Fertilizer Research **44**: 37–49, 1996.

Nitrogen, phosphorus and potassium relations in five major cereals reviewed in respect to fertilizer recommendations using simulation modelling

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Key words: millet, sorghum, rice, maize, wheat, nutrient harvest index, post-anthesis nutrient uptake, recovery fraction, simulation modelling

Abstract

In land use plans, fertilizer recommendations are indispensable to avoid soil nutrient depletion or soil water pollution. Nutrient relations of five cereals have been evaluated on the basis of a literature review with the aim of arriving at such fertilizer recommendations at regional level. Nutrients considered were nitrogen, phosphorus and potassium for millet, sorghum, maize, rice and wheat. The relevant nutrient relations are fertilizer nutrient application to nutrient uptake, and nutrient uptake to crop yield. In addition, post-anthesis nutrient uptake is considered. Subsequently, obtained results are used in simulation modelling exercises to calculate the time required to attain an equilibrium nutrient balance and to investigate the effect of erosion control and straw recycling. Although fertilizer requirements could be assessed for each of the five cereals, monitoring of nutrient supply from natural sources remains necessary. Moreover, research on fertilizer use should focus on improvement of fertilizer recoveries and multiperiod models for both N and P uptakes by crops to allow quantitative land use planning where the time scale is included.

Introduction

Analysis of the relation between crop production and nutrient availability during the last decades has shown that even in drier parts of the world, nutrients are often the most limiting factor for crop growth (Penning de Vries and Djitèye, 1982; Piéri, 1989; Seligman and van Keulen, 1992; Stangel *et al.*, 1994). In addition to uptake by crops and their subsequent removal from the field, nutrients are also constantly removed by wind and water erosion, leaching to deeper soil layers, and for nitrogen by ammonia volatilization and denitrification. Hence, in the absence of replenishment through chemical or natural fertilizers, soil nutrients are depleted. This results in lower crop yields as demonstrated in long-term experiments (e.g. Cretenet *et al.*, 1994; Pichot *et al.*, 1981; Steiner and Herdt, 1993). Farmyard manure as the only fertilizer is not always a feasible alternative because of quality and quantity aspects, especially when the animals are fed on (over-exploited) natural pastures, with (very) low nutrient contents (Cretenet *et al.*, 1994; Romney *et al.*, 1994; van den Broek and Gbégo, 1994). Moreover, a considerable part of the nutrients in manure that is transported from one site to another and stored, may be lost (de Haan, 1992; Powell *et al.*, 1994; Romney *et al.*, 1994). Consequently, with the increasing population in many developing countries, attainment of food self-sufficiency becomes increasingly difficult without the use of inorganic fertilizer. Despite national fertilizer recommendations in many developing countries (Euroconsult, 1989; IFA, 1992; KARI, 1993], chemical exhaustion of soils still continues (Cretenet et al., 1994; Stoorvogel and Smaling, 1990; van Reuler and Prins, 1993) as the use of inorganic fertilizers is restricted by such factors as marketing constraints and long distances from importer to farmers (Stangel *et al.*, 1994; Thompson and Baanante, 1988; van den Broek and Gbégo, 1994).

To derive fertilizer recommendations, expensive and time-consuming fertilizer experiments are carried out, of which two types can be distinguished. The first is of the dose-response type, where the fate of the fertilizer nutrients applied is not part of the analysis. The other type includes determination of nutrient contents in the various crop parts, allowing establishment of two crucial relations: (i) that between nutrient application and nutrient uptake and (ii) that between nutrient uptake and yield (de Wit, 1953; van Keulen, 1977). The relation between nutrient application and nutrient uptake generally shows that only a fraction of the nutrients applied is taken up by the crop (apparent recovery fraction), while the remainder is lost in various processes (e.g. leaching, ammonia volatilization, denitrification and irreversible fixation) or contributes to the nutrient store of the soil. The relation between nutrient uptake and yield reflects the efficiency of nutrient utilization expressed in economic product (e.g. grains).

Considering the quantity of data available from the latter type of fertilizer experiments (cf. van Duivenbooden, 1992), it may be questioned whether it is necessary to continue expensive dose-response experiments, or that generally applicable nutrient relations can be used to formulate fertilizer recommendations. In this paper, an attempt is made to answer this question by evaluating results of nitrogen, phosphorus and potassium fertilizer experiments on five major cereals. They also form the basis for identification of general crop nutrient uptake characteristics, as they may determine crop selection in land use plans. Dynamics of fertilizer recommendations are included in scenarios to illustrate the importance of erosion control, recycling of organic material in the field, and type of fertilizer (for P) as relevant aspects of a land use plan. Finally, brief recommendations are made on further fertilizer experiments with the aim of increasing the total nutrient use efficiency ((nutrient taken up/nutrient applied) × (yield/nutrient taken up)).

N, P and K have been selected, because they are often the first limiting nutrients. Although the elements are interacting in the plant (de Wit, 1992; van Duivenbooden, 1992; van Keulen and van Heemst, 1982), results are presented for each element separately for simplicity reasons. The tropical grain crops considered are millet (*Pennisetum americanum* (L.) Leeke, synonym *P. thyphoides* (Burm.), Stapf & Hubb.), sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays* L.) and rice (*Oryza sativa* L.). Although wheat (*Triticum aestivum* L.) is a temperate crop and is mainly grown at higher altitudes in the tropics, it is included because it is increasingly consumed in the tropics, leading to increased interest in its growth and (potential) yield. Moreover, much is known about its morphology and physiology.

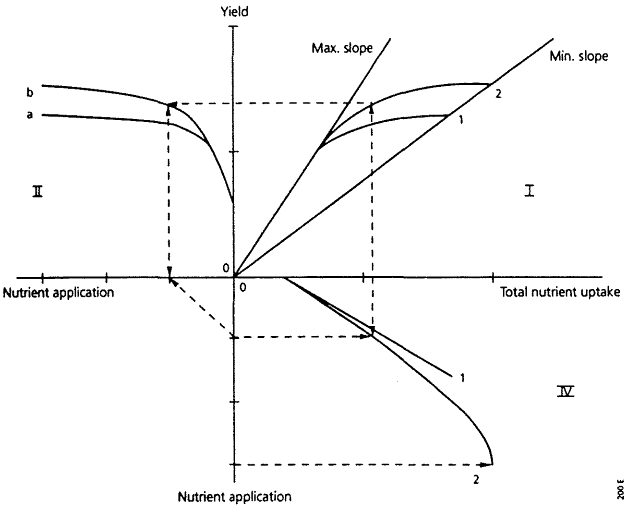

Fig. 1. Schematic graphical presentation of the relation between total nutrient uptake (Uf) and yield (Y) (Quadrant I), that between nutrient application (Af) and nutrient uptake (Quadrant IV), and that between nutrient application and yield (Quadrant II) [all kg ha^{-1}].

Analyses and data

Fertilizer experiments are analysed on the basis of two relations, i.e. that between nutrient application and aboveground crop nutrient uptake (equal to crop nutrient content) and that between nutrient uptake and crop yield. These relations are best illustrated in so-called three quadrant diagrams (Figure 1; cf. de Wit, 1953):

a. Quadrant II shows the mirror-image of the classical response curve: the relation between the amount of a nutrient applied and crop yield.
b. Quadrant I shows the relation between crop nutrient uptake at maturity and crop yield. Generally, the relation is linear at low uptake levels, reflecting that under conditions of limited supply the crop makes maximum use of the nutrient that is taken up (minimum concentration). This linear part of the line represents the maximum slope or initial nutrient use efficiency (INUE) [kg grain per kg nutrient]. It is calculated by:

$$
\begin{aligned}
INUE &= HI \\
&\quad \times\ 100/((HI \times NU_{min}grain) \\
&\quad +\ (1 - HI)\times NU_{min}straw) \qquad (1)
\end{aligned}
$$

where,

$HI = harvest\ index\ (grain\ dry\ matter\ /total\ aboveground\ dry\ matter)\ [-];$
$NU_{min} = minimum\ nutrient\ contents\ [\%].$

At higher nutrient uptake levels the line deviates from linearity, reflecting higher concentrations of the element in plant tissues at maturity. Finally, it levels off, indicating that the element under consideration is no longer a constraint for unrestricted growth. If higher uptake does not lead to increased yield, the additional uptake can be considered as 'luxury consumption' (van Keulen and Seligman, 1987). The level of the plateau is determined by the growth factor in short supply and is, in the 'potential growth' situation (no water or nutrient shortages, and in the absence of weeds, pests and diseases), a function of temperature and available solar energy during the crop's growth period (van Keulen, 1982). In addition to this envelope, representing 'best' nutrient utilization, a second line is drawn, referred to as the minimum slope, i.e. the situation with maximum nutrient concentrations in crop tissues.

c. Quadrant IV shows the relation between the amount of a nutrient applied and crop nutrient uptake, from which two characteristics can be derived:
   - the supply from natural sources and residual effects of nutrients applied in preceding years. It is represented by crop nutrient uptake in the absence of nutrient application in the year under consideration, and equals the intercept with the nutrient uptake axis.
   - the (apparent) recovery fraction (RE), representing the proportion of nutrients applied taken up by the crop. This characteristic depends on fertilizer type, time and method of application and environmental conditions, and is defined as the ratio of the difference in crop nutrient uptake at application A_f and zero fertilizer application, and A_f. It is best calculated by linear regression of total nutrient content at harvest on fertilizer application, for the whole range of fertilizer applications.

The relation between nutrient application and nutrient uptake generally appears to be linear over the full range of application rates for nitrogen and potassium. For phosphorus, the relation may either be linear or curvilinear (van Keulen and van Heemst, 1982). In the latter case, only the more or less linear part is considered in this study. The linearity suggests that all processes that compete for the nutrient, such as uptake, chemical and microbiological fixation, leaching (and for N denitrification) can be described by first order reactions, i.e. with rates proportional to concentration. However, uptake shows diminishing returns when maximum tissue contents are approached, due to a limited capacity to take up, transform and synthesize the nutrient in structural biomass. This occurs, however, generally at fertilizer application rates beyond the optimum range (de Wit, 1994).

To distinguish between farmyard (and other forms of organic) manure and inorganic fertilizer as a source of nutrients for the crop, treatments with and without organic amendments should be presented separately in this quadrant. The effect of manure application in terms of nutrient supply is then represented by the distance between the intercepts with the nutrient uptake axis.

The fertilizer response is thus characterized by the minimum and maximum nutrient contents in grain and straw, the harvest index, the plateau of the uptake-yield curve at high nutrient supply, the recovery fraction and the uptake of nutrients in the absence of fertilizer application.

Although three quadrant diagrams are originally intended for monofactorial experiments (either N, P or K; (de Wit, 1953)), results of compound fertilizers have been included in this study (e.g. N recovery for NP fertilizer) because of the scarcity of monofactorial experiments in combination with nutrient uptake data. Moreover, a mixture of inorganic fertilizers is generally applied in agricultural practice. Compared to monofactorial experiments, this results in an increase in: (i) uptake in the situation that the nutrient under consideration is not supplied (point 1 to 2, Figure 1); (ii) the recovery fraction because of positive interactions between the uptake of different nutrients (de Wit, 1992) and (iii) yield level (line a to b).

With respect to data used in the analysis, the agro-ecological demands of the five grain species considered are so different that direct comparison at the same location under the same experimental conditions is meaningless. Therefore, a statistical approach has been taken, in which for each of the species and for all available locations the two relations are analysed.

To ensure that the data refer more or less to the agroecological domain of the species, only field experiments have been considered and (except for rice) little attention was given to experimental results under irrigated conditions. Data were obtained from literature, either directly from tables or derived from graphs or histograms. Where basic data were missing (e.g. straw weight and concentration were not available, but total N uptake was reported) no attempts have been made to retrieve those by contacting authors. For a complete bibliography of the experiments, reference is made to van Duivenbooden (1992).

As a detailed discussion of individual data is not feasible here, pooled data have been analysed, despite inter-species and intra-species differences in experimental conditions (soil, weather and fertilizer treatments) and genetic properties which may cause considerable variation. Results were analysed with the statistical language Genstat (Payne *et al.*, 1988). Homologous means were compared with Wilcoxon's rank sum test (two sided, $p = 0.05$; (Hollander and Wolfe, 1973)). It should be noted that the way in which the data have been collected does not permit derivation of statistical proof of the existence of a relationship within a crop or of some difference among the species, because of the inherently different environmental conditions for the five species. The statistical procedures only check whether an apparent effect might have been caused by a selected simple chance mechanism (no spurious relation) rather than by an actual effect. Observed relations within a crop indicate that the underlying mechanism acts independently of environmental conditions.

To study dynamics of fertilizer application, a modelling approach is used. Many crop simulation models have been developed for one growing season, where either N or P uptake is included (de Willigen and van Noordwijk, 1987; Sedogo, 1993; van Duivenbooden and Cissé, 1989; van Keulen and Seligman, 1987; van Noordwijk and Wadman, 1992; van Noordwijk *et al.*, 1990). Here, however, two multiperiod models are used, each including the various pools of either N or P in the soil (Wolf *et al.*, 1987; Wolf *et al.*, 1989), to simulate N and P fertilizer application requirements (to our knowledge, such a model is not available for K). As it is beyond the scope of this paper to describe these models in more detail, reference is made to the original articles.

Results and discussion

General fertilizer response characteristics

The general fertilizer response characteristics based on 50 to 100 experiments for each of the species and nutrients are summarized in Table 1. This table shows that for rice the minimum nitrogen content of the seed is 0.97% and of the straw 0.44%. These values appear to be characteristic for the species and largely independent of growing conditions (van Keulen, 1977; van Keulen, 1982). Hence, at an average harvest index of 0.44 (n is about 400), the maximum slope of the yield-uptake curve (Figure 1, Quadrant I) equals 65 kg seed/kg N. Maximum N contents of seed and straw are 1.36 and 0.82%, respectively, so that at the same harvest index, the minimum slope is 42 kg seed/kg N. At about an average slope, both extremes, i.e. a limited supply of nitrogen and luxury consumption are avoided, so that for a target yield of 1000 kg ha^{-1}, N uptake has to be about $2 \times 1000 / (65 + 42) = 18.5$ kg ha^{-1}. Similarly, P and K uptake for the same target yield have been calculated at 2.5 and 24.7 kg ha^{-1}, respectively.

Similar calculations for the other four grain species (Table 1) indicate that the uptake levels necessary to reach a certain target yield are lowest for rice, because of its generally highest harvest index and because the kernel is enclosed by a husk with a nutrient content that is about equal to that of straw. The high value for millet is due to the high N content in the straw, which is a much appreciated animal feed.

Harvest index and yields that can normally be realized under a sufficient supply of nutrients can be determined in simple fertilizer experiments that do not require analyses of nutrient contents in seed and straw. It is then possible to calculate on the basis of the data in Table 1 the uptake values necessary to attain such yields. For instance, for a target millet grain production of 2500 kg ha^{-1}, an uptake of 87 kg N, 13 kg P and 122 kg K ha^{-1} is required, whereas for the same target yield for maize only 59 kg N, 9 kg P and 42 kg K ha^{-1} would have to be taken up. Explicit selection of the most suitable cereal in a land use plan can then be made on the basis of soil fertility characteristics.

Furthermore, if crop material is analysed for either N or P, the other can be calculated by means of the P/N ratio. Note that this value exceeds the P/N value of 0.10 obtained for annual grasses (Penning de Vries and Djitèye, 1982). One of the explanations for these higher values is different nutrient relations, such

Table 1. Harvest index and fertilizer response characteristics of five major cereals based on statistical averages of 50–100 experiments. Different letters ($^{d-f}$) denote a significant difference at 95% probability for each characteristic. s.e.: standard error.

	Millet	Sorghum	Maize	Rice	Wheat
Harvest index [-]					
minimum[a]	0.16	0.25	0.25	0.34	0.35
maximum[a]	0.40	0.56	0.56	0.55	0.49
average	0.26^{d}	0.27^{d}	0.42^{e}	0.44^{e}	0.41^{f}
s.e.	0.08	0.11	0.12	0.08	0.07
Nutrient contents [%]					
Nitrogen					
Grain – minimum	1.47	1.26	1.21	0.97	1.62
Grain – maximum	2.35	2.02	1.87	1.36	2.65
Straw – minimum	0.38	0.39	0.48	0.44	0.30
Straw – maximum	1.07	0.94	0.91	0.82	0.69
Phosphorus					
Grain – minimum	0.24	0.18	0.21	0.10	0.25
Grain – maximum	0.37	0.34	0.40	0.27	0.49
Straw – minimum	0.05	0.03	0.03	0.05	0.03
Straw – maximum	0.13	0.12	0.14	0.19	0.08
Potassium					
Grain – minimum	0.39	0.25	0.20	0.22	0.33
Grain – maximum	0.63	0.46	0.53	0.54	0.66
Straw – minimum	1.27	0.57	0.68	1.18	1.06
Straw – maximum	2.01	1.61	1.88	2.70	1.92
Yield-uptake[b] [kg seed kg nutrient^{-1}]					
Nitrogen – minimum	19	22	32	42	27
Nitrogen – maximum	39	43	53	65	49
Phosphorus – minimum	135	151	169	195	165
Phosphorus – maximum	262	383	398	611	341
Potassium – minimum	16	21	32	25	29
Potassium – maximum	25	56	88	56	54
Uptake for target yield[b] of 1000 kg grain ha^{-1}					
Nitrogen	34.6	30.7	23.4	18.7	26.3
Phosphorus	5.0	3.7	3.5	2.5	3.9
Potassium	48.8	26.0	16.6	24.7	24.1
P/N ratio	0.14	0.12	0.15	0.13	0.15
Average recovery fraction [-]					
Nitrogen	0.40^{d}	0.35^{d}	0.36^{d}	0.39^{d}	0.42^{d}
s.e.	0.21	0.15	0.19	0.19	0.20
Phosphorus	0.17^{d}	0.15^{d}	0.12^{d}	0.12^{d}	0.12^{d}
s.e.	0.11	0.09	0.10	0.09	0.09
Potassium[c]	0.38^{d}	-	0.34^{d}	0.34^{d}	0.24^{d}
s.e.	0.20	–	0.19	0.21	0.22

[a] minima and maxima refer to 12.5 and 87.5 quantile, respectively;
[b] at average HI;
[c] relatively few data were available, except for rice.

Table 2. Average value and standard error (s.e.) of relative post-anthesis nitrogen (RNU), phosphorus (RPU) and potassium (RKU) uptake for five major cereals (n = number of observations). Different letters (^{a}–^{c}) denote a significant difference at 95% probability for each characteristic.

	Millet	Sorghum	Maize	Rice	Wheat
RNU	0.35^{a}	0.35^{a}	0.33^{a}	0.18^{b}	0.20^{b}
s.e.	0.19	0.16	0.15	0.17	0.17
(n)	(59)	(96)	(144)	(89)	(221)
RPU	0.30^{a}	0.47^{b}	0.44^{b}	0.10^{c}	0.32^{a}
s.e.	0.21	0.17	0.19	0.10	0.18
(n)	(45)	(40)	(46)	(34)	(52)
RKU	0.17^{a}	0.17^{a}	0.14^{a}	0.18^{a}	0.04^{b}
s.e.	0.13	0.16	0.14	0.17	0.07
(n)	(15)	(14)	(49)	(60)	(29)

Table 3. Average recovery fractions of nitrogen for five major cereals in the various continents. Number of observations between brackets.

Continent	Millet	Sorghum	Maize	Rice	Wheat
Europe	-	-	0.40 (3)	-	0.48 (34)
Africa	0.40 (25)	0.45 (6)	0.51 (11)	0.28 (30)	0.39 (4)
Asia	0.40 (4)	0.38 (9)	0.41 (12)	0.39 (66)	0.45 (22)
North–America	-	0.18 (4)	0.29 (22)	0.53 (1)	0.51 (4)
South–America	-	0.32 (9)	0.32 (42)	0.55 (17)	0.34 (32)
Australia	-	0.35 (9)	0.45 (3)	0.50 (9)	0.43 (12)

as post-anthesis nutrient uptake. Table 2 presents the average relative post-anthesis nutrient uptakes, i.e. the amount taken up after flowering as a fraction of total aboveground nutrient uptake. During the post-anthesis period, average relative uptake of phosphorus exceeds that of nitrogen in sorghum, maize and wheat, but not in millet and rice. Hence, the P/N ratio in the latter two species must have been even higher at anthesis. Consequently, the value of 0.10 cannot be considered optimum for cereals, and a general value of 0.14 is proposed instead.

The average recovery fraction of nitrogen appears for each of the five species close to 0.38, but the standard deviation is considerable (Table 1). In addition, the results per continent show relatively large differences (Table 3) with relatively low recovery fractions for sorghum and maize in North America, for maize and wheat in South America, and for rice and wheat in Africa. It is beyond the scope of this article to explain these differences, but environmental conditions and management may have played major roles. An analysis per agro-ecological zone would have been more appropriate, but was not possible due to lack of information.

High recovery fractions can be realized under favourable growing conditions, allowing a well-developed root system to be active for a long time. Such conditions require optimum values for other nutrients, soil pH and soil moisture. This follows the law of the optimum: 'a production factor that is in minimum supply contributes more to production the closer other production factors are to their optimum' (Liebscher, 1895).

To increase the N recovery fraction, the competitive ability of the crop should be increased. This can be realized, for instance, by split application of nitrogen, adjusted to the uptake pattern of the crop. All five species take up nitrogen after flowering, with highest values for millet and sorghum and lowest for rice (Table 2). This implies that the last N application for millet and sorghum can be given around anthesis, but not for rice.

On the other hand, losses can be reduced. In general, under semi-arid conditions nitrogen is hardly lost by leaching and denitrification, so that the recoveries are high. Under humid conditions, where rainfall exceeds evapotranspiration the opposite generally holds. For rice, for instance, high recoveries can only be achieved if nitrogen is given in reduced form in the anaerobic layer of the irrigated or flooded soil (de Wit, 1953). If urea is given in the aerobic surface layer (or in the flood water), part is lost by volatilization and part is transformed to nitrate and leached to deeper anaerobic layers, where it is subsequently lost by denitrification (Leffelaar, 1987). N losses from the crop at the end of the growing season are more likely to occur under tropical conditions than in temperate regions, i.e. N losses from wheat at the end of the growing season were considerable in Argentina (Echeverria et al., 1992), but negligible in the Netherlands (Spiertz and Ellen, 1978). These N losses (expressed as percentage of maximum content) were, on average, for sorghum 1, for wheat and maize 3, for rice 6 and for millet 10% (van Duivenbooden, 1992). Hence, average N recovery fractions, measured at the moment of maximum N uptake, would only have been slightly different.

The recovery of phosphorus is much lower than that of nitrogen, with an average value of 0.14. Millet and sorghum tend to show higher values than the other three species, but that difference is non-significant (Table 1). The recovery fraction may increase under split application as the average residence time is shorter (van Keulen and Van Heemst, 1982), and because the relative post-anthesis uptake is even higher than that for nitrogen (Table 2).

With respect to losses, soil type determines the proportion of phosphorus fixed in soil particles and incorporated in soil organic matter, as summarized in Table 4. The magnitude of P losses at the end of the growing season is comparable to that of nitrogen, i.e ranging from 0 (sorghum) via 4–5 (millet, maize and wheat) to 9% (rice) (van Duivenbooden, 1992). Consequently, the P recovery fraction at anthesis would only have been slightly higher.

The K recovery fraction is about identical for millet, maize and rice (Table 1). For sorghum no data were available. The relatively low K recovery fraction at maturity for wheat may be explained by the high K loss (between anthesis and maturity) of 35% of the maximum uptake compared to 2 (millet), 7–9 (maize, sorghum) and 13% (rice) (van Duivenbooden, 1992). Taking this into account, the recovery fraction would have been about identical for the four species if calculated at the moment of maximum K content.

As for N and P, the recovery fraction of potassium can be increased by split application. Again, post-anthesis uptake may contribute to total uptake, but for potassium it is lower than for the other two nutrients (Table 2). The low value for wheat may be explained by the fact that translocation of potassium in wheat is governed by storage capacity of the grains rather than K availability (Schenk and Feller, 1990). Although the reason remains obscure, in wheat and sorghum the relative post-anthesis K uptake is positively correlated with that of nitrogen.

A third factor that may play a role in the K uptake relations is the possible substitution between potassium, calcium and magnesium. Calcium regulates osmotic and ionic processes (membranes) and magnesium works as cofactor in enzymatic reactions (Baligar et al., 1990). Evidence may be derived from two observations: (i) in cases where the relative post-anthesis K uptake was zero, uptake of calcium and magnesium continued (Arrivets, 1976; Barraclough, 1984; Gasser and Thorburn, 1972; Jacquinot, 1964) and (ii) the scatter in the relation between K content and aboveground dry matter is substantially reduced by combining the K content with that of calcium and magnesium. For all five species, a linear relation is obtained (van Duivenbooden, 1992), suggesting that if the three elements are available in sufficient amounts, some functions of potassium may be taken over by magnesium or calcium. This confirms earlier findings (De Wit *et al.*, 1963; van Keulen and van Heemst, 1982).

Towards planning of crop species, their use and cultivation

The first question to be answered in land use planning is "what crop is best for an agro-ecological zone? " Sometimes, the agro-ecosystem is so specific that only one crop species can be grown. However, often, more than one crop can be grown, and depending on goals of farmers, a specific crop or a combination is selected. For instance, millet and sorghum are being replaced by maize in the cotton-cereal cropping system in West Africa (Fusillier, 1994). In addition to other selection criteria (e.g. productivity, adaptation to environ-

Table 4. Indicative recovery fraction of phosphorus from broadcast superphosphate, as determined by soil material (Driessen and Konijn, 1992).

Recovery fraction	Soil material
0.30	Quartzitic sand
-	Organic soil material
-	Young, neutral, coarse and medium textured alluvial material
0.15	Young, near neutral alluvial clay
-	Near neutral, strongly humic soil material
-	Vertic 2:1 clays
0.10	Neutral to weakly alkaline, calcareous soil material
-	Old, acid, red or yellow soil material, rich in iron and aluminium
-	Very acid podsolized soil material
-	Strongly acid oxidized pyritic material
0.02	Volcanic soil material, rich in allophane

ment, post-harvest techniques, labour requirements), the variation in nutrient content, harvest index, and post-anthesis nutrient uptake may also be taken into consideration. The importance of these characteristics is highlighted below.

Grains are used for both human consumption and animal feed, while straw is used as animal feed, building material, fuel and mulch to prevent erosion (Okaiyeto, 1984; Quilfen and Milleville, 1983; Richard *et al.*, 1989; Singh and Schiere, 1993; Stangel *et al.*, 1994; Thompson and Baanante, 1988). This implies that both quantity and quality of grain and straw are important. The quality of straw is further examined here.

Maximum N concentrations in the straw of all species, except millet (Table 1), are well below the maintenance requirements of ruminants, i.e. for nitrogen 1.1% (Agricultural Research Council, 1980). Maximum P concentrations are also well below the minimum P requirements, that range from 0.16 to 0.60% in dependence of animal species and growth stage (Guéguen *et al.*, 1989; Kincaid, 1988). Average K concentrations in the straw of all five species, however, exceed largely the dietary K requirements of 0.5 to 0.8%, except for the period of lactation (Kincaid, 1988).

On the basis of the nutrient concentrations only, straw of the five cereals cannot be classified as good feed. Apparently, other characteristics (i.e. digestibility, energy content, palatability) compensate for the nutrient contents. The N and P contents of feed intake can be increased by mixing it with supplements (e.g. (Kaasschieter *et al.*, 1994), but an alternative could be to increase straw quality by specific fertilizer applications. However, fertilizer trials have so far mainly been focused on increased grain production.

Considering the various agro-ecological zones, the range in use of cereals should be safeguarded and selection for a higher harvest index (Donald and Hamblin, 1976) may not be desirable for all agro-ecological zones. Also Sattelmacher *et al.* (1994) conclude that selection for the nitrogen harvest index (which is strongly correlated to HI; e.g. (van Duivenbooden, 1992)) is only promising for conditions where soil fertility is relatively high. Hence, in sub-Saharan Africa, a millet variety with a HI and relative post-anthesis nutrient uptake similar to those for wheat would probably not meet the farmers' requirements. If grain production is the production goal, replacement of millet by maize (Fusillier, 1994) seems appropriate (lower N, P, K uptake per kg grain). This may also be a farmer's adaptation to lower soil fertility.

The importance of post-anthesis nutrient uptake is probably best illustrated by higher yields for sorghum varieties with a shorter pre-anthesis period, despite water stress (Blum *et al.*, 1992). Furthermore, post-anthesis P uptake suggests post-anthesis root growth, because root hairs have to grow to the P source to take up that nutrient (Clark, 1990; Hofland, 1991; van Noordwijk and de Willigen, 1991). Consequently, ratooning belongs to the possibilities for crops with post-anthesis nutrient uptake. Ratoon crops can be attractive under certain climatic or socio-economic conditions, where no second crop can be sown (Doorman, 1991; International Rice Research Institute, 1988). The potential of sorghum as a ratoon crop (cf.

Table 2) has already been recognized in various parts of the world (Escalada and Plucknett, 1977; Purseglove, 1988). Rice, despite its low post-anthesis root growth (cf. Table 2) is also cultivated as ratoon crop, although yields are lower than those of the sown crop (Doorman, 1991; Evatt and Beachell, 1960; International Rice Research Institute, 1988). Results of N fertilizers applied to main and ratoon crops are conflicting, but P fertilizers applied to the main crop resulted in an increase in ratoon yield (International Rice Research Institute, 1988). For the other crops, however, no information was available.

Without trying to be exhaustive in examples, it may be concluded that formulation of production goals of crops, and their cropping techniques (e.g. ratoon crop) for specific agro-ecological zones is important for an optimum setting of fertilizer application rates. Such an approach has been followed in definition of production systems for a region in Mali (van Duivenbooden and Gosseye, 1990; van Duivenbooden and Veeneklaas, 1993).

Towards planning of fertilizer applications

The first step in calculating fertilizer requirements is assessment of nutrient supply from natural sources. This eventually equals crop nutrient uptake on soils that are exhausted by continuous cropping without external amendments. For nitrogen, the only sources are rain and nitrogen fixing organisms and in a sub-Saharan environment (annual rainfall about 600 mm), the supply equals about 4 kg ha^{-1} yr^{-1} (cf. (Penning de Vries and Djitèye, 1982)). For phosphorus, the supply from natural sources also originates from rain (0.4 kg ha^{-1}, cf. (Penning de Vries and Djitèye, 1982)) and from weathering of parent material (3.5 kg ha^{-1} yr^{-1} for a savanna (Nye & Greenland in Steiner, 1991)). Its total supply, however, is estimated at only 1 kg ha^{-1} under non-fertilized conditions (Bationo *et al.*, 1993). For potassium, no data for weathering are found, but Bationo *et al.* (1993) measured a K uptake of 16 kg ha^{-1} in their non-fertilized plots.

Such amounts are only sufficient for grain yields less than 300 kg ha^{-1} (cf. Table 1), with phosphorus being the main limiting nutrient. Hence, in most situations where higher yields are aimed at, nutrient availability has to be increased by the application of manure, inorganic fertilizer, or for nitrogen only the growth of leguminous species, or a combination. Longer fallow periods are not feasible anymore, because of the high demands for crop land. Using the general recovery fractions (Table 1) and the supply from natural sources (including residual nutrients available for plant uptake from prior fertilization), the fertilizer application rates for the target crop yield can now be calculated on the basis of Equation 1. Such recommendations are not accurate enough for an individual farmer, but for large areas without detailed information, this approach provides insight in the required amounts of external nutrients to be imported into a region.

The next step in the calculation of fertilizer requirements, may be based on 'an equilibrium nutrient balance' as often advocated as one of the criteria for sustainability (Stoorvogel and Smaling, 1990; van Duivenbooden and Gosseye, 1990; van Duivenbooden and Veeneklaas, 1993; van Erp and Oenema, 1993). Eventually, this equilibrium situation may be reached, where the fertilizer compensates for crop uptake and losses and soil fertility does not change. However, main questions in land use planning are then how long such a transition period lasts and what the fertilizer rates should be during this period and in the equilibrium situation. This has been analysed on the basis of multiperiod simulation models (Wolf *et al.*, 1987; Wolf *et al.*, 1989). Rice with a target yield of 4000 kg ha^{-1} is taken as an example, and the nutrient relations as presented in Table 1 are applied.

For nitrogen, two scenarios have been examined: (i) for the warm and humid agro-ecological zones with high nutrient losses because of the relatively short growing period and considerable leaching and denitrification, hence, recovery fractions are accordingly low (Scenario I, Table 5) and (ii) drier regions where water supply matches the demand better, so that the recovery fraction is about twice as high. Variations of these scenarios include recycling of crop residues. The amount of nitrogen removed from the field equals total N uptake times the nitrogen harvest index, NHI (calculated similarly to HI, and which significantly varies among the five species at 0.47 for millet, 0.58 for sorghum, 0.61 for rice, 0.66 for maize and 0.74 for wheat (van Duivenbooden, 1992)). Hence, the fraction (1-NHI) can be recycled. In this example, 40% of the nitrogen in the straw is assumed to be recycled in the field.

Due to the low recovery fraction in Scenario I, inorganic fertilizer requirements are excessively high (Table 5). Recycling of straw reduces this fertilizer requirement and the losses to some extent. Assuming a recovery fraction of 0.45 (Scenario II) reduces the inorganic fertilizer requirements by about a factor 2.5 and the losses even more. These values are of the same

Table 5. Simulated inorganic N fertilizer requirements and losses [kg ha^{-1}] in the course of time [yr] to allow N uptake of 75 kg ha^{-1}, with and without N recycling.

	No N recycling				N recycling			
	1	10	20	50 yr	1	10	20	50 yr
Scenario I, R = 0.20								
N requirement	354	338	336	335	339	294	291	288
Losses	284	280	280	280	282	272	272	273
Scenario II, R = 0.45								
N requirement	157	155	155	155	150	136	134	133
Losses	94	96	96	96	101	111	112	114

Table 6. Simulated P fertilizer requirements [kg ha^{-1}] in the course of time [yr] for two scenarios with (at a rate of 0.02 yr^{-1}) and without erosion.

Scenario	1	2	3	5	10	20	50	100 yr
– erosion	54	19	18	17	15	12	8	7
+ erosion	81	26	26	25	23	21	19	18

magnitude as obtained for maize with the same model (Osmond *et al.*, 1992).

For simulating the P requirements, first the fraction of P that can be recycled is assessed, on the basis of PHI, which varies significantly among the five species, at 0.53 for millet, 0.61 for sorghum and maize, 0.67 for rice and 0.78 for wheat (van Duivenbooden, 1992). In this example the recycling fraction is set at 35%.

Two scenarios for P fertilizer requirements have been examined, both starting from a rather P deficient soil (P supply 3.5 kg ha^{-1}), one without and the other with erosion. In the absence of erosion, it takes well over 100 years to reach an equilibrium stage where the fertilizer rate equals uptake minus mineralization (Table 6). The concept of equilibrium fertilization, where the amount of fertilizer applied equals that exported (crop removal plus unavoidable losses), as advocated in the Netherlands (van Erp and Oenema, 1993) seems thus inappropriate and will lead to P deficiency for crops in the near future.

An annual loss of phosphorus by erosion from the top soil (2%) would require considerably (37%) higher fertilizer rates to maintain soil fertility. This is in agreement with data presented by Stoorvogel & Smaling (1990) who indicated the importance of these losses. In the long run a two times higher fertilizer rate would be required to compensate for phosphorus losses by erosion.

The quantity of phosphorus in the form of rock phosphate or superphosphate required to increase P uptake linearly from a minimum of 3.5 kg ha^{-1} to a maximum of 25 kg ha^{-1} in a period of fifty years was also calculated (Table 7). Due to its low availability, large amounts of rock phosphate are needed during the first years in comparison to superphosphate. However, after 50 years the differences are negligible, because application of rock phosphate leads to accumulation of phosphorus in the soil. A major problem, however, in using rock phosphate is that it requires large investments in early years when resources for such investments are limited. Total application of rock phosphate (with 10% P) is in the first 30 years a staggering 15 t ha^{-1}. This quality in terms of P content can only be achieved with amorph (partially acidulated) rock phosphate. However, the risk exists that the soil will be poisoned with cadmium (also present in rock phosphate). Therefore, in a land use plan, superphosphate may be chosen despite its higher costs, because total application is far lower and its cadmium content can be kept under control.

Although the data listed in Tables 5 to 7 may vary when different (i.e. more location specific) data are

Table 7. Simulated P fertilizer requirements [kg ha^{-1}] in the course of time in the form of superphosphate or rock phosphate to allow for an increase in target P uptake.

	1	5	10	20	30	40	50 yr
target uptake	3.5	5.7	7.9	12.2	16.5	20.9	25.3
Superphosphate	6	11	19	30	38	45	52
Rock phosphate	44	47	47	51	55	60	64

used, the simulation exercises illustrate the importance of the changing fertilizer recommendations in the course of time. Hence, dynamic fertilizer recommendations should be included in land use plans.

Conclusions

The nutrient relations presented in this paper allow assessment of fertilizer requirements for each of the five cereals as required in a land use plan. Assessment for a steady-state situation requires a few steps: (i) to apply crop growth simulation models to calculate the potential and water-limited yields of crops (for one or more agro-ecological zone) and (ii) to apply the data from Table 1 and nutrient supply from natural sources, to derive the required nutrient uptake and application rates. However, as the chemical and physical characteristics of soils may vary considerably within and among agro-ecological zones, determination of nutrient uptake under non-fertilized conditions remains necessary. Furthermore, the recovery fraction of the various inorganic fertilizers is of crucial importance. For optimization of this factor, fertilizer experiments, including evaluation on the basis of principles of the three-quadrant figures are indispensable. An alternative method is presented by Huggins and Pan (1993). The problems of acidification and low organic matter contents (e.g. (Cretenet *et al.*, 1994; Pichot *et al.*, 1981; Sedogo, 1993), the substitution of inorganic fertilizer by locally available fertilizers, manure or legumes (Osmond *et al.*, 1992), and validation of simulation models for both N and P uptake should also be addressed in such experiments. De Wit (1992) has pointed out that fertilizer experiments should address the actual needs of the farmers and that external production factors should be used in such a way that the production possibilities of all other available resources are fully exploited on a sustainable basis. Depending on the local environmental and socio-economic conditions, the target yield level may thus vary within one agro-ecological zone from potential to nutrient-limited production level. Optimization of fertilizer use requires continuous monitoring of the actual situation. 'Nutrient bookkeeping' by the farmer is crucial to gain further insight in the processes that determine actual fertilizer use efficiency. Consequently, instead of fixed national fertilizer recommendations, specific fertilizer recommendations for each farming system should be formulated each year. At a higher level of planning, in addition to 'how' to use the land, 'what' to use it for is as important (Lal, 1994). This implies the requirement for quantitative land use planning with various scenarios including different sustainable land use systems. An example for such a steady-state study in sub-Saharan Africa is presented by van Duivenbooden (1993).

Results of modelling studies as illustrated in this paper indicate that multiperiod models are useful, and future models should include both N and P uptake relations. For quantitative land use planning the temporal scale should also be considered, as it is of extreme importance to know the starting point (e.g. nutrient supply from natural sources) and the time required to attain a certain sustainable land use system.

Acknowledgements

This paper has originally been set up by the first two authors, but as Prof. C.T. de Wit suddenly passed away it has been completed with the help of Prof. H. van Keulen.

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