5 Large-scale Fluxes of Crop Nutrients in Food Cause Environmental Problems at Sources and at Sinks

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Introduction

Only since the early 1990s has the topic of nutrient fluxes at scales beyond crops or fields become a topic of scientific interest. A number of studies were published recently that address the fluxes of nutrients implied in the transport of harvested raw materials and food products between rural and urban areas, between regions and between countries. Such fluxes often result in a net transport of nutrients from a source to a sink.

> The logic of a nutrient budget is on first inspection simple, consisting of nutrient inflows and outflows and resulting in a net balance. However, its application is far from straightforward.
>
> (Lesschen *et al.*, 2005).

Conceptually, a budget, or balance, can be produced for any geographic area (a farm, a water catchment, a country) and over a certain period of time (a year, a decade), but at all scales, quantification of a nutrient balance has important methodological difficulties (de Jager *et al.*, 1998). Yet, we should not let questions about quantification distract us from the real issue: increasingly, food-related nutrient fluxes on large scales are creating large and harmful imbalances at the source and at the sink side of the flux.

In food and feed, large amounts of nutrients are transported towards livestock and human concentrations. The main nutrients of concern for this analysis are nitrogen (N), phosphorus (P) and possibly potassium (K). Very roughly, food contains 1.5% of its dry matter in the element N (mainly in proteins), 0.2% in P (in nucleic acids) and 3% K (in salts). Most nutrients are not retained in humans or in peri-urban livestock, and are excreted in urine and faeces (the fraction retained in livestock gets consumed a little later). When excreted, nutrients are returned to the land, and a closed ecological cycle can be maintained so that the production–consumption process is sustainable. For instance, intensive cultivation of land combined with an extensive system of returning nightsoil to the fields in China's rural areas constituted a closed system that was productive for many centuries. In medieval European agriculture, livestock roaming common fields brought manure with nutrients to the fields close to homesteads and created concentric circles of soil depletion and enrichment. With the advent of cheap energy (oil) to facilitate long-distance transport and the development of large cities, the distances over which food and feed are transported increased. But returning N, P and K in the form of various types of organic waste, faeces and urine from cities to their sources is

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(eds D. Bossio and K. Geheb)

logistically challenging, expensive and is nowadays hardly practised. Nutrient depletion of the soils is counteracted by biological N-fixation and weathering of parent rock, and by the application of manure and industrial fertilizer. The first process occurs at a low rate and the second only where fertilizers are available and affordable. As a result, fertilizers and natural regeneration of soil fertility together amount to only half of what is taken from the soil (Sheldrick *et al.*, 2002), the other half depleting the nutrient stock in the soils. Gruhn *et al.* (2000) estimated that by 2020, the annual global net nutrient removal from productive lands will reach more than 350.10^9 kg NPK. Global inorganic fertilizer production in 2001 was only 157.10^9 kg. Gruhn *et al.* (2000) projected that the supply of fertilizer in 2020 will fall short of covering the gap (not to mention the current mismatch and geographic disparity between societies that can or cannot afford fertilizers). Continued depletion undermines the long-term sustainability of vast areas of land. At the same time, there is still little recovery of the N, P and K from city waste, as most of it gets discarded in one way or another and leads to pollution.

A few authors have expressed concern over the ultimate destination of crop nutrients. Miwa (1992) calculated the influx of nutrients into Japan, which imports much of its food, and found a slow but significant build-up of the nutrient base in this country. An even stronger building-up occurred in the Netherlands in the 1980s and 1990s, where the large import of feed for cattle production has locally raised the concentration of nutrients in soils through manure to a level where they easily leach and cause ground- and surface water pollution. In the context of the future of large European cities, Magid *et al.* (2001) point that one-way flows of nutrients to cities are basically unsustainable, and urge research into ways to recycle crop nutrients in human waste to rural areas. Craswell *et al.* (2004) address explicitly the international trade of food in relation to nutrient flows and concerns about sustainability, and propose various ways for reducing these flows. Other authors do point at the considerable amounts of nutrient-rich wastewater from cities that could be used to irrigate crops (Rashid-Sally *et al.*, 2003). Deelstra and Girardet (2000) argue that agriculture in urban areas can contribute significantly to both food security and the recycling of nutrients. But overall, there is little movement away from the current one-directional practice, and the nutrient disequilibrium accelerates, driven by urbanization, income growth and global trade.

> At the global level and at non-geological time scales, we assume all carbon and nutrient cycles are closed. At all levels below, however, mankind has, over the past century, been responsible for a steep increase in the transport of carbon and nutrients. … The transport of carbon and nutrients will continue to increase now that trade liberalization will further enhance the number of agricultural commodities shipped from place to place.
>
> (Smaling *et al.*, 1999)

A closed ecological balance is not merely a sympathetic academic theory. The uncoupling of productive and consumptive sites causes ecological disequilibria that disturb production and livelihoods. Mining the soil for NPK at the source sites degrades or destroys the productive capacity of marginal and fragile soils. In addition, reduced soil fertility leads to lower yields and hence to a lower water-use efficiency (see Bossio *et al.*, Chapter 2, this volume, for a more detailed treatment of this subject). At the other end, the accumulation of organic waste, pathogens and nutrients has very serious health implications. The mining and accumulation problems are more significant in developing countries than in rich and developed countries due to the lack of tax income to tackle sanitation. This disequilibrium is particularly strong where large numbers of people gather, in megacities and in coastal zones, and where wastewater treatment and alternatives for recycling nutrients are limited. The combination of factors that enhance disequilibria is found in many of the large Asian and African cities, with a rapidly growing number of urban inhabitants with rising incomes (and hence food demands) on the one hand, and relatively poor rural producer communities on the other. Already, roughly half of the population in these countries lives in cities and eats food produced well outside the city zone, and the numbers are increasing (FAO, 2000). In summary: it is clear that soil nutrients, soil fertility and the production capacity of soils are not only dynamic at any particular site or farm but that nutrients and soil fertility do flow from productive land to sites where they either are neutralized (dumps) or cause harm (pollution and health hazards).

Nutrient Losses at the Sources: Soil Mining

Soil fertility dynamics and movements of nutrients within a farm have been studied since Von Liebig in the mid-1800s. Early research was directed towards sustainable management, and brought extensive studies about humus, organic and inorganic fertilizers, and the uptake of nutrients by crops. The increase in soil fertility (and in NPK) through organic manure was a key point for demonstration in the famous long-term trials at the Rothamstead Experimental Station in the UK.

The study of nutrient balances across larger geographic scales is of a more recent date and has gained attention since the publications by Stoorvogel and Smaling (1990), Van der Pol (1992) and Smaling (1993, unpublished thesis) showed significant average losses of N, P and K in most African countries (Table 5.1). This drew attention to 'nutrient mining' and 'nutrient export', even though later the accuracy of the method used for upscaling of the field data became a subject of discussion (see below). It is now widely accepted that contents of plant-available nutrients in many soils and in many countries have already decreased by 30–60% over the past century (Wood *et al.*, 2000; Penning de Vries *et al.*, 2002).

Van der Pol (1992) argued that soil nutrient mining on farms in Mali contributed significantly to farm household incomes, even though it exploits and ultimately destroys the natural resource. To show the importance of soil mining in sub-Saharan Africa (SSA) at national levels, Drechsel *et al.* (2001) expressed the rates of nutrient loss in economic terms (the economic cost of replacing the nutrients) and compared this with the agricultural gross domestic product (AGDP), assuming natural replenishment by weathering and N_2-fixation to be small. Figure 5.1 portrays the results. The cost of replacement was over 10% of AGDP in at least three countries, and in at least 14 countries was between 5 and 10%. Drechsel *et al.* (2004) provide updated methods to express changes in soil fertility status in economic terms.

Mutert (1995) provided nutrient balance data for soils in ten Asian countries. These generally show a significantly larger removal rate than re-supply in the form of chemical fertilizer or manure, but numbers are different by country, by crop and by plant nutrient. He emphasizes the need for balanced fertilizer use. National-level nutrient balance data from Latin America and the Caribbean provide a similar message (Henao and Baanante, 1999). In central and Eastern Europe, nutrient balances at the national scale caught the eye of soil scientists concerned about sustainability when fertilizer use dropped significantly in the mid-1990s (Krauss, 2001). The nutrient balance in Western Europe has gone down from a high point of enrichment of +65 kg/ha/year (N, P and K together) in the 1970s to less than +10 in 2000 (Krauss, 2001) due to adjustments in fertilizer policies in most countries and concerns for environmental damage. The chapter also argues that the nutrient balance of the developing world together, *grosso modo*, has improved from clearly negative values for N and P to nearly zero in 2000, but is still becoming more negative (–50 kg/ha/year) for K.

Table 5.1. Average nutrient balances of N, P and K (difference between uptake and fertilizer application, in kg/ha per year, negative values means soil depletion) of the arable land of some East and southern African countries as reported for 1982–1984 and projected for 2000 (after Smaling, 1993 and Stoorvogel *et al.*, 1993).

Country	N 1982–1984	N 2000	P 1982–1984	P 2000	K 1982–1984	K 2000
Botswana	0	–2	1	0	0	–2
Ethiopia	–41	–47	–6	–7	–26	–32
Kenya	–42	–46	–3	–1	–29	–36
Malawi	–68	–67	–10	–10	–44	–48
Rwanda	–54	–60	–9	–11	–47	–61
Tanzania	–27	–32	–4	–5	–18	–21
Zimbabwe	–31	–27	–2	2	–22	–26

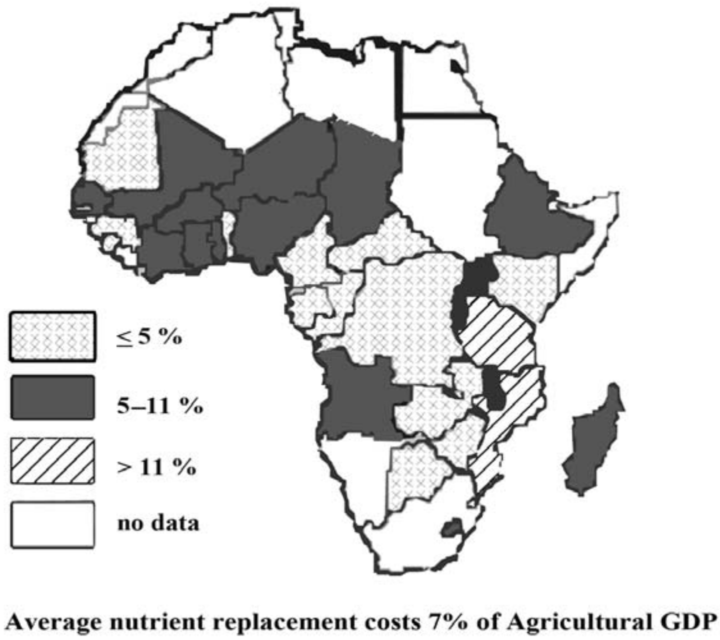

Fig. 5.1. Economic cost of NPK depletion at a national level as a percentage of the Agricultural Gross Domestic Product; categories of percentages are shown in different shades of grey (source: Drechsel et al., 2001).

A more detailed analysis by Sheldrick *et al.* (2002) provides a less positive picture. They developed a detailed model to calculate the national average nutrient balance for arable land and applied it to the FAO production data from 197 countries. The core of the model is shown in Fig. 5.2. It addresses major nutrient flow segments: crop production, fodder production and livestock production. Food processing, consumption and human waste disposal are not included. The results of their analyses are data on the average rate of loss or gain in N, P and K (separately) on arable land in each country. The overall global picture is one of N, P and K loss from arable lands (at an overall global average rate of 12, 4 and 8 kg/ha/year, respectively), but there are large differences between the countries. Nearly all of Africa's and Latin America's countries show negative balances, while those of northern Europe positive ones. In many other cases, the balance is positive for one or two nutrients and negative for the other. They also provide a dynamic analysis for Japan for the last few decades, and show a changeover from negative to positive balances, reflecting the intensification of agriculture and use of fertilizers, and for Kenya, where the balance was negative and has recently become even more negative.

Craswell *et al.* (2004) thoroughly review a comprehensive set of publications and data and present nutrient depletion diagrams with data by country for Africa and Latin America. We selected data from Sheldrick (2002) for similar Asian data, which are shown in Fig. 5.3.

Even though results differ by author, there is no disagreement that there are very significant depletions of crop nutrients occurring in many countries. Yet there is little or no analysis of the causes of large differences between seemingly similar countries. Further efforts to make consistent nutrient balance assessments would provide greater insights into the spatial and temporal patterns of agroecosystem productivity (Wood *et al.*, 2000).

This chapter briefly explores the hypothesis that 'soil mining' may be accepted, even unavoidable, when the level of economic productivity is low, so that a relation exists between the rate of mining and the average level of economic activity per unit of agricultural land (by combining GNP data for 1994 from ITM

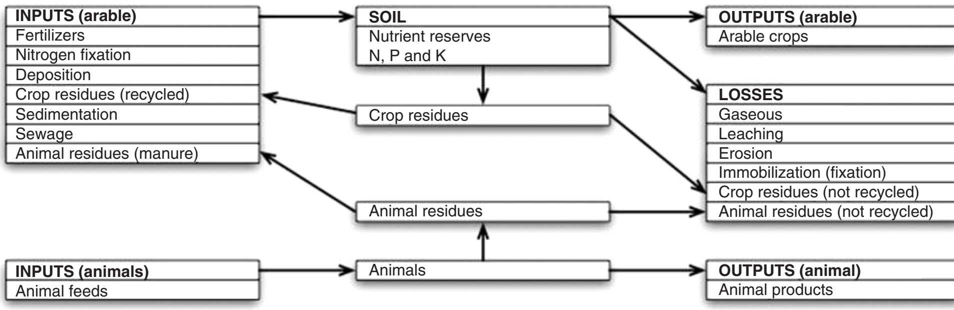

Fig. 5.2. A conceptual model to establish national averages of nutrient balances for arable fields. Inputs to the soil are on the left, outputs on the right-hand side. (Source: Sheldrick *et al.*, 2002).

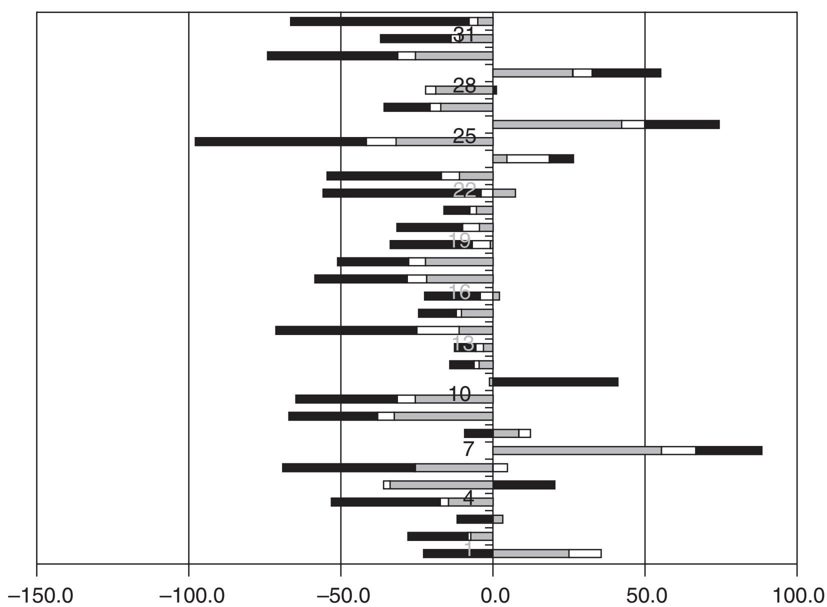

Fig. 5.3. The nutrient balance of Asian arable land by country, in kg/ha/year of N (grey), P (white) and K (black). Data from Sheldrick (2002). Individual countries are identified by number: Cyprus 1, Iran 2, Iraq 3, Israel 4, Jordan 5, Lebanon 6, Qatar 7, Saudi Arabia 8, Syria 9, Turkey 10, West Bank 11, Yemen 12, Afghanistan 13, Bangladesh 14, Bhutan 15, India 16, Myanmar 17, Nepal 18, Pakistan 19, Sri Lanka 20, Cambodia 21, China 22, Indonesia 23, Japan 24, Korea DRP 25, Korea Republic 26, Laos 27, Malaysia 28, Mongolia 29, Philippines 30, Thailand 31, Vietnam 32.

(1997), land and population data for 2002 from FAOSTAT (FAO, 2004), and the nutrient balance data for N, P and K for 1996 from Sheldrick (2002, unpublished thesis)).

The result is shown in Fig. 5.4: the many rural, large and poor countries are near the origin, and highly urbanized, populous, rich countries are on the right-hand side of the *x*-axis. This loose correlation resembles, maybe coincidentally, an environmental Kuznets Curve (Borghesi, 1999; a curve that relates average income levels to environmental pollution) and shows that most of the low-agricultural income countries are mining the soil, while all countries at an income level of US$150,000/ha or more do gain (exceptions in the figure are the

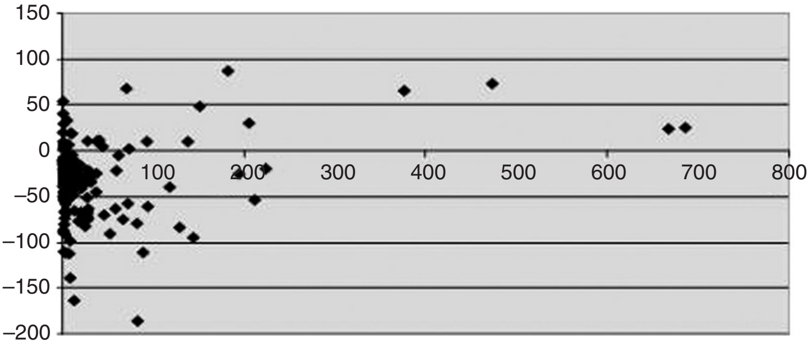

Fig. 5.4. Correlation between the nutrient balance of arable land (the annual change in soil N, P and K, in kg/ha, *y*-axis) and the average national product per unit of agricultural land (thousand US$/ha, *x*-axis).

Netherlands, Israel and Belgium, which lose mainly K from already fertile soils). The broad message is that soil nutrient depletion is the rule in rural areas while accumulation occurs in urbanized countries where much food and feed is imported.

International Trade in Food and Feed

To address the concern that large-scale food imports disturb the ecology of the country, Miwa (1992) carried out an analysis of the national nutrient balance of Japan. He found that rapidly growing net imports of nutrients in food had consequences for land and water pollution. Landfills do provide temporary solutions. To estimate the total international flow of nutrients, Craswell *et al.*'s (2004) analysis was based on model-based projections of global food trade by Rosegrant *et al.* (2001).

> Aggregate data on net flows in trade vary widely across regions and countries. The countries and regions showing major gains of NPK through imports of traded commodities are WANA (West Asia and North Africa) and China. Both show major increases between 1997 and 2020 … These imports will probably mainly go to cities … Other countries and regions with moderate imports are EC15 (15 countries of the European Union), Japan, South-east Asia and SSA (sub-Saharan Africa). The USA, Canada, Australia and Latin America … which represent the major food exporting countries, also show the largest loss of NPK in agricultural commodity trade.
>
> (Craswell *et al.*, 2004)

The authors put these numbers in perspective by calculating that for the largest food exporter (USA), the export of soil nutrients in agricultural products is equal to 18% of the fertilizer input, while for the largest importer (China), the NPK import is only 2% of the national fertilizer use. In sub-Saharan Africa (SSA) and in WANA, the international trade in food brought an amount of N, P and K roughly equal to 20% of their fertilizer use, a figure that could increase to 50% (in 2020) if fertilizer use does not expand. Since the nutrients brought into a country in the form of food will not be distributed as waste or compost homogeneously across the country but are concentrated in cities, waste dumps and river water pollution, NPK transport in food trade does not mitigate nutrient depletion in rural areas (but does slow it down).

There are important policy implications that arise from the disequilibria due to nutrient fluxes (Lynam *et al.*, 1998) as there are for trade and structural adjustments (Kuyvenhoven *et al.*, 1999). Gruhn *et al.* (2000) suggest that the FAO introduce a Code of Conduct with respect to national and international 'nutrient management'. Craswell *et al.* (2004) propose that regulations for trade in food need to take into account the complexities of the nutrient recycling, and that societies need to think about optimal integrated management of nitrogen at the country level.

The concept of 'virtual water' (Van Hofwegen, 2004) for international food trade is used to indicate the water that has transpired and evaporated in the process of growing food and feed crops and that was part of a hydrological cycle in a river basin. For consumers of food in other river basins, the water appears 'virtual' because it does not affect water in their basins. Virtual water is real water but used far from its origin: one kg of imported food that is consumed in one basin may well have taken 500–1000 l of water to produce in another basin. Actual water contained in traded food products typically amounts to 1% or less of the amount that was used to grow the food, thus 'virtual water' is much more important than actual traded water.

The concept of 'virtual NPK' can be coined as a parallel to 'virtual water', as more of NPK is used to grow the food and feed crops than is contained in traded commodities themselves. The N-harvest index in crops ranges from 70% (leguminous crops) to almost 0% (sugar crops), and is about 40% for the major cereal crops. In an approximation: for every 1 kg NPK exported in food, 2.5 kg NPK was absorbed from the soil. If fertilizer is applied, about 2 kg needs to be applied for every kg absorbed. So for food crops, virtual NPK is one and a half to four times the food NPK. The equivalent of the N-harvest index is 10% (beef) to 50% (fish), so that for meat-rich meals the virtual NPK is probably higher. Hence, it may be estimated that three to six times more nutrients are involved in growing crops than are ultimately eaten: one kg of N, P and K in food eaten in one basin may have required another 2–5 kg of the nutrients in another basin. That quantity is 'virtual NPK'. But there are important differences between virtual water and virtual NPK: (i) virtual NPK is not as spectacular in magnitude as virtual water; (ii) a part of virtual NPK gets recycled to the soil in crop residues and manure, unlike virtual water, which transpires and evaporates and is lost to the production site, (iii) there is a multi-year effect for virtual NPK that does not occur for 'virtual water': nutrients exported are not replaced naturally, whereas the next year's rain returns the water; and (iv) virtual NPK can be replaced through imported organic or inorganic fertilizer, and this is far more common than trans-catchment import of virtual water.

The concept of an 'ecological footprint' of people or cities (RP, 2004) is also applicable. It refers to the use of, or claim for, natural resources and services beyond the city borders for food, shelter, clothing and all other amenities. To apply this concept to the NPK in food, it is illustrative to compute the 'food-print' of an average city dweller. It appears that a person with a vegetarian diet annually consumes all N, P and K contained in 40 m^2 of land of average quality, or 2800 m^2 in a lifetime. A person with a healthy vegetarian diet annually consumes the equivalent of 300 kg grain with 6 kg N. This is equal to the amount of N in 40 m^2 of soil with a medium–low content of organic matter (OM) in the topsoil (1% = 300 kg soil/m^2, at 2% OM = 6 kg OM, at 2.5% N = 0.150 kg N/m^2). The eight million inhabitants of Bangkok annually consume a quantity of N, P and K equivalent to that in 320 km^2 of average land. For city dwellers consuming a meat-rich diet, the production of which requires a considerable amount of feed, the quantities of N, P and K taken from the soil are much larger: approximately twofold for chicken factories, and eightfold for stable-fed cattle, so that for these people the annual food-print amounts to 80–320 m^2. The fact that crops will not extract all N, P and K (farmers will abandon the land when the reduced fertility no longer supports a fair field crop) makes that food-print considerably larger. Ruaysoongnern (2001) showed that 50% of the nutrients in some Thai soils had been lost in the 40 years since exploitation started, seriously reducing the economic productivity of the mined soils, and undoubtedly contributing to pollution in Thailand's large cities.

Problems at the Sinks: Urban Food Water Concentrations and Accumulations

What about nutrient accumulation in cities where food is consumed and in peri-urban areas where raw materials are transformed into marketable food and livestock is reared? There are only a few studies about the concentration of nutrients 'sink-side'. One of these looks at Bangkok, which, with eight million inhabitants is slightly below the ten million threshold needed to qualify as a 'megacity'. Faerge *et al.* (2001) calculated from the volumes of food and feed consumed in the city and their nutrient contents that some 20 million kg N and a little over one million kg P enter the city annually. They estimated the outflow of N plus P from the city as the sum of recycled organic waste, which was insignificant, and the flow of the River Chao Praya across the city and the N and P concentrations in its water (in organic and inorganic materials). They concluded that most (97%) of the N that came into the city in food left it in the river, and also much of the P (41%); insufficient data were available on K to make similar calculations. Recovery in urban agriculture was small for both N and P (7 and 10%, respectively). Faerge *et al.* estimated that even when planned sewage treatment plants become operational, the recovery of N and P would still be only 17 and 33%. So the larger part of the N and P is dumped in the Gulf of Thailand, where it causes eutrophication or accumulates in the city, where it causes pollution and health problems. In other words: possibilities for health and environmental disasters are building up. Molden *et al.* (2002) observed that water extraction for agriculture reduces the amount of water that flows into the oceans, which leads to higher pollution concentrations. Most megacities are close to the sea and in these cases opportunities to use the nutrient-loaded water to 'fertigate' crops are limited. Van Drecht *et al.* (2001) calculated the levels of pollution of major rivers due to the food production and consumption processes for 1995. They show that already major levels of pollution exist in the rivers of the ten largest basins. In closed basins (i.e. those from which hardly any water now flows into the sea) the situation is most difficult: environmental flows are or will become highly loaded with nutrients.

Drechsel and Kunze (2001) present many examples of activities to promote composting and recycling of nutrients in African cities. The main constraint in these cases, as well as in case studies from Asia and Latin America, is the lack of resources (suitable land, finance and transport) rather than a lack of information (Harris *et al.* 2001), as is underlined by the existence of a Decision-Makers Guide to Compost Production (Niemeyer *et al.*, 2001). A large challenge is that moving low-value products out of cities is not economically viable in itself. In rich countries, this is financed through taxes and fees. In low-income countries, it is not feasible, as cost recovery is marginal and sanitation already consumes a major share of municipal budgets (Danso *et al.*, 2005).

About 50% of the world's people live in cities, and urban areas cover about 5–10% of agricultural land. This implies that most nutrients extracted from soils will be concentrated in cities that cover areas five to ten times smaller than the area of the producing land. In addition, 24% of the global population already lives within 60 km of the coast (ICLARM, 2000) and the large majority in large cities. Both these features show that the concentration side of the nutrient equation is significantly more skewed than it appears in national statistics. So, in order to recognize and address the biggest problems, we need to pay more attention to rural–urban N, P and K imbalances.

Scoones and Toulmin (1999) indicate that nutrient balances can be used to guide the policies and practices of farmers, technicians and planners, provided that they encourage debate and dialogue to develop policy interventions. In Australia, there is a clear interest in auditing nutrient fluxes in order to steer land management towards sustainable use through recycling fertilizers and other practices (Reuter *et al.*, 1996). Integrated Economic and Environmental Accounting may provide a practical method for monitoring nutrient fluxes (Moukoko-Ndoumbe, 2001).

Monitoring Nutrient Balances

The quantification of nutrient balances at the urban–rural scale is prone to several data and conceptual problems. There are four areas of concern: (i) multidimensionality, variability and heterogeneity; (ii) issues of scale; (iii) integrating economic and environmental concerns; and (iv) non-food nutrient flows, particularly in water.

1. Multidimensionality, variability, heterogeneity. NPK and other micronutrients, such as the elements Ca and Mg, all 'behave' very differently in the way they are taken up by crops from the soil, in fertilizers, during transport and food processing, and in pollution and recycling. There are also issues about sampling, bias, and plain error due to temporal and spatial variability (Oenema and Heinen, 1999). In addition, site- and situation-specific management may well lead to larger heterogeneity, as farmers tend to improve the best land at the expense of other plots (Lynam *et al.*, 1998). This leads to further heterogeneity of farms and regions, and to a mosaic landscape, with patches of good agricultural land mixed with wasteland. This may be attractive to the farmer but can be overwhelming for the scientist.

2. Nutrient balances are scale-dependent. A part of the nutrients that are removed from one location are returned to the soil not far from the source, such as in manure or crop residues or organic waste. Scale-dependency for natural processes was captured by Van Noordwijk *et al.* (1998) in a theoretical approach to transport processes, such as nutrient fluxes and erosion, where movement occurs over short and long distances. They suggested that, conceptually, upscaling of nutrient flow (NF) data from a field (NFf) to a district (NFd) can be done with a power-scale factor (sf):

$$NF(d) = NF(f)sf *area$$

where the value of sf is between 1 (no sedimentation or recycling) and 0 (complete sedimentation or recycling). The larger the spatial scale is, the lower the value of sf. Since a part of long-distance nutrient fluxes is directed by humans along corridors, this type of analysis will need to be adapted to cope with the transport of feed to livestock production centres or of food to cities. Van der Hoek and Bouwman (1999) argue that by upscaling from lower levels to the national level, much knowledge and many insights are lost that are actually needed to form solutions. De Ridder (1997, unpublished thesis) presents case studies of hierarchical levels in nitrogen flows that highlight the complexities of scale. For purposes of intervention and management, the farm scale is an appropriate unit to monitor nutrient balances. The 'marketshed' is likely to be a more practical territorial unit than watershed (or catchments) for nutrient accounting and for governments to monitor and regulate.

3. Integrating economic and environmental concerns. As described above, negative nutrient balances affect farmer-producers through less productive and/or unsustainable farming practices; and consumers through environmental impacts at the source and through pollution and health hazards at the sink. Moukoko-Ndoumbe (2001) proposes 'integrated economic and environmental accounting' as a way to bring economic and environmental aspects into a single framework by integrating nutrient inflows, outflow and balances into conventional accounting at the farm level. Craswell *et al.* (2004) also highlight the need for environmental costs to be factored into the debate on nutrient management, as otherwise the international flow of food across the globe will cause 'major perturbations of nutrient cycles'.

4. Non-food and non-feed nutrient fluxes can confound the nutrient flows moving in food and feed, particularly in organic materials and particles or dissolved in water. Natural fluxes of nutrients occur due to erosion and sedimentation, burning and atmospheric transport (of the macroelement for N only). They can affect nutrient balances at local and at the national levels significantly. From nutrient balance calculations for cassava, Howeler (2001) concludes that all our balances are, in fact, only 'partial'. Shindo *et al.* (2003) calculated the N-load of land and rivers in Asia that results from natural erosion, leached fertilizers, human waste and the deposition of NOx. The authors reported major fluxes of N across countries and suggested that more than 90% of the N in rivers resulted from food production and human and animal waste, suggesting that non-food and non-feed nutrient fluxes are in the order of 10% of total N in Asian rivers.

A Conceptual Framework

This chapter promotes the principle of a closed ecological balance, even though its realization will be very difficult for economic reasons. A conceptual framework illustrating the current situation and an idealized framework for an ecologically balanced system are useful to understand the challenges to recycling.

The NPK fluxes between rural and urban areas are illustrated in Figs 5.5 and 5.6. They show the main flows of N, P and K from their sources to sinks under 'current' conditions and a 'closed ecological balance' situation. The transport media for N, P and K are food and feed, water (fertilizer leaching upstream and waste disposal downstream) and air (NO_x, N_2). Figure 5.5 shows nutrient recycling under current conditions, even though the volumes are still

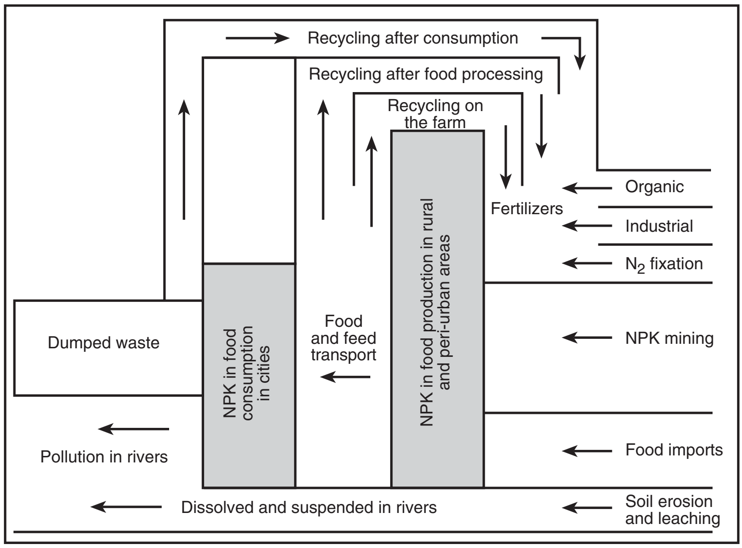

Fig. 5.5. A conceptual framework for fluxes of NPK from sources to sinks and their conversions into and out of 'food and feed' in the current situation. The height of each section is an indication of the volume of nutrients currently involved. The diagram shows that many nutrients are either 'lost' in rivers or immobilized and that many sources of NPK are involved.

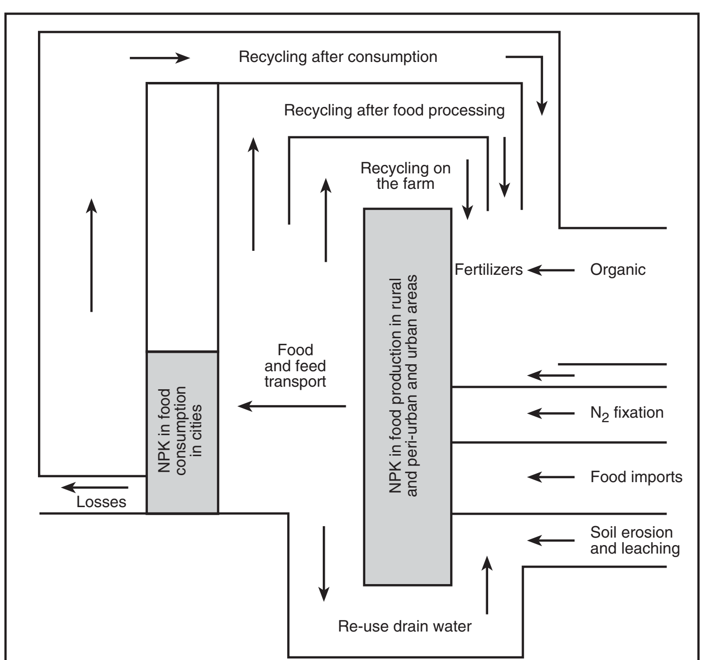

Fig. 5.6. A conceptual framework for fluxes of NPK from sources to sinks and the conversions into and out of 'food and feed' that are ecologically sustainable. The height of each section is an indication of the volume of nutrients involved. Because there is more recycling in rural areas, the actual amount of NPK that flows into urban and peri-urban areas is smaller.

generally insignificant. The main differences in comparison with Fig. 5.2 are that the figures below focus on sources and sinks of nutrients, rather than on food production processes, and show where the challenges to recycling lie. The significant loss in pollution to rivers, as suggested in Fig. 5.5, applies particularly to developing countries, where wastewater treatment is limited and water bodies flow through the city. In countries where such treatment does take place, most of the trapped NPK gets dumped or incinerated rather than recycled, so that the overall picture with respect to an ecological balance is not really different. In most low-income countries, waste management cannot keep pace with urbanization and waste recycling is considered a luxury (Danso *et al*., 2005).

An ecological approach to these problems (Fig. 5.6) would aim at a higher degree of nutrient-loss prevention in rural areas (precision agriculture and the reduction of non-point pollution from agricultural lands, conservation agriculture), more recycling in rural areas (rural food processing and rearing livestock), and a larger degree of nutrient retrieval from wastewater and compost. It is a challenge to reflect how aquaculture could play a role (Y. Niino, pers. comm.). It is also argued (Deelstra and Girardet, 2000; de Zeeuw *et al*., 2000) that cities often provide sufficient space to produce food and to recycle nutrients and that urban agriculture can provide a win–win situation for both. The outflow of nutrients from this system is small: ideally equal to the natural regeneration of soil fertility in the marketshed.

A final thought: Smil (2001) argued that the industrial process of N fixation from the air into ammonia and in fertilizer is a key 20th-century invention, owing to the massive food production increases that this has enabled. In 1997, about half of all N in human food and feed was industrially fixed through the Haber–Bosch process (Vlek *et al*., 1997). It has, however, been calculated that increases in global food supply could have been sustainably achieved without N-fertilizer by making maximum use of N_2-fixing crops and recycling (WRR, 1994; Penning de Vries *et al*., 1997). If so, then net regional and global nutrient flows could have been much smaller and ecological balances maintained to a much higher degree. Rather then labelling industrial reduction of N_2 a key invention, it may be more accurate to argue that the Haber–Bosch process bought us time, but that we still need to proceed towards a more ecological approach.

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