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Optimizing Resource Use Efficiency
for Sustainable Intensification of Agriculture

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GLOBAL ECONOMICS OF NUTRIENT CYCLING

Bert H. JANSSEN
Wageningen University, THE NETHERLANDS

Wageningen University
Plant Production Systems Group
P.O. Box 430, NL-6700 AK Wageningen
The Netherlands
E-mail: Bert.Janssen@wur.nl

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"Global economics of nutrient cycling "

Bert H. Janssen and Oene Oenema [2]

[1] Plant Production Systems Group, Wageningen University, P.O. Box 430, NL-6700 AK Wageningen, The Netherlands

[2] Environmental Sciences Group, Alterra, Wagenintgen UR, P.O. Box 338, NL-6700 AH Wageningen, The Netherlands

ABSTRACT

This paper briefly discusses global human requirements of protein nitrogen (N) from crops and animals and then estimates the need for fertilizer N as function of N use efficiency and the recycling of N from animal manure and sewage wastes. These estimates are based on various assumptions and simple calculations.

Results suggests that globally only 1% of the N input is retained, 28% is lost to the wider environment and some 70% is potentially available for recycling, via manure and sewage. In addition, large amounts of nutrients recycle via crop residues. In practice, only a fraction of this potential is realized, in part because of the segregation of crop production systems from animal production (land-less livestock) systems, and of the lack of economic incentives for recycling. As a consequence, nutrient use efficiency is low and nutrients are spoiled to the environment and create a cascade of unwanted side-effects.

To economize on nutrients, side-effects of their use have to be internalized in decision making. This may be done via deposits and/or taxes to emphasize its non-disposal nature of nutrients. Increasingly, governmental policies provide incentives for recycling of nutrients, but there are clear limits to implementation of environmental regulations. Instead, we foresee a role for the fertilizer industry in processing and recycling animal manure from land-less livestock systems.

1. INTRODUCTION

The title of this paper sounds ambitious and may promise more than can be offered within the limits of one article. Therefore we will first explain what is understood by the four terms global, economics, nutrients, and cycling.

Global has two meanings. The first is: worldwide; the second is: general. In this paper both meanings do apply. Worldwide denotes that we are not dealing with specific regional cases, and that we assume that there are no limitations to international trade of nutrient containing commodities, and of course not to natural nutrient cycling. The second aspect of global finds expression in this paper in the theoretical and simplified approach of the subject of nutrient cycling. We restrict the discussion to the most fundamental task of agriculture of feeding the world population, and to nitrogen, being the major nutrient strongly correlated to the productivity of agro-ecosystems of the world (Goudriaan et al., 2001). In our indicative calculations, the nutrient requirements of the world population, of six and half billions at present, will be represented by the needs of one "average" person.

Economics is the scientific study of the production, sale, distribution and use of goods and wealth. It entails the theory of maximizing profits, based on rational cost - benefit analyses and rational choices. This paper does not explicitly examine prices and trade statistics related to nutrient cycling. We presume that consumers and farmers try to avoid waste of money and of anything of value, and are aware of the economics of scale and efficiency of specialization. At the same time, however, we take into consideration that neither the choices by consumers nor those by farmers are always rational but may also be based on irrational preferences (Knetsch, 1995). These presumptions are helpful in understanding the way nutrients move around the world.

The major “nutrients” are energy, proteins and fats for humans and animals, and nitrogen (N), phosphorus (P), and potassium (K) for plants. The simplest relation between human and animal nutrition on one hand, and crop nutrition on the other, goes via the mass ratio of proteins to nitrogen, usually set at 6.25. It is another reason why we limit the discussion of this paper to protein and nitrogen.

Only for part of cycled nutrients men act as an intermediary and pays, the major part cycles for free. That cycling is to be considered as an ecosystem service. Its value was estimated at $17 \cdot 10^{12}$ US dollar per year by Costanza et al. (1997), which roughly translates to 100 US$ per kg of nutrient. Moomaw and Birch (2005) calculated that the aggregated damage costs of nitrogen are 16 US$ for each kg emitted into the atmosphere, 1 US$ per kg N emitted to terrestrial areas and 6.9 US$ per kg N emitted into freshwater. All these estimated costs are (much) large than the cost of 1 kg fertilizer nutrient, suggesting that careful recycling is cost-effective. However, the topic of the costing of nutrient cycling and of ecological economics in general has been little explored so far, and scientific literature is scarce (e.g., Edwards-Jones et al., 2000).

We focus the discussion on nutrient cycling within agro-ecosystems. It entails interference by humans in terms of labor, fossil energy, materials and capital, but also nature of course. Here economics come into play: what is the net return to fertilizers, what is cheapest packing (in feed, animal products, chemical fertilizers, manure, compost) for nutrient transportation, how can we avoid (penalties for) environmental pollution, etc. Because there is little demand for nutrients packed in manure and sewage sludge, these nutrients form the closing end of men-mediated nutrient recycling. At the same time they are the major agriculture-related causes of environmental troubles and related costs (Pretty et al., 2005).

Several authors arrived at the conclusion that for the next 3 to 5 decades, the needs of food, feed and fiber will increase by about 30-50% relative to 2000 (Smil, 2000; Bruinsma, 2003; Woods et al., 2004; Oenema and Tamminga, 2005). If nutrient use efficiency does not increase dramatically, the need for fertilizer will have to grow more than proportionally, which will have dramatic effects on the environment and biodiversity (e.g., Tilman et al., 2001)

Sparing nutrients may be more effective in satisfying the nutrients needs of growing food, feed and fiber crops than increasing nutrient input in the agro-ecosystems. The objective of this paper is to examine what effects on required nutrient inputs can be attained by increasing nutrient use efficiency and by recycling of nutrients present in manure and sewage sludge. In our opinion simple indicative calculations suffice for that purpose. The exercises were based on assumed world averages of crop yields and nitrogen contents, and of use efficiency of nitrogen applied with chemical fertilizers, manure and compost. Starting points were the protein requirements per “average” person, and the division of plant and animal products for human nutrition. In general the basic data on human diet, crop yields and nutrient use efficiency we used are rather optimistic , in order to get a picture of the minimum land requirements per human being. In the discussion we compare these optimistic outcomes (for an ideal situation) with statistical data and try to explain what the causes and the implications of the differences are.

2. NITROGEN AND LAND REQUIREMENTS FOR FOOD AND INFRASTRUCTURE

2.1. Requirements and sources of protein for human nutrition

The requirements per head for energy, proteins and fats vary with sex, age, and activity. We assumed that an adult man needs per day 2800 kcal, 70 g protein, and 45 g fat, an approximate average of values used in similar studies (e.g., Luyten, 1995; Smil, 2000, 2002a,b). Taking into account that females, children and aged persons need less, we assumed that an “average” person needs 70 to 75% of these amounts. For protein this comes down to about 50 g per day. Applying the generally accepted rule that the mass of protein is equal to 6.25 times the mass of N, the annual requirement of an average person was estimated at 3 kg N.

It was supposed that half of this quantity of N is derived from vegetative products and the other 1.5 kg N from animal products. The sources of animal protein were milk and meat, each one half. The protein in animal products stems from feed. The conversion of feed protein via animal products into human edible protein varies with the type of animal. We used for the ratio feed protein/human edible protein a value of 2.5 for milk, and of 15 for meat. The value of 15 is the weighted average of a meat diet consisting for one third of beef with a ratio feed protein/human edible protein of 25 and for two thirds of pork feed with a ratio protein/human edible protein of 10 (Oenema and Tamminga, 2005).

2.2. Minimum land requirements for crop production and infrastructure

For the calculation of the minimum required area to produce food and fodder crops we used rather optimistic yield data and supposed that in many cases there are two growing seasons for food crops per year. For some fodder crops there may be an almost continuous production.

Table 1. Estimation of the minimum area needed per average person for food and fodder production.

	Destination	Required crop N, kg	N production, kg per ha	Required area, ha
Food	Direct consumption	1.5	150	0.01
Fodder	Meat (0.75 kg N)	11.25		
	Milk (0.75 kg N)	1.875		
	Losses	1.275		
	Total N in fodder	14.4	180	0.08
Total crop area				0.09

Most of the protein derived from vegetative products used for human consumption is offered via cereals (wheat, rice, maize). Estimating the annual grain yield at 10 Mg per ha, and the N mass fraction of grains at 15 g per kg, the annual N production of food crops was set at 150 kg per ha. Fodder crops are soybeans, also cereals, grass and others. We estimated the N production of fodder crops at 180 kg per ha per year. We do realize that these estimates are extremely high. They are, however, not outside the range of really measured yields. We spend more attention to this subject in the discussion section of this paper.

Table 1 shows the calculation of rounded values of the required areas per average person. For food crop 0.01 ha is needed, and for fodder crops 0.08 ha. These values represent minimum sizes indeed, because the assumed yields are high and the losses between harvest and consumption were assumed to be negligible (which is not the case in practice).

Table 2 presents the area needed for the food and fodder production and the infrastructure of a big city (ten millions inhabitants) in an assumed ideal situation. The population density was set at 10,000 per square kilometer. Food production, partly in the shape of horticulture, and land-less livestock industry are supposed to be close to the city itself. It turns out that a square of 100 by 100 km would suffice, and that the maximum distance of transport of food to the city centre would be not more than 71 km. The maximum distance for transport of manure between the livestock area and the fodder crop area, calculated as the difference between the maximum distances to the centre for the total area and the city itself is 71 minus 22 or about 50 km.

Table 2. Minimum dimensions of a ten millions city and surrounding area for food and fodder crops. Population density is 10,000 per square km.

	City	City plus food crops	City plus food and fodder crops
Area, sq km	1000	2000	10000
Diameter, km	36	50	113
Square side, km	32	45	100
Max. distance to centre, km	22	32	71

2.3. Nitrogen requirements in an agricultural system of livestock, food and fodder crops

To compensate for the output of nitrogen present in harvested food and fodder crops, and for losses by leaching, volatilization and denitrification, inputs of nitrogen are required. Table 3 depicts the partitioning of nitrogen under steady-state conditions in fields planted to food crops or fodder crops. Details of the food crop system have been published by Janssen and De Willigen (2006, in press). The recovery of applied fertilizer N is expected to be 50 %: the removal of N in grains and straw (200 kg) is half the total quantity (400 kg) of N involved. In the present paper we assume that straw is incorporated into the soil. Hence the output of N is the sum of N in grains and losses, being 300 kg. To keep the soil in steady state, also the input of N must be 300 kg. For fodder crops the output is 260 kg, and hence the required input is also 260 kg of N.

In Figure 1 the N flows are calculated per ha arable land, planted to food and fodder crops in the same ratios as shown in Table 1. Hence one ha of arable land contains 0.11 ha of food crops and 0.89 ha of fodder crops, which is supposed to be sufficient for 1/0.09 or 11 persons. The part with food crops receives an external input of 33 kg (= 0.11 times 300 kg) and the part with fodder crops 231 kg (= 0.89 times 260), together 264 kg N. Clearly, these N inputs are high; they hold for intensively managed arable cropping systems and for intensively managed, foraged-based dairy and beef cattle farming. For situations with lower yields and lower inputs, a larger area is needed for the production of food and fodder, and the area ratio of fodder crops to food crops may deviate from 8, as calculated in Table 1.

Table 3. Partitioning of nitrogen under steady state conditions with food crops and fodder crops.

		Partitioning expressed in	
		Kg per ha	Percent
Food crops	Grain	150	37.5
	Straw	50	12.5
	Roots and immobilization	50	12.5
	Leaching	100	25
	Gaseous losses	50	12.5
	Total	400	100
Fodder crops	Harvested components	180	56
	Roots and immobilization	60	19
	Leaching	55	17
	Gaseous losses	25	8
	Total	320	100

In case of chemical fertilizers, the N input to the food crops field is equally divided over leaching plus gaseous losses from the field and grains (Table 3, Figure 1); the latter is used for human consumption. A quarter of the N input to the fodder crop N is lost and 56% is taken up in the fodder crop. The fodder losses, representing 15 kg N in Figure 1 are proportionally the same as in Table 1. In practice the fraction of fodder that gets lost usually is considerably greater. Finally 17 kg of the 158 kg of N eaten by the animals is used as human food, half as milk, half as meat. The animals excrete the major portion of N to dung and urine (manure). The total human consumption of N is 34 kg consisting of two equal portions of 17 kg, one of animal products and one of crop products. We assumed that 10% of the human consumption is spent for the growth of children and the remainder released to the sewerage system.

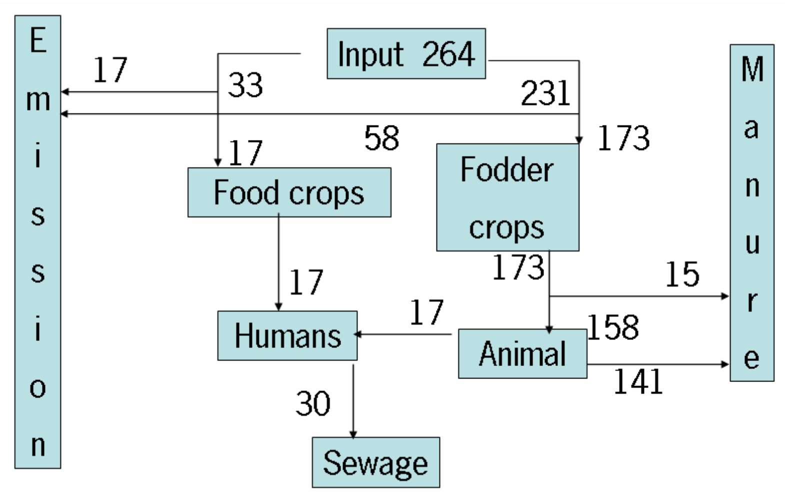

Figure 1. N flows (kg per ha per year) at standard high efficiency and no recycling of manure and sewage.

The human consumption itself is about 13% of the input of N. In practice less than 13% of the input will be consumed by humans. Only the three to four kg of N that is stored in the growing bodies of children does not become available for recycling immediately. The amount lost to the wider environment via gaseous N emissions is 75 kg per person per year, and the amount that becomes potentially available for recycling via manure and sewage sludge is 156 and 30 kg. Altogether, roughly 1% of the N input is retained and 28% is lost and 70% is potentially available for recycling (59% via manure and 11% via sewage sludge). It should be emphasized that our assumptions about the losses were optimistic.

These simple calculations clearly demonstrate that there is a huge potential for N recycling. The calculations also illustrate the wasting in human consumption, and there are serious doubts about the possibilities continuing this way of live (e.g., Tilman et al., 2001).

However, it must be kept in mind that large numbers of animals serve other functions than simply meat and milk production. Also, many of these animals graze marginal lands and live of offal as scavengers. The excrements (droppings) of these animals are recycled in the grazing areas or are collected for fuel, cement or for soil amendment elsewhere. There is a huge diversity in livestock keeping.

2.4. Land-less livestock production and environment

Manure ‘problems’ (surpluses) exist regionally because humans produce and use milk and meat regionally in high concentrations. A very drastic mitigation of the environmental problem would be a completely vegetarian diet. The required external input in Figure 1 would be only 66 kg, to be divided over crop (33) and emission (33); there would be no manure but sewage would still be 30. So the total potential burden to the environment would be reduced from 261 to 63 kg of N per ha per year, i.e per 11 persons per year. Other contributions to lowering the environmental burden are by increasing the efficiency of conversion of feed into animal products or by redirecting the diet from the products with the least efficient conversion (beef) towards products with better conversion efficiencies (sheep, pork, chicken, fish). That would reduce the quantity of manure. In Figure 1, manure makes up about 60% of the total potential environmental burden, and reuse of the nutrients in manure is imperative. In practice this proves easier said than done.

When farmers apply manure they can economize on fertilizers. So, energy is saved that otherwise would be required for the production of those fertilizers. Van Dasselaar and Pothoven (1994) compared these savings with the energy needed for the transport of manure. They found that from an energy point of view it is justifiable to transport pig slurry by trucks over a maximum distance of 75 to 100 km, and cattle slurry over maximum distances of 35 to 50 km. Theoretically no serious transportation problems would arise when urban and agricultural areas were distributed as indicated in Table 2, provided cattle farms are further away from the city than pig farms.

In practice, fodder crop areas usually are far (even oceans) apart from the livestock and human population centers (Lanyon, 1995), making the distances far too big for the transport of manure. Apart from the unfavorable energy spending, costs become prohibitive. Oenema and Tamminga (2005) calculated that the proportions of the costs of transportation for animal feed, live animals, animal products and animal manure are: 1 : 4 : 2 : 25. It is obvious that feed is the commodity of this food chain that is preferred for transportation, followed by animal products.

Both are currently transported over distances of five to ten thousand kilometers. Shorter transportation distances are found for live animals, although they can still be around a thousand kilometer. Farmers try to keep transport of manure as limited as possible, say less than 20 to 30 km. In West Europe and northern America, quite often there is not sufficient land nearby to apply the manure, and the cycling of nutrients breaks down. That is the essence of the environmental problems in areas with intensive livestock production. There is an urgent need for methods to reduce the volumes of manure and to pack the manure nutrients in manageable fertilizers. That is why there is so much interest in manure processing currently, also because governmental policies set increasing restrictions to manure disposal.

3. SAVING OF NITROGEN

3.1. Recycling

As mentioned, recycling of manure would save fertilizer nutrients and by that spare the finite supplies of fossil energy sources, and of P and K deposits. Replacing fertilizer N by manure N is not an 1:1 exchange, because of their differences in availability to plants. Table 4 presents the relative allocation of applied nitrogen to crop, soil and losses for fertilizers, manure and compost. For the calculation of these coefficients, the partitioning of N in the crops in Table 3 formed the basis. The allocation can directly be assessed for fertilizers, for manure and compost the efficiency index or substitution ratio must be known. For the values of manure, the subdivision of manure N in mineral N (50%), easily decomposable organic N (25%) and resistant organic N (25%), and the procedure for the calculation of “efficiency index”, as introduced by Sluysmans and Kolenbrander (1977), were followed. For compost we based the calculations on the assumption of a nitrogen efficiency index of 0.12, a little bit higher than the value of 0.1 used in the Netherlands. There temperature is a little lower than the global temperature, and hence the decomposition of organic matter goes slower and the efficiency index is lower.

The relative allocation of N to the crops is lower for food than for fodder crops because we assigned the nutrients present in stover to the soil. For fertilizers we assumed steady-state soil fertility, implying that the soil supplies a same amount of N to the crop as it receives from the applied fertilizer. In the case of manure and compost a considerable greater portion of applied N is allocated to the soil. The consequence is that the nitrogen stock will gradually increase in a soil that is in steady state under chemical fertilizers, once one starts applying manure or compost. Finally a new steady state is reached with an higher organic matter content than the original content.. Application of manure and compost serves then to compensate the annual mineralization, and the application rate can be considerably lower than in the first year of application.

Table 4. Coefficients (%) for the allocation of nitrogen from chemical fertilizers, manure and compost, to crop, soil and losses. Nutrient use efficiency is maximum when there are no losses.

		Fertilizers	Manure	Compost
Standard high nutrient use efficiency				
Food crops	Crop grain	37.5	24.5	6.1
	Soil[a]	25	40	83.0
	Losses	37.5	35.5	10.9
	Total	100	100	100
Fodder crops	Crop	56.25	37.6	8.35
	Soil	18.75	37.2	82.25
	Losses	25	25.3	9.40
	Total	100	100	100
Maximum nutrient use efficiency				
Food crops	Crop grain	60	49	15
	Soil[a]	40	51	85
Fodder crops	Crop	75	59	17
	Soil	25	41	83

[a] Nutrients taken up in stover of food crops are allocated to soil, since it is supposed that stover (straw) is ploughed under.

To be able to estimate the effects of recycling of manure and sewage (compost is derived from sewage in Figure 1), first of all the allocation coefficients of Table 4 must be known. There are, however, some other complications. Figure 1 shows that there is more than enough manure N for the required input to food crops, but it is not wise to satisfy the need for N by manure and sewage sludge alone. An important reason is that the N to P ratio in manure is lower than the optimum ratios for crops. Application of large quantities of manure and sewage may result in over-application and accumulation of phosphorus and various metals like copper and zinc in soils, and ultimately in leaching of phosphorus and copper and zinc to surface waters. This has happened in some areas of the Netherlands and United States and has caused a lot of environmental problems since the seventies (Beek et al., 1977; Van der Meer et al., 1987; Van der Zee and Van Riemsdijk, 1988; Moolenaar et al., 1997; Schoumans and Groenendijk, 2000; Sims et al., 2005). Currently, it happens in many developing countries too, including China (e.g. Ju et al., 2005).

At present the concern is how to mine phosphorus from phosphorus enriched soils (Koopmans, 2004). In our calculations, the maximally allowed application of available manure N was set at 40% of the amount of food crop N for the case of standard high efficiency, and at 65% for the case of maximum efficiency (in Table 5). The quantity of compost that was applied was equal to the required crop N divided by the compost coefficient of allocation to crop. Two situations are distinguished: (i) application to food crops only because these crops are supposed to grow in the vicinity of (city and) livestock industry; the food crops cannot utilize all available manure and compost, (ii) application of the same quantity of manure and compost to food crops, and the remaining quantities of all available manure and compost to fodder crops.

Results of the calculations show that fertilizer N requirement greatly depends on N use efficiency and the recycling of manure and sewage (Table 5). Recycling of manure and compost to food crops alone reduces the need for fertilizer N only by 7% in our calculations. This small effect is related to the relatively small area of food crops (only 11% of the total cropped area) in our calculations, and to the assumption that manure provides only 40 % of the food crop N requirement. When manure and compost are recycled to both food and fodder crops, the decrease in fertilizer N requirement is much larger (Table 5). Clearly, recycling of manure and sewage (compost) has a huge effect on fertilizer N requirement.

Table 5. Fertilizer- N requirement (% of standard 264 kg per ha per year), as affected by nutrient use efficiency and recycling. Data refer to the first year of application of manure and compost.

	Nutrient use efficiency	
	Standard high	Maximum
No recycling	100	67
Compost and manure to food crops only	93	61
All compost and manure to food and fodder crops	66	32

Recycling of nutrients in manure and sewage effectively is not without costs. In general, economic costs of the recycling of manure nutrients increase from essentially zero for grazing systems, to moderate for mixed livestock systems, and to high to very high for specialized, land-less livestock systems. Indeed, disposal of manure from land-less livestock systems in an environmental friendly sound way is very expensive. For example, land-less livestock farmers in the Netherlands pay about 10-15 US$ for the disposal of 1 m^3 of animal slurry (mixture of dung and urine, with a dry matter content of about 10%). Approximately half of this cost is for the transport of the slurry, and the other half is the goodwill fee for arable farmers that accept the slurry as nutrient source. The cost for manure disposal has increased dramatically over the last 25 years, following a tightening of the environmental regulations. Currently, land-less livestock farm in the Netherlands pay US$ 10,000 - 40,000 per farm for manure disposal (e.g. RIVM, 2004; Oenema and Berentsen, 2004), and these costs may increase further, when environmental regulations become more strict. Evidently, the cost of manure disposal in an environmental sound way is a serious economic burden, and a increasing threat for the competitiveness of land-less livestock farms. Unless economically feasible and environmentally sound and socially acceptable manure processing technology becomes available, there seems to be no sustainable future for large conglomerations of land-less livestock farms, separated far from large crop production areas (e.g. Sims et al., 2005)

3.2. Repairing the nutrient leaking holes: maximum nutrient use efficiency

The caption "maximum nutrient use efficiency" in Table 5 means that losses of applied nitrogen are completely avoided. For the calculation of the effect of improvement of nutrient use efficiency the coefficients of allocation to losses in Table 4 were set at zero. The proportions of the allocation coefficients to crop and soil remained the same in the case of chemical fertilizers, e.g. the ratio 37.5/25 equals the ratio 60/40. For manure and compost, however, these ratios do change. The reason is that N losses refer to available N only. If these losses are avoided, the quantity of available N increases, but that of not-immediately available nutrients, which by definition are allocated to the soil does not. As a result the ratio of the coefficients of allocation to crop and soil increases upon repairing the leaking holes. As a logical consequence, the effect of increasing nutrient use efficiency is the stronger the more animal manure and compost are applied (Table 5). Clearly, the effects of increasing recycling and increasing use efficiency are strongly complementary.

3.3. Saved fertilizer N

Though our assumptions are too optimistic as far as it concerns crop yields and nutrient use efficiency, and also as regards the utilization of harvested products, the results of our simple calculation do provide insight in the potential of nutrient recycling.
We acknowledge that the data of Table 5 may receive a strongly colored interpretation depending on the position of the reader. For the fertilizer industry the potential for reduction in fertilizer needs sounds alarming, for the farmer it could be a message he has been waiting for. The environmentalist sees confirmed what he knew for longtime: fertilizers apparently are produced to go through the drain.

At the same time the data are challenging the industry. Measures must be taken to minimize losses to the environment, and to transport nutrients in other vehicles than feeds only. Transport of manure nutrients requires concentration. Here we see a task for the fertilizer industry. One aspect of recycling of manure is that it may help to compensate for reduced fertilizer sales. The fertilizer industry may consider recycling also as its responsibility towards the society. Fertilizers are too beneficial to let them go through the drain.

Similar to the situation with energy, for nutrients it holds that saving is better than speeding up the depletion of finite supplies, Consumers, farmers and governments too have a responsibility here.

4. DISCUSSION

4.1. Internalizing unwanted side-effects of nutrients

Life on earth is self-supporting but for sun light (energy). For nutrients, our earth acts as a 'closed system'; there is a continuous recycling, transformation and redistribution of nutrients from one pool to another. These pools are found in the biosphere, lithosphere, hydrosphere and atmosphere, and greatly vary in size and in turnover. Nutrients are transferred from one pool to another via plants, animals, humans, water and wind. Commonly, only a small fraction of the nutrients in the various pools is directly available for life on earth, and as a result biomass production and ecosystem functioning is strongly related to the availability of nutrients, especially nitrogen. Numerous site-specific factors affect the recycling and availability of nutrients and this site-specificity contributes to the diversity of ecosystems and biomass production.

Especially during the last century, humans have greatly affected the flows and cycling of available (reactive) nutrients in the biosphere through mining activities, fossil energy use, soil cultivation and crop production, domestication of animals, fertilizer production, deforestation and growing leguminous crops. As a consequence, the flow of available and reactive nutrients to the atmosphere and biosphere has increased greatly, with a cascade of unwanted side-effects. By large, these side-effects are still externalized, i.e., the effects are not included in decision making and cost-benefit analyses of enterprises. The neglect is exaggerated by the diffuse nature of the side-effects, the complex and site-specific cause – effect relationships and the delays involved. Hence, there is little incentive for saving and recycling nutrients, unless nutrients sources are scarce or environmental policy forces polluters to do so.

Waste is created by all societies, but the more so when living in wealth. Well-organized societies impose deposits on non-disposable goods and taxes for collecting and recycling wastes. By doing so, side effects are internalized (economized) in our decision making. The higher the deposits, the more goods are returned, the higher the taxes on waste collection, the less waste is produced and disposed off and the more waste is recycled by producer and consumer. These general principles drive the economics of nutrient cycling globally. They are applicable to animal manure and sewage waste too.

4.2. Comparison of calculated and measured flows of nutrients

It were not statistical data on flows of nutrients packed in feeds, food crop and animal products or fertilizers that formed the starting point of our paper, but simple calculations of the nutritional needs per caput and the related requirements of yields and areas of food and fodder crops. The purpose was to keep the picture simple and basic. Multiplication of the values per average person by $6.5 \cdot 10^9$, being the number of the present world population, would result in data referring to the whole world. In Table 6 our estimates are compared with real-world statistical numbers.

For the conversion of 0.75 kg N per caput per day, we assumed 14% protein in meat, and for the conversion of 0.75 kg N in milk (read dairy products) we assumed 3.5 % protein or 0.5% N in milk. Our estimates of the production of meat and animal manure in Table 6 seem rather realistic. They are directly derived from daily needs of human consumption. We overestimated the share of dairy products in the human diet by almost a factor 2.

The real area planted to crops is much greater than our estimate. We have set annual yields, which partly consist of two and even three yields, at 10 Mg per ha, for both food and fodder crops. Based on these estimates we arrived at the simple outcomes of Tables 1 and 2. Smil (2002a) estimated that 0.08 ha per caput is required for the food crop production of a vegetarian diet, and 0.4 ha per caput for a typical Western diet. Our estimates are 0.02 and 0.09 ha per caput, respectively. The difference is a factor of four. Arable land and Permanent Pasture as given in the FAO statistics (Table 6) are not exactly comparable with our areas for food and fodder crops, respectively. The FAO area data are more than 20 and 6 times as high as our estimates.

Because we overestimated yields and underestimated the required area for crops, our estimate of fertilizer N needs has to be higher than the real use. Another reason is that we did not take into account in the estimate of Table 6 that a part of the manure is used and replaces fertilizers. The difference between reality and our estimate is a factor two, not as great as the differences in cropped area. This may partly be ascribed to the high standard nutrient use efficiency we assumed in our calculations (Table 4), which is roughly two times as great as the usually reported nutrient use efficiency (Dobermann,and Cassman, 2004).

The figures for fertilizer use look somewhat confusing. We estimate a fertilizer need that is two times the real use, when manure and compost are not recycled, but we also conclude (Table 5) that the fertilizer need can be reduced to one third under complete recycling and maximum nutrient use efficiency. Even further reduction is possible, when that recycling continues and soil fertility is built up.

Table 6. Comparison of data on food consumption, manure, fertilizer use, and area of cropped land as estimated in this paper with statistical data.

	As estimated in this paper		Statistical data
	Per caput	World, Gg	
Meat consuption, per year	37.5 kg	244 Gg	200 Gg (Smil, 2002)
Milk consumption, per year	150 kg	975 Gg	500 Gg (Smil, 2002)
Animal manure N, per year	14 kg	91 Gg	100 Gg (Smil, 2002)
Fertilizer N[a], per year	24 kg	158 Tg	In 2002/2003: 85 Tg http://www.fertilizer.org/ifa/statistics/
Area for food crops, ha	0.01 ha	$65 \cdot 10^6$ ha	$1400 \cdot 10^6$ ha [b] http://faostat.fao.org/faostat
Area for fodder crops and grazing	0.08 ha	$520 \cdot 10^6$ ha	$3400 \cdot 10^6$ ha [c] http://faostat.fao.org/faostat

[a] No recycling of manure and compost
[b] Arable land
[c] Permanent Pasture

4.3. Concluding remarks

Is our approach a purely academic exercise? The least we can say is that the differences between real world and our optimistic estimates show that there is still much to win. The estimates confirm what has been stated by many others: the world can be fed with a much smaller area of arable land that is in use at present. Another conclusion is that present day separation of fodder crop growing and livestock production results in a tremendous spoiling of nutrients if manure is not used.

Given the fact that transportation of animal manure, in the slurry form it is now, is limited to say 20 km, two major options do exist to reverse the present unfortunate situation. The first and most straight-forward recommendation is to keep animals, where the feed is. Nutrients can then be transported in the shape of meat and dairy products, which is relatively cheap. We realize that this option has tremendous effects on economy and employment. The second option is to concentrate the nutrients in manure. The attempts made so far proved too costly. In view of the negative prices of manure in some areas of intensive livestock keeping, and in view of the fact that farmers do not easily give up farming, the cost of the conversion of manure will become less prohibitive than it used to be. The technological know-how for this process is in hands of the fertilizer industry, just as the network for the distribution of the converted-manure-nutrients. Why to wait longer? The sympathy is for those who bring the wisdom into practice that it is better to save than to spoil the limited supplies of natural resources.

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