PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Nutrient resources for crop production in the tropics

Paul L. G. Vlek, Ronald F. Kühne and Manfred Denich

Phil. Trans. R. Soc. Lond. B 1997 **352**, 975-985
doi: 10.1098/rstb.1997.0076

Nutrient resources for crop production in the tropics

PAUL L. G. VLEK*, RONALD F. KÜHNE AND MANFRED DENICH

Institute of Agriculture in the Tropics, University of Goettingen, Grisebachstrasse 6, D-37077 Goettingen, Germany

SUMMARY

For the foreseeable future a majority of the population, and almost all the mal- and under-nourished, will continue to be found in the tropics and subtropics. Food security in these parts of the world will have to be met largely from local resources. The productivity of the land is to a large extent determined by the fertility of the soil, which in turn is mostly determined by its organic matter content and stored nutrients. Soil organic matter is readily lost when organic matter inputs are reduced upon cultivation and more so upon intensification. The concomitant loss of topsoil and possible exposure of subsoil acidity may cause further soil degradation.

Plant nutrients to replenish what is yearly taken from the soil to meet the demands for food and fibre amount to 230 million tonnes (Mt). Current fertilizer consumption stands at about 130 Mt of N, P_2O_5, and K_2O, supplemented by an estimated 90 Mt of N from biological nitrogen fixation worldwide. Although 80 % of the population lives in the developing world, only half the world's fertilizer is consumed there. Yet, as much as 50 % of the increase in agricultural productivity in the developing world is due to the adoption of fertilizers. World population growth will cause a doubling in these nutrient requirements for the developing world by 2020, which, in the likely case of inadequate production, will need to be met from soil reserves. Because expansion of the cultivable land area is reaching its limits, the reliance on nutrient inputs and their efficient use is bound to grow.

With current urban expansion, nutrients in harvested products are increasingly lost from the rural environment as a whole. Estimates of soil nutrient depletion rates for sub-Saharan Africa (SSA) are alarmingly high. The situation may be more favourable in Latin America and Asia where fertilizer inputs are tenfold those of SSA. Closing the nutrient cycle at a community level in rural areas may be tedious; on an inter-regional level it is associated with considerable costs of collection, detoxification and transportation to the farms. Yet, at the rate at which some of the non-renewable resources such as phosphorus and potassium are being exploited, recycling of these nutrients will soon be required.

1. NUTRIENT REQUIREMENTS AND SUPPLIES

The productivity of the soil is largely determined by its fertility, which in turn is dependent on rootable soil depth and the nutrients stored in its mineral and organic constituents. The rootable soil depth may be restricted by physical constraints such as water table, bedrock or other impenetrable layers, as well as by chemical problems such as soil acidity, sodicity, salinity or toxic substances. Large reserves of stored nutrients are in themselves no guarantee of high soil fertility as plant availability of nutrients requires the release of these nutrients from their mineral or organic matrix or surfaces, processes that can be physical, chemical, as well as biological in nature. Finally, a fertile soil can be of benefit to the plant only in the presence of sufficient soil water to allow the transport of these nutrients to the plant's roots.

Loss of soil productivity is often related to the loss of soil organic matter, which not only leads to a reduction in soil fertility, but also in the structure, water holding capacity and biological activity of a soil. Soil organic matter (SOM) is readily lost when organic matter inputs are reduced upon cultivation, and this occurs more rapidly under tropical conditions (Jenkinson & Ayanaba 1977). Jenny & Raychaudhuri (1960) studied 522 soils in India and calculated the percentage loss of SOM as a result of cultivation. They found carbon losses ranging from near 0 % for paddy soils up to around 70 % for the most fragile environments. Organic nitrogen followed a similar trend. The introduction of intensive agriculture with its reliance on NPK fertilizers has placed inordinate demands on the soil to provide the remaining essential nutrients. Moreover, in many developing countries fertilizer use favours nitrogen disproportionately to the crops' demands (Bumb 1995). As a result, the long-term use of chemical fertilizers may disturb soil nutrient balances or cause soil acidification. Thus, intensive agriculture may have amplified the magnitude and increased the rate of the age-old problem of soil degradation (Hillel 1991). As much as 17 % of the biomass-producing area of the world has been seriously degraded between 1945 and 1990 (UNEP-ISRIC 1991).

---

* Author for correspondence (`gvlek@gwdg.de`).

Table 1. *Composition of nutrient balance* (*N*, *P*, *K in* kg ha^{-1}) *in sub-Saharan Africa for 1983*

(Recalculated from Stoorvogel & Smaling (1990).)

	N		P		K	
	flux (kg ha^{-1})	total	flux (kg ha^{-1})	total	flux (kg ha^{-1})	total
input		10.7		1.8		4.9
fertilizer	2.5		0.7		0.8	
manure	0.8		0.2		1.7	
deposition	2.5		0.4		1.7	
sedimentation	0.4		0.1		0.3	
BNF	3.6		—		—	
fallow	0.9		0.4		0.4	
output		32.6		4.4		21.7
harvested residues	2.4		0.6		4.9	
harvested product	8.7		1.8		5.6	
leaching	2.8		0.0		2.6	
erosion	12.5		2.0		8.6	
gaseous losses	6.2		—		—	
balance		−21.9		−2.6		−16.8

Table 2. *Regional supply–demand balances by 2000* (*optimistic scenario*) *and 2020 based on effective demand, not accounting for soil nutrient balances*

	2000			2020		
region	N	P_2O_5	K_2O (Mt yr^{-1})	N	P_2O_5	K_2O
North America	(1.2)[a]	5.9	6.2	(3.2)	4.8	5.4
Western Europe	(0.5)	(0.6)	1.8	(1.0)	(1.3)	1.2
Eastern Europe	1.9	0	(1.4)	0.4	(0.9)	(2.6)
Eurasia	5.8	1.4	4.0	2.3	(0.3)	1.5
Oceania	0.4	(0.2)	(0.3)	(0.8)	(0.6)	(0.5)
Africa	(0.1)	4.0	(0.7)	2.6	3.0	(1.3)
Latin America	1.0	(1.3)	(2.2)	(1.4)	(3.2)	(3.7)
Asia	(4.3)	(6.8)	(4.1)	(22.3)	(16.0)	(7.9)
World	3.3	2.3	3.3	(28.6)	(14.5)	(7.9)

[a] Figures in brackets represent deficits.
Source: Bumb & Baanante (1996).

Quantification of nutrient losses from agricultural systems is risky. For sub-Saharan Africa (SSA), an effort was made to assess the depletion rates for the various countries and land/water classes (Stoorvogel & Smaling 1990). The results, summarized in table 1, deliver a compelling message: soils in SSA are losing their fertility at exceedingly high rates. Vlek (1993) estimated from production statistics that a minimum of 4 Mt of nutrients (N, P_2O_5, K_2O) are harvested annually in SSA, only one-fourth of which are returned in the form of fertilizer. Assuming a typical annual consumption rate of 300 kg maize or 7 kg N, P_2O_5, K_2O per head and per year, one arrives at a very similar nutrient consumption rate for the region. The situation may be more favourable in Latin America and Asia, where fertilizer inputs far exceed those in SSA. However, it is doubtful that the balance will turn out to be favourable when losses due to erosion and declining SOM levels are taken into account.

World-wide, harvested nutrients may be roughly estimated on the basis of the cereal production (*ca.* 2000 Mt) and their average nutrient content (N, P_2O_5 and K_2O)—about 40 kg t^{-1} (Cooke 1982)—which amounts to 80 Mt annually. With cereals contributing about half of the harvested produce, total harvested nutrients may reach 160 Mt, not counting the large amounts of straw that are taken from the fields. Bumb & Baanante (1996), using similar considerations, but including removal in straw, conservatively estimated current needs for plant nutrients to replenish what is taken yearly from the soil to meet the demands for food and fibre to be a minimum of 230 Mt world-wide.

Fertilizer supply projections, based on planned changes in plant capacities and likely operating rates and losses for the year 2000 (Bumb 1989) were calculated by Bumb (1995). World ammonia production capacity of 119.5 Mt today will increase to 127.9 Mt, with a concomitant shift in production capacity from the developed and reforming economies to the developing markets. Phosphoric acid capacity will increase by about 3.7 Mt (P_2O_5) to 40.4 Mt, whereas potassium (K_2O) capacity will increase by 1.5 Mt to 39.2 Mt, with most of the expansion occurring in the developing markets. Assuming two demand and two supply scenarios, Bumb (1995) predicted that inadequate supply of fertilizer on a world-wide basis until the year 2000 was very unlikely. The situation might become tight for nitrogen if the reforming economies of East Europe recover from their set-back in fertilizer consumption, and operating rates of fertilizer plants remain low at the same time. However, regional differences in these balances are to be expected, as shown in table 2 (Bumb & Baanante 1996).

Current world fertilizer consumption stands at about 130 Mt of N, P_2O_5, and K_2O per year. In addition, an estimated 170 Mt of nitrogen is biologically fixed in soil worldwide (Paul & Clark 1989), of which an estimated 80–90 Mt of N accrue in cropping systems. Nearly 60% of the world's fertilizers are consumed in the developing world (Bumb 1995), and over the past quarter century, as much as 50% of the increase in agricultural productivity in the developing world has been due to the adoption of fertilizers (FAO 1987). Because expansion of the cultivable land area is reaching its limits (WRI 1990), the reliance on nutrient inputs and their efficient use is bound to grow. World population growth will cause a doubling in the nutrient requirements for the developing world by 2020 (Bumb & Baanante 1996). If this fertilizer demand cannot be met, these nutrients will need to be provided by soil reserves if starvation is to be avoided.

Extrapolated to the year 2020, based on projected effective demand, table 2 provides an indication of the location of the fertilizer production capacity that needs to be installed, excluding replacement capacity, to meet the expected 50% increase in demand. For the developing world, projected demand would increase from 62 Mt in 1990 to 122 Mt in 2020. However, to meet the anticipated food demand targets of 2020 would require 185 Mt of nutrients, while concurrent replenishment of the nutrients removed by crops would boost these needs to 251 Mt, for which substantial further fertilizer production capacity would have to be installed.

Table 3. *Composition of nutrient balance* (*N*, *P*, *K in kg ha*$^{-1}$) *in eastern Amazonia*

(In contrast to the text, balances have been expressed as annual means for the nine-year crop/fallow rotation. Recalculated from Hölscher (1995).)

	N		P		K	
	flux	total	flux	total	flux	total
	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
(*a*) With fertilizer						
input		18.8		3.6		6.4
fertilizer	2.4		2.8		3.8	
deposition	2.6		0.8		2.1	
BNF	13.3		—		—	
restituted product (straw, etc.)	0.5		0.0		0.5	
output		36.7		2.2		14.3
harvested product	13.2		1.4		8.7	
leaching	1.4		0.4		1.7	
burning losses	22.1		0.4		3.9	
balance		−17.9		+1.4		−7.9
(*b*) Without fertilizer						
input		16.2		0.8		2.4
deposition	2.6		0.8		2.1	
BNF	13.3		—		—	
restituted product (straw, etc.)	0.3		0.0		0.3	
output		30.3		1.4		11.7
harvested product	6.2		0.6		5.9	
leaching	2.0		0.4		1.9	
burning losses	22.1		0.4		3.9	
balance		−14.1		−0.6		−9.3

2. AGRO-ECOSYSTEM DIFFERENTIATION

Nutrient requirements are widely different and dependent on the crop and the production potential of the environment. The natural vegetation often reflects the constraints to primary production of that environment such as proneness to drought, excess water or heat, soil acidity or salinity. It is tempting to infer nutrient requirements of an agro-ecosystem from biomass produced by its natural vegetation, but this often leads to the wrong conclusions as it overlooks the time factor involved in arriving at this biomass. Moreover, human interference often changes the system from one with a closed nutrient cycle to one that is more or less open, depending on the severity of the human impact, with the resulting degradation of the resource base discussed above. Conversely, human intervention may overcome most soil constraints, but often only at a considerable, sometimes prohibitive cost. As a result, the production potential may vary in space and time. The costs associated with soil fertility improvement are a function of the expected resulting outputs and vary from region to region. The differentials in these costs lead to different strategies to satisfy plant nutrient demands.

(*a*) *Traditional agriculture*

The area of the eastern Amazon of Brazil, known as the Bragantina region, was colonized some 100 years ago and has since been converted from a primary forest region to a natural forest–fallow cultivation system. Slashing and burning has been used traditionally to prepare the land for the 1–2 year cultivation phase. With increasingly shorter fallow cycles, approaching 3–7 years instead of the traditional 15–25 years, the productivity of the system has gradually diminished, attributable in large part to the loss of nutrients from the system. The problem is common to many moist tropical forest areas and has been given ample attention in the literature. A rather extensive research programme in the area has allowed a preliminary assessment of the nutrient budgets in this system.

In the current land use cycle with about seven years fallow, yields of maize (*Zea mays* L.), cowpea (*Vigna unguiculata* L.) and cassava (*Manihot esculenta* Crantz) grown in a relay sequence are typically around 500, 500, and 10000 kg ha^{-1} in the region (IBGE, 1991), respectively. During a cropping period of two years, the estimated net losses (balancing the nutrient losses by burning, leaching and harvesting against the gains by fertilization, biological nitrogen fixation and atmospheric deposition) for this system amount to approximately 270 kg N, 10 kg P, 35 kg S, 90 kg K, 135 kg Ca and 25 kg Mg ha^{-1}, with burning and harvesting being the prime causes of loss and leaching the least important (Hölscher 1995). Given the inputs from the atmosphere (rain, dust, and fly-ash as well as biological nitrogen fixation) that were measured in this system, we calculated that fallow periods of 10–15 years would be required for S and Mg, and 20–25 years for N and P, in order to compensate for these losses. However, in the case of Ca and K, periods of more than 100 years would be needed. Soil weathering might reduce this requirement, but the highly weathered Ultisols of the region are inherently poor in these cations. Under these conditions, degradation of the system is to be expected in the long run. Even if, as is increasingly seen, farmers apply 11 kg N, 12.5 kg P, and 17 kg K per hectare each to maize and cowpea, the nutrient losses remain nearly the same for all nutrients, with the exception of P which shows a positive balance of about 10 kg ha^{-1} (table 3). Fertilizer increases the yields of maize twofold, and of the following cowpea crop by a factor of 4.5, thus increasing the NPK taken off in the harvested product.

Burning is the key loss mechanism determining the nutrient balance in this system. Losses amount to 96%

of the N present in the slashed vegetation (seven-year-old fallow vegetation; above ground biomass 22 t DM ha^{-1}) and litter (9 t DM ha^{-1}). Corresponding figures are 47% for P, 76% for S, 48% for K, 35% for Ca and 40% for Mg (Hölscher 1995). Elimination of the burning practice by producing a suitable mulch from the slashed vegetation, and the application of 22 kg N, 25 kg P and 34 kg K per hectare, appear to provide a viable alternative and would yield positive nutrient balances for P and S, while N, K, Ca and Mg losses would be reduced to around 65, 45, 30 and 10 kg ha^{-1}. There would still be a need for fallow periods of over 25 years to restore the harvested Ca and 60 years for K. However, fire-free land preparation based on mulching implies the slow release of nutrients and leads to dramatic yield reductions of nearly 50%, which would not be attractive to farmers (Kato *et al.* 1997). Through the application of moderate amounts of NPK fertilizer, these differences in performance between the two land preparation methods could be partly eliminated, but the K and Ca balance would remain problematic from a sustainability standpoint.

The ability of trees to serve as a nutrient pump, scavenging nutrients released over the entire rooting depth of the vegetation and bringing them to the surface, has been known for over 100 years (Van Noordwijk & Garrity 1995). In the eastern Amazon's secondary forests we found roots down to 6 m. Nearly 30% of the root biomass, which varied between 20 and 30 t^{-1} ha^{-1}, was present in soil layers below 1 m (Sommer 1996). Moreover, estimated water extraction by the vegetation below a depth of 1 m exceeded 300 mm during the dry season (Hölscher 1995), thus providing conditions in which a nutrient pump could be active. However, with subsoil exchangeable K and Ca values below 0.01 and 0.1 cmol(+) kg^{-1} between 150 and 600 cm (Thielen-Klinge, unpublished data), respectively, the scavenging of at least K appears unlikely (Suwanarit 1995). Unless adequate amounts can be liberated through weathering, these elements will have to be applied.

In contrast to K, which has to be deliberately supplied, the requirement of Ca as a plant nutrient is often inadvertently covered by the application of Ca-bearing P fertilizers (SSP or phosphate rock). Most compound fertilizers lack Ca, thus requiring special measures to assure a positive balance. Mamaril *et al.* (1991) demonstrated in an experiment with an acid Ultisol in the Philippines that annual applications of small amounts of lime (0.75 or 1.5 t ha^{-1}) sustained yield levels for six years. Such application rates are considered affordable for the resource-poor farmer.

(*b*) *Modern agriculture*

Rice cultivation in the wetland regions of South and South-east Asia has evolved from a traditional practice, with stable yields over millennia, into an intensive form of agriculture within a period of a few decades. Yields appear to have been stable at around 1000–2000 kg ha^{-1}, which posed low to moderate demands on the soil for nutrients. Between 1936 and 1952, grain yields in over 3000 fertilizer trials were slightly over 1700 kg ha^{-1} in the absence of N-fertilizer (Yates *et al.* 1953, cited by De Geus (1967)). Sharsabuddhi (1928) estimated the associated nutrient removal by grain and straw for a crop of rice in India at 32 kg ha^{-1} of N, 10 kg ha^{-1} of P and 56 kg ha^{-1} of K. Takahashi (1966) reported removal by the crop (grain and straw) in Japan of 17 kg of N, 4 kg of P and 22 kg of K for each tonne of rough grain. Similar figures were reported for Taiwan by Chiu (1968) with 20 kg of N, 4 kg of P and 20 kg of K for each tonne of rice grain, of which 8 kg of N, 1 kg of P and 16.5 kg of K were in the straw. Thus, if straw is left in the field, a large share of the nutrients will be returned, particularly K.

The long-term productivity of rice paddies was traditionally assured through natural inputs such as biological nitrogen fixation and the rejuvenation of the soils by inundating water and weathering of soil minerals. The stability of the system, sometimes over thousands of years, allows an estimation of these inputs based on the outputs of 15–25 kg of N, 3–5 kg of P and 10–15 kg of K ha^{-1} yr^{-1}, depending on yield level and the rate of residue restitution. The same principle of steady state would have held true for the secondary and micronutrients. With increasing opportunities for double or even triple cropping, and with yields of rice moving through the ten tonne barrier, nutrient extraction rates in intensive agriculture have greatly increased.

Von Uexkull (1976) tabulated extraction rates to reach around 109 kg of N, 25 kg of P and 142 kg of K ha^{-1} yr^{-1}, with annual double crop yields of approximately 6 t when no fertilizer application or straw restitution took place. Our calculations are more conservative, particularly with regard to K (table 4). Still, at such rates of nutrient extraction the assumed yields of grain of 3 t ha^{-1} season^{-1} would not be sustainable. However, rice straw in modern rice cultures is largely returned to the fields, which would reduce the removal of N, P and K from the field to 72 kg ha^{-1} of N, 18 kg ha^{-1} of P and 21 kg of K ha^{-1}. With recommended fertilizer rates of 100 kg N ha^{-1}, 26 kg P ha^{-1} and 50 kg K ha^{-1} on average per season, the nutrient balance is more than restored even if 10 t ha^{-1}.yr^{-1} of grain were the combined yield.

In fact, fertilizer use on cereals has seen a meteoric rise over the past 30 years (figure 1), and is reflected directly in cereal production. In the early Nineties, 7 Mt of N (100 kg N ha^{-1}) were applied on around 70 million hectares of irrigated rice of South, East and South-east Asia, with a mean yield of rice of 5 t ha^{-1} (Cassman & Pingali 1995). However, with N:P:K ratios in the region of 1:0.15:0.1 (Bumb & Baanante 1996), actual application rates of P and K are below those recommended, approaching a mere 15 kg P and 10 kg K. Moreover, N fertilizer losses in rice are notoriously high, reaching 30–50% of the applied N (Vlek & Fillery 1984; Simpson & Freney 1988), negating possible N gains. Thus, at yield levels of 5 t, the major nutrient balances would be close to neutral. If biological nitrogen fixation were to be eliminated by the introduced N, the overall N balance would likely be negative. Indeed, steady yield declines in

Table 4. *Estimated annual nutrient balance in irrigated traditional (single crop) and modern (double cropped) rice culture*

			nutrient removal			nutrient restoration[a]		
rice culture	straw management	annual grain yield	N	P (kg ha^{-1} yr^{-1})	K	N	P (kg ha^{-1})	K
traditional	remove	1500	30	6.0	30	as removal		
	return	1500	18	4.5	5.3	30	6.0	30
double HYV cropping								
no fertilizer	remove[b]	6000	108	22	66	30	6.0	30
	return	6000	72	18	21	30	6.0	30
with N/P/K								
200/52/100	return	10 000	120	30	35	130[c]	58	130
200/30/20	return	10 000	120	30	35	130[c]	36	50

[a] The assumption is that natural inputs have historically balanced the removal with grain and straw, and this remains the case to date. In fact, N and P fertilization affects biological N fixation, and nutrient loads in irrigation waters have increased with the use of fertilizers.

[b] Assuming straw production of high yielding varieties (HYV) at two-thirds of that by traditional varieties.

[c] Assuming a fertilizer N loss of 50%.

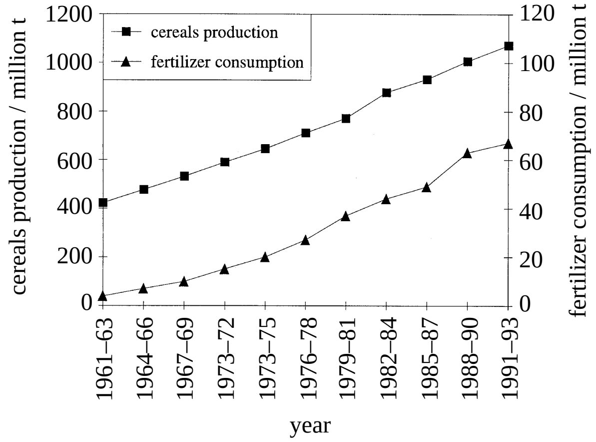

Figure 1. Cereals production and NPK fertilizer consumption ($N+P_2O_5+K_20$) in developing countries (compiled from FAOSTAT online, 1996).

rice–rice cropping systems have been reported recently, and appear to be related to declining N supply (Cassman & Pingali 1995). Other regions are, however, experiencing declines in yield associated with an exhaustion of sulphur or micronutrients such as zinc, which are increasingly found to be deficient (Blair & Till 1983; Vlek 1985).

The lesson to be extracted from these calculations is that nutrient budgets in agro-ecosystems are fragile and adapt poorly to the pressures associated with intensification of agriculture. In the West, a concerted effort has been made to find means of assessing the amounts of nutrients needed to supplement those provided by the soil. After four decades of intensive agriculture, we have belatedly recognized that these methods are inadequate, and the approach may need to be changed altogether. The alternative approach involves a closing of the nutrient cycles at the agro-ecosystem level to the extent possible, and a replenishment of all nutrients that are taken out of the system, in order to conserve the resource base.

3. CONSTRAINTS TO FERTILIZER ADOPTION

Constraints that may prevent the adoption of fertilizers can be related to a lack of access to markets, unfavourable market prices, as well as to climatic and edaphic uncertainties. In the least developed economies, factors such as lack of money or credit, and unfamiliarity with fertilizer predominate, as was demonstrated in surveys of farmers in Ghana, Togo and Niger (Acheampong & Thompson 1995). Moreover, farm gate costs of fertilizers in such countries often far exceed those in developed economies, due to excessive marketing costs. In West African countries, these add between 22 and 43% to the total cost of fertilizer, of which transportation takes the lion's share, 39% on average (Dahoui & André 1992). In less accessible countries such as Zambia and Ethiopia transportation costs are 50% or more of the marketing costs (Coster 1990). Short of subsidies there are few short term remedies to overcome the problems associated with market prices and access. Subsidy policies vary enormously by country and product. In 1988/89 subsidies on fertilizers ranged from 6–12% in Togo to 60–67% in neighbouring Ghana. Rapidly changing subsidy policies, often imposed by donors' structural adjustment plans, provide little stability in long-term planning by farmers.

Farming is a business, and as such is interested in efficiency of resource utilization and reasonable returns on investments. As agriculture intensified in Europe and the USA, soil-testing services emerged as a means of optimizing the use of fertilizers, one of the most important cash outlays by the farmer at the time. A host of soil tests were developed to assess the extent to which plant requirements could be met from the soil, which, together with yield targets and nutrient requirements of the specific crop formed the basis for fertilizer recommendations (Brown 1987). The considerable investment made in this methodology has not been able to prevent inefficiencies, leading to substantial accumulations of plant nutrients and the associated pollution in some highly intensified agricultural and horticultural regions of the modern world. This is due, in part, to the decreasing relative cost of fertilizers for Western farmers, which has led to wasteful application rates. Environmental concerns and a more competitive agriculture are now leading to precision nutrient management (Wollenhaupt *et al.* 1994; Dobermann *et al.* 1996).

In the tropics, fertilizer still constitutes one of the main costs associated with crop production. Most tropical countries have adopted soil-testing methods from the USA, but few services are available to farmers. Moreover, adequate critical levels have yet to be established for most tropical crops. For those that have been studied in more detail, correlations between these tests and the response to the respective nutrients in the field are poor (Diamond 1985; Xie *et al.* 1989; Dobermann 1995). In part, this may be due to the importance of SOM and the soil biomass in the maintenance of soil fertility in the tropics (Woomer *et al.* 1994). Since the role of SOM diminishes with long term fertilization (Pieri 1989), most soil-testing methods were not designed to capture the important contribution that SOM can make in the course of the season to crops' nutrient requirements. Recently, new efforts are being made to capture these dynamic aspects of soil fertility (Yang *et al.* 1991). The complexity of many cropping systems found in the tropics (Francis 1986) is further complicating the development of fertilizer recommendations. In short, a major effort is needed to develop better methods of assessing the fertilizer needs for tropical crops and cropping systems. More importantly, methods are needed to evaluate the long-term effects of fertilizer use and the sustainability of fertilizer-based systems (Blair *et al.* 1995), particularly in the more fragile environments, in order to guide farmers better in their quest to meet the growing food demand.

Risk is a problem facing many farmers using fertilizers in the tropics. These risks can be biotic and abiotic in nature. Biotic constraints have led to a dramatic surge in the use of biocides, whereas some abiotic constraints are overcome through irrigation (drought), subsoiling (fragipan), liming (soil acidity), or drainage (soil salinity). For instance, fertilizer use in the semi-arid tropics (SAT) can be profitable, particularly if combined with improved cultural practices and High Yielding Varieties (HYV) (Venkateswarlu 1987). In dry years, however, response to N may not pay for the investment or, in extreme cases can be negative due to impaired grain production (haying-off). Nitrogen or other nutrients may frequently be more limiting to crop growth in the SAT than water, and may lead to poor water-use efficiency when rainfall is adequate. Moreover, soil nitrate can be left unused in the soil in the absence of rainfall, or be lost through leaching by excessive rains (Huda *et al.* 1988). The complexities of these interactions give rise to highly variable yields and use efficiencies of applied N. The high risk is reflected in low fertilizer adoption rates in the SAT regions, covering around 2000 million hectares (Ryan 1974) and supporting more than 900 million people, according to recent information from International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). In India, where the efforts to reach the SAT farmer are probably the most intensive, fertilizer consumption increased ten-fold between 1970/1971 and 1985/1986 (Biswas 1988), but still amounts to less than 10% of the Indian N consumption.

In those regions where adequate returns on investment cannot be guaranteed, the farmer's options to increase long-term crop production are rather limited. Bationo & Mokwunye (1991) argue convincingly that good organic matter management is the key to soil fertility management. Research results reported by them and those summarized by Pieri (1989) show that no less than 15–20 t ha^{-1} of manure are needed to obtain the effect otherwise achieved by chemical fertilizers. Young (1989) estimated requirements of crop residues to range from 2 t ha^{-1} in the semi-arid zones to over 8 t ha^{-1} for the humid tropical regions. With the many alternative needs for organic material such quantities are not generally available (Bationo & Mokwunye 1991). The best one probably could hope for is that organic matter levels be maintained, through a combination of crop residue restitution, fallowing, or green manuring. The positive experience in India with incorporation of legumes in the cropping system was recently reviewed by Lee & Wani (1989).

Numerous other constraints can depress the efficiency and profitability of fertilizer use. Soil acidity is one of the most serious problems, affecting an area of 580 million hectares of potentially arable land in the humid tropics. The key nutritional disorders in acid soils are related to toxic manganese and aluminium levels, the associated lack of phosphorus, and the secondary nutrients S, Ca and Mg. The common solution to these problems is liming to pH levels around 6.5, where P availability is judged to be maximized (Lindsay *et al.* 1989) and Al toxicity is eliminated (Haynes 1984). The primary effect of lime is to reduce the free Al-species, which, as was shown for an acid Ultisol in Malaysia (Shamshuddin *et al.* 1991), correlates well with crop yield. Lime or dolomitic lime also serves as a source of Ca and/or Mg.

Most commonly, the liming rate is based on the titration curve established for the soil type in question. In the case of Oxisols, Reeve & Sumner (1970) recommend basing lime requirements on the exchangeable Al index. Responses to up to 10 t of lime are not uncommon (Fagaria *et al.* 1991), and residual effects may last several years (Friesen *et al.* 1982). Such recommendations are of little use to small farmers that could ill-afford these investments without government support. They were, however, adopted by the Brazilian Government as a condition of sale of Cerrado land, together with substantial investments in P and Zn (Goedert 1989). Thus, 50 million hectares of land were opened up for agriculture, mostly for mechanized farming on larger farm holdings.

Phosphate application rates needed to satisfy the fixing capacity of acid soils may vary considerably. The low-fixing acid soils of West Africa require as little as 13 kg ha^{-1} P to support crop growth adequately (Bationo *et al.* 1986), whereas the high-fixing acid soils of Latin America will show little crop response with P rates below 88 kg ha^{-1} P, although much higher application rates are common. The cost to the farmer may be prohibitive. One of the attractive options extensively studied in the past decades has been the application of phosphate rock (PR) as a slow-release source of P and Ca for direct application on acid soils. The topic has been exhaustively reviewed by Khasawneh & Doll (1978) and Hammond *et al.* (1986). Although some details on the optimum management practices are still being argued, there is little doubt that direct application of PR, many deposits of which are found in the tropics, provides a low cost option to supply P to acid soils. The effectiveness of application not only depends on soil characteristics, but also on the quality of the PR. The reactivity of tropical PRs varies widely, leading to differences in the availability of P from these sources (Hammond *et al.* 1986).

If low P availability is primarily related to low native P levels in soil, P additions are unavoidable if soil productivity is to be restored. Whether this P originates from neighbouring pastures and is added as manure, or from subsoil P reserves pumped to the surface through fallow vegetation, or from chemical fertilizers, is up to the farmer. In general, he will be basing his choice on land and resource availability considerations. In high fixing soils, a number of alternatives are being studied. One of these options is to look for crops or crop varieties that have a greater tolerance for low soil P (Vlek *et al.* 1995). Many plant species have developed mechanisms to help overcome P constraints by reducing the distance to the P source through increased root growth, improved acid tolerance, an increased exudation of P-solving acids or chelates (Nye & Kirk 1987) or with the help of omnipresent mycorrhiza (AMF) hyphae (R. Lange-Ness 1997).

4. THE NEED FOR FERTILIZERS AND RECYCLING

Fertilizer supplies are assured in the coming century. Nitrogen is involved in a cycle between the atmosphere and the biosphere with rates of fixation by electrical discharges, and biological and industrial processes of 250 Mt yr^{-1}. At this rate the atmosphere could supply N for about 20 million years but would sooner run out of O_2 (Schlesinger 1991). The fixed N is largely returned by denitrification, with little net accrual globally. As long as energy is available to transform it to the ammoniacal form, the nitrogen supply is assured. Phosphate reserve estimates vary from 3.4 to 51 Gt of P, dependent on what is considered economically feasible. Fertilizer consumption in 1990 amounted to 16 Mt yr^{-1}of P (FAO 1994). Even with the lowest estimate of 3.4 Gt of P by the Global 2000 model (Barney 1980), P reserves would represent a supply for 90–130 years. However, considering the estimated 23 Mt yr^{-1} of P that are irretrievably lost to the oceans (Howarth *et al.* 1995), P use may have to be increased to compensate for this waste. Somewhere between 29 and 93 Gt of K reserves are documented, and others are known to exist that have yet to be explored (IFDC 1987). At the current (FAO 1994) rate of production of around 21 Mt yr^{-1} of K, these reserves will last another millennium.

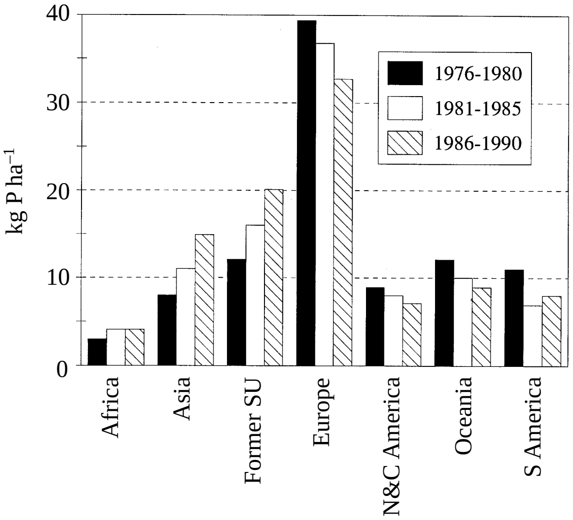

Figure 2. Global P balance on a per hectare of arable land basis (total P in crop and livestock imports + fertilizer consumption − total P in crop and livestock exports) averaged over three periods (Beaton *et al.* 1995, p. 25). Losses others than exports are not accounted for.

Trade in fertilizers and crop and livestock commodities is leading to a net transfer of nutrients from producing continents to the consuming regions. The net movement of P amounts to a transfer from North and Central America and North Africa to Asia and Europe (Beaton *et al.* 1995). The resulting accumulations in P, depicted in figure 2, are translated into accrual rates of around 30 kg P ha^{-1}, causing serious problems in some regions with highly intensified agriculture. The P accrual rates for Africa and Latin America are likely to be insufficient to compensate for losses due to erosion and accumulations in city waste, and are consistent with the warnings of serious nutrient mining in Africa (Stoorvogel & Smaling 1990, table 3).

Nearly half the current population (2.6 billion) are city dwellers, two-thirds of them inhabit the developing world. The population growth in the coming ten years (0.7 billion) will almost entirely end up in cities (Bergstein 1996). The rural population will be increasingly influenced by urban centres, as it will be called upon to produce food for its population. On the other hand, the recent migrants, constituting around 40 % of the growth in urban populations, increasingly rely on urban agriculture to cover part of their food needs (UNDP 1996). With current urban expansion rates, nutrients in harvested products are increasingly lost from the rural environment as a whole (Vlek 1993).

Closing the nutrient cycle at a community level in rural areas may be tedious: on an inter-regional level it is associated with considerable costs of collection, detoxification and transportation to the farms. Yet, at the rate at which some of the non-renewable resources such as P and K are being exploited, recycling of these nutrients will soon be required. Here indeed, political foresight is needed to translate our awareness into action programmes. Very few examples exist today of regions that purposely set out to close the disrupted nutrient cycle. In fact, the increasing problems in disposing of household garbage and sewage are causing many advanced communities to reassess their energy and material flows. For a middle-sized urban community (St Gallen) in Switzerland, Baccini & Bader (1996) estimate that of the 1000 kg of consumables entering a private household per person per year, approximately 600 kg end up in sewage and 50 kg as compostable materials. Around 80% of the P flowing through the urban household enters as food. Of the 5 kg of P and 18 kg of N that enter the aboveground parts of the crops per person per year to produce food, about 1 kg of P and 8 kg of N actually leave the farm and are eventually discarded in sewage.

Environmental awareness is putting pressure on farmers to shift their strategy towards soil fertility maintenance based on natural resource conservation, biological nitrogen fixation, and input efficiency. The continuation or adoption of these resource conservation techniques requires awareness by the farmer of the long-term consequences of soil mining. In contrast to soil erosion, the process of soil mining is not obvious and is difficult to discern, even though the ultimate consequences are not. Under the pressures of meeting the food demands of a region, farmers are often encouraged to adopt fertilizer practices. Often, the success of these chemicals is tempting farmers to abandon sound agronomic practices, such as mixed cropping. In China alone, millions of hectares of *Azolla*-based rice paddies have been turned into urea-based monocultures (Van Hove 1989). As long as the products remain within the community, the nutrient cycle can be restored if the political will exists and the necessary infrastructure and incentives are provided. The traditional restitution of 'night soil' by Chinese farmers is an excellent example of such a process (IRRI 1978).

The strategy of closing the nutrient cycle at the farm level by using fallow fields, returning residues, and maintaining the biologically fixing organisms, is often referred to as integrated soil fertility management. Using the latest knowledge regarding cultural practices, cropping systems and nutrient cycles, it aims to optimize and stabilize agricultural production within a given ecological and socio-economic environment. Nutrient depletion, as well as accumulation, is avoided but imbalances are corrected. Integrated soil fertility management does not preclude the use of fertilizers, but weighs their use against the alternatives in terms of direct and long-term environmental costs in meeting the demand for food and fibre. The resulting strategies may differ considerably for similar ecosystems due to varying infrastructure, population or policy settings, resulting in different market conditions. Therefore, it is difficult to provide a blueprint for nutrient management in defined environments without considering these externalities. The concept is equally applicable to marginal and favourable environments, irrespective of their current soil nutrient status. Principles of mixed cropping, alley cropping, residue conservation or fallowing are, however, slow to find their way back into modern agriculture, and where these practices are still existent they are in fact disappearing, e.g. the *Azolla*-based rice culture in China. The resulting soil degradation spells hunger for future generations. As we enter a new millennium, we will have to come to terms with these different short- and long-term expectations from our natural resource base.

REFERENCES

Acheampong, K. & Thompson, T. P. 1995 Constraints and social impact of fertilizer use in West Africa. *African Fert. Market* **8** (4), 3–5 (IFDC-Africa, Lomé, Togo).

Baccini, P. & Bader, H.-P. 1996 *Regionaler Stoffhaushalt: Erfassung, Bewertung und Steuerung*. Heidelberg, Germany: Spektrum.

Barney, G. O. (ed.) 1980 *The global 2000 report to the President entering the twenty-first century*. Washington, DC: US Government Printing Office.

Bationo, A. & Mokwunye, A. U. 1991 Role of manures and crop residue in alleviating soil fertility constraints to crop production: with special reference to the Sahelian and Sudanian zones of West Africa. *Fert. Res.* **29**, 117–125.

Bationo, A., Mughogho, S. K. & Mokwunye, A. U. 1986 Agronomic evaluation of phosphate fertilizers in tropical Africa. In *Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa* (ed. A. U. Mokwunye & P. L. G. Vlek), pp. 283–318. Dordrecht, NL: Martinus Nijhoff.

Beaton, J. D., Roberts, T. L., Halstead, E. H. & Cowell, L. E. 1995 Global transfers of P in fertilizer material and agricultural commodities. In *Phosphorus in the global environment* (ed. H. Tiessen), pp. 7–26. New York: John Wiley & Sons.

Bergstein, S. 1996 *Welt-Bevölkerungs-Bericht*, 1996. Bonn, Germany: DGVN.

Biswas, B. C. 1988 Fertilizer production and consumption trends–India. In *Soil fertility and fertilizer management in semiarid tropical India* (ed. C. B. Christianson), pp. 15–22. Muscle Shoals, AL, USA: IFDC.

Blair, G. J. & Till, A. R. (eds) 1983 *Sulphur in South-East Asian & South Pacific agriculture*. Armidale, Australia: University of New England.

Blair, G. J., Lefroy, R. D. B. & Lisle, L. 1995 Soil carbon fractions based on their degree of oxidation and the development of a carbon management index for agricultural systems. *Austr. J. Agric. Res.* **46**, 1459–1466.

Brown, J. R. (ed.) 1987 *Soil testing: sampling, correlation, calibration and interpretation*. Madison WI, USA: SSSA.

Bumb, B. L. 1989 *Global fertilizer perspective, 1960–95*. Muscle Shoals, AL, USA: International Fertilizer Development Center (Technical Bulletin T-34, T-35).

Bumb, B. L. 1995 *Global fertilizer perspective, 1980–2000*. Muscle Shoals, AL, USA: International Fertilizer Development Center (Technical Bulletin T-42).

Bumb, B. L. & Baanante, C. A. 1996 *The role of fertilizers in sustaining food security and protecting the environment: trends to 2020*. Washington, DC: International Food Policy Research Institute (Food, Agriculture, and the Environment Discussion Paper 17).

Cassman, K. G. & Pingali, P. L. 1995 Intensification of irrigated rice systems: learning from the past to meet future challenges. *GeoJournal* **35**, 299–305.

Chiu, T. F. 1968 *Nutrient removal by rice plants in Taiwan & soils and fertilizers in Taiwan*. Taiwan: *Society of Soil Science and Fertilizer Technology* 7pp.

Cooke, G. W. 1982 *Fertilizing for maximum yield*. Frogmore, UK: Granada Publishing.

Coster, R. 1990 Fertilizer marketing costs and margins in selected countries in sub-Saharan Africa 1988/89. *African Fert. Market* **3** (6), 3–6 (IFDC-Africa, Lomé, Togo).

Dahoui, K. P. & André, M. 1992 Overview of fertilizer marketing costs and margins in West Africa in 1989/1990. *African Fert. Market* **5** (9), 5–9 (IFDC-Africa, Lomé, Togo).

De Geus, J. G. 1967 *Fertilizer guide for tropical and subtropical farming*, Zurich, CH: Centre d'Etude de l'Azote.

Diamond, R. B. 1985 Availability and management of phosphorus in wetland soils in relation to soil characteristics. In *Wetland soils: characterization, classification and utilization*, pp. 269–283. Los Banos, Philippines: IRRI.

Dobermann, A. 1995 Assessing soil nutrient supplying capacity in intensive irrigated rice systems. In *Field variabilities of soil and plant*, pp. 271–295. Los Banos, Philippines: IRRI.

Dobermann, A., Cassman, K. G., Peng, S. *et al.* 1996 Precision nutrient management in intensive irrigated rice systems. In *Maximizing sustainable yields through improved soil and environmental management*. Symp. Paddy Soil Fertility Working Group of the International Soil Science Society, Khon Kean, Thailand.

Fagaria, N. K., Wright, R. J., Baligar, V. C. & Carvalho, J. R. P. 1991 Response of upland rice and common bean to liming on an Oxisol. In *Plant–soil interactions at low pH* (ed. R. J. Wright, V. C. Baligar & R. P. Murrmann), pp. 519–531. Dordrecht, NL: Kluwer.

FAO 1987 *Agriculture: toward* 2000. Rome, Italy: Food and Agriculture Organization of the United Nations.

FAO 1994 *FAO fertilizer yearbook 1993. Vol 43.* Rome, Italy: Food and Agriculture Organization of the United Nations.

Francis, A. F. (ed.) 1986 *Multiple cropping systems*. New York: Macmillan.

Friesen, D. K., Juo, A. S. R. & Miller, M. H. 1982 Residual value of lime and leaching of calcium in a kaolinitic Ultisol in the high rainfall tropics. *Soil Sci. Soc. Am. J.* **46**, 1184–1189.

Goedert, W. J. 1989 Cerrado region: agricultural potential and policy for its development. *Pesq. Agropec. Bras.* **24**, 1–17.

Hammond, L. L., Chien, S. H. & Mokwunye, A. U. 1986 Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. *Adv. Agron.* **40**, 89–140.

Haynes, R. J. 1984 Lime and phosphate in the soil–plant system. *Adv. Agron.* **37**, 249–315.

Hillel, D. J. 1991 *Out of the earth*. New York: Free Press & Macmillan.

Hölscher, D. 1995 *Wasser- und Stoffhaushalt eines Agrarökosystems mit Waldbrache im östlichen Amazonasgebiet*. Goettingen, Germany: Goltze (Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen, Heft 106).

Howarth, R. W., Jensen, H. S., Marino, R. & Postma, H. 1995 Transport to and processing of P in near-shore and oceanic waters. In *Phosphorus in the global environment* (ed. H. Tiessen), pp. 323–345. New York: John Wiley & Sons.

Huda, A. K. S., Pathak, P., Rego, T. J. & Virmani, S. M. 1988 Agroclimatic considerations for improved soil and water management of Vertisols. In *Vertisols and rice soils of the tropics*. Trans. 12th Int. Congress of Soil Science, New Delhi, India, pp. 61–79.

IBGE 1991 *Censos Econmicos de* 1985 : *Censo Agropecuário, Numero* 6: *Pará*. Rio de Janeiro, Brazil: Fundaçao Instituto Brasileiro de Geografia e Estatistica.

IFDC 1987 *Fertilizer manual*. Muscle Shoals, AL, USA: International Fertilizer Development Center.

IRRI 1978 *Rice research and production in China: an IRRI teams review*. Los Banos, Philippines: IRRI.

Jenkinson, D. S. & Ayanaba, A. 1977 Decomposition of carbon-14 labeled plant material under tropical conditions. *Soil Sci. Soc. Am. J.* **41**, 912–915.

Jenny, H. & Raychaudhuri, S. P. 1960 *Effect of climate and cultivation on nitrogen and organic matter reserves in Indian soils*. New Delhi, India: ICAR.

Kato, M. S. A., Kato, O. R., Denich, M. & Vlek, P. L. G. 1997 The effect of management of the slashed fallow vegetation on the performance of maize, rice and cowpea on acid soils of the eastern Amazon region of Brazil. (In preparation.)

Khasawneh, F. E. & Doll, E. C. 1978 The use of phosphate rock for direct application to soils. *Adv. Agron.* **30**, 159–206.

Lange-Ness, R. 1997 *Differential uptake of calcium and phosphate from sparingly soluble calcium phosphates by mycorrhizal plants*. Ph.D. Dissertation, Institute of Agronomy in the Tropics, University of Goettingen, Germany. (In preparation.)

Lee, K. K. & Wani, S. P. 1989 *Significance of biological nitrogen fixation and organic manures in soil fertility management*. In *IFDC Special publication SP*-11, pp. 89–108. Muscle Shoals, AL, USA: IFDC.

Lindsay, W. L., Vlek, P. L. G. & Chien, S. H. 1989 Phosphate minerals. In *Minerals in soil environments* (ed. J. B. Dixon & S. B. Weed), pp. 1089–1130. Madison, WI, USA: SSSA.

Mamaril, C. P., Estrella, D. & Lapitan, E. E. 1991 Phosphorus lime interaction in a strongly acid upland soil grown to rice in Cavinti, Philippines. In *Plant–soil interactions at low pH* (ed. R. J. Wright, V. C. Baligar & R. P. Murrmann), pp. 475–484. Dordrecht, NL: Kluwer.

Nye, P. H. & Kirk, G. J. D. 1987 The mechanism of rock phosphate solubilization in the rhizosphere. *Plant Soil* **100**, 127–134.

Paul, E. A. & Clark, F. E. 1989 *Soil microbiology and biochemistry*. London: Academic Press.

Pieri, C. 1989 Fertilité des terres de savannes. Paris: CF/CIRAD.

Reeve, N. G. & Sumner, M. E. 1970 Lime requirements of Natal Oxisols based on exchangeable aluminum. *Soil Sci. Soc. Am. Proc.* **34**, 595–598.

Ryan, J. G. 1974 *Socio-economic aspects of agricultural development in the semi-arid tropics*. Patencheru, A. P. India: ICRISAT (Econ. Prog. Occasional Paper 6).

Schlesinger, W. H. 1991 *Biogeochemistry: an analysis of global change*. San Diego, USA: Academic Press.

Shamshuddin, J., Che Fauziah, I. & Sharifuddin, H. A. H. 1991 Effect of limestone and gypsum application to a Malaysian Ultisol on soil solution composition and yields of maize and groundnut. *Plant Soil* **134**, 45–52.

Sharsabuddhi, D. L. 1928 Dept. of Agric. Bull. 154, Bombay. Cited by Von Uexkull, 1976 .

Simpson, J. R. & Freney, J. R. 1988 Interacting processes in gaseous nitrogen loss from urea applied to flooded rice fields. In *Proc. Int. Symp. Urea Technology and Utilization* (ed. E. Pushparajah, A. Husin & A. T. Bachik), pp. 281–290. Kuala Lumpur, Malaysia: The *Malaysian Society of Soil Science*.

Sommer, R. 1996 *Kohlenstoffvorräte in Böden unter intensiv genutzten Sekundärwaldflächen im östlichen Amazonasgebiet*. University of Goettingen, Germany: Institute of Agronomy in the Tropics (Diploma thesis).

Stoorvogel, J. J. & Smaling, E. M. E. 1990 *Assessment of soil nutrient depletion in sub-Saharan Africa*. Wageningen, NL: The Winand Staring Centre (Report 28, Vols I–IV).

Suwanarit, A. 1995 Potassium dynamics and availability in strongly weathered and highly leached soils in the humid tropics. In *Potassium in Asia*, pp. 73–94. Basel, CH: International Potash Institute.

Takahashi, J. 1966 Potash and the cultivation of rice. *Fertility* **11**, 13–22.

UNDP 1996 *Urban agriculture: food, jobs and sustainable cities*. New York: United Nations Development Programme.

UNEP–ISRIC 1991 *GIS evaluation of GLASOD map*. Nairobi, Kenya: UNEP/ ISRIC.

Van Hove, C. 1989 Azolla and its multiple uses with emphasis on Africa. Rome, Italy: FAO.

Van Noordwijk, M. & Garrity, D. P. 1995 Nutrient use efficiency in agroforestry systems. In *Potassium in Asia*, pp. 245–280. Basel, CH: International Potash Institute.

Venkateswarlu, J. 1987 Efficient resource management systems for drylands of India. *Adv. Soil Sci*. **7**, 165–221.

Vlek, P. L. G. 1985 *Micronutrients in tropical food crop production*. Dordrecht, NL: Martinus Nijhoff.

Vlek, P. L. G. 1993 Strategies for sustaining agriculture in sub-Saharan Africa: the fertilizer technology issue. In *Technologies for sustainable agriculture in the tropics* (ed. ASA, CSSA, SSSA), pp. 265–277. Madison, WI, USA: ASA.

Vlek, P. L. G. & Fillery, I. R. P. 1984 Improving nitrogen efficiency in wetland rice soils. The Fertilizer Society Proceedings No. 230, pp. 32.

Vlek, P. L. G., Lüttger, A. B. & Manske, G. G. B. 1995 The potential contribution of arbuscular mycorrhiza to the development of nutrient and water efficient wheat. Paper presented at the 9th Regional Wheat Workshop for Eastern, Central and Southern Africa. Addis Ababa, Ethiopia, 1995.

von Uexkull, H. R. 1976 *Aspects of fertilizer use in modern, high-yield rice culture*. Bern, CH: International Potash Institute (IPI-Bulletin No. 3).

Wollenhaupt, N. C., Wolkowski, R. P. & Clayton, M. K. 1994 Mapping soil test phosphorus and potassium for variable-rate fertilizer application. *J. Prod. Agric*. **7**, 441–448.

Woomer, P. L., Martin, A., Albrecht, A., Resck, D. V. S. & Scharpenseel, H. W. 1994 The importance and management of soil organic matter in the tropics. In *The biological management of tropical soil fertility* (ed. P. L. Woomer & M. J. Swift), pp. 47–80. Chichester, UK: John Wiley & Sons.

WRI (World Resources Institute) 1990 Land cover and settlements. In *World resources 1990–91* (ed. A. L. Hammond), pp. 267–275. Oxford University Press.

Xie, L. C., Zheng, S. L. & Xie, X. W. 1989 A study on soil testing and fertilisation recommendations for rice crop. In *Soils and their management; a Sino-European perspective* (ed. E. Maltby & T. Wollersen), pp. 133–248. London, UK: Elsevier.

Yang, J. E., Skogley, E. O., Georgitis, S. J., Schaff, B. E. & Ferguson, A. H. 1991 Phytoavailability soil test: development and verification of the theory. *Soil Sci. Soc. Am. J*. **55**, 1358–1365.

Young, A. 1989 *Agroforestry for soil conservation*. Wallingford, UK: CAB International, ICRAF.

Discussion

T. Henzell. Have you studied the spatial aspects of your nutrient balance sheets?

P. L. G. Vlek. The research we are currently involved in, in the eastern Amazon, is assessing balances for water and nutrients at the field level. However, plans do exist to scale-up our research to the watershed level, in which we hope to gain some insight into spatial variability. In our paper, we discuss nutrient balances at different scales but, in sorting through the literature, we have concluded that far too little information exists to address this issue adequately.

P. Wood. What are the prospects of recovering nutrients (especially phosphorus) from the sea in the very long run?

P. L. G. Vlek. The global P cycle is, for all practical purposes, not closed (human time-scale), and the recovery of P from the ocean water or bottom would appear unlikely given its great dispersion. It might be better to recover the P before it reaches the ocean. There may, however, be some P deposits within reasonable reach on the ocean floor that may, given high enough prices for the product, eventually be mined.

P. Wood. The paper by Dr Pedro Sanchez is all about change (improvement) and monitoring this change. What is, in your opinion, the baseline against which change should be judged?

P. L. G. Vlek. The baseline against which we monitor change might differ with the scale on which we monitor and the parameter of interest. In our field studies, we have used the undisturbed forest. In our paper, we used the age-old rice cultivation system without fertilizer. In some cases, health criteria are used (e.g. heavy metal or biocide accumulations), in others one may get concerned about the quantities involved (e.g. the total quantity of nutrients exported from Africa as compared to those returned).

P. J. Leggo. In view of the fact that recent work has shown that the high adsorptive capacity of many natural zeolitic rocks can be used to recycle ammonia from animal waste products, and that such rocks occur in the South African Republic, Tanzania and Kenya, I would be interested to know the status of zeolite resource studies in African countries.

P. L. G. Vlek. I cannot provide you with the requested information. However, I might warn you not to expect too much from exotic solutions such as zeolites in a region where the infrastructure is not capable of transporting low-grade materials at an acceptable cost. The overall tendency is to look for high-grade products, in order to minimize marketing expenses.

K. Giller. In your talk you alluded to ‘interactions’ between inorganic/organic sources of nutrients with respect to growth and nutrient uptake of millet in West Africa. We found little evidence of interactions in similar work in Malawi on maize, where ^{15}N recovery was not affected by the addition of 1–2 t ha^{-1} of organic matter. I wonder to what extent we should expect such interactions?

P. L. G. Vlek. The graph I showed with interactive effects only depicted grain yields. I am not sure that possible interactive effects of N fertilizer and residues should necessarily be related to the efficiency of N-fertilizer recovery. The organic matter may, for instance, provide the needed P that allows the harvest index to increase without a change in N recovery. Long-term interactions of the kind we reported were found in numerous experiments in the tropics.

D. S. Powlson. I agree with Dr Vlek’s comment that there is an urgent need to adapt expertise and new approaches to the role of organic matter turnover and nutrient supply that exists in Europe to the tropical situation. Much is known, or is currently being researched, on chemical forms of organic matter in soils and physical factors regulating decomposition rate. The challenge is now to identify fractions which are measurable and can be modelled that are relevant to (i) nutrient supply–fast turnover fractions; and (ii) C sequestration and, perhaps, physical reactive–slow turnover fractions.

M. H. B. Hayes. Your emphasis on the role of organic matter on soil fertility and on its sustainability is highly relevant. Your diagram for depletion of SOM with time and cultivation practices has the same shape as that of Mr A. E. Johnston of Rothamsted for the temperate region.

There have been enormous advances made in recent years on the chemistry and aspects of the structures of humic substances, which constitute 80% of the SOM. It would be very important to extend this awareness to studies of OM in tropical soils. There appears to be an urgent need to try to build back into the soil some of the OM lost. It would be very appropriate to study the changes to the OM content and composition which take place during transformations from the original equilibrium state to the steady state after several years of cultivation. In order to understand the reversibility of the process, it would be appropriate to also study the changes which take place when OM amendments are made to soils which have reached steady state OM contents.

P. Sanchez. A comment on Professor Hayes's comment: my paper suggests the recapitalization of soil organic N as well as fixed P. It is possible to replenish SOM to its original levels—but difficult to go beyond that. SOM replenishment can be done with organic inputs because they provide both C and N, while inorganic fertilizers don't provide C. The trick is to replenish the most active pools of SOM, in contrast with passive SOM or charcoal, which is good only for C sequestration.