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Global Economics of Nutrient Cycling

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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 a 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 suggest that globally only 1% of 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 lost 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 the non-disposal nature of nutrients. Increasingly, government policies provide incentives for recycling nutrients, but there are clear limits to the implementation of environmental regulations. Instead, we foresee a role for the fertilizer industry in processing and recycling animal manure from land-less livestock systems.

Key Words: crop production, economics, land requirement, livestock, manure, nutrient cycling

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 4 terms: global, economics, nutrients, and cycling.

Global has 2 meanings, the first is worldwide and the second is general. In this paper both meanings apply. Worldwide denotes that we are not dealing with specific regional cases and that we assume that there are no limitations to the 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, which is to feed the world population, and to nitrogen, the major nutrient strongly correlated to the productivity of the agro-ecosystems of the world (Goudriaan et al., 2001). In our indicative calculations, the nutrient requirements of the world population, 6.5 billion at present, will be represented by the needs of 1 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 wasting money and anything else 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 relationship between human and animal nutrition, on one hand, and crop nutrition on the other, is via the mass ratio of proteins to N, usually set at 6.25. It is another reason why we limit the discussion in this paper to protein and N.

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Only for a portion of cycled nutrients does man act as an intermediary and pay, whereas the major portion cycles for free. That cycling is to be considered an ecosystem service. Its value was estimated at 17×10^{12} US dollars per year by Costanza et al. (1997), which roughly translates to $100 per kg of nutrient. Moomaw and Birch (2005) calculated that the aggregated damage cost of N is $16 for each kg emitted into the atmosphere, $1.00 per kg N emitted into terrestrial areas, and $6.90 per kg N emitted into freshwater. All these estimated costs are (much) larger than the current cost of 1 kg of fertilizer nutrient, suggesting that careful recycling is cost-effective. However, the cost of nutrient cycling and of ecological economics in general, to date, has been seldom explored, and the scientific literature offers few examples (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 by nature, of course. Here, economics come into play; what is the net return to fertilizers, what is the cheapest packing (in feed, animal products, chemical fertilizers, manure, and 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 man-mediated nutrient recycling. At the same time they are the major agriculture-related causes of environmental problems and related costs (Pretty et al., 2005).

Several authors arrived at the conclusion that for the next 3-5 decades the need for food, feed, and fiber will increase by about 30%-50% relative to 2000 (Smil, 2000; Bruinsma, 2003; Wood et al., 2004; Oenema and Tamminga, 2005). If nutrient use efficiency does not increase dramatically, the need for fertilizer will have to increase more than proportionally, which will have dramatic effects on the environment and biodiversity (e.g., Tilman et al., 2001; 2002).

Sparing nutrients may be more effective for satisfying the nutrient needs of growing food, feed, and fiber crops than increasing nutrient input in agro-ecosystems. The objective of this paper was to examine what effects on required nutrient inputs can be attained by increasing nutrient use efficiency and by recycling the 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 N contents, and of N use efficiency 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 were rather optimistic in order to obtain 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.

Nitrogen and Land Requirements for Food and Infrastructure

Requirements and Sources of Protein for Human Nutrition

The requirements per person for energy, proteins, and fats vary with sex, age, and activity. We assumed that an adult man needs 2800 kcal, 70 g of protein, and 45 g of fat per day, an approximate average of values used in similar studies (e.g., Luyten, 1995; Smil, 2000, 2002a, 2002b). Taking into account that females, children, and elderly persons need less, we assumed that an average person needs 70%-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 to be 3 kg of N.

It was supposed that 50% of this quantity of N is derived from vegetative products and the other 1.5 kg of N from animal products. The sources of animal protein were milk and meat (50% each). 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. For the feed ratio we used a protein/human edible protein value of 2.5 for milk and of 15 for meat. The value of 15 is the weighted average of a meat diet consisting of $^1/_3$ beef with a feed ratio for protein/human edible protein of 25 and $^2/_3$ pork with a feed ratio for protein/human edible protein of 10 (Smil, 2002a, 2002b; Oenema and Tamminga, 2005).

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 2 growing seasons for food crops per year. For some fodder crops there may be almost continuous production.

Most of the protein derived from vegetative products used for human consumption is offered via cereals (wheat, rice, and maize). Estimating the annual grain yield at 10 Mg per ha and the N mass fraction of grains at 15 g per kg, annual N production of food crops was set at 150 kg per ha. Fodder crops are soybeans, as well as 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 actually measured yields. We elaborate more on this subject in the discussion section of this paper.

Table 1 shows the calculation of rounded values of the required areas per average person. Food crops require 0.01 ha and 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 food and fodder production, and the infrastructure of a big city (10 million inhabitants) in an assumed ideal situation. The population density was set at 10,000 per km^2. Food production, partly in the form of horticulture, and land-less livestock production are supposed to be close to the city itself. It turns out that a circle 113 km in diameter or a square of 100 × 100 km would suffice, and that the maximum distance of transport of food to the city center would not

Table 1. Estimation of the minimum area needed per average person per year for food and fodder production. It is assumed that human consumption is without losses.

Crop	Destination	Required crop N, kg capita^{-1} year^{-1}	N production, kg ha^{-1} year^{-1}	Required area, ha capita^{-1} year^{-1}
Food	Direct consumption	1.5	150	0.01
Fodder	Meat (0.75 kg N)	11.25		
	Milk (0.75 kg N)	1.875		
	Fodder losses by animals	1.275		
	Total N in fodder	14.4	180	0.08
Total				0.09

Table 2. Minimum dimensions of a city of 10 million, and the surrounding area for food and fodder crops. Population density is 10,000 per km^2.

	City	City plus food crops	City plus food and fodder crop
Area (km^2)	1000	2000	10,000
Diameter (km)	36	50	113
Max. distance to center,(km)	18	25	57
Square side (km)	32	45	100
Max. distance to center (km)	22	32	71

be more than 71 km. It is supposed that manure is transported from the area of land-less livestock near the city to the fodder crop area on the same side of the city. In most cases the distance of transport is then less than 50 km.

Nitrogen Requirements in an Agricultural System of Livestock, Food, and Fodder Crops

To compensate for the output of N present in harvested food and fodder crops, and for losses due to leaching, volatilization, and denitrification, inputs of N are required. Table 3 depicts the partitioning of N 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). The recovery of applied fertilizer N is expected to be 50%; the removal of N in grains and straw (200 kg) is 50% of 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 (300 kg). To keep the soil in a steady state, the input of N also must be 300 kg. For fodder crops the output is 260 kg, and, therefore, the required input is also 260 kg of N.

In Figure 1 N flows are calculated per ha of arable land planted to food and fodder crops in the same ratios as shown in Table 1. Hence, 1 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 × 300 kg) and the part with fodder crops 231 kg (= 0.89 × 260), together, 264 kg of 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. In 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.

In the case of chemical fertilizers, N input into 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 into the fodder crop is lost directly to the environment. The fodder losses, representing 15 kg of N in Figure 1, are proportionally the same as in Table 1. In practice the fraction of fodder lost usually is considerably greater. Animals excrete the major portion of N in dung

Table 3. Partitioning of nitrogen under steady-state conditions with food crops and fodder crops (explanation in text).

		Partitioning expressed in	
		Kg ha^{-1}	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

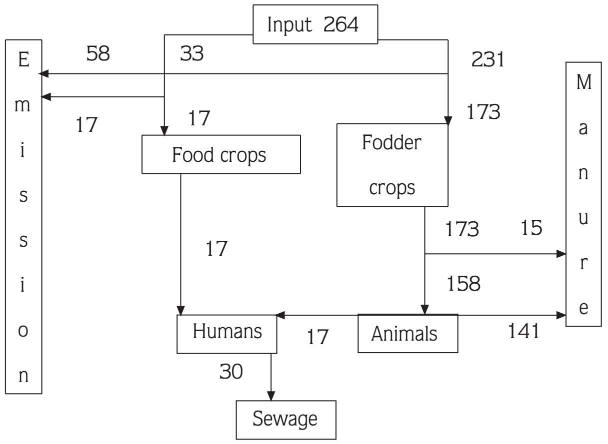

Figure 1. N flows (kg ha^{-1} $year^{-1}$) at standard high efficiency, without recycling manure or sewage (for explanation see text).

and urine (manure). Finally, 17 kg of the 158 kg of N eaten by the animals is used as human food; 50% as milk, 50% as meat. The total human consumption of N is 34 kg, consisting of 2 equal 17-kg portions, 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 is released to the sewerage system. 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 3-4 kg of N stored in the growing bodies of children does not become available for recycling immediately.

Of the total input of 264 kg N, the amount lost to the wider environment is 75 kg per ha per year, and the amount that becomes potentially available for recycling via sewage sludge and manure is 30 kg and 156 (= 15 + 141) kg (Figure 1). Altogether, roughly 1% of the N input is retained, 28% is lost, and 70% is potentially available for recycling (11% via sewage sludge and 59% via manure). 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 waste in human consumption, and there are serious doubts about the possibility of continuing this way of life (e.g., Bleeken and Bakken, 1997; Tilman et al., 2001; Smil, 2002a, 2002b; Galloway et al., 2007).

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

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 solution to the environmental problem would be a completely vegetarian diet. The required area for the production of food crops for 11 persons would then be 0.22 ha. The required external input in Figure 1 would be only 66 kg, to be divided over crop (33) and emissions (33); there would be no manure, but sewage would still be 30 kg. So, the total potential burden to the environment would be reduced from 261 to 63 kg of N per 11 persons per year. Other contributions to lowering the environmental burden are by increasing the efficiency of the 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 efficiency (sheep, pork, chicken, and 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 would otherwise be required for the production of those fertilizers. Van Dasselaar and Pothoven (1994) compared these savings to 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 75-100 km, and cattle slurry over a maximum distance of 35-50 km. Theoretically, no serious transportation problems would arise when urban and agricultural areas are distributed as indicated in Table 2, provided cattle farms are farther away from the city than pig farms.

In practice, fodder crop areas are usually far (even oceans) from livestock and human population centers (Lanyon, 1995; Galloway et al., 2007), making the distances far too great for the transport of manure. Apart from the unfavorable energy spending, costs become prohibitive. Oenema and Tamminga (2005) calculated that the ratio of the costs of transportation for animal feed, live animals, animal products, and animal manure is 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 5000-10,000 km. Shorter transportation distances are found for live animals, although they can still be around 1000 km. Farmers try to keep the transport of manure as short as possible, say less than 20-30 km. In western Europe and North America, quite often there is insufficient land nearby to apply the manure, and the cycling of nutrients breaks down. That is the essence of the environmental problem in areas with intensive livestock production. There is an urgent need for methods of reducing the volume of manure and to pack the manure nutrients into manageable fertilizers. That is why there is currently so much interest in manure processing, in addition to government policies that set greater restrictions on manure disposal.

Saving Nitrogen

Recycling

As mentioned previously, recycling manure would save fertilizer nutrients and, as a consequence, spare the finite supplies of fossil energy sources, and of P and K deposits. Replacing fertilizer N with manure N is not a 1:1 exchange, because of the differences in their availability to plants. Table 4 presents the relative allocation of applied N from fertilizers, manure, and compost, to crop, soil, and losses. The calculation of these coefficients was based on the partitioning of N in the crops, as shown in Table 3. The allocation can directly be assessed for fertilizers, whereas 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 the efficiency index, as introduced by

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

		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.

Sluijsmans and Kolenbrander (1977), were followed. For compost made from household waste, we based the calculations on the assumption of an N efficiency index of 0.12, a little bit higher than the value of 0.1 used in the Netherlands. There, the temperature is a little lower than the global temperature, and hence, organic matter decomposes 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 receives from the applied fertilizer the same amount of N as it supplies to the crop. In the case of manure and compost, a considerably greater portion of applied N is allocated to the soil. The consequence is that the N 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 higher soil organic matter content than the original content. Application of manure and compost then serves to compensate the annual mineralization and the application rate can be considerably lower than in the first year of application.

To be able to estimate the effects of recycling manure and sewage (compost is derived from sewage in Figure 1), first 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 for this is that the N:P ratio in manure is lower than the optimum ratios for crops. Application of large quantities of manure and sewage may at times be excessive, resulting in the accumulation in soils of P and various metals, like copper and zinc, and ultimately in the leaching of P, copper, and zinc into surface waters. This has happened in some areas of the Netherlands and United States, and has been the cause of many environmental problems since the 1970s (Beek et al., 1977a, 1977b; 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 other countries too, including China (e.g. Ju et al., 2005). At present the concern is how to mine P from P-enriched soils (Koopmans, 2004).

In our calculations the maximum 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 applied was equal to the required crop N divided by the compost coefficient of allocation to crop. Two situations stand out: (i) Application to food crops only; these crops are supposed to grow in the vicinity of the city and the livestock industry, but they cannot utilize all available manure and compost: (ii) Application of the same quantity of manure and compost to food crops as for (i) and the remaining quantities of all available manure and compost to fodder crops.

Table 5. Fertilizer N requirement (% of standard 264 kg ha^{-1} $year^{-1}$), as affected by nutrient use efficiency and recycling. Data refer to the first year of application of manure and compost (difference in application of compost and manure is explained in text).

	Nutrient use efficiency		
	Standard high	Maximum	Maximum/ standard high
No recycling	100	67	0.67
Compost and manure to food crops only	93	61	0.66
All compost and manure to food and fodder crops	66	32	0.48

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 manure and compost to food crops alone reduces the need for fertilizer N by only 7%, according to our calculations. This small effect is related to the relatively small area of food crops in our calculations (only 11% of the total cropped area), 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 manure and sewage (compost) has a huge effect on the fertilizer N requirement.

Effective recycling of nutrients in manure and sewage is not without cost. In general, the economic cost of recycling manure nutrients increases from essentially zero for grazing systems, to moderate for mixed livestock systems, and then high to very high for specialized, landless livestock systems. Indeed, disposal of manure from landless livestock systems is an environmentally friendly and sound method, but very expensive. For example, landless livestock farmers in the Netherlands currently pay about \$10-\$40 for the disposal of 1 m^3 of animal slurry (a mixture of dung and urine, with a dry matter content of about 10%), depending on slurry type and distance to be transported. Approximately 50% of this cost is for the transport of the slurry and the other 50% is for the goodwill fee paid to arable farmers that accept the slurry as a nutrient source. The cost for manure disposal has increased dramatically over the last 25 years, following a tightening of environmental regulations. Currently, landless livestock farms in the Netherlands pay \$10,000-\$40,000 per farm for manure disposal (e.g. RIVM, 2004; Oenema and Berentsen, 2004), and these costs may increase further, following the tightening of environmental regulations. Evidently, the cost of manure disposal in an environmentally sound way is a serious economic burden and an increasing threat to the competitiveness of landless livestock farms. Unless manure processing technology that is economically feasible, environmentally sound, and socially acceptable becomes available, there seems to be no sustainable future for large conglomerations of landless livestock farms located far from large crop production areas (e.g. Sims et al., 2005)

Repairing the Nutrient-Leaking Holes: Maximum Nutrient Use Efficiency

The caption, "maximum nutrient use efficiency", in Table 5 means that the loss of applied N is completely avoided. To calculate the effect of improving 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 (Table 4). 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 nutrients that are not-immediately available, 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 from standard high to maximum increases as more animal manure and compost are applied, as seen in the maximum:standard high ratio in Table 5. Clearly, the effects of increased recycling and increased use efficiency are highly complementary.

Saved Fertilizer N

Though our assumptions are too optimistic regarding crop yields, nutrient use efficiency, and utilization of harvested products, the results of our simple calculation do provide insight into the potential of nutrient recycling. We acknowledge that the data in Table 5 may create a strong reaction, depending on the position of the reader. For the fertilizer industry the potential for reducing fertilizer needs is 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 down 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 vehicles other than feeds. Transport of manure nutrients requires concentration. Here we see a task for the fertilizer industry. One aspect of recycling manure is that it may help to compensate for reduced fertilizer sales. The fertilizer industry may also consider recycling as its responsibility to society. Fertilizers are too beneficial to let them go down the drain.

Similar to the situation with energy, for nutrients saving is better than depleting finite supplies. Consumers, farmers, and governments too have a responsibility here.

Discussion

Internalizing Unwanted Side-Effects of Nutrients

Life on Earth is self-supporting, but for sun light (energy). For nutrients, Earth acts as a closed system; there is 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 (e.g., Gruber and Galloway, 2008). 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 N. 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 flow 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. Largely, these side-effects are still externalized, i.e. the effects are not included in decision making and cost-benefit analysis of enterprises. This neglect is exaggerated by the diffuse nature of the side-effects, the complex and site-specific cause and effect relationships, and the delays involved. Hence, there is little incentive for saving and recycling nutrients, unless nutrient sources are scarce or environmental policy forces polluters to do so.

Waste is created by all societies, but more so by those that are wealthy. 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 deposit, the more goods that are returned, the higher the taxes on waste collection, the less that waste is produced and disposed of, and the more that waste is recycled by producers and consumers. These general principles drive the economics of nutrient cycling globally. They are applicable to animal manure and sewage waste too.

Comparison of Calculated and Measured Flows of Nutrients

It wasn't data on the flow of nutrients packed in feeds, food crops, animal products, or fertilizers that were the starting point of our paper, but simple calculations of the nutritional needs per capita, 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 6.5×10^9, being the number of the present world population, would result in data referring to the entire world. In Table 6 our estimates are compared with real-world statistical numbers.

For the conversion of 0.75 kg of N per capita per day, we assumed 14% protein in meat, and for the conversion of 0.75 kg of 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 were directly derived from the daily needs of human consumption. We overestimated the share of dairy products in the human diet by a factor of almost two.

The actual area planted to crops is much greater than our estimate. We set annual yields, which partly consist of 2 and even 3 yields, at 10 Mg per ha for both food and fodder crops. Based on these estimates we arrived at the simple outcomes shown in Tables 1 and 2. Smil (2002a) estimated that 0.08 ha per capita is required for the food crop production of a vegetarian diet, and 0.4 ha per capita for a typical Western diet. Our estimates are 0.02 and 0.09 ha per capita, 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, respectively.

Because we overestimated yields and underestimated the required area for crops, our estimate of fertilizer N needs has to be higher than actual use. One of the reasons is that we did not take into account in the estimate of

Table 6. Comparison of the data on food consumption, manure, fertilizer use, and area of cropped land estimated in this paper with statistical data (explanation in text).

	As estimated in this paper		Statistical data
	Per caput	World, Gg	
Meat consumption (per year)	37.5 kg	244 Gg	200 Gg (Smil, 2002a)
Milk consumption (per year)	150 kg	975 Gg	500 Gg (Smil, 2002a)
Animal manure N (per year)	14 kg	91 Gg	100 Gg (Smil, 2002a)
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	65×10^6 ha	1400×10^6 ha[b] http://faostat.fao.org/faostat
Area for fodder crops and grazing	0.08 ha	520×10^6 ha	3400×10^6 ha[c] http://faostat.fao.org/faostat

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

Table 6 that a portion of the manure is used and replaces fertilizers. The major reason is that in reality a large portion of the land used for food and fodder production receives little or no fertilizer. In other words, in reality a large portion of the nutrients required for crop production is derived from the soil and from natural inputs, while in our calculations the output of nutrients is fully compensated for by fertilizer input. The difference in fertilizer N use between reality and our estimate is a factor of two, not as great as the differences in cropped areas, again indicating that in reality less fertilizer is applied per ha than follows from our calculations. The difference may also be partly ascribed to the high standard N use efficiency we assumed in our calculations (Table 4), which is roughly 2-fold greater than the usually reported N use efficiency (Dobermann and Cassman, 2004).

The figures for fertilizer use look somewhat confusing. We estimated a fertilizer need that is 2-fold greater than the actual use, when manure and compost are not recycled, but we also conclude (Table 5) that the fertilizer need could be reduced to $^1/_3$ under complete recycling and maximum N use efficiency and, hence, could be less than the present use. Even further reduction is possible, when recycling continues and soil fertility is built up. Improving nutrient use efficiency must go hand in hand with improving water use efficiency and requires a well-balanced blend of efforts (e.g., Tilman et al., 2002).

Concluding Remarks

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

Given the fact that transportation of animal manure (in slurry form) is limited to say 20 km, 2 major options exist for reversing 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 the economy and employment. The second option is to concentrate the nutrients in manure through manure processing. The attempts made so far were proven to be too costly. In view of the negative prices of manure in some areas of intensive livestock production, and in view of the fact that farmers do not easily give up farming, the cost of converting manure will become less prohibitive than it is. The technological know-how for this process is in the hands of the fertilizer industry, just as the network for the distribution of the converted manure nutrients. Why wait longer? We sympathize with those who bring the following wisdom into practice: It is better to save than to waste the limited supplies of natural resources.

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