for the formation of useful plant material. Indeed the nitrogen content of the grain is high and the protein yield is less affected, but the main effect is that much more nitrogen remains in the straw.

3.3.2.2. *Pot experiments*

The results presented in Figure 4 show that also in the case of pot experiments the yield-uptake curve levels off. It must be assumed that also here the amount of radiant energy absorbed determines the level of the plateau. However, the radiation climate in potted plants differs considerably from that in the field. Single

plants receive light not only from the top, but also from the sides. Specially for the lower leaves, this may create more favourable conditions for photosynthesis. The grain yields, measured in pot experiments can therefore not be extrapolated to the field situation on a per plant or per area basis. Calculating the grain yield of rice, planted at different spacings, from the results of plants grown in containers (13) will therefore give misleading information.

The effect of inadequacies in other growth factors is illustrated again in these experiments. In Figure 4a it is shown that low phosphorus availability affects the potential production level. The effect of moisture stress clearly shows up in Figures 4b and 4f: Increasing soil moisture tension during the growth period, decreases the level of the plateau. It is doubtful whether at these levels of water potential in the soil, moisture stress as such could be responsible for this effect, or that it is intermediated by some other factor. The data presented by Obermueller and Mikkelsen (1974) would suggest that it is a disguised phosphorus effect but that is contradicted by other results.

3.3.2.3. *Other small grains*

With respect to the level of the plateau there is no difference between rice and other small grains. However in the case of wheat, oats and barley this level is generally reached at a higher nitrogen uptake. This is a result of the fact that under conditions of optimum nitrogen supply, the nitrogen content of the grains reaches higher values. Whereas for rice grains nitrogen contents above 1.6% (which is equivalent to a protein content of $\cong 10\%$) are seldom reported (6), wheat grains may easily reach 2.5% N (9). This has a feedback to the level of the plateau. Plant tissue with a high protein (nitrogen) content is more "expensive" than with a low N-content. Each gram of primary photosynthesis products (glucose) will yield only about 0.4 g. of nitrogenous structural material but about 0.8 g. of carbohydrates (36). Moreover the maintenance of protein-rich structures requires also more energy, as a result of continuous breakdown and rebuilding of the proteins. This energy is withdrawn from the dry matter (37). Taking this into account,

one would expect a rice crop, of comparable growth duration, growing under the same environmental conditions, and with liberal N-supply to produce a higher grain yield than for instance a wheat crop. So far however experimental evidence supporting this hypothesis has not come to the author's attention.

3.4. The fertilizer rate-uptake function

The relation between the rate of fertilizer application and the uptake of nitrogen by the plant tissue (graphs of type b in Figure 1) for the various experiments, summarized in Figures 3, 4 and 5, is in practically all cases a straight line. This line is characterized by two parameters: the intercept with the horizontal axis and the slope with respect to the vertical.

3.4.1. Uptake at zero fertilization

The value of the intercept with the horizontal axis, representing the amount of nitrogen available from the soil and from non-symbiotic fixation, mainly by blue-green algae, shows a large variation in the various experiments. It difficult to interpret these differences as in general the history of the fields is not reported. Generally speaking it may be expected that availability in the soil of easily decomposable organic matter, with a favourable C/N ratio, will increase the net amount of nitrogen being mineralized. However, to predict or calculate the amount of nitrogen that will become available from the soil during one growing season, a rather detailed knowledge of the soil, its organic components and their composition and the prevailing environmental conditions is necessary (49). The amount of nitrogen that can be fixed by blue-green algae and free living bacteria, also depends on the conditions in the soil. For a dozen soil types in Thailand, Matsuguchi et al. (1974) reported average values ranging from 0.7. to 7.5 kg N ha⁻¹ year⁻¹, while the highest value was even over 50 kg N ha⁻¹ year⁻¹.

Although it is therefore difficult to explain the numerical value in each of the experiments reported, a number of factors appear important:

Phosphorus level

The results presented in Figure 3g (Nigeria), 3i (Burma) and 3u (Mali) show the effect of phosphate application. In all these cases nitrogen availability at zero N application increases with increasing P application. The same effect is also reported by Hagenzieker (1970) in a survey of fertilizer experiments on Java and Madura. It seems most likely that this increase must be attributed to enhanced activity of the blue-green algae present in the rice field. These organisms show a better growth in the presence of P (29) and hence increased nitrogen fixation activity. This activity seems not to be influenced by the presence of fertilizer nitrogen as indicated by the constancy of the slope. The results shown in figure 3k (Indonesia) are contradictory to the general trend, but that is probably because the experiments refer to different growing seasons.

Management practices

The influence of management practices can be seen in figure 3f (California). Whether the rice straw of the previous crop is directly worked into the soil, or burned first does not influence the availability of nitrogen. Incorporation in the soil of a leguminous crop as green manure however, significantly increases the amount of nitrogen released as an additional 25 kg N is taken up.

In figure 3o it is shown that puddling of the soil increases the amount of N at zero fertilizer application. This could be due to more favourable conditions for blue-green algae in the puddled soil. Why after puddling the row-seeded crop extracts more nitrogen than the transplanted one is not clear.

Seasonal influences

As to the results of IRRI, shown in Figure 3j, one would have expected the availability of soil born nitrogen to be higher in the dry season. The higher temperatures create more favourable conditions for microbial activity and hence increased N-mineralization and fixation from the atmosphere. It is not clear what cultivation or other management practices might explain a more ample soil born

N-supply in the wet season. This holds also for the results from Sri Lanka (Figures 3p and 3q) where the difference between the two seasons is even more pronounced.

Cropping history

The large variation in N-supply in the Australian experiment (Figure 3n) is attributed by its author to the cropping history of the fields, without specifying that any further.

From the pot experiments (Figure 4) not much additional information can be extracted. Figure 4b shows that under flooded conditions the zero-level is considerably higher than under upland conditions. This must be attributed again to the contribution of the blue-green algae, which cannot develop in the upland soil. When flooding is deferred, (Figure 4e) the nitrogen that is mineralized is converted into nitrate. Upon flooding these nitrates are lost by denitrification. The longer the delay, the greater the proportion of N that is in nitrate form, and hence the lower the uptake at zero fertilization.

From the foregoing discussion it is obvious that the amount of nitrogen available at zero fertilizer application in each case has to be estimated from the knowledge of soil and external conditions.

3.4.2. Recovery of applied fertilizer

As shown in graphs b of Figures 3, 4 and 5, large variations in the slope of the fertilizer rate-uptake function occur. The minimum value is $\approx 0.10 \text{ kg kg}^{-1}$, while maximum values of over 0.70 are reported. This variation is understandable considering the dynamics of nitrogen in the sawah rice system as explained in section 2.1.

Denitrification, volatilization and leaching, the main processes causing nitrogen losses are being counteracted by uptake of nitrogen by the plants. The rate of uptake is therefore one of the factors influencing the efficiency of the applied fertilizer. Experiments carried out in Thailand, showed that ammonium sulfate broadcast onto the field before transplanting showed an average recovery of $\approx 17.5\%$. The values for applications at the stages active tillering, panicle initiation and flowering were 21.6, 37.5 and 55 respectively (25). These figures reflect the shorter residence time of the ferti-

lizer in the soil-water system as the nitrogen demands, and hence the rate of uptake, increases with age.

In Figure 3l (Muara, Indonesia) the effects of various fertilization practices is shown. The standard practice of broadcasting urea in three equal splits led to a recovery of only 27%. Placement of the total amount of urea however at a depth of \approx 10 cm at transplanting in a mud ball or in briquet form, gave a recovery of 56%. This prevents the conversion of ammonia into nitrates and hence the subsequent denitrification (11). When it is assumed that about 10% of the nitrogen is in the root system, still \approx 30% of the applied nitrogen is not available to the plant. This could be due to leaching losses, as even in the dry season rainfall in Muara is over 200 mm/month (33). Denitrification could still have taken place when the soil was not yet anaerobic at the time of placement. A temporary immobilization of mineral N in the soil organic matter may also be an explanation. A similar pattern is visible in Figure 3m (Louisiana, USA) where the effect of placement at various depths of ammonium and nitrate fertilizers is shown. The recovery after deep placement of ammonium is still low (for whatever reason), but it is twice as high as with the normal practice. For sodium nitrate the tendency is in the reversed direction. Placement at a depth where anaerobic conditions prevail decreases its recovery to a value as low as 12%. The very low recovery fractions found in Burma (Figure 3i) and Nigeria (Figures 3g and 3h) are in agreement with the results reported by Koyama et al. (1973), that fertilizer applied as basic dressing at transplanting is used very inefficiently.

In two cases the fertilizer rate-uptake curve levels off at high nitrogen application (Figures 3n and 3u). For the Australian experiment (Figure 3n) the uptake pattern as given by Chaplin (1972) shows that uptake stopped at practically the same moment for all treatments, except the zero application. This could lead to the conclusion that nitrogen uptake rather than availability was responsible for this phenomenon. The most likely would be development of water shortage in the upper soil layers, preventing the uptake of nitrogen. However, no indication of this is given in the paper. As to Mali (Figure 3u) there is not enough information available to permit any conclusions. Figure 4b shows that the

recovery of applied nitrogen is considerably lower for upland conditions than for flooded conditions. Additional information by Shiga (1975) shows that in upland conditions a large proportion of the applied nitrogen is immobilized in the soil organic material. The growth of decomposing micro-organisms is apparently hampered by the anaerobic conditions in the submerged soil and hence less of the nitrogen is immobilized.

For the other small grains, the recovery fraction is in general appreciably higher than with rice, values as high as 0.90 kg kg^{-1} being reported (Figure 5c). Under upland conditions the main processes rendering fertilizer N unavailable to the plant would be leaching and microbial immobilization. The fertilizer rate-uptake curve of oats in Figure 5c seems to be composed of two parts. Up till a fertilizer rate of 80 kg ha^{-1} a straight line is found originating at $\approx 50 \text{ kg ha}^{-1}$. Above that level another straight line can be drawn which would after extrapolation originate at $\approx 25 \text{ kg N ha}^{-1}$. The limited amount of information available provides no clue for this effect.

From the discussion in this section two conclusions may be drawn.

a. The efficiency of applied nitrogen in terms of grain yield is largely determined by the recovery fraction.

b. In rice the recovery fractions are very low. They may be increased on most soils by placing the fertilizer at or shortly after transplanting in the reduced soil layer.

4. ANALYSIS OF NITROGEN FERTILIZER EXPERIMENTS ON JAVA

4.1. Presentation of the data

Nitrogen fertilizer experiments have been carried out on Java for many years. In some cases (22, 43, 20) sufficient data have been presented to permit analysis as explained in section 3, but usually only fertilizer rate-yield curves are given.

The constant initial slope of the uptake-yield function and the climate-dependent level of its plateau (which can be calculated, (24)) enables construction of the uptake-yield curve for any place with fair accuracy. The only prerequisite is that the radiation

and the temperature are known in sufficient detail (i.e. \approx 10-day averages).

An example of a graph constructed in this way is given in Figure 9 for the Muara substation of the Central Research Institute for Agriculture, located near Bogor. The wet and the dry season are considered separately as the difference in radiation intensity between the two seasons leads to a difference in the maximum grain yield of $\approx 1500 \text{ kg ha}^{-1}$. The curve starts with a slope of 14 kg N per 1000 kg grain and begins to deviate from that at a value of about 50% of the maximum yield. The maximum itself is finally approached at the uptake point equivalent to the maximum nitrogen levels in grain and straw under optimum conditions. These values are assumed to be 1.3% and 0.7% for grain and straw respectively, while a grain/straw ratio of one is taken into account. The uptake-yield curve therefore reaches the maximum yield level at the point, where the nitrogen uptake is equal to maximum yield (kg ha^{-1}) times 0.02. It should be realized that the central part of the constructed relation may deviate up to 10% from the real one, for any given situation. The exact nitrogen content in grain and straw not only depends on the total amount of N available, but also on the "timing" of this availability. The latter factor determines for instance, whether during the grain filling period the required nitrogen can still be supplied by the soil, or that part or all of it must be translocated from the vegetative tissue. For the present purpose of analyzing previous fertilizer experiments however the "standard" relation between uptake and yield is accurate enough.

Once the uptake-yield curve is available it is of course possible to derive the fertilizer rate-uptake curves from the reported fertilizer rate-yield relation. This is demonstrated in Figure 9b, using data from an experiment carried out by the Agronomy Department of CRIA (Table 2). Firstly the observed yield is located at the vertical axis of graph (a). A horizontal is drawn from that point until it crosses the uptake-yield curve. From the intersection a vertical is drawn and at the horizontal axis the corresponding uptake is found. Continuation of the vertical into quadrant b, till the fertilization rate at which the yield was measured, gives a point of the fertilizer rate-uptake function. Completing this procedure for the full range of fertilizer rates applied in a particular experiment, gives the

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required relation. Now the slope of the line can be determined (in this case $.24 \text{ kg kg}^{-1}$) which represents the recovery fraction.

When fertilizer experiments are analysed in this way, it is possible to discriminate between possible causes of ineffective nitrogen application (viz. section 3.1): either the fertilizer was not taken up, because it was applied at the wrong time, in the wrong place or in the wrong from, or it was taken up, but did not lead to increased production, in which case other growth factors could be limiting. An example of the fertilizer rate-uptake curves that are obtained with this procedure is given in figure 10. The experimental results were made available by various departments of CRIA.

The maximum yields for each location and growing season, calculated according to the method described earlier (24) are given

Table 2. The effect of nitrogen fertilizer application on grain yield.
Pengaruh pemupukan nitrogen terhadap hasil gabah.

N-fertilization kg ha^{-1}	grain yield (kg ha^{-1}) (14% MC)
0	3486
20	3707
40	4021
60	4607
80	4684
100	4994
120	5063

Location: Muara (Indonesia)	Varieties: PB 5
Time : Wet season 1969/1970	C4 — 63
Fertilizer: Urea	average IR 20
Application: 1/3 / 1/3 / 1/3 (standard)	Dewi Ratih

Horizontal solid arrowed line indicates potential grain yield (24). The dotted arrowed lines illustrate the procedure to determine nitrogen uptake from measured grain yields (for details see text).

Gambar 9. Hubungan "standar" antara absorpsi nitrogen total dan hasil gabah untuk varietas padi berumur sedang yang tumbuh di Muara, Indonesia, pada musim kering (a) dan musim penghujan (b). Garis horisontal yang tebal berbentuk panah menunjukkan potensi hasil gabah (24). Garis terputus-putus berbentuk panah menggambarkan prosedur untuk menentukan absorpsi nitrogen dari hasil gabah yang diukur (untuk keterangan terperinci lihat teks).

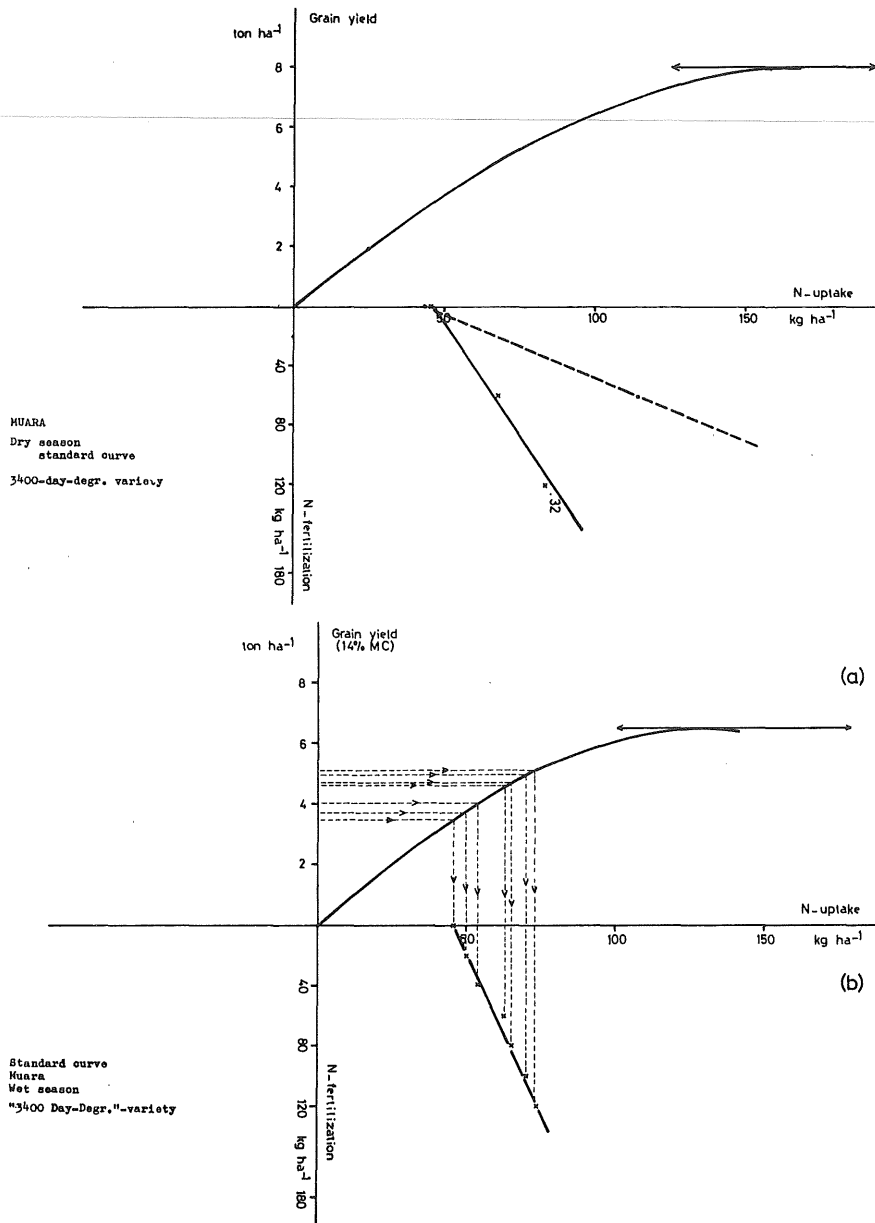


Figure 9. The "standard" relation between total nitrogen uptake and grain yield for a medium duration rice variety grown in Muara, Indonesia, in the dry (a) and wet season (b). (Cont. on page 44).

Table 3. Potential grain yield at various stations on Java in wet and dry season.

Potensi hasil gabah diberbagai kebun percobaan di Jawa pada musim penghujan dan musim kering.

Location	Longitude	Latitude	Elevation	Y max (kg ha ⁻¹ , at 14% MC)	
				season	
				dry	wet
Muara	106° 45'E	6° 40'S	260 m	8000	6450
Mojosari	112° 30'E	7° 30'S	30 m	8850	6900
Singamerta	106° 15'E	6° 10'S	0 m	7000	6800
Genteng	114° E	8° 20'S	171 m	7750	7200
Ngale	111° 10'E	7° 20'S	55 m	7150	6500
Kuningan	108° 24'E	6° 58'S	559 m	7850	7500
Kendalpayak	112° 20'E	8° 05'S	450 m	8050	7400
Pusakanegara	107° 45'E	6° 18'S	7 m	7800	7200

in Table 3, so that all "standard" uptake-yield curves can be constructed.

4.2. Interpretation of the results

When interpreting the measured fertilizer rate-yield curves according to this procedure, some special cases may be encountered. These originate in principle from the fact that a unique uptake-yield curve is assumed for each combination of location and season. When however a situation would have existed as illustrated in figure 3k (phosphate shortage), than reading the uptake from the yield will result in values which are too low affecting the fertilizer rate-uptake curve. This effect is illustrated in Figure 11, where the measured data (solid line) are compared with the ones that would result from the interpretation procedure (dashed line). In the latter case it would be concluded that the fertilization-uptake curve levels off at high fertilizer applications, which is an artefact. Similar effects may be expected at very high levels of fertilizer application when the plateau-value of the uptake-yield curve is approached. Increased uptake at that point does not lead to increased yields, and this will also be interpreted as a vertical part in the fertilization-uptake curves. Another possibility is, that the fertilizer rate-uptake

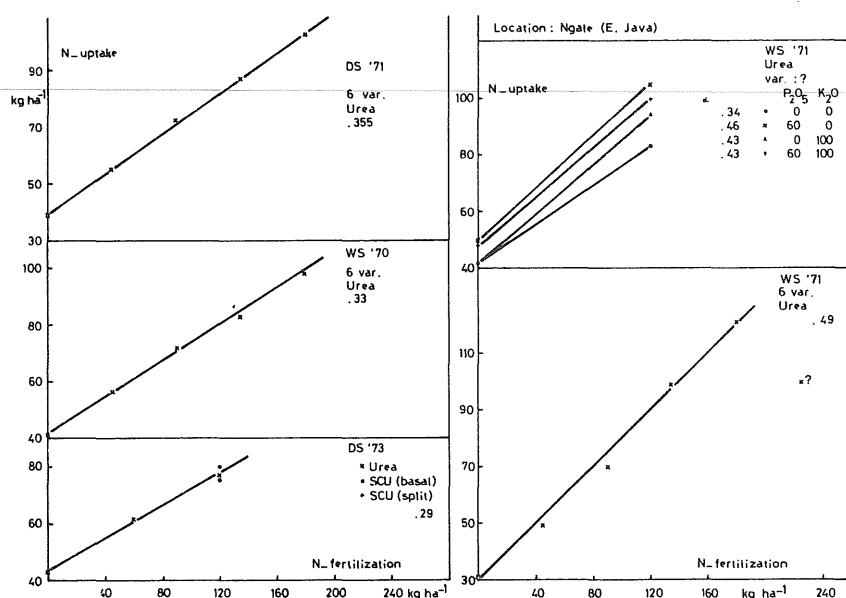


Figure 10. Example of rate of fertilizer application-uptake curves derived from experimentally determined rate of fertilizer application vs. grain yield relations. Source: Agronomy Department CRIA, Bogor.

Gambar 10. Contoh tingkat pemberian pupuk - kurva absorpsi yang diperoleh dari percobaan tingkat pemupukan terhadap hasil gabah. Sumber: Bagian Agronomi, LP3, Bogor.

curve really levels off. This will be the case when the fertilizer is applied too late, so that the crop, due to low root activity or otherwise, is unable to extract it from the soil. This will also happen when at a certain moment water shortage develops in those parts of the soil profile that contain the nitrogen. Although water may then be extracted from deeper layers, the nitrogen has become immobile. All these phenomena may lead to deviations from a straight line in the fertilizer rate-uptake curves. Therefore only the linear part of these curves is used for the interpretation in terms of recovery fractions.

In order to put the results obtained from this analysis to practical use, the calculated recovery percentages have been grouped, again according to location and growing season. The groups of data

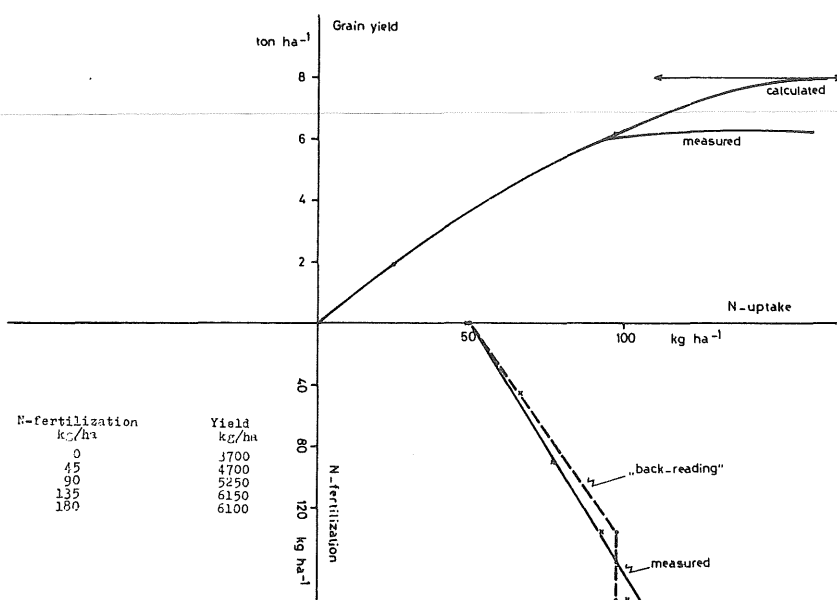
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Figure 11. The influence of phosphate shortage in experimentally determined rate of fertilizer application vs. grain yield relations, on the relation between rate of fertilizer application and uptake derived from the procedure illustrated in figure 9.

Gambar 11. Pengaruh kekurangan fosfat yang diperoleh dari percobaan pemupukan terhadap hasil gabah, dalam hubungannya antara tingkat pemberian pupuk dan absorpsi yang berasal dari prosedur yang digambarkan pada Gambar 9.

obtained in this way are plotted on probability paper, with the recovery fraction on the vertical axis and the cumulative relative frequency on the horizontal, as is shown in Figure 12. Examination of these graphs reveals that for each group—that is for each location in a given season—the recovery fractions show a normal distribution. This presentation of the data yields also at first glance the mean value and the standard deviation for each situation. The relevant parameters for all conditions are summarized in Table 4. The normal distribution of the recovery fractions indicates that the variations around the mean value are caused by chance factors. The most important ones of these are probably the weather conditions (governing the degree and extent of anaeroby), pre-treatment of the soil (wet or dry), previous crop and the exact

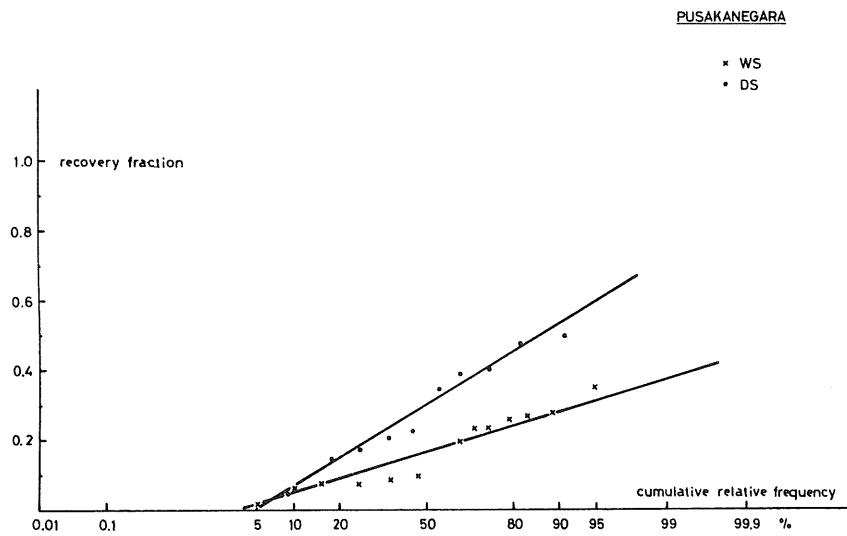
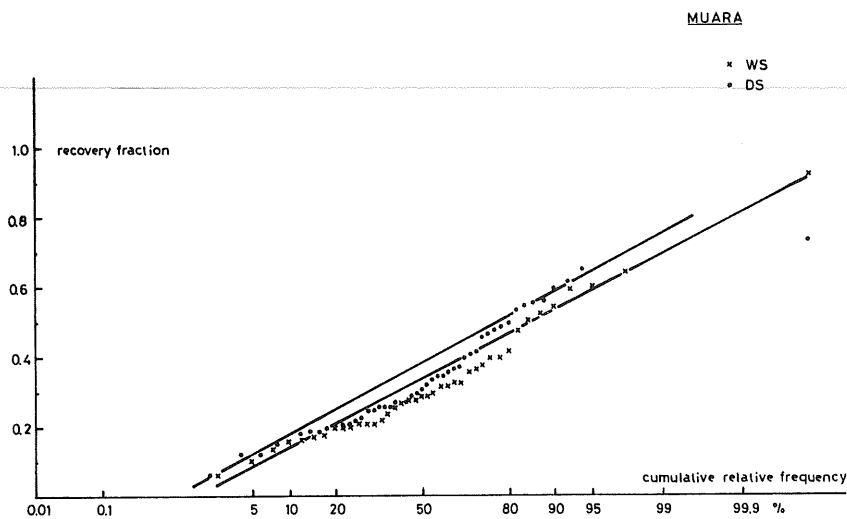


Figure 12. Cumulative relative frequency distribution of recovery fractions for nitrogen fertilizer, for eight locations on Java.

Gambar 12. Frekuensi relatif distribusi kumulatif dari fraksi yang diketemukan kembali dari pupuk nitrogen yang dipakai, untuk delapan lokasi di Jawa.

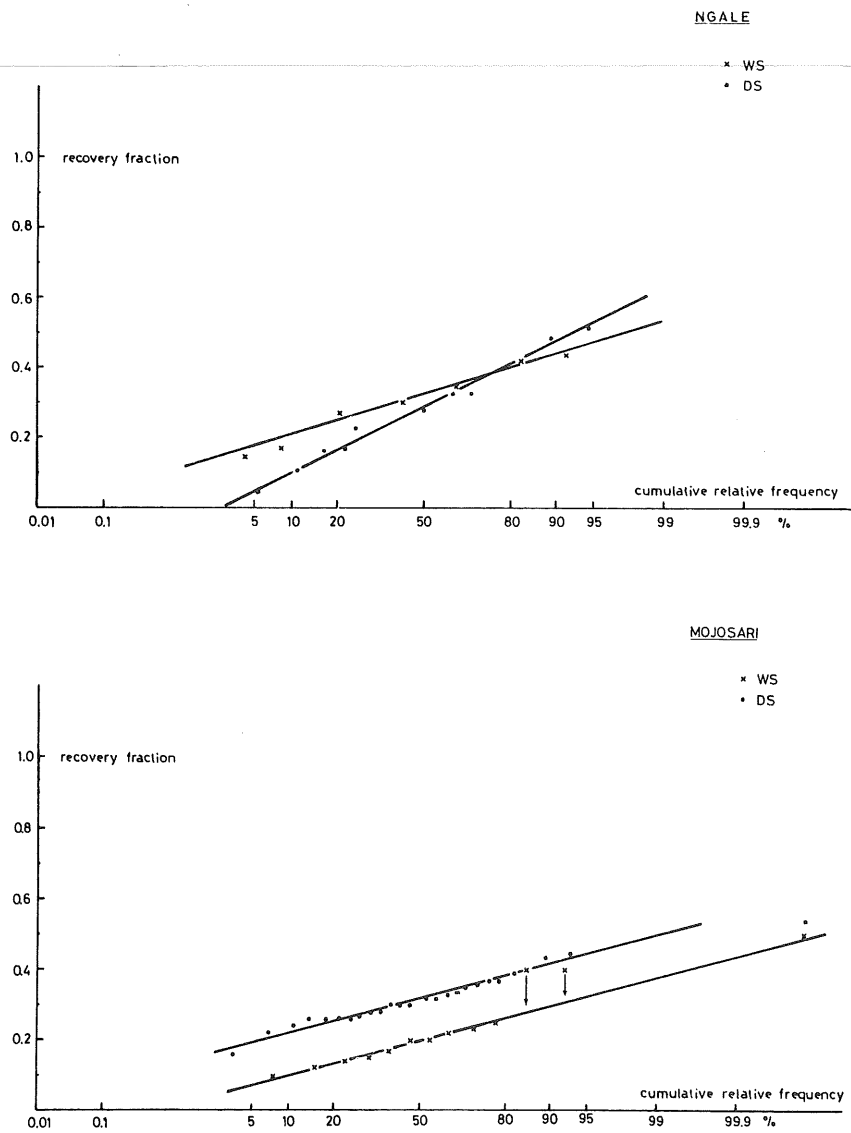
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Figure 12 (Cont.)

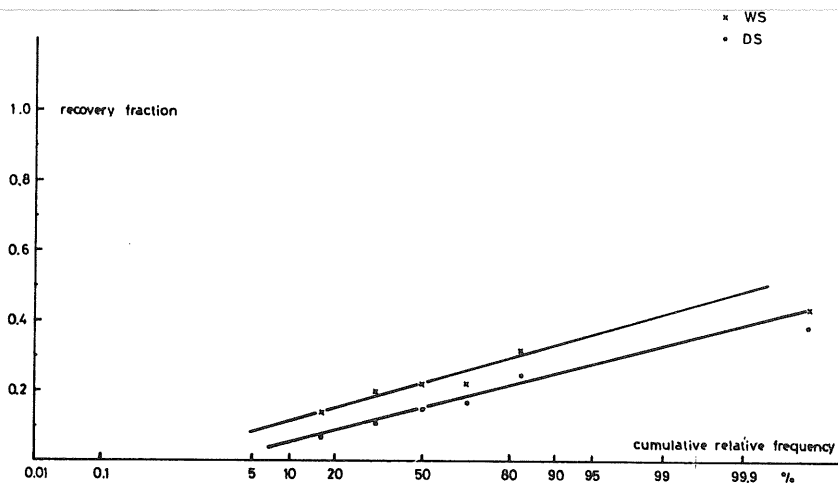
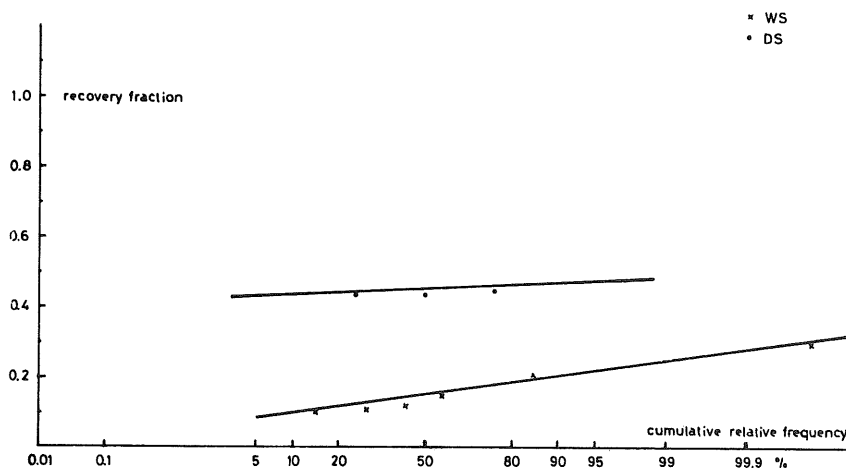
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Figure 12 (Cont.)

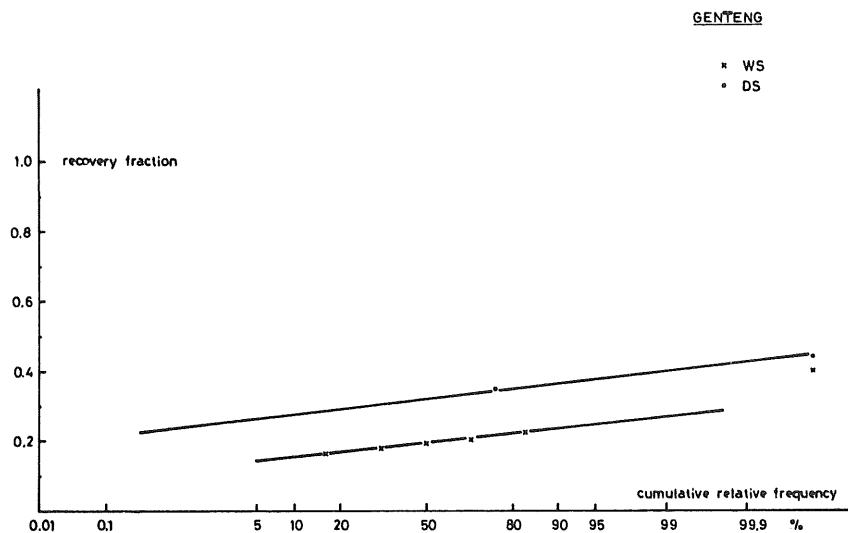
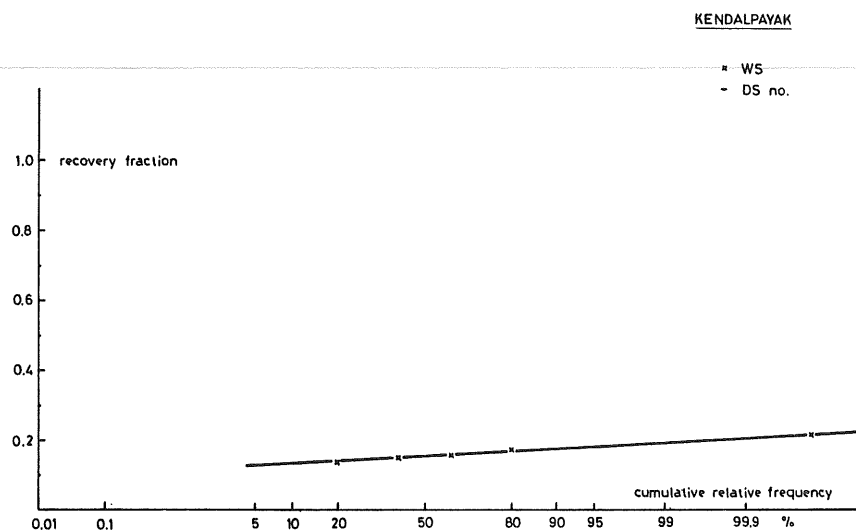
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Figure 12 (Cont.)

fertilization scheme. In this analysis no distinction was made between various methods of split application nor between kinds of fertilizer applied.

The data in Table 4 show that at four out of the six stations for which results are available for both seasons, the average recovery percentage is higher in the dry than in the wet season. This could be due to several factors:

- Generally crop growth rates are higher in the dry season, because of higher radiation intensity (Table 2). As a result, the nitrogen will be taken up faster after application and denitrification and leaching are less important.
- Rainfall is higher in the wet season, causing increased drainage rates. Even if in the dry season water is supplied from an irrigation system, heavy rainfall in the wet season will result in the passing of larger amounts of water. This will lead to an increase in the rate at which nitrates enter the anaerobic layer and in greater leaching losses.

Whether a combination of these factors could be responsible for the observed difference is difficult to judge off hand. A better quantitative description of the dynamics of nitrogen in the sawah-soil system will be necessary for that purpose.

The differences in the mean values among various stations in the same season cannot easily be explained. Variations in soil characteristics might be responsible for part of the observed differences.

Differences in hydraulic conductivity could lead to variations in drainage rate. This in turn affects both the leaching losses, which are probably not so important, but also the rate at which the water layer disappears from the field in case of insufficient rain. Alternate drying and wetting is very unfavourable for the nitrogen availability.

Differences in soil pH could affect microbiological processes connected with the nitrogen cycle, although under flooded conditions the soil pH tends to stabilize around 7, irrespective of the original pH.

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Table 4. Summary of results of normal distribution.

Ringkasan hasil dari distribusi normal.

Station	N	XAV	S	Srel.
Wet season				
Muara	40	0.34	0.18	0.53
Pusakanegara	19	0.17	0.09	0.53
Ngale	18	0.29	0.125	0.43
Mojosari	13	0.20	0.08	0.40
Singamerta	6	0.22	0.08	0.36
Kuningan	6	0.155	0.045	0.29
Kendalpayak	5	0.16	0.02	0.125
Genteng	4	0.32	0.04	0.125
Dry season				
Muara	50	0.385	0.16	0.42
Mojosari	28	0.32	0.08	0.25
Ngale	24	0.33	0.09	0.27
Pusakanegara	11	0.30	0.18	0.60
Singamerta	6	0.15	0.075	0.50
Genteng	6	0.20	0.04	0.20

N = number of experiments examined

XAV = mean recovery fraction

S = standard deviation

Srel. = relative standard deviation, as a fraction of XAV

The very low value reported for Pusakanegara in the wet season (0.17 kg kg^{-1}) could probably be explained by the fact that at this substation a fairly unfavourable situation exists with respect to pests and diseases. When the observed yields are low because of insects pests, rat damage and the like, the "read-back" procedure will lead to a systematic underestimation of the amount of nitrogen which is taken up. Without additional information however this argument cannot be proven.

It seems at this stage not fruitful to speculate about possible explanations for the observed differences, without knowing the relative importance of the processes involved. For the time being the observed values of the recovery fractions may be used to develop fertilizer recommendations.

A quantitative explanation of the observed phenomena is being studied in a simulation model which is being developed concurrently by the author.

5. NITROGEN FERTILIZER RECOMMENDATIONS — A SYNTHESIS

5.1. Explanation of procedure

The description of the nitrogen-crop growth interaction as given in the previous sections can now be used as a tool to provide nitrogen fertilizer recommendations for any given situation. The method is illustrated in Figure 13.

Once again, we start from the nitrogen-uptake yield curve, which can be constructed for a certain place when the expected potential grain yield is known. Suppose that it is 6500 kg ha^{-1} for a specific combination of location and rice variety. Introduction of the constant initial slope described in section 3, yields graph (a) which relates the expected yield to the amount of nitrogen taken up.

For the construction of graph (b) we first consider the intercept with the horizontal axis. Generally the yield at zero fertilizer application will be known or can be estimated. Of course this value is dependent on soil type and cropping history of the field under consideration. It will most likely be in the order of 2 to 2.5 tons ha^{-1} in the absence of serious pests and diseases. Going from the "zero-yield" on the vertical axis to graph (a) and down in vertical direction provides the first point of curve (b). The slope of the straight line depends on the method of application of the fertilizer and is furthermore influenced by chance factors, which cannot be predicted.

As an illustration of value of 0.30 is assumed. This then provides graph (b). When the relations (a) and (b) are known, graph (c) follows from elimination of the uptake. For each fertilization

rate of (b) the corresponding uptake is determined, leading in turn to a certain yield. This is then entered in graph (c) at the earlier mentioned rate of fertilizer application. The procedure is illustrated in Figure 13 by the arrows marked with "2". From the curve constructed in this way one can read the expected yield increase for any given amount of fertilizer applied. As expected the law of diminishing returns shows up rather pronounced in this relation. This is the result of the increasing nitrogen content of the material, produced at higher rates of fertilizer application.

Finally the economics have to be taken into account to determine till what yield level it is profitable for the farmer to use increased amounts of nitrogen fertilizer. This is achieved by introducing in graph (c) also the price ratio between nitrogen that has to be purchased and grain that may be sold. An average farm gate price of Rp. 70/kg urea with a nitrogen content of $\approx 45\%$ may be assumed. Modern rice varieties like IR26 yield a farm gate price of \approx Rp. 60/kg for reasonably clean rice grain. From these numbers it is clear, that increased fertilizer application remains profitable till the point is reached where application of one extra kg of pure nitrogen yields an additional 2.6 kg of dry grain. This slope is introduced in quadrant (c) as the tangent of B, which has then been shifted to the point where that slope equals the slope of the fertilization rate-yield curve. In the given situation this is at a fertilizer application rate of ≈ 290 kg N ha⁻¹ or very close to the projected maximum yield.

5.2. Application in the farmer's situation

To apply the procedure explained in section 5.1 to a specific case a number of the parameters used have to be considered in more detail.

The main determinant in the decision whether or not to apply nitrogen fertilizer is the price ratio between fertilizer added and increase in grain yield. The prices quoted in the example are net prices, which is in many cases an oversimplification. Application of nitrogen fertilizer will often imply that the farmer has to borrow money or that the fertilizer has to be bought on credit.

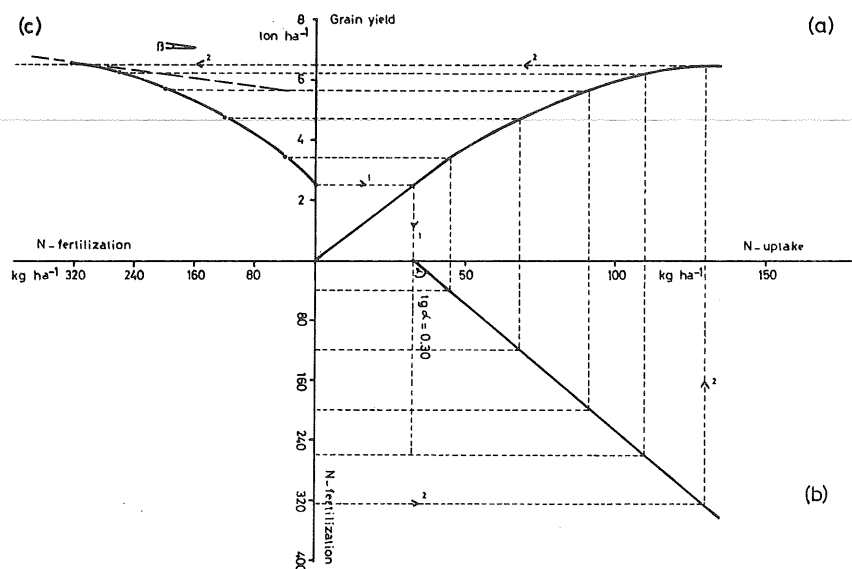


Figure 13. Illustration of the procedure to arrive at nitrogen fertilizer recommendations from the estimated recovery of nitrogenous fertilizer (b) and the standard relation between total nitrogen uptake and grain yield (a). Tangent B is the price ratio between nitrogen and rice per unit weight. For further details see text.

Gambar 13. Gambaran dari prosedur yang menuju ke arah rekomendasi pemupukan yang dihitung dari perkiraan pupuk nitrogen yang diketemukan kembali (b) dan hubungan standar antara absorpsi nitrogen total dan hasil gabah (a). Tangens B adalah rasio harga antara nitrogen dan gabah per unit berat. Untuk keterangan terperinci lihat teks.

This means that interest costs have to be added to the price. Moreover it is usually wise -at least in certain areas- to supplement nitrogen fertilization with the application of phosphate and potassium fertilizers to assure optimum efficiency of the applied nitrogen. Finally there may be costs involved in application to the field, especially when labor intensive methods like placement are used. So the real cost of the fertilizer may exceed considerably the net price assumed above. The price ratio will also be unfavourably affected when the recovery fraction turns out to be very low. Considering the data given in Table 4 it seems reasonable to assume a minimum value of 0.10 kg kg^{-1} , which is equal to the lowest mean value minus the standard deviation. This leaves only a small

proportion of the farmers with the risk of still more unfavourable conditions. In that case each kg of nitrogen fertilizer applied leads to the uptake of 0.1 kg and a yield increase of 7.2 kg of grain (For the decision whether or not to use fertilizer the initial slope of the uptake yield curve is used). At the present rice price this will provide the farmer with an additional income of ∞ Rp. 425, per kg of nitrogen applied. Comparing that to the net price of nitrogen (Rp. 160/kg N) indicates that even when additional costs run as high as 150% of the net price it is still profitable for Indonesian farmers to apply nitrogen fertilizers.

For the calculation of the actual amount that may be applied profitably the expected recovery fraction is the most important parameter. When a too low value is assumed i.e. when the actual ratio between application and uptake turns out much more favour-

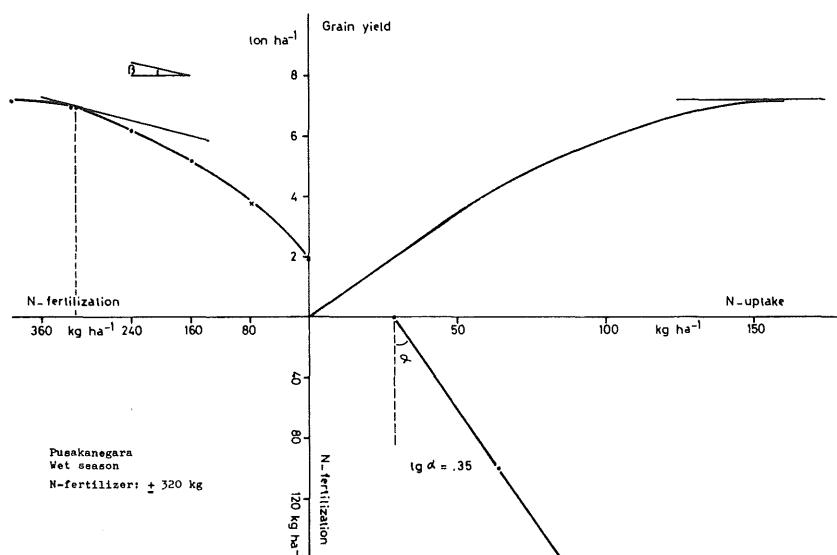


Figure 14. Calculated nitrogen fertilizer recommendation for a medium duration rice variety growing in Pusakanegara (West Java) in the wet season. The horizontal line indicates potential grain yield (24). Tangent B is the price ratio between nitrogen and rice per unit weight.

Gambar 14. Kalkulasi rekomendasi pupuk nitrogen untuk varietas padi berumur sedang yang tumbuh di Pusakanegara (Jawa Barat) pada musim penghujan. Garis horisontal menunjukkan potensi hasil gabah (24). Tangens B adalah rasio harga antara nitrogen dan gabah per unit berat.

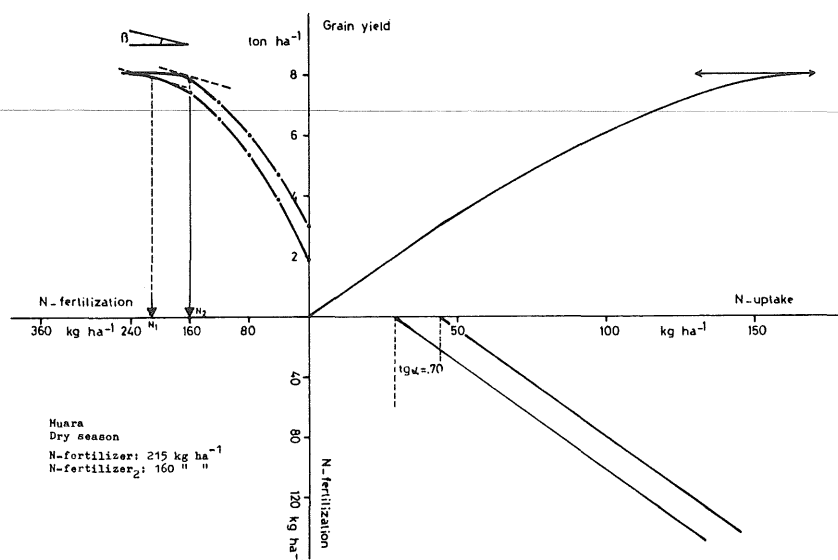


Figure 15. Calculated nitrogen fertilizer recommendation for a medium duration rice variety growing in Muara (West Java) in the dry season. The arrowed horizontal line indicates potential grain yield (24). N1 and N2 indicate two different levels of soil-borne nitrogen.

Gambar 15. Kalkulasi rekomendasi pupuk nitrogen untuk varietas padi berumur sedang yang tumbuh di Muara (Jawa Barat) pada musim kering. Garis horisontal terputus-putus berbentuk panah menunjukkan potensi hasil gabah (24). N1 dan N2 menunjukkan dua macam tingkat nitrogen yang berasal dari tanah.

able than the expected one, the farmer could be tempted to use so much fertilizer, that the "limiting" point of the uptake-yield curve could be exceeded. There is also a risk that at such high levels of nitrogen uptake even improved varieties may lodge under unfavourable weather conditions or may be more susceptible to pests and diseases. Such effects will be detrimental for the final yield and invalidate the very reasoning on which the recommendation is based. The actual recommendation should therefore be based on assumptions that will minimize the risk of overfertilization. This may be achieved by assuming a recovery fraction that in effect will not be reached in most cases. When for a given place it is taken as the calculated mean increased by two times the standard deviation (Table 4), only in $\approx 10\%$ of the cases there is a risk that it turns out higher in the end.

The result of the proposed procedure in terms of fertilizer recommendation in two contrasting situations is shown in Figures 14 and 15. For the calculations it is assumed that the "gross" price of nitrogenous fertilizer is equal to twice the net price. As shown in these figures, the marginal nitrogen applications are reached at 320 and 215 kg N ha⁻¹ respectively. In Figure 15 also the effect of a higher zero level is shown: an increase of ≈ 15 kg N ha⁻¹ supplied from the system, leads to a decrease in the marginal fertilizer rate of about 50 kg N ha⁻¹.

The foregoing calculations are all based on optimum growing conditions i.e. a liberal supply of mineral elements other than nitrogen and the absence of serious pests and diseases. The first condition i.e. lack of other mineral elements should not be too serious a problem. As explained earlier the additional costs of supplying other fertilizers can easily be absorbed, without seriously affecting the incentive for nitrogen application. When however pests and diseases are interfering, the calculations should be based on a different uptake-yield curve. Construction of that curve is somewhat arbitrary. The actual yield level may influence the degree of damage to the crop by changing its susceptibility to pests and diseases. Moreover attacks by different organisms may not have the same effects. In a first attempt to take pest and diseases into account it is assumed however, that a yield depression affects the uptake-yield curve in the same way over the full range of uptakes. An estimate of the magnitude of the depression that could be expected may be obtained from a comparison of the calculated maximum yield, with the yield-levels that are measured under conditions that are considered optimum. Suppose that a yield depression of 20% is expected, then both the initial slope and the plateau level of the uptake-yield curve have to be adjusted. For the case given in Figure 15 the procedure has been repeated in Figure 16, where it is shown that under these conditions the marginal application of N-fertilizer will be reached at ≈ 150 kg N ha⁻¹.

Application of the procedure outlined in this section for the determination of fertilizer recommendations leads on the one hand to the use of a price ratio, which leaves sufficient incentives for the farmer to apply nitrogen, while on the other hand the risk of "overfertilization" is minimized.

It is the intention of the author to prepare a schematized procedure for the determination of N-fertilizer application, that could be used by field workers.

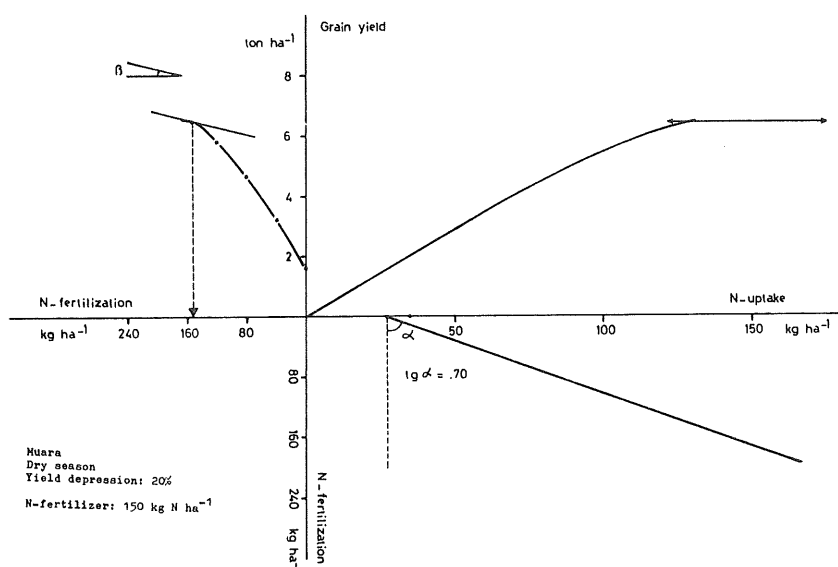


Figure 16. Calculated nitrogen fertilizer recommendation for a medium duration rice variety growing in Muara (West Java) in the dry season, when a 20% yield depression due to pests and diseases is expected.

Gambar 16. Kalkulasi rekomendasi pupuk nitrogen untuk varietas padi berumur sedang yang tumbuh di Muara (Jawa Barat) pada musim kering, apabila hasil berkurang 20% karena perkiraan serangan hama dan penyakit.

6. CONCLUSIONS

6.1. Introduction of a uniform method of analyzing fertilizer experiments, along the lines proposed, will lead to a better understanding of the causal relationships that are involved. It is therefore highly recommended that fertilizer experiments are accompanied with chemical analysis of the plant material, both grain and straw, that is harvested.

- 6.2. Understanding of the processes governing the dynamics of nitrogen in the rice-growing system can result in more meaningful fertilizer recommendations. Such recommendations are based on extrapolated results of experimental work, local field knowledge and the economic factors involved.
- 6.3. Improved methods of fertilizer application may lead to a greater efficiency of nitrogen use and hence to savings in fertilizer use, or to improvement of the cost-profit ratio for farmers.
- 6.4. Under conditions of limited nitrogen supply, all small grains behave the same.

RINGKASAN

Kebutuhan pupuk nitrogen pada padi sawah, khususnya untuk pulau Jawa

Nitrogen merupakan salah satu faktor yang sangat penting untuk pertumbuhan dan produksi padi. Dalam tulisan ini dibahas kelakuan nitrogen di tanah sawah dan di dalam tanaman. Analisa secara teliti dari hasil-hasil percobaan pemupukan disajikan dalam tulisan ini. Ditunjukkan, bahwa interpretasi respons hasil dapat dijelaskan dengan lebih baik, apabila disamping data hasil terdapat pula data analisa kimia tanaman. Apabila data-data ini tersedia, maka dapat disajikan dalam bentuk grafik, dimana dapat dibedakan antara pupuk yang tak diserap dan pupuk yang diserap oleh tanaman akan tetapi tak dimanfaatkan.

Analisa dari kurva absorpsi hara yang diukur menunjukkan bahwa apabila nitrogen dalam keadaan terbatas maka reaksi tanaman padi-padian praktis sama. Hal ini memungkinkan pembuatan kurva hasil — absorpsi hara untuk tiap lokasi. Dari kurva-kurva ini hubungan antara pemberian dan absorpsi pupuk nitrogen untuk delapan lokasi di pulau Jawa telah dianalisa dengan mempergunakan data dari percobaan-percobaan pemupukan akhir-akhir ini. Terdapat indikasi bahwa antara kisaran dosis pemupukan yang luas terdapat proporsi absorpsi hara yang konstan. Proporsi ini, yaitu bagian yang terdapat di dalam tanaman, adalah sangat rendah untuk padi sawah. Perbaikan mengenai cara pemberian pupuk dapat meningkatkan efisiensi pemupukan. Analisa selanjutnya menunjukkan

bahwa setiap lokasi dan musim, bagian yang dapat diketemukan kembali di dalam tanaman menunjukkan distribusi yang normal.

Kombinasi antara kurva absorpsi — hasil dan fraksi yang diketemukan kembali di dalam tanaman memungkinkan pembuatan kurva respons pupuk, yaitu hasil gabah terhadap tingkat pemupukan. Apabila kurva ini dikombinasikan dengan rasio antara harga pupuk dan gabah, maka tingkat ekonomi marginal yang menguntungkan dapat ditentukan untuk keadaan yang spesifik.

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