4.2 Nutrient demand and fertilizer requirements

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In Section 4.1 the effects of the main plant nutrients nitrogen, phosphorus and potassium on crop yield and the relations between nutrient supply and nutrient uptake were discussed using a three quadrant presentation. If these principles are applied to actual cropping situations, four practical questions must be answered:

- how can a nutrient shortage be recognized in a certain situation?
- how much of that nutrient does the unfertilized soil supply?
- what is the recovery of a certain fertilizer – nutrient if applied in a specific way?
- how much fertilizer must be applied to realize Production Situation 2, where crop yield is solely determined by weather conditions and water availability?

As is evident from the discussion of the principles of nutrient demand and supply, such questions pertaining to a specific cropping situation can only be answered with the aid of information collected in field experiments and from chemical analyses. The purpose of this section is to show how these questions can be answered on the basis of minimal information. For practical reasons, the discussion will be limited to situations in which the availability of nitrogen and/or phosphorus determines crop performance; situations where yields are limited by potassium shortage are less common.

4.2.1 Recognition of nutrient limitation

The easiest way to recognize nutrient stress in a crop is through chemical analysis of such biomass components as straw and seed, or – if the deficiency is serious enough to manifest itself in the physical appearance of the crop – through identification of specific deficiency symptoms such as discolouration or necrosis of plant organs. The information needed for correct diagnosis can only be collected with the backing of an adequately equipped plant analytical laboratory. This is the major reason that such data are scarce. Soil chemical data are more commonly available as they are routinely collected in soil surveys. Unfortunately, there is not a generally valid quantitative correlation between soil analytical data and crop performance. Soil analysis data can at best give an indication of likely element deficiency or of the occurrence of unfavourable soil conditions which would conceivably obstruct the normal functioning of plants. This subject will be further elaborated in Section 5.3.

A convenient way to recognize nutrient limitation is by comparing actual plant production in the field with the calculated production in Production Situation 2. Obviously, such calculations must be done for a crop species and variety with similar properties as the one grown in the field and for weather conditions and a water regime the same as that in the field. Likewise, the actual field production must have been obtained under conditions that apply to Production Situation 2, viz. in a weed – free environment, with adequate control of pests and diseases and with optimum harvesting methods. In addition, chemical and physical soil conditions must be such that they have no adverse effect on plant performance. The outcome of such a comparison can be either of two possibilities:

- one is that the actual production is close to the calculated production. In that case growth is not limited by a defiency of nitrogen or mineral elements.
- the other is that the actual production is clearly lower than the one calculated for Production Situation 2. For identification of the element that is in short supply it is then inevitable to perform a chemical analysis of crop components.

If, for example, the nitrogen concentrations of the analysed plant parts are distinctly higher than the minimum values as given in Section 4.1, it may be concluded that nitrogen availability is not the limiting factor and the concentrations of other nutrients must be checked. Phosphorus shortage is then a likely candidate. If, on the other hand, the nitrogen concentrations of the analysed plant parts approach their minimum values, it may be concluded that nitrogen shortage limits crop production. It is then worthwhile to consider application of a nitrogen fertilizer. The improved plant growth resulting from this N application will also increase the demand for other elements such as phosphorus and potassium. If this additional demand cannot be met by the soil, i.e. if the effect of N application remains below expectations, mineral elements must be applied in addition to nitrogen.

In practical plant nutrition research, nutrient demands are not identified sequentially, but simultaneously. This is done in fertilizer experiments, which involve cropping a number of identical fields, arranged in a randomized design and each planted to the same variety and fertilized in a similar fashion but with different combinations of N, P and K fertilizers. The advantage of such experiments is that possible effects of nitrogen application, mineral element(s) application, or combinations thereof, become apparent after only one cropping season with one weather and one water regime which facilitates their interpretation. Obviously, the number of plots included in a particular experiment depends on the number of types/combinations and doses of fertilizers tested; it is often considerable. Moreover, the experiments must be done with a number of replications to rule out misinterpretation of the situation due to local anomalies or human failure. Each experiment includes at least one unfertilized plot, the 'control plot'. The function of this control plot deserves particular attention, as it is instrumental in answering the second practical question posed at the beginning of this section: How much of a nutrient does the unfertilized soil supply?

Exercise 57

In Section 2.3 (discussing Production Situation 1, where water, nitrogen and mineral elements are optimally supplied) an example was given in which the production of the high yielding rice variety IR8 was calculated for a bunded experimental site near Paramaribo, Suriname. Suppose that on this same station an unfertilized field planted to IR8 (on the same date) produced a total above-ground dry weight of 2000 kg ha^{-1} with a grain-straw ratio of 1.0. The total quantity of nitrogen contained in the above-ground production was 14 kg ha^{-1}.

- Identify the total above-ground biomass production and the grain yield calculated for Production Situation 1 in Section 2.3; calculate the production of straw in this situation.
- What would the above-ground biomass production be at Production Situation 2? (Remember: bunded rice fields)
- Do you think that fertilizers must be used for high production on that location?
- If so, is nitrogen the first element that has to be supplied? (Recall that minimum nitrogen concentrations in rice grain and straw are around 0.01 and 0.004 kg kg^{-1}, respectively)

4.2.2 Nutrient uptake from unfertilized soils

As unfertilized soils can normally still support a crop, they cannot be entirely devoid of nutrients. Influx of elements with wind, rain or irrigation water is a possibility, but more commonly these nutrients originate from sources in the soil itself. Nitrogen is predominantly supplied through microbial breakdown of soil organic matter, which – depending on its botanical origin and genetic history – normally has a nitrogen concentration between 0.01 and 0.05 kg kg^{-1}. Mineral nutrients are also supplied in this process but, with the possible exception of phosphorus, only in rather negligible quantities. The bulk of the mineral elements originates from weathering rock fragments.

The rate at which indigenous nutrients are supplied depends partly on soil characteristics such as organic matter content and composition, soil mineral composition and soil pH, but also on a score of exogenous factors that are often highly variable (Section 4.1). An example is soil temperature, subject to daily and seasonal fluctuations, and also influenced by weather conditions, vegetation cover and the action of man. To complicate things even more, not all the nutrients released are available for uptake by plant roots, as they may leach out of the root zone, precipitate as low-solubility compounds, etc.

This complexity makes it virtually impossible to predict the uptake of nutrients from an unfertilized soil on the basis of theoretical considerations only. For the time being, the quantity of the growth limiting element taken up by a certain crop from the unfertilized soil can best be established by simply dividing the control yield by the slope of the yield-uptake curve for that element.The growth limiting element can be identified, as explained, by determining element concentrations in the plant tissue. The slope of the yield-uptake curve is established on the basis of the ratio of economic product and crop residues and their minimum element concentrations.

If fertilizer trials are continued at an experiment station over a number of years, it is not uncommon that the 'base uptake', i.e. the quantity of nutrients taken up from unfertilized plots, increases in successive years. To understand this, it must be realized that the location of the control plot changes each year, because the individual fields of the experiment are laid out in a randomized design. Nutrients applied, but not completely taken up in one year may to some extent remain in the soil and increase the level of soil-supplied nutrients in subsequent experiments. The same happens in practical farming where fertilizers are used: natural soil fertility improves in the course of the years and base uptake reaches a new (higher) level. The magnitude of this improvement depends on both cultivation practices and environmental conditions. This may be illustrated by two extreme examples: in the case of nitrogen application to bunded rice, carry-over effects are often low because most of the nitrogen that is not directly taken up is lost through denitrification and/or leaching. A completely different situation exists in natural pastures in semi-arid regions, where almost no nitrogen is lost from the soil except by plant uptake.

Phosphorus is less mobile in the soil-plant-atmosphere system than nitrogen. Therefore, losses of phosphorus from the system are normally lower than losses of nitrogen and, consequently, the carry-over of phosphorus is higher. In practical farming, phosphorus is sometimes applied in high doses, which promise a satisfactory P supply over a number of years. However this effect should not be overestimated, as a large part of the fertilizer not taken up in the first year is transferred to forms that are far less available to plants.

Exercise 58

Table 44, from 'A Summary Report on Yield Response of some Thai Rice Varieties to Varying N and P_2O_5 Combinations' (Thai Rice Department, 1956), presents average yields of some Thai lowland rice varieties obtained in

Table 44. Average yields (kg ha^{-1}) of Thai lowland rice varieties at different levels of N and P combinations at Bangkhen Experiment Station.

Rates of nitrogen applied (kg ha^{-1})	Rates of phosphorus applied (kg ha^{-1})			
	P-0	P-37.5	P-75.0	P-150.0
A. Crop year 1952-1953				
N-0	1214.4			
N-37.5		2107	2232	2493
N-75.0		2211	2394	2551
N-150.0		2389	2484	2727
B. Crop year 1953-1954				
N-0	1529.4			
N-37.5		2706	3048	3164
N-75.0		3074	3220	3303
N-150.0		3159	3665	3649
C. Crop year 1954-1955				
N-0	1755.6			
N-37.5		3547	3686	3649
N-75.0		4188	4166	4291
N-150.0		4682	4647	4691

three consecutive seasons at Bangkhen Experiment Station.

- Identify the control plot yields obtained in the three consecutive crop years.
- Can you explain why the control yields obtained in the three consecutive years are different?
- Experience with traditional Thai rice varieties has shown that their rough grain* – straw ratio is normally close to 0.5 ('long straw varieties'). The minimum nitrogen concentrations of rough grain and straw are 0.0078 and 0.0036, respectively.

Calculate with these numbers the slope of the rough grain yield N uptake curve and use this slope to calculate the nitrogen uptake from the control plots in the three consecutive crop years.

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* Rough grain pertains to unhusked rice with 12 percent water; one kilogram of rough rice is equivalent to 0.8 kg husked rice (Section 5.4).

4.2.3 The recovery of nutrients applied in fertilizers

In Section 4.1 it was shown that the increase in nutrient uptake following fertilizer application is generally proportional to the quantity of that nutrient added, at least in the case of nitrogen and potassium. It was also shown that there are exceptions to this rule, e.g. in the case of immobilization or fixation of the added element by the soil. In this section not all possible exceptions will be treated, but element recovery in a normal situation where application – uptake relations are linear in the relevant range will be discussed. It was also explained in Section 4.1 that the slope of the application – uptake relation, i.e. the quantity of a certain element taken up from a fertilized soil minus the quantity taken up from the same but unfertilized soil divided by the quantity of that element contained in the applied fertilizer, is called the recovery fraction, or in a mathematical notation:

$$R_x = (u_{f,x} - u_{o,x})/A_x \tag{79}$$

where

R_x is the recovery fraction of element x (kg kg^{-1})
$u_{f,x}$ is the uptake of nutrient x from fertilized field (kg ha^{-1})
$u_{o,x}$ is the uptake of nutrient x from control field (kg ha^{-1})
A_x is the application of nutrient x to fertilized field (kg ha^{-1})

Theoretically, R_x ranges in value from close to 0 to close to 1.0; it expresses the efficiency with which a certain fertilizer is used.

The actual recovery of an element depends on the competitive position of the plant relative to processes in the plant – soil – atmosphere system that render the element unavailable to the plant. Taking nitrogen as an example, volatilization of ammoniacal nitrogen, leaching of nitrogen in nitrate form, denitrification to gaseous N forms and immobilization of nitrogen by soil microbes are processes lowering the recovery of applied fertilizer N. It follows, therefore, that a low recovery can be improved by either increasing the uptake activity of the plant roots or by decreasing the impact of the competing processes, or both. In the case of nitrogen, about one – tenth of the nitrogen taken up is needed in the root system, so that the maximum N recovery in the above – ground parts of a crop would be of the order of 0.9 kg kg^{-1}. In practice, it is often difficult to reach a higher recovery than 0.5 kg kg^{-1}. If the actual N recovery is well below this value it is worthwhile to try to improve the situation. It is this aspect, viz. indication of the need for adaptation of variety and/or cultural practice, that makes it so important to quantify the recovery of applied fertilizer nutrients in the analysis of a cropping situation.

The recovery of a certain element can be calculated from fertilizer experiments, if the biomass components are analysed for that element. It was explained why such complete experiments are rather scarce. Their number and regional distribution may be sufficient to indicate whether in a certain region a situation exists or has been created where shortage of a certain element is prominent, but complete experiments are nearly always too few in number to allow sufficiently reliable estimation of the recovery of that element from applied fertilizers. In practical farming, nutrient recovery depends not only on plant properties and environmental conditions but also on management factors, such as the type of fertilizer used and the timing and mode of fertilizer application. If, for instance, a high dose of a nitrogen fertilizer is broadcast at the beginning of the cropping season, when the nitrogen demand of the crop is still low, high losses of nitrogen from the root zone can be expected and, consequently, low N recovery values. Adapted application methods and good timing of fertilizer application may lead to increased N recovery in such situations, as will be explained later.

Where complete experimental information is scarce, the limited amount available must be used as efficiently as possible. If it is known which element is most likely limiting the growth of a certain crop in a particular situation, a first estimate of nutrient recovery can be made without further chemical analysis of plant components. This is possible because it may be assumed then that the limiting element in the crop is diluted to its minimum concentration in the various plant parts. The simplest experiment that still yields the required information, consists of a control plot and a fertilized plot whose production components, viz. economic yield and crop residues, are separately weighed. It must be realized that the reliability of only one recovery value, calculated in this way, is low and that such results are only indicative. The results of properly conducted experimental series, normally published as average yields per treatment with specified standard deviations, are a sound basis for recovery calculations.

Exercise 59

In Table 44 average yields of rough rice are given for three consecutive years of N – P fertilizer experiments at Bangkhen Experiment Station, Thailand.

- From the average yield values for 1954 – 1955, it can be observed that at a given level of nitrogen application different P applications do not result in significant yield differences. Which conclusion can be drawn with regard to the P supply to the crop in this situation?
- What has caused this situation? (Note: look also at the effects of P application on yields in 1952 – 1953 and 1953 – 1954). Is it logical that the same situation has apparently not been reached for the soil's nitrogen status?
- Calculate the nitrogen recovery fractions realized in 1954 – 1955 for the fertilizer combinations N 37.5 – P 37.5, N 75.0 – P 37.5 and N 150.0 – P

37.5. Assume the same grain – straw ratio and minimum N concentrations as in Exercise 58.

Earlier in this section it was argued that unsatisfactory recovery of fertilizer nutrients can be remedied by adaptation of crop characteristics, environmental conditions or management, alone or in combination. Agricultural research has developed crop varieties that can recover nutrients and realize an acceptable yield level under conditions that would be prohibitive for unimproved varieties, for example acidity – tolerant varieties and varieties which can successfully be grown in a brackish environment. Better nutrient recovery is not, or only marginally, involved in the success of the modern high yielding rice varieties (HYV's) developed at the International Rice Research Institute in the Philippines. The key to the success of these varieties is their high grain – straw ratio, which is of the order of 1.0; HYV's are so – called 'short straw varieties'. The high grain – straw ratio is associated with a high initial efficiency of the yield – uptake relation, i.e. a high increment in grain yield per kg nitrogen taken up. Their short posture allows uptake of considerable quantities of nitrogen with less risk of lodging, which quickly follows too luxuriant vegetative growth of traditional long – straw rices. In combination, these two effects result in very high grain yields per hectare, provided that the crop is grown under favourable environmental and management conditions that allow a high nutrient recovery. Under unfavourable conditions such as nutrient shortage or heavy weed infestation, traditional rice varieties, which have evolved in the course of centuries of natural selection by rice farming communities, may well perform better.

Increasing nutrient recovery by adaptation of the environment has been practiced as long as agriculture exists. Bunded rice fields are an example: nutrient recovery is promoted by the artificially created conditions in the puddled top layer of a wet rice field. Often, manipulation of the environment involves management measures. In the management sphere, too, wetland rice cultivation offers many practical examples of how nutrient recovery can be manipulated and improved. Illustrative of the great practical significance of good management is the mode of nitrogen fertilizer application to bunded rice. In many rice areas, urea is used as a nitrogen source and broadcast on the flooded field at the time of transplanting. The average recovery fraction of the fertilizer N is then often only 0.2, or even lower. This low recovery may be understood as follows: the favourable temperature conditions and oxygen-rich environment of the shallow water layer on top of the rice field promote rapid transformation of urea N to ammonium ions (NH_4^+) and subsequently to nitrate ions (NO_3^-) . The nitrate ions are highly mobile and move downward into the soil with percolating water or by diffusion. The oxygen in the waterlogged soil is rapidly depleted by microbes decomposing soil organic matter, and subsequently some bacterial species use the nitrate ions as an oxygen source. Nitrate N is then converted to gaseous forms (N_2 or N_2O) and escapes to the atmosphere. A good way to combat this nitrogen loss and improve the nitrogen recovery is placement of the urea directly into the low-oxygen layer. There urea N is only converted to NH_4^+ ions that are, in contrast with anions like NO_3^- to some extent protected against leaching because they are retained by the soil through adsorption at the surfaces of negatively charged clay and organic matter particles (the process of ion adsorption will be discussed in some detail in Section 5.3). Placement of urea in the puddled surface layer may well bring the recovery of nitrogen to a value of 0.5 or higher. In general, losses of fertilizer N can be reduced and recovery improved, if only small doses of fertilizer are given at a time, so that most of the nutrient applied can be absorbed by the roots in a relatively short time. Therefore, repeated application of smaller doses spread over the growing season ('split application') is often superior to application of all fertilizer in one dressing.

Exercise 60

The Technical Division of the Thai Rice Department in Bangkok has conducted fertilizer experiments with bunded rice to investigate the recovery of nitrogen from different types of fertilizer, applied at different moments and in different ways (Lusanandana et al., 1966). Nitrogen application was 60 kg ha^{-1} on all fields. In addition, each field received phosphorus at a rate of 26 kg ha^{-1} and potassium at a rate of 50 kg ha^{-1} at the beginning of the growing season to eliminate the possibility of P or K shortages.
Table 45 presents essential information on the different treatments, as well as grain and straw yields and the results of chemical plant analyses.

- Examine carefully the different treatments tested in this experiment. Note that four different nitrogen fertilizers were used, applied either at transplanting or at the time of ear primordium initiation, and at three modes of application.
- Calculate for each treatment the P/N ratio at the time of primordium initiation. Answer the following questions:
  Do the P/N ratios indicate that nitrogen availability is the growth – limiting factor in this experiment? Are there indications that N fertilization at transplanting (16 July) has a measurable beneficial effect on production at the time of primordium initiation (21 September)?
- Calculate the grain – straw ratios at harvest time. Are the rice varieties used in the experiment modern HYV's or traditional long – straw varieties?
  What does this mean for the slope of the yield-N uptake curve? Check your answer by calculating this slope with the results obtained for one or more of the treatments.

Table 45. Nitrogen and phosphorus concentration at primordium initiation, and in grain and straw at harvest; and dry weight of grain and straw of Thai rice varieties at different fertilizer treatment.

Treatment	Harvest at primordium initiation (21 September 1966)			Final harvest (22 November 1966)			
	dry weight (g)	N ($kg\ kg^{-1}$)	P ($kg\ kg^{-1}$)	grain weight ($kg\ ha^{-1}$)	N ($kg\ kg^{-1}$)	straw weight ($kg\ ha^{-1}$)	N ($kg\ kg^{-1}$)
A Ammonium sulphate 16 July 1966; in rows at 5 cm depth	8.51	0.0186	0.0012	3335	0.0086	12410	0.0032
B Urea, 16 July 1966; in rows at 5 cm depth	8.32	0.0178	0.0013	3325	0.0089	11825	0.0032
C Ammonium nitrate 16 July 1966; in rows at the surface	7.26	0.0168	0.0012	2685	0.0088	9585	0.0036
D Sodium nitrate 16 July 1966; in rows at the surface	5.31	0.0156	0.0014	2300	0.0091	5785	0.0036
E. Ammonium sulphate 21 September 1966; broadcast on surface	7.17	0.0281	0.0014	3015	0.0099	8840	0.0040
F Urea, 21 September 1966; broadcast on surface	5.72	0.0255	0.0013	2900	0.0094	7555	0.0039
G Ammonium nitrate, 21 September 1966; broadcast on surface	5.74	0.0271	0.0015	2775	0.0088	7185	0.0038

Table 45. (continued)

Treatment	Harvest at primordium initiation (21 September 1966)			Final harvest (22 November 1966)			
	dry weight (g)	N (kg kg^{-1})	P (kg kg^{-1})	grain weight (kg ha^{-1})	N (kg kg^{-1})	straw weight (kg ha^{-1})	N (kg kg^{-1})
H Sodium nitrate, 21 September 1966; broadcast on surface	5.35	0.0251	0.0014	2740	0.0091	6790	0.0035
K Control (blanket) dressing only				1930	0.0091[a]	4085	0.0036[a]

[a] Estimated value.

(Source: Lusanandana et al., 1966).

- Calculate the total nitrogen uptake for each of the treatments and for the control (on the basis of above – ground parts). Then, calculate the nitrogen recovery realized in each of the eight treatments and answer the following questions:

a. Are the recoveries realized under Treatments A and B satisfactory? If so, can you explain why (for both treatments)?
b. Compare the recoveries realized in Treatments C and D.
Is there reason to expect high losses of fertilizer nitrogen in these treatments? Can you explain the difference in N recovery between Treatment C and Treatment D?
c. Compare the N recoveries realized in Treatments D and H, where sodium nitrate was applied at different stages of the growth cycle. Can you explain the difference in nitrogen recovery if you consider for each treatment the competitive position of the plant relative to other processes removing nitrogen from the root zone?
d. It has been stated in this section that N recovery from urea, broadcast at the time of transplanting is often lower than 0.2. Consider the N recovery realized under Treatment F and explain why you have found a different recovery value.

4.2.4 The nutrient requirement from fertilizer

The quantity of fertilizer that must be applied to realize Production Situation 2, can now be established. It has been discussed in which way the limiting element can be identified. In Section 4.1 the minimum concentrations of the three elements in the relevant plant parts are given. The total uptake of a certain element required for maximum production can therefore be calculated by multiplying the dry weights of economic product and crop residue calculated for Production Situation 2, with the respective minimum nutrient concentrations. Part of the total required uptake is covered by the natural soil fertility or base uptake. This base uptake is established through analysis of the production obtained on an unfertilized field. The difference between the required uptake at Production Situation 2 and base uptake must be supplied as fertilizer nutrient, the recovery of which is established for a given situation by making use of published fertilizer experiments.

This recapitulation demonstrates that the quantity of fertilizer nutrient needed to create Production Situation 2, i.e. the 'fertilizer nutrient requirement', D_x, can be quantified by subtracting from the calculated total uptake under Production Situation 2, $u_{m,x}$, the uptake under unfertilized (control) conditions, $u_{o,x}$, and subsequent division by the recovery fraction, R_x. In a mathematical notation:

$$D_x = (u_{m,x} - u_{o,x})/R_x \tag{80}$$

Earlier in this section it was shown that the same nutrient can be supplied by different fertilizer materials. In the case of nitrogen, urea, ammonium fertilizers and nitrate fertilizers have been mentioned, but others, both chemical and 'natural' (e.g. farmyard manure) are available. Table 46 lists some common commercial fertilizers and their concentration of pure nutrient. From this table it may be deduced that a calculated nitrogen fertilizer requirement of 100 kg ha^{-1} can be met with an application of 100/0.21 kg ammonium sulphate, but also with 100/0.45 kg urea, provided that nitrogen recovery is the same from both sources. This difference partly explains the popularity of urea as a nitrogen source, especially when transport costs are high.

Exercise 61

In Exercise 57 an experiment with a HYV near Paramaribo, Suriname was treated. Assume that in that experiment nitrogen availability is the growth determining factor at any level of production. Assume furthermore that urea is used as a fertilizer and that the recovery fraction from this N source is 0.55. Dry – grain yield of an unfertilized field was 1000 kg ha^{-1}.

- Calculate the total N uptake required to realize the production calculated for Production Situation 2. Grain weight and total above – ground dry weight at maturity are given in Subsection 2.3.2.
- Calculate the slope of the yield – N uptake relation and the nitrogen uptake if fertilizers are not used.
- Calculate the nitrogen requirement of the crop and decide how many 25 kg bags of urea you must reserve for one hectare. (Use Table 46).

So far the concept of nutrient requirement was illustrated using nitrogen as the limiting element and Production Situation 2 as the pursued production target. It is well possible, however, that a farmer is not interested in producing the maximum yield of Production Situation 2, e.g. if there is no market for all the produce. He may then aim at a lower yield and adapt his fertilizer use accordingly.

It is also possible that crop growth is not limited by nitrogen supply but by the supply of some other nutrient. Experience has shown that in many such cases phosphorus supply is the limiting factor. Then, the phosphorus requirement can be calculated with Equation 80, i.e. by quantifying the total phosphorus uptake needed to realize the production target, subtracting from that amount the uptake of P from an unfertilized field and dividing by the P recovery fraction. The calculation procedure is identical for any nutrient but

Table 46. Common commercial N and P-fertilizers and their nutrient concentration.

Nitrogen fertilizers	*N concentration (kg kg^{-1})*
Ammonium sulphate	0.21
Urea	0.45
Ammonium nitrate	0.33
Sodium nitrate	0.16
Calcium nitrate	0.155
Calcium ammonium nitrate	0.205
Phosphorus fertilizers[a]	***P concentration (kg kg^{-1})***
Superphosphate	0.08
Triple superphosphate (T.S.P.)	0.20
Rock posphate[b]	0.16

Data from De Geus, 1973; ILRI, 1972; Jacob and V. Uexküll, 1958.

a) Phosphorus contents are often expressed in P_2O_5; 1 kg P_2O_5 corresponds with 0.44 kg P.
b) Phosphorus contents of phosphate rocks vary greatly; the P-content given refers to Christmas Island Rock Phosphate (C.I.R.P.)

the behaviour of the different nutrients in the soil – plant – atmosphere system is not. Unlike nitrogen, phosphorus is in general not lost from the system in significant amounts. Its chemistry in the soil is, on the whole, more complicated than that of nitrogen and that is often reflected in non – linear application-uptake curves. Levelling off at higher application rates, as signalled in Section 4.1 and illustrated in Figure 45, is not uncommon. It should be realized that in situations with non – linear application – uptake relations, nutrient recovery is not independent of the fertilizer application rate anymore! Most problems with phosphorus recovery are related to the low solubility of many P compounds. Low P solubility may be due to a secondary reaction in the soil solution, e.g. precipitation of phosphorus from a soluble fertilizer as insoluble calcium, iron or aluminium phosphates, but there are also P fertilizers that are themselves hardly soluble such as rock phosphates. P recovery from rock phosphate is therefore commonly less than 0.05 (Penning de Vries & van Keulen, 1982), but it does have the advantage that the effect may persist for quite some years even after only one application. Obviously such low recoveries are inadequate to make rock phosphate a suitable fertilizer for realizing Production Situation 2. By treating rock phosphate with sulphuric acid, the fertilizer industry produces so-called superphosphate which has a higher P concentration than rock phosphate and is more readily soluble. Consequently, P recovery from superphosphate is higher than from rock phosphate. A recovery of 0.3 may be obtained on some soils, but on soils that strongly immobilize phosphorus, recovery from superphosphate is still very low. Phosphorus immobilization in soils is complex and difficult to predict. As a first approximation, Table 47 lists a number of common soil groups arranged according to the phosphorus recovery that may be achieved if they are cropped with an annual crop, optimally supplied with water and nitrogen.

In production situations where water may at times be in suboptimum supply, recovery may be lower due to the reduced activity of plants under water stress. The uncertainty with respect to phosphorus availability in soils makes it generally advisable to be generous in the estimation of P requirements. Especially as too much phosphorus does not do any harm and what is not taken up on short notice is added to the phosphorus stock of the soil and may be used by a subsequent crop. This does not apply to soils that strongly immobilize phos-

Table 47. Indicative P recovery fractions of superphosphate applied to a grain crop. The soils are arranged according to decreasing P recovery.

Class	Recovery fraction ($kg\ kg^{-1}$)	Soil type
I	0.30-0.15	— quartzitic sandy soils — organic soils/peats — young, neutral, coarse and medium-textured alluvial soils
II	0.15-0.08	— weakly acid to neutral alluvial clay soils of intermediate age — weakly acid to neutral soils with a thick black organic surface layer — weakly or medium acid well structured clay soils — churning heavy clay soils — neutral to weakly alkaline, calcareous soils
III	0.08-0.02	— permanently waterlogged mucky soils, low in bases — old acid red and/or yellow soils, rich in iron and aluminium — very acid leached 'podzol' soils, rich in iron — strongly acidified soils in pyrite-containing marine sediments, rich in aluminium — young brown or black volcanic soils, rich in allophanes

phorus. With them the availability of fertilizer – P decreases dramatically in the course of time.

Exercise 62

In Exercise 61 the nitrogen requirement of a HYV rice near Paramaribo, Suriname, was calculated under the assumption that nitrogen availability determined crop growth. In this exercise it is assumed that the availability of phosphorus is the limiting factor at any level of production.

- Calculate the total P uptake under Production Situation 2. Grain weight and above – ground dry weight at maturity are given in Subsection 2.3.2. Minimum P concentrations in grain and straw dry matter are 0.0011 kg kg^{-1} and 0.0005 kg kg^{-1}, respectively.
- Calculate the slope of the yield – P uptake relation and the phosphorus uptake if fertilizers are not used. Assume a dry – grain yield on the control plot of 1000 kg ha^{-1}.
- Calculate the P requirement of the crop and the quantity of rock phosphate that must be applied for realization of Production Situation 2. Assume that P recovery from rock phosphate is 0.02 kg kg^{-1} (Consult Table 46).
- Calculate how much triple superphosphate (TSP) would have to be applied to realize Production Situation 2. Assume a P recovery from TSP of 0.15 kg kg^{-1} (Consult Table 46).
- Assume that there is a rice glut and that the production target is lowered to 0.8 times the production calculated for Production Situation 2. How much TSP would have to be applied then? Explain why this quantity is less than 0.8 times the amount needed to realize the production calculated for Production Situation 2.

So far it was assumed that only one nutrient is in short supply: the nitrogen requirement was discussed for a situation with phosphorus sufficiency or the phosphorus requirement for a situation where nitrogen supply was optimal. It is, of course, possible to create such conditions, e.g. by applying a generous P dressing at the beginning of cropping in a situation where nitrogen supply is known to be limiting. There would be little risk involved in a high P application, but the same cannot be said of a high blanket dressing of nitrogen if phosphorus is known to be in short supply. Excessive nitrogen losses could be the undesirable result. It is therefore necessary to establish the need for nitrogen fertilizers, if the P concentration of the plant is known to be limiting, and the P fertilizer requirement in the reverse case. It was shown in Section 4.1 that relative nutrient shortage is witnessed by the ratio of element concentrations in the plant tissue. In the case of phosphorus and nitrogen, the P/N ratio varies between a maximum of about 0.15 and a minimum of about 0.04. This knowledge can be put to use: if, for instance, the availability of phosphorus is limiting, the overall P concentration of an unfertilized grain crop with a grain straw ratio of 1.0 has a minimum value of:

$$\frac{1 \times 0.0011 + 1 \times 0.0005}{2} = 0.008 \text{ kg kg}^{-1}$$

Its overall N concentration cannot be higher than 0.0008/0.04 = 0.02 kg kg^{-1}. It is also unlikely that the nitrogen concentration is much lower than 0.02, because N uptake is not dictated by nitrogen availability but is entirely a function of P availability. Addition of P would probably result in further nitrogen uptake without any addition of nitrogen fertilizer (see also Figure 50 in Section 4.1).

Assume that in a particular situation the dry–grain yield and dry–straw production of an unfertilized crop are 1000 kg ha^{-1} and that for Production Situation 2 the calculated grain yield equals 5000 kg ha^{-1} and the straw yield also 5000 kg ha^{-1}. Let TSP be used as a P fertilizer and assume a recovery of 0.1 kg kg^{-1}. From this information the fertilizer phosphorus requirement, D_P, can be established according to Equation 80:

$$D_P = ((5000\text{x}0.0011 + 5000\text{x}0.0005) - (1000\text{x}0.0011 + 1000\text{x}0.0005))/0.1$$

Hence, D_P amounts to 64 kg ha^{-1}, which can be satisfied with TSP at a rate of 320 kg ha^{-1}.

To quantify an accompanying N fertilizer application to ensure optimum nitrogen supply at the high production level of Production Situation 2, the same reasoning is followed. However, it would be unrealistic to estimate N uptake from an unfertilized field on the basis of minimum N concentrations, because the real (overall) N concentration of the control material has already been estimated. Let ammonium sulphate be the selected N fertilizer with an N recovery (established under conditions of mineral element sufficiency) of 0.5 kg kg^{-1}. Then the maximum possible fertilizer nitrogen requirement amounts to:

$$D_N = \frac{5000 \text{ x } 0.01 + 5000 \text{ x } 0.004) - (2000 \text{ x } 0.02)}{0.5} = 60 \text{ kg ha}^{-1}$$

This requirement can be satisfied with an ammonium sulphate application of 286 kg ha^{-1}. Compared with a calculation based on assumed minimum N concentrations in an unfertilized situation, this represents a reduction in calculated fertilizer input by no less than 114 kg ha^{-1}.

It should be realized that the so calculated N requirement guarantees N sufficiency at a production as calculated for Production Situation 2, but that there is still a likely overestimation of the N requirement. The total N uptake from an unfertilized field (now estimated at 2000 x 0.02 = 40 kg N ha^{-1}) was limited by P deficiency and could conceivably have been higher in a situation with P sufficiency. In other words: natural soil fertility may contribute more than 40 kg N ha^{-1} if the TSP has been applied as calculated.

The practical consequences of this – mild – overestimation are normally not prohibitive. It appears that, in general, the stock of readily available nitrogen is rapidly exhausted and that withholding N fertilization for only one or two years creates already a situation where P is in sufficient supply and N is limiting. In normal soils that do not strongly immobilize phosphorus, a comparatively small maintenance application of P fertilizer will suffice to maintain P sufficiency once a favourable phosphorus level has been established. To what extent a certain soil immobilizes P, how high the maintenance dose of a certain P fertilizer should be, and for how long that maintenance dose would probably ensure P sufficiency, can only be judged (in a rather qualitative way) if analyses of soil chemical conditions and soil mineralogical composition are available. Some attention will be paid to this in Section 5.3. In practice, maintenance applications are largely a matter of experience, gained from years of fertilizer experiments and transferred to the farming community by agricultural extension services.

Above, a situation was considered in which P availability limits plant growth in an unfertilized situation (sufficient N available to realize the control yield but no guaranteed N sufficiency at Production Situation 2). There is no need to argue that the same reasoning applies – with the respective differences considered – to a situation in which the control yield is dictated by nitrogen shortage and P sufficiency at Production Situation 2 is uncertain.

Exercise 63

In Exercise 60, an experiment with traditional rice varieties at Bangkhen Experiment Station, Thailand, was considered. In that experiment different N fertilizers were applied at various moments and with different application techniques. To make sure that the effects of nitrogen application were not blurred by P shortage, superphosphate was given to all fields at the time of transplanting. The P application of this blanket dressing was 26 kg ha^{-1}. The value of that P application can now be judged (refer to Exercise 60 and Tables 45 and 47).

- Calculate the total N uptake from the control plot and divide this value by the total dry weight of grain and straw to establish the overall N concentration of the dry matter produced under control conditions. Assume a moisture content of 0.12 kg kg^{-1} in the field produce.
- Was the control yield limited by nitrogen shortage? If so, approximate the maximum possible P concentration of the dry control material at harvest

by multiplying the overall N concentration with the appropriate P/N ratio.

- The total P uptake by the control plot can now be estimated.
- The crop under treatment A (Table 45) produced the highest amount of plant matter, viz. 3335 kg grain plus 12410 kg straw. Assume an average moisture content of 0.12 kg kg^{-1} and calculate the total P uptake, which is minimally required to realize the dry matter production in Treatment A (minimum P concentrations of dry grain and straw are 0.0011 and 0.0005 kg kg^{-1}, respectively).
- Bangkhen Experiment Station is situated on soils belonging to the Rangsit Soil Series. This soil has, under inundated conditions, properties which place it in the upper half of P recovery class II in Table 47. Calculate the P requirement for the production as obtained under Treatment A. Assume a P recovery from superphosphate of 0.15 kg kg^{-1}.
- Was the blanket phosphorus dressing of 26 kg ha^{-1} a realistic one?