Global Soil Nutrient Depletion and Yield Reduction

Z. X. Tan
R. Lal
K. D. Wiebe

ABSTRACT. Nutrient depletion in soils adversely affects soil quality and reduces crop yield and consequently poses a potential threat to global food security and agricultural sustainability. With an emphasis on human-induced nutrient depletion, this paper described the causality among soil nutrient depletion, soil quality, crop production, socio-economic variables, and environmental condition. Then, global soil nutrient budgets of nitrogen (N), phosphorus (P), and potassium (K) were estimated for wheat (*Triticum aestivum* L.), rice (*Oryza sativa*), maize (*Zea mays* L.), and barley (*Hordeum vulgare*) production for the year 2000. As a result, there were unbalanced fertilization with surplus N in some developing countries and insufficient inputs in many developing and all least developed countries. Globally, soil nutrient deficits were estimated at an average rate (kg ha^{-1} yr^{-1}) of 18.7 N, 5.1 P, and 38.8 K, covering 59%, 85%, and 90% of harvested area in the year 2000, respectively, and annual total nutrient deficit was 5.5 Tg (1 Tg = 10^{12} g) N, 2.3 Tg P, and 12.2 Tg K, coupled with a total potential global production loss of 1,136 Tg yr^{-1}. Besides socio-economic factors, the soil nutrient depletion can

Z. X. Tan and R. Lal are affiliated with the Carbon Management and Sequestration Center and the School of Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210.

K. D. Wiebe is affiliated with the USDA Economic Research Service, Washington, DC 20036.

Address correspondence to: Z. X. Tan (E-mail: tan.129@osu.edu).

The views expressed here are those of the authors, and may not be attributed to the Economic Research Service or the US Department of Agriculture.

Journal of Sustainable Agriculture, Vol. 26(1) 2005
Available online at http://www.haworthpress.com/web/JSA

Digital Object Identifier: 10.1300/J064v26n01_10

be attributed to insufficient fertilizer use, unbalanced fertilization, and nutrient depletion-induced soil fertility problems. Soil fertility problems associated with human-induced nutrient depletion are widespread worldwide.

KEYWORDS. Human-induced nutrient depletion, nutrient deficit, rice, soil fertility, soil nutrient depletion, wheat

INTRODUCTION

Soil nutrient depletion is an important concern directly linked to food insecurity in developing and least developed countries due to the intensification of land use for agricultural production without proper application of external inputs (Henao and Baanante, 1999). The continued lack of required nutrient replenishment of nutrient depleted soils as well as nutrient losses through wind and water erosion are not only exacerbating soil degradation, but also jeopardizing agricultural sustainability in these regions (Ayoub, 1999; Sheldrick et al., 2002). This is evident in the long-term decline in crop yields under conditions of low-input and unbalanced fertilization in many parts of Africa, Asia, and Latin America (FAO/UNDP/UNEP/World Bank, 1997). Many efforts have been made to assess soil nutrient budgets for agroecosystems based on a universal mass balance principle, but few studies have focused on specific crop production. Therefore, it is difficult to interpret how the soil nutrient budget relates to either soil nutrient losses caused by natural events or nutrient deficits due to insufficient compensation for crop harvest, and it is also difficult to evaluate impacts of human-induced nutrient deficits on specific crop productions. Based on a general review of the process and consequence of soil nutrient depletion, this paper focused on and analyzed impacts of human-induced nutrient depletion on soil fertility. Furthermore, a simplified approach was proposed to estimate global average rates of human-induced nutrient depletion for four major crop production systems and the attendant yield losses in the year 2000. Finally, factors associated with human-induced nutrient depletion and relationships to soil fertility were evaluated.

GENERIC SOIL NUTRIENT DEPLETION AND ASSESSMENT

The process of soil nutrient depletion is a potentially serious threat to world food security and sustainable agriculture. Since the early 1990s, numerous investigators (Cooke, 1958 and 1986; Follett et al., 1987; Gigou et al., 1985; Pieri, 1983; Smaling et al., 1993; Stoorvogel et al., 1993; Van Duivenbooden, 1990) have assessed soil nutrient budgets for agricultural ecosystems using various approaches and methods. Follett et al. (1987) and Miller and Larson (1992) specified the nutrient balance for N, P, and K in soils of agroecosystems at national or regional scales. Then, the conceptual model for soil nutrient budgeting based on a universal mass balance principle has been developed to identify components and parameters that are used to characterize both nutrient inputs and outputs (Table 1), and the net difference between inputs and outputs of nutrients integrated over a certain area and time is defined to determine the net soil nutrient budget (*NSNB*):

$$NSNB = \int_{area} \int_{time} \left(\sum_{i=1}^{5} \mathrm{In}i = \sum_{j=1}^{5} \mathrm{Out}_j \right) \quad \text{(Equation 1)}$$

The *NSNB* depends on the difference between inputs and outputs and may also vary with crop production systems. Agricultural practices with high external inputs likely result in a positive *NSNB* and may lead to environmental problems by leaching or runoff. On the other hand, agricultural practices with low external inputs likely result in a negative *NSNB* or *nutrient depletion*. *Nutrient balance* is achieved when the nutrient inputs compensates the outputs.

Estimates of parameters for different components in Table 1 are derived from either pedogenic transfer functions or empirical models (Bouma and Van Lanen, 1987; Van Diepen et al., 1991; Smiling et al., 1993; Stoorvogel et al., 1993). The quantification of individual flows of soil nutrients (i.e., In 1-5 and Out 1-5) requires different approaches, as defined by Stoorvogel and Smaling (1990 and 1993) and Stoorvogel et al. (1993) in the study on rates of soil nutrient depletion in sub-Sahara Africa (SSA).

The nutrient budgeting approach was used by Stoorvogel et al. (1993) and Smaling et al. (1993) to highlight the serious situation of soil nutrient depletion in many African countries of SSA, and to demonstrate the important part that nutrient balance can play in assessing fu-

TABLE 1. Components of input and output for soil nutrient budgeting.

Input		Output	
In 1	Mineral fertilizer	Out 1	Crop products
In 2	Organic fertilizer	Out 2	Crop residues
In 3	Deposition	Out 3	Leaching
In 4	N-fixation	Out 4	Gaseous loss
In 5	Sedimentation	Out 5	Soil erosion

ture prospects for food production and security. Similar studies have also been conducted in Africa by others (De Jager et al., 1998; De Koning et al., 1997; Dougill et al., 2002; Folmer et al., 1998; Geurts et al., 1999; Hartemink, 1997a and 1997b; Krogh, 1997; Nandwa and Bekunda, 1998; Rhodes, 1995; Scholes and Scholes, 1999; Wortmann and Kaizzi, 1998), including the economic performance of nutrient flows (Drechsel et al., 2001; Van der Pol, 1992). Using Farm-NUTMON model for a generic soil nutrient budget (De Jager et al., 1998), Van den Bosch et al. (1998) reported that the mean balance of all farms at district level in Kenya was −71 kg N, +3 kg P and −9 kg K $ha^{-1}yr^{-1}$. Similar trends in soil nutrient budgets in Africa were also reported by Henao and Baanante (1999).

Soil nutrient depletion and imbalance are also widespread problems in Asia. Dobermann et al. (1995) computed nutrient balances for rice-based farming systems in several eastern Asian countries, and reported that the K deficit ranged from 25 kg $ha^{-1}yr^{-1}$ to 70 kg $ha^{-1}yr^{-1}$. Lin et al. (1996) estimated nutrient balances on 71 rice-paddy farms in south China and found a surplus of N and P but a deficit of K. Mutert (1996) reported negative balances of N, P, and K in Bangladesh, Indonesia, Myanmar, the Philippines, Thailand, and Vietnam. In contrast, an oversupply of nutrients was observed in Japan, the Republic of Korea, and Malaysia. Therefore, Mutert (1996) concluded that in Asia negative nutrient balances for major crops and rice occurred in lower-income countries with large and growing populations, whilst an oversupply and positive balance occurred in high-income countries with small and stable populations.

Bach and Frede (1998) investigated the N, P, and K balances in German agriculture between 1970 and 1995. The OECD (1997) provided a report on nutrient budgets for OECD countries between 1985 and 1995. Sibbesen and Runge-Metzger (1995) focused on P balances for European countries and net P balances in total agricultural land for 1989. Their results show an average annual P surplus of 12.6 kg P $ha^{-1}yr^{-1}$ in Europe and the highest surplus of 57.2 kg P $ha^{-1}yr^{-1}$ in the Netherlands.

Surplus of N, P, and K is generally observed in large, mixed farming systems in some Western European countries and in Japan. In contrast, food production has caused and is causing depletion of large quantities of soil nutrients in both developing and least developed countries. Henao and Baanante (1999) summarized the existing research results and reported the rates of soil nutrient depletion in agricultural lands of all African nations. Sheldrick et al. (2002) developed a conceptual model for conducting nutrient audits at regional and global scales, by which the global average soil nutrient depletion rate in the year 1996 was estimated at 12.1 kg N $ha^{-1}yr^{-1}$, 4.5 kg P $ha^{-1}yr^{-1}$, and 20.2 kg K $ha^{-1}yr^{-1}$, leading to the average nutrient use efficiency at the global scale of approximately 50% for N, 40% for P, and 75% for K.

HUMAN-INDUCED NUTRIENT DEPLETION

Definition

The rates of generic (or total) soil nutrient depletion have been computed for different scales. However, to what extent such nutrient depletion and its impacts on crop production can be explained by human-induced nutrient depletion remains to be assessed on the basis of an appropriate definition. It is thus necessary to define soil nutrient depletion as a human-induced process with respect to nutrient loss by harvest and other anthropogenic activities rather than erosion and leaching. In contrast to natural processes, human-induced losses can be controlled and their impacts minimized, despite the difficulties in isolating these from numerous geological processes.

The term *soil nutrient depletion* (or *generic soil nutrient depletion*) refers to all nutrient losses from a soil through both natural and human-induced processes. Dynamically, it is the process by which the soil nutrient stock is shrinking because of continuous nutrient mining without sufficient replenishment of nutrients harvested in agricultural products, and of nutrient losses by soil erosion and leaching. Soil erosion is mainly a natural process and usually treated as an independent issue. And the nutrient loss from leaching is also driven by a natural process although it is exacerbated by application of fertilizers, especially N.

Therefore, *human-induced nutrient depletion* is defined as a soil nutrient mining process driven by biomass removal without adequate replenishment of the required nutrients. It constitutes a majority of generic soil nutrient depletion, and can be evaluated in term of the annual nutrient deficit within a specific cropping system.

Factors for Human-Induced Nutrient Depletion and Consequence

By definition, human-induced nutrient depletion can be attributed to following factors: over-cultivation, insufficient inputs of replacement nutrients, accelerated soil erosion caused by inappropriate land uses and poor soil management practices, unbalanced fertilization, etc. However, low input of the required nutrients may be a key factor in case of resource-poor farms in both developing and least developed countries. Osgood (2001) and Lipper (2001) observed that there are causal links between poverty and soil degradation in Africa. The causality among the factors associated with human-induced nutrient depletion is illustrated in Figure 1. Continuous nutrient depletion leads to deterioration in socio-economic welfare, soil resource sustainability, deterioration in environment quality, and reduction in crop yield caused by soil degradation.

Adverse impacts of human-induced nutrient depletion on soil nutrient cycling and productivity were forewarned by Miller and Larson (1992). Worldwide, about 135 Mha of soils have been reportedly prone to nutrient exhaustion, of which 97% have occurred in developing and least developed countries, and about 45 Mha of soils in Africa have been affected by over-cultivation and inadequate application of replacement nutrients, whilst 71 Mha in South America have been affected by tropical deforestation (Table 2). Human-induced nutrient depletion can accelerate soil erosion because of continuous loss of soil organic matter (SOM) and decline in soil structural stability. Heavy application of N fertilizers coupled with less K fertilization has worsened the imbalance among the three major nutrients, resulting in a low use-efficiency of N fertilizers, and causing environmental hazards (Duwig et al., 1998; Kirchmann et al., 2002; Lal, 2001; Lal, 2002; Nielsen et al., 1982; Saka et al., 1998; Singh et al., 1996; Tonmanee and Kanchanakool, 1999). For example, irrespective of the method of application, N recovery efficiencies rarely exceed 50% (FAO, 1994a), and much of the unrecovered N ends up in groundwater (N-nitrate), in the wetlands (N-ammonia), or in the atmosphere (N-N_2O). When carried into waterways with surface runoff, it causes eutrophication, proliferation of algal growth, and

FIGURE 1. Human-induced soil nutrient depletion and its impacts on soil quality, crop production, and environment, assuming that other nutrient losses caused by natural events are related to geological processes and unavoidable for all lands (⇨ Direct influence; → Influence to a large extent).

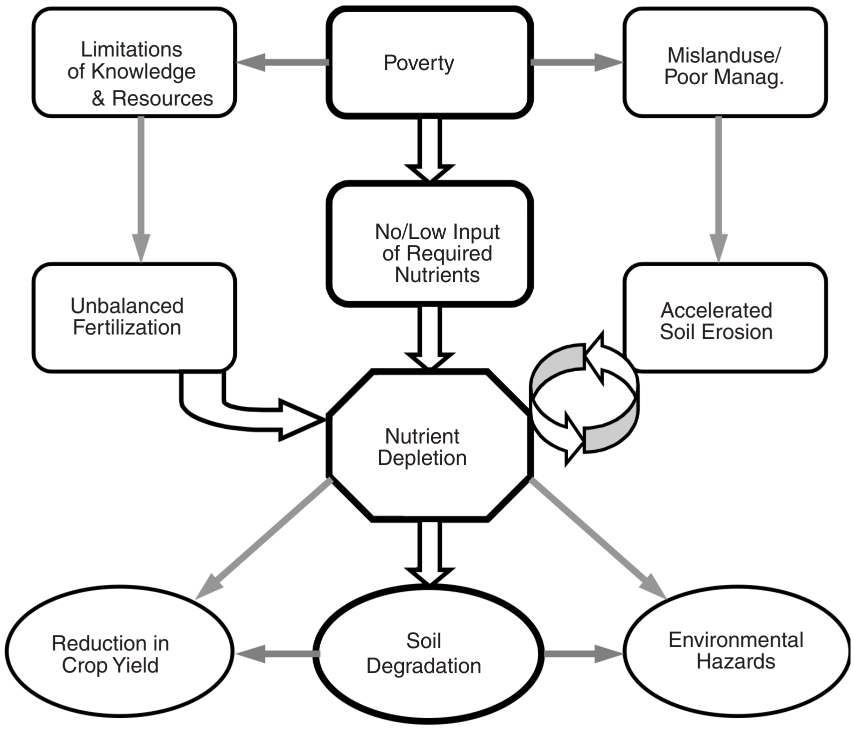


TABLE 2. Land area affected by nutrient depletion.†

Region	Severity and extent of nutrient depletion (Mha)			
	Light	Moderate	Strong	Total
Africa	20.4	18.8	6.2	45.4
Asia	4.6	9.0	1.0	14.6
South America	24.6	34.1	12.7	71.4
Other Regions	2.8	1.2	0.0	3.9
Globe	52.4	63.1	19.9	135.3

† Derived from UNEP/ISRIC, 1990; UNDP/UNEP/FAO, 1994a; Scherr and Yadav, 1996; FAO, 1999.

exhaustion of dissolved oxygen (hypoxia or anoxia) with severe consequences to fish and other aquatic species (FAO/RAP, 1999).

ASSESSMENT OF HUMAN-INDUCED NUTRIENT DEPLETION FOR MAJOR CROP PRODUCTION SYSTEMS IN THE YEAR 2000

An Approach to Nutrient Budgeting

As indicated in Equation 1 and Table 1, of all inputs of nutrients, both inorganic and organic fertilizer inputs can be easily quantified. Of all outputs of nutrients, crop products and residues can be estimated. Nutrient loss through soil erosion can be estimated from soil loss magnitude, which is usually accounted into soil erosion effects on crop yields, and has been extensively studied (Den Biggelaar et al., 2001; Harden, 2001; Hopkins et al., 2001; Kaihura et al., 1999; Lal, 2001; Lal et al., 2000; Lal and Singh, 1998; Mantel and Van Engelen, 1999). Therefore, nutrient inputs from inorganic and organic fertilizers and nutrient outputs by crop products and residues can be used for general estimation of the nutrient budget and its effects on crop production. Although data on crop production are incorporated in national statistics and/or regional databases, a number of required management data and quantities of leaching are typically unknown (Bindraban et al., 2000). Nutrient inputs from mineral fertilizer (In 1) can be estimated from agricultural statistics or obtained from surveys. Inputs from manure and other organic sources (In 2) depend on livestock management systems and crop residues returned to the soil. Nutrients "returned" through plant biomass are recycled in the soil-plant system and became a part of a net input. The data on deposition by rain and dust (In 3) are not readily available though some transfer functions have been derived based on precipitation (Stoorvogel and Smaling, 1990). Biological N-fixation (In 4) may be important to rice production. Sedimentation (In 5) can be ignored for almost all cultivated areas.

Nutrients in harvested products (Out 1) can be estimated from nutrient contents of specific crops and their yields obtained from agricultural statistics. Crop residues removed (Out 2) can be estimated from grain yields but depend largely upon management practices and socio-economic factors. Leaching (Out 3), mostly for soluble N and K, and volatilization (gaseous) losses (Out 4), in case of N, are correlated with soil fertility, fertilizer application, crop nutrient uptake, soil clay content and precipitation (Stoorvogel and Smaling, 1990) and may be insignificant in crop production systems compared with total nutrient depletion. Nutrient losses through soil erosion (Out 5) can be obtained by multiplying soil erosion with soil nutrient concentrations, but are beyond the scope of human-induced nutrient depletion as defined in this study.

Assuming that losses of the applied fertilizers caused by other factors (including erosion, leaching, denitrification and volatilization, deposition, mineralization, symbiotic N-fixation, etc.) are accounted for the *nutrient use efficiency (NUE)*, the rate of soil nutrient depletion can be estimated at the national scale by knowing fertilizer input, use efficiency, and harvested biomass output. Therefore, for calculating the soil nutrient budget for a unit area in a specific year, Equation 1 can be simplified as follows:

$$\text{Soil Nutrient Budget} = \text{NUE}^* (\text{In}_1 + \text{In}_2) - (\text{Out}_1 + \text{Out}_1) \qquad \text{(Equation 2)}$$

Where components in Equation 2 are defined as follows:

Out 1 and Out 2: Crop products and residues. The outputs of nutrients from soils are primarily in the form of crop products and their residues. Wheat, rice, maize, and barley were selected for estimating nutrient flows in respective farming systems and assessing impacts of nutrient depletion on crop yields. The grain yields of these crops were obtained from FAOSTAT database (FAO, 2001) and their residues were estimated based on the residue/grain ratios. The nutrient contents in both grains and residues were computed separately because the nutrient content in crop residues is usually different from that in grains. The grains and residues of these crops also have different nutrient contents (Table 3) that were used to calculate national nutrient outputs.

TABLE 3. Global averages of nutrient uptake in grains and residues by four cereal crops.†

Crop	N Grain	N Residue	P Grain	P Residue	K Grain	K Residue	Ratio‡ Residue/Grain	N Whole crop	P Whole crop	K Whole crop	NPK Ratio Whole crop N	NPK Ratio Whole crop P	NPK Ratio Whole crop K
	kg Mg^{-1}							kg Mg^{-1}			N	P	K
Wheat	22.3	6.4	4.8	1.2	4.6	20.1	1.5	31.9	6.7	34.8	100	21	109
Barley	15.8	6.3	2.5	0.8	6.9	17.1	1.5	25.3	3.7	32.5	100	15	129
Rice-paddy	14.6	7.6	2.6	1.3	2.7	17.0	1.5	26.0	4.6	28.2	100	18	108
Maize	16.1	11.9	2.8	1.7	4.0	14.4	1.0	28.0	4.5	18.3	100	16	66

† Derived from Henao and Baanante, 1999; PPI, 1988; Sanchez, 1976; Soorvogel and Smaling, 1990.
‡ Lal, 1995.

In 1: Mineral fertilizers. Total fertilizer consumption data for each country were obtained from FAOSTAT database (FAO, 2001). It was assumed that most mineral fertilizers were used on arable land though there are some exceptions. The average fertilizer consumption by each crop in 1996 for 94 individual countries was obtained from the report of Fertilizer Use by Crop (FAO/IFDC/IFA, 1997).

In 2: Crop residues and manure (organic fertilizers). The proportion of residues remaining in the field may vary widely from country to country, and from place to place even in the same country. In this study, the percentage of residues remaining in fields used was assumed to be 100% for developed countries, 30% for both developing and least developed countries, and 20% for China (Stauffer and Beaton, 1995). Then, the proportion of nutrient inputs from crop residues and manure was estimated at an average of 20% of nutrients available in arable land (Houghton et al., 1997; Lander et al., 1998; Nutrient Sources, 1997; Xie et al., 1998).

NUE (Nutrient use efficiency). It is defined as the percentage of nutrient input that is recovered as nutrient output in crops (Sheldrick et al., 2002). Global use efficiency has been estimated at 50% for N, 40% for P, and 75% for K, which were used in this study.

The rates of individual nutrient depletion in each country were estimated based on the crop production for the same year obtained from the FAOSTAT database (FAO, 2001). The fertilizer use by crops in the year 2000 was then extrapolated by comparing both crop yields and total amount of each fertilizer applied, assuming that each type of fertilizer use by each crop was proportional to total national consumption on the basis of the fertilizer use rates provided by FAO/IFDC/IFA (1997), because the average rate of human-induced nutrient depletion depends on the socio-economic conditions of individual countries. All data were collected and analyzed at the national scale, and further aggregated at continental and global scales [i.e., developed countries, developing countries, and least developed countries (FAO, 2001)] using area-weighted averages. Nutrient surplus and deficit of N, P, and K for the four crops were calculated and expressed separately because any nutrient deficit in one area cannot be compensated by the nutrient surplus in another. The estimation of potential loss of crop yield due to the nutrient deficit was made by assuming that all nutrient deficits would be fully used by each crop for photosynthesis of all biomass including grains and residues.

Nutrient Deficits at Global Scale

Results show that there was no country without any nutrient problems in any crop production systems in the year 2000, though some nutrient surplus occurred in some developed countries and an oversupply of N occurred in a few developing countries. Of the global cultivated area for the four crops in the year 2000, 56% was affected by N deficit at an average rate of 17.4 kg $ha^{-1}yr^{-1}$, 80% by P deficit at that of 5.0 kg $ha^{-1}yr^{-1}$ and 56% by K deficit at that of 38.7 kg $ha^{-1}yr^{-1}$ (Table 4). At the global scale, a shortage of N, P, and K was observed in developing and least developed countries, particularly K deficit. The affected area was 175 Mha (57% of cultivated area) for N, 266 Mha (86%) for P, and 283 Mha (91%) for K in developing countries and 31 Mha (69%) for N, 32 Mha (70%) for P, and 31 Mha (69%) for K in least developed countries. Developed countries were still deficit in N and P in an area of 108 Mha (52%) for N and 151 Mha (73%) for P despite being less serious than in other countries.

The estimates of total nutrient deficits at the global scale can also be seen from Table 4. A total NPK deficit for all four crops in the year 2000 was estimated to be 20 Tg (10^{12} g), of which 75% occurred in developing countries, 14% in developed countries, and 11% in least developed countries. On an individual nutrient basis, K deficit accounted for 60% of the total, N deficit for 28%, and P deficit for 12%. Similarly, signifi-

TABLE 4. Mean rates† of nutrient depletion and total nutrient deficits in the year 2000.

Country category‡	Harvested area	Nutrition depletion rate N	P	K	Affected area N	P	K	Total nutrient deficit N	P	K	NPK
	Mha	kg ha^{-1} yr^{-1}			Mha			Gg (10^9 g) yr^{-1}			
Developed countries	207.0	−15.0	−4.9	−0.7	107.7	151.3	1.3	−1,610	−745	−0.9	−2,356
Developing countries§	309.6	−18.4	−5.1	−39.5	175.1	266.4	283.3	−3,213	−1,354	−11,188	−15,755
Least developed countries	45.5	−20.7	−4.9	−32.6	31.4	31.8	31.5	−651	−155	−1,028	−1,833
Global mean	562.1	−17.4	−5.0	−38.7	314.2	449.6	316.0	−5,474	−2,253	−12,216	−19,944

† Area-weighted average of wheat, rice, maize, and barley production systems.
‡ Cited from 2001 FAOSTAT database (http://apps.fao.org).
§ Excluding the least developed countries.

cant differences were observed among crop production systems: 42% of the total NPK deficit occurred in rice production, 39% in wheat cultivation, 17% in maize production, and only 2% in barley production. Note that either partial deficit or total deficit of each nutrient for individual crops varied substantially from country to country.

ESTIMATION OF YIELD REDUCTION AND PRODUCTION LOSS FROM NUTRIENT DEFICITS

It is difficult to obtain primary data about the impacts of nutrient depletion on crop yields at the national scale. Therefore, these impacts were estimated from the individual nutrient depletion rates as addressed above. The yield reduction of each crop estimated for the year 2000 at the global scale is presented in Table 5. The magnitudes of yield reductions of all four crops due to K deficit in developing countries were more significant than those from N and P deficits. Worldwide, the average yield decline (equivalent rice yield) due to the deficit in K, P, and N was 1,372, 1,093, and 670 kg $ha^{-1}yr^{-1}$, respectively. These reductions were equivalent to 27% of the average crop yield in the year 2000. The average yield reduction from N, P, and K deficits was 35% in least developed countries, 27% in developing countries, and 11% in developed countries. The wheat yield reduction due to P deficit in developed countries was, however, more significant, which may have partially resulted from the low P fertilizer proportion in total NPK fertilizers applied in 2000 (36% in developed countries, 44% in developing countries, and 56% in least developed countries) and wheat's high requirement for P

TABLE 5. Losses of crop yield and production from nutrient deficit in the year 2000.

Country category	Average yield loss†			Total production loss‡		
	N	P	K	N	P	K
	kg ha^{-1} yr^{-1}			Tg yr^{-1}		
Developed countries	−575	−1,074	−24	−61.9	−162.5	−0.03
Developing countries	−706	−1,108	−1,401	−123.6	−295.3	−397.00
Least developed countries	−796	−1,061	−1,157	−25.0	−33.8	−36.50
Global mean	−670	−1,093	−1,372	−210.6	−491.5	−433.40

† Averages of wheat, rice, maze, and barley grain yields that are equivalent rice grain yield.
‡ Sum of all four crop grain productions (Equivalent rice grain yield).

(50% more than other crops). The total production loss (equivalent rice production) in the year 2000 caused by nutrient deficit was estimated to be 211 Tg from N, 492 Tg from P, and 433 Tg from K (Table 5). Of global total production loss, rice represented 41%, wheat 33%, maize 24%, and barley 3%; 80% occurred in developing and least developed countries and 20% in developed countries.

DISCUSSION

Facts in Association with Human-Induced Nutrient Deficits

Human-induced nutrient deficits in soils have led to considerable production losses worldwide. The noticeable amounts of nutrient deficits and variations in nutrient depletion rates presented above may be directly related to the following facts.

Unbalanced Fertilization

Soil nutrient depletion is coupled by the unbalanced fertilization due to limitations of knowledge and nutrient resource availability, as has been confirmed by long-term fertilizer consumption records of the FAOSTAT database (FAO, 2001) (Table 6). The proportion of N in total fertilizer use increased from 49% in 1961 to 71% in 2000, while the proportions of P and K decreased from 20% and 31% in 1961 to 12% and 16% in 2000, respectively. In both developing and least developed countries, the proportion of N fertilizer use has remained high, fluctuating from 73% to 77% and from 79% to 83%, respectively, whereas, the

TABLE 6. Total NPK fertilizer consumption and proportion of each nutrient element‡ in three fertilizers applied since the 1960s.

Country category	1961				1970				1980				1990				2000			
	TFC†	N	P	K	TFC†	N	P	K	TFC†	N	P	K	TFC†	N	P	K	TFC†	N	P	K
Developed countries	27.5	46	21	33	55.5	53	18	29	78.0	58	15	27	72.9	60	15	25	49.8	67	12	21
Developing countries	3.6	73	16	12	13.4	76	13	10	37.8	77	13	10	63.3	76	13	11	84.4	74	13	13
Least developed countries	0.1	83	8	8	0.4	78	12	10	1.0	79	14	7	1.6	79	13	8	2.2	80	11	9
Global sum	31.2	49	20	31	69.3	58	17	25	116.7	64	15	21	137.8	68	14	18	136.4	71	12	16

† Total N, P (P_2O_5), and K (K_2O) fertilizer consumption (Tg yr^{-1}) (FAO, 2001).
‡ Proportion (%) based on the content of element N, P, and K in respective fertilizer.

proportion of K fertilizer use has stayed at between 10% to 13% and between 7% to 9%, respectively. The imbalance of fertilization was particularly evident in all least developed countries. In developed countries, despite a decline in average fertilizer use from 32.6 kg $ha^{-1}yr^{-1}$ in the year 1980 to 17.2 kg $ha^{-1}yr^{-1}$ in the year 2000, the use ratio of N, P and K fertilizers has been properly maintained.

The proportion of fertilizers applied in developing countries was 13% and 13% for K and P, respectively, whereas N fertilizer use was as high as 74%, and accordingly, 9%, 11%, and 80% for K, P and N fertilizer, respectively, in least developed countries (Table 6). Clearly, the fertilization was dominated by N fertilizers in both developing and least developed countries. For example, in India, N:K use ratio was between 5 and 7.5 before the 1990s, and rose to between 8 to 10 in the last decade, which was far above the recommended N:K ratio of 4:1 (Roy, 2003). When fertilizers are first applied to a soil, a high response is frequently obtained from N. Meanwhile, the improved crop growth and increased removals of biomass exhaust other nutrients from soils. In fact, N in such cases is simply used as a shovel to mine the soil of other nutrients (Tandon, 1992). The deficiencies of other nutrient elements, particularly micronutrients, have been increasingly reported in major crop production systems of the world.

Differentiating Crop Nutrient Requirements

Different crop species have different requirements for each nutrient element. For example as shown in Table 3, in all wheat biomass including both grains and residues, the N:P:K ratio is about 100:21:109, of which the largest proportion of N is needed for grain formation and the highest content of K is in residues. The ratio of N, P, and K required by maize is about 100:16:66. Theoretically, the rate of P depletion should be proportional to the P requirement by individual crop species assuming that the chemical fixation of P is offset by the release of previously applied P fertilizer. And the less serious P deficit in the production of rice, maize, and barley can be partially attributed to their lower demand for P nutrient vs. wheat.

Production Level

Because the above nutrient budget was directly derived from the nutrient amount contained in the removed biomass, the extent of nutrient deficits was thus likely related to the production level of each crop. In other words, high nutrient depletion rates were associated with high crop yields if nutrient inputs were the same, which, however, depended on socio-economic condition of individual countries. In the present study, the NP deficits in developed countries were probably more related to an oversupply of K and high production levels. On the other hand, the serious nutrient depletion accompanied by low production in both developing and least developed countries may be attributed to the unbalanced fertilization and low fertilizer use rates, especially in least developed countries.

The Proportion of Residues Remained in or Returned to the Field

It is assumed that 100% of residues in developed countries were retained in or returned to the field, whereas, only 30% was assumed to return to soils in developing and least developed countries, and about 20% in China (Stauffer and Beaton, 1995). This might be one of the reasons why K stock was sufficient in developed countries and most depleted in others.

Interaction Between Human-Induced Nutrient Depletion and Soil Fertility

Human-induced nutrient depletion, either as a consequence of all anthropogenic activities, or a process, is coupled with the decline in soil fertility, and both interact with each other.

Soil Organic Matter Depletion

Soil fertility is a dynamic concept and comprises chemical, physical, and biological properties of the soil. Its importance lies in its ability and capacity to support agricultural production and its sustainability for such purpose. Soil fertility decline includes the deterioration in the chemical, physical, and biological properties of the soil that affect plant nutrition, and is a result of specific processes (FAO, 1994b; Lal and Singh, 1998) such as reduction of SOM and soil biological activity, adverse changes in soil nutrient resources and development of nutrient imbalances, and build-up of toxicities and acidification through incorrect fertilizer use, etc. Soil organic carbon (SOC) is diminishing in the majority of developing and least developed countries with soil nutrient depletion because crop residues are widely used as fuel and fodder rather than returned to the soil, which in turn accelerates soil nutrient depletion.

Dependence of Crop Yields on Fertilizer Use

Mineral fertilizer use has become globalized since the 1950s. The annual global use of fertilizers has increased from about 31.2 Tg (10^{12} g) in 1961 to about 136.4 Tg in 2000, of which the total use of N fertilizer increased from 11.6 Tg in 1961 to 81.6 Tg in 2000 (Table 6). As a result, the average rate of fertilizer use per cultivated area has consistently increased (except for developed countries since the 1980s) (Figure 2). Meanwhile, the average world cereal crop yields have increased from 1.03 Mg ha^{-1} in 1950 to 3.55 Mg ha^{-1} in 2000 (Figure 3). In fact, an increasing demand for mineral fertilizers is due not only to an increase in crop yields but also to the declining soil capacity to provide necessary nutrients to crops. Bockman et al. (1990) reported that in 1970 at the global scale, 48% of the nutrients used by crops were obtained from the soil, 13% from manure, and 39% from fertilizers, while in 1990 these percentages were changed to 30%, 10% and 60%, respectively. By 2020 the projected percentages will be 21% from soils, 9% from manure, and 70% from fertilizers. In other words, the increase in crop production has, to a large extent, been at the expense of the decrease in soil fertility. Data in Table 6 suggest that fertilizer-supported crop production would continue to dominate future agricultural production, espe-

FIGURE 2. Average rates of NPK fertilizers applied in arable land and permanent crop areas since the 1960s (FAO, 2001).

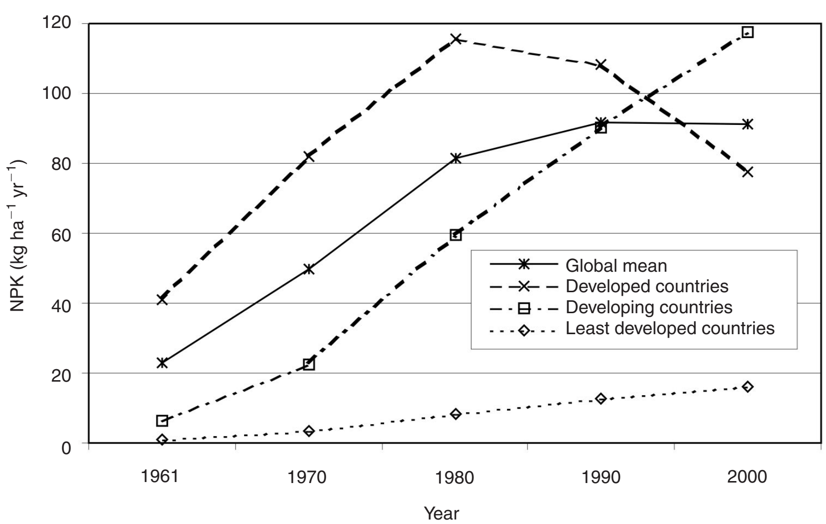
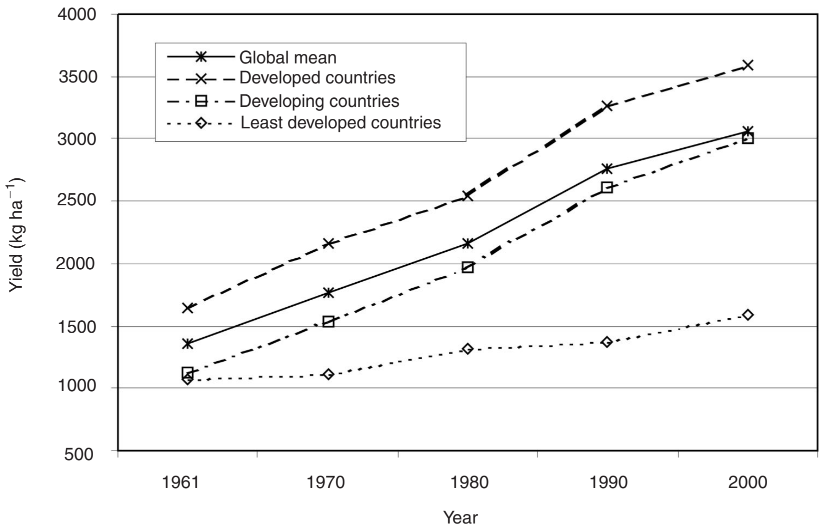


FIGURE 3. Global mean yield change of all cereal crops since 1960s (FAO, 2001).



Note: Developing countries excluding least developed countries.

cially in developing and least developed countries. And continuing soil nutrient exhaustion is leading to an increasing dependence of crop yields on fertilizers.

Low Responses of Crops to Fertilizers

The data in Table 7 show that, in both developing and least developed countries, the rate of increase in crop yield has decreased with increasing fertilizer use since the 1960s. The ratio of yield/NPK fertilizer decreased sharply to 71 kg kg^{-1} in 2000 from 494 kg kg^{-1} in 1961 in developing countries. The greatest decline in the yield/NPK fertilizer ratio was observed in least developed countries, which was a result of low input into and high depletion of nutrients out from soils. These data also suggest that an increase in fertilizer use was not reflected in an increase in crop yield in the majority of developing and least developed countries though the cereal crop yield has been raising with increasing fertilizer use at a global scale, which is in agreement with earlier results reported in South Asia where an increment of crop yields is hardly proportional to an increase in the fertilizer use (FAO, 1994b).

TABLE 7. Ratio of cereal crop yield to NPK fertilizers applied since the 1960s.

Country category	Yield: NPK (kg kg^{-1})				
	1961	1970	1980	1990	2000
Developed countries	110	73	61	83	127
Developing countries	494	190	91	80	71
Least developed countries	3,150	931	436	301	272
Global mean	161	98	73	83	93

Data source: Derived from FAOSTAT 2001 (FAO, 2001).

Low response can be attributed to two reasons: the limited yield potential of a crop, and the effect of the most limited nutrient element. Obviously, the yield potential of a crop should not become a limit to these four crops because their actual yield levels in both developing and least developed countries were much lower than those in developed countries (Figure 3). Therefore, it is true that low or zero response to particular nutrient elements is inevitable when one or more other nutrients are deficient (Mengel et al., 2001).

A sufficient fertilizer supply along with an appropriate ratio of principal nutrients applied is necessary to optimize the fertilizer use efficiency and maximize crop yields (Mengel et al., 2001). The unbalanced fertilization could directly result in soil nutrient depletion and has become one of the key factors responsible for low response of crops to fertilizer input due to the limitations from the deficiencies of any required nutrient(s), though the low response to fertilizers can also be attributed to the law of diminishing return in crop response as crop yields increase. Ironically, the unbalanced fertilization is widely practiced and continues in both developing and least developed countries (Table 6). Of course, crop yield level and fertilizer use efficiency depend also on many other factors such as climatic parameters, management practices, especially water supply, control of pests and diseases, etc.

Continuing Negative Soil Nutrient Balance

The removal of nutrients in crop harvest from a soil tends substantially to exceed the input as natural replacement and fertilizers. Negative soil nutrient balances of all three major nutrients have been reported in Bangladesh and Nepal, P and K in Sri Lanka (Tandon, 1992), and a large K deficit in most Asian countries (Dobermann et al., 1995). In India it has been estimated that the nutrient deficit averaged

60 kg $ha^{-1}yr^{-1}$, or 9 Tg for the whole country (Tandon, 1992). The average rate of nutrient depletion ranged from 20 kg to 50 kg NPK $ha^{-1}yr^{-1}$ in majority of developing countries to higher than 100 kg NPK $ha^{-1}yr^{-1}$ in least developed countries of Africa (Henao and Baanante, 1999). Though there has been a trend in increasing fertilizer use in developing countries since the 1960s (Figure 2), the average rate of fertilizer use is, however, much less than that needed to compensate for nutrient removal by biomass, especially in the least developed nations. That such a soil nutrient mining process is, despite the self-evident consequence, occurring in many developing and least developed countries, is usually associated with poverty.

CONCLUSIONS

Severe nutrient deficits of N, P, and K occurred widely in harvested areas in both developing and least developed countries, particularly in the rice and wheat production systems in Asia, Central and South America, and Africa. Continuous depletion of soil N, P, and K in most African countries and other least developed countries, coupled with low crop production levels, poses a real threat to agricultural sustainability and food security. Soil nutrient depletion caused by high production levels and decline in fertilizer use in recent decades in many developed countries are also a concern. Worldwide, soil fertility problems associated with the human-induced nutrient depletion are expected to continue.

REFERENCES

Ayoub, A.T. 1999. Fertilizers and the environment. *Nutrient Cycling in Agroecosystems* 55:117-121.

Bach, M. and H.G. Frede. 1998. Agricultural N, P, and K balances in Germany 1970 to 1995. Pflanzenernaherung *Bodenkunde* 161:385-393.

Bindraban, P.S., J.J. Stoorvogel, D.M. Jansen, J. Vlaming and J.J.R. Groot. 2000. Land quality indicators for sustainable land management: Proposed method for yield gap and soil nutrient balance. *Agric. Ecosyst. Environ*. 81:103-112.

Bockman, O.C., O. Kaarstad, O.H. Lie and I. Richards. 1990. *Agriculture and Fertilizers*. Agricultural Group, Norsk Hydro a.s, Oslo, Norway.

Bouma, J. and H.A.J. van Lanen. 1987. Transfer functions and threshold values: From soil characteristics to land qualities. In K.J. Beek, P.A. Burrough, and D.E. McCormack (Eds.) *Quantified land evaluation procedures*. ITC Pub 6:106-110.

Cooke, G.W. 1958. The nations's plant food larder. *J. Sci. Food Agric*. 9:716-722.

Cooke, G.W. 1986. Nutrient balances and the need for potassium in humid tropical regions. Pp. 22-23. In *Proceedings of the 13th IPI-Congress*. Reims, France.

De Jager, A., S.M. Nandwa and P.F. Okoth. 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON). I. Concepts and methodologies. *Agric. Ecosyst. Environ*. 71:37-48.

De Koning, G.H.J., P.J. Van de Kop and L.O. Fresco. 1998. Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador. *Agric. Ecosyst. Environ*. 65:127-139.

Den Biggelaar, C., R. Lal, K. Wiebe and V. Breneman. 2001. Impact of soil erosion on crop yields in North America. *Adv. Agron*. 72:1-51.

Dobermann, A., P.C. Santa Cruz and K.G. Cassman. 1995. Potassium balances and soil potassium supplying power in intensive irrigated rice ecosystems. Pp. 199-229. In *24th Colloquium of IPI*. Chiang Mai, Thailand.

Dougill, A.J., C. Twyman, D.S. Thomas and D. Sporton. 2002. Soil degradation assessment in mixed farming systems of southern Africa: Use of nutrient balance studies for participatory degradation monitoring. *The Geogr. J*. 168:195-210.

Drechsel, P., L. Gyiele, D. Kunze and O. Cofie. 2001. Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. *Ecol. Econ*. 38:251-258.

Duwig, C., T. Becquer, B.E. Clothier and M. Vauclin. 1998. Nitrate leaching through Oxisols of the Loyalty/Islands New Caledonia under intensified agricultural practices. *Geoderma* 84:29-43.

Follett, R.F., S.C. Gupta, and P.H. Hunt. 1987. Soil conservation practices: Relation to the management of plant nutrients for crop production. In *Soil fertility and organic matter as critical components for production systems*. Spec. Pub. 19. SSSA, Madison, WI, U.S.A.

Folmer, E.C.R., P.M.H. Geurts and J.R. Francisco. 1998. Assessment of soil fertility depletion in Mozambique. *Agric. Ecosyst. Environ*. 71:159-167.

Food and Agriculture Organization of the United Nations (FAO). 1994a. *Cherish the Earth–Soil Management for Sustainable Agriculture and Environmental Protection in the Tropics*. Land and Water Development Division, FAO. Rome.

Food and Agriculture Organization of the United Nations (FAO). 1994b. Land Degradation in South Asia: Its Severity, Causes and Effects Upon the People. *World Soil Resources Reports* 78. FAO. Rome.

Food and Agriculture Organization of the United Nations (FAO). 2001. FAOSTAT database (http://apps.fao.org).

Food and Agriculture Organization of the United Nations (FAO). 1999. *Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and East Africa*. AGL/MISC/23/99. Rome.

FAO/RAP. 1999. *Poverty alleviation and food security in Asia: Land resources*. RAP Publication 1999/2. Bangkok (*http://www.fao.org/DOCREP/*).

FAO/IFDC/IFA. 1997. *Fertilizer Use by Crop*. FAO/IFDC/IFA Report, 4th edition.

FAO, UNDP, UNEP and World Bank. 1997. *Land Quality Indicators and Their Use in Sustainable Agriculture and Rural Development*. FAO, Rome.

Geurts, P.M.H., L. Fleskens, J. Löwer and E.C.R. Folmer. 1999. Nutrient balances at field level of mixed cropping systems in various agroecological zones in Mozambique. Pp. 191-210. In E.M.A. Smaling, O. Oenema and L.O. Fresco (eds.) *Nutrient*

Disequilibria in Agroecosystems: Concepts and Case Studies. CAB International, Wallingford, UK.

Gigou, J., F. Ganry and J. Pitchot. 1985. Nitrogen balance in some tropical agrosystems. In *Nitrogen management in farming systems in humid and subhumid tropics. Proceedings of IITA symposium*. Oct. 23-26, 1985, Ibadan, Nigeria.

Harden, C.P. 2001. Soil erosion and sustainable mountain development. *Mountain Research and Development* 21:77-83.

Hartemink, A.E. 1997a. Input and output of major nutrients under monocropping sisal in Tanzania. *Land Degrad. Dev*. 8:305-310.

Hartemink, A.E. 1997b. Soil fertility decline in some Major Soil Groupings under permanent cropping in Tanga Region, Tanzania. *Geoderma* 75:215-229.

Henao, J. and C. Baanante. 1999. *Estimating rates of nutrient depletion in soils of agricultural lands of Africa*. International Fertilizer Development Center (IFDC), Muscle Shoals, Alabama, USA. 76 pp.

Hopkins, J.W., R. Lal, K.D. Wiebe and L.G. Tweeten. 2001. Dynamic economic management of soil erosion, nutrient depletion, and productivity in the North Central USA. *Land Degrad. Dev*. 12:308-318.

Houghton, J.T., L.G. Meira Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, and B.A. Callander (eds.). 1997. *Revised 1996. IPCC Guidelines for National Greenhouse Gas Inventories*. Volumes 1-3. Hadley Centre Meteorological Office, United Kingdom.

Kaihura, F.B.S., I.K. Kullaya, M. Kilasara, J.B. Aune, B.R. Singh and R. Lal. 1999. Soil quality effects of accelerated erosion and management systems in three eco-regions of Tanzania. *Soil Tillage Res*. 53:59-70.

Kirchmann, H., A.E.J. Johnston and L.F. Bergström. 2002. Possibilities for reducing nitrate leaching from agricultural land. *AMBIO: A J. the Human Environ*. 31: 404-408.

Krogh, L. 1997. Field and village nutrient balances in millet cultivation in northern Burkina Faso: A village case study. *J. Arid Environ*. 35:147-159.

Lal, R. 2001. Soil degradation by erosion. *Land Degrad. Dev*. 12:519-539.

Lal, R. 2002. Soil carbon sequestration in China through agricultural intensification, and restoration of degraded and desertified ecosystems. *Land Degrad. Dev*. 13: 469-478.

Lal, R. and B.R. Singh. 1998. Effects of soil degradation on crop productivity in East Africa. *J. Sustainable Agric*. 13:15-36.

Lal, R., M. Ahmad and R.M. Bajracharya. 2000. Erosional impacts on soil properties and corn yield on Alfisols in central Ohio. *Land Degrad. Dev*. 11:575-585.

Lander, C.H., D. Moffitt and A. Klause. 1998. *USDA-NRCS, Resource Assessment and Strategic Planning Working*. Paper 98-1.

Lin, X., C. Yin and D. Xu. 1996. Input and output of soil nutrients in high-yield paddy fields in South China. Pp. 93-97. In *Proceedings of the International Symposium on Maximizing Rice Yields through Improved Soil and Environmental Management*. Khon Kaen, Thailand.

Lipper, L. 2001. Dirt poor: Poverty, farmers and soil resources investment. In *FAO Economic and Social Development Paper 149* (*http://www.fao.org/DOCREP/*).

Mantel, S. and V.W.P. Van Engelen. 1999. Assessment of the impact of water erosion on productivity of maize in Kenya: An integrated modeling approach. *Land Degrad. Dev*. 10:577-592.

Mengel, K., A. Kirkby, H. Kosegarten, and T. Appel (eds.). 2001. *Principles of Plant Nutrition*. Kluwer Academic Publishers. Dordrecht/Boston/London. 849 pp.

Miller, F.P. and W.E. Larson. 1990. Lower input effects on soil productivity and nutrient cycling. Pp. 549-568. In C.A. Edwards, R. Lal, P. Madden, R.H. Miller and G. House (eds.) *Sustainable Agricultural Systems*. Soil Conservation Soc. Am. Ankeny, IA, USA.

Mutert, E. 1996. Plant nutrient balance in Asia and the Pacific region: Facts and consequences for agricultural production. Pp. 73-112. In *APO-FFTC Seminar on Appropriate Use of Fertilizers*.

Nandwa, S.M. and M.A. Bekunda. 1998. Research on nutrient flows and balances in East and Southern Africa: State-of-the-art. *Agric. Ecosyst. Environ*. 71:5-18.

Nielsen, D.R., P.J. Wierenga and J.W. Biggar. 1982. Nitrogen transport processes in soil. Pp. 423-442. In F.J. Stevenson (ed.) *Nitrogen in Agricultural Soils*. Am. Soc. Agron., Madison.

Nutrient Sources. 1997. A Report by Levington Agriculture Ltd for the European Fertilizer Manufacturers Association.

OECD Secretariat. 1997. *OECD National Soil Surface Nutrient Balances 1985 to 1995, Explanatory Notes*.

Osgood, D. 2001. Dirt poor: Poverty, farmers and soil resources investment. In *FAO Economic and Social Development Paper 149* (*http://www.fao.org/DOCREP/*).

Pieri, C. 1983. Nutrient balances in rainfed farming systems in arid and semi-arid regions. Pp. 181-209. In *Nutrient Balances and the Need for Fertilizers in Semi-Arid and Arid Regions Proc. 17th Colloquium*. International Potash Institute, Rabat, Morocco.

Rhodes, E.R. 1995. Nutrient depletion by food crops in Ghana and soil organic nitrogen management. *Agricultural Systems* 48:101-118.

Roy, A.H. 2003. Fertilizer needs to enhance production–challenges facing India. Pp. 53-68. In R. Lal, D. Hansen, N. Uphoff, and S. Slack (eds.) *Food Security and Environmental Quality in the Developing World*. CRC Press LLC, Boca Raton, FL, USA.

Saka, A.R., J.D.T. Kumwenda, P.S.C. Rao and R.E. Jessup. 1998. Simulation of nitrogen leaching and plant uptake in the maize root zone under rain-fed conditions in Malawi. Pp. 227-245. In L. Bergström and H. Kirchmann (eds.) *Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems*. CAB International, Wallingford, Oxon, UK.

Scholes, R.J. and M.C. Scholes. 1999. Nutrient balances at field level of mixed cropping systems in various agroecological zones in Mozambique. Pp. 191-210. In *E.M.A. Smaling et al. (eds.) Nutrient Disequilibria in Agroecosystems, Concepts and Case Studies*. CABI Publishing, New York, NY.

Sheldrick, W.F., J.K. Syers and J. Lingard. 2002. A conceptual model for conducting nutrient audits at national, regional, and global scales. *Nutrient Cycling in Agroecosystems* 62:61-72.

Sibbesen, E. and A. Runge-Metzger. 1995. Phosphorus balance in European agriculture–status and policy options. Pp. 43-57. In H. Tiessen (ed.) *Phosphorus in the Global Environment: Transfers, Cycles, and Management*. John Wiley & Sons, Chichester: SCOPE 54.

Singh, B., Y. Singh and G.S. Sekhon. 1996. Fertilizer-N use efficiency and nitrate pollution of groundwater in developing countries. *Environmental Pollution* 93: 366-366.

Smaling, E.M.A. and L.O. Fresco. 1993. A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON). *Geoderma* 60:235-256.

Smaling, E.M.A., J.J. Stoorvogel and P.N. Windmeijer. 1993. Calculating soil nutrient balances at different scales: II. District scale. *Fert. Res*. 35:227-235.

Stauffer, M.D. and D.B. Beaton. 1995. *Importance of plant nutrients in increasing agricultural productivity: Chinese experience*. The Fertilizer Association of India, New Delhi.

Stoorvogel, J.J. and E.M.A. Smaling. 1990. Assessment of soil nutrient depletion in sub-Sahara Africa: 1983-2000, 4 Volumes. *Report 28*. The Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands.

Stoorvogel, J.J., E.M.A. Smaling and B.H. Jansen. 1993. Calculating soil nutrient balances at different scales: I. Supra-national scale. *Fert. Res*. 35:227-235.

Stoorvogel, J.J. and E.M.A. Smaling. 1998. Research on soil fertility decline in tropical environments: Integration of spatial scales. *Nutrient Cycling in Agroecosystems* 50:151-158.

Tandon, H.L.S. 1992. Assessment of soil nutrient depletion. *FADINAP seminar*. Fertilization and the Environment. Chiang Mai, Thailand.

Tonmanee, N. and N. Kanchanakool. 1999. Agricultural diffuse pollution in Thailand. *Wat. Sci. Tech*. 39:61-66.

UNDP/UNEP/FAO. 1994. Land degradation in South Asia: Its severity, causes and effects upon the people. *World Soil Resources Reports No. 78*. FAO, Rome.

UNEP/UNIDO/IFA. 1996. Mineral Fertilizer Production and the Environment. A Guide to Reducing the Environmental Impact of Fertilizer Production. *UNEP Technical Report No. 26*. UNEP/UNIDO/IFA.

Van den Bosch, H., J.N. Gitari, V.N. Ogaro, S. Maobe, and J. Vlaming. 1998. Monitoring nutrient flows and economic performance in African farming systems (NUTMON): III. Monitoring nutrient flows and balances in three districts in Kenya. *Agric. Ecosyst. Environ*. 71:63-80.

Van der Pol, F. 1992. Soil mining: An unseen contributor to farm income in Southern Mali. *Bull. 35*. The Royal Tropical institute, Amsterdam, The Netherlands.

Van Diepen, C.A., H. Van Keulen, J. Wolf, and J.A.A. Berkhout. 1991. Land evaluation: From intuition to quantification. *Adv. Soil Sci*. 15:141-204.

Van Duivenbooden, N. 1990. *Sustainability of West African cropping systems in terms of nutrient elements: A study for the 5th region of Mali*. CABO, Wageningen, The Netherlands.

Wortmann, C.S. and C.K. Kaizzi. 1998. Nutrient balances and expected effects of alternative practices in farming systems of Uganda. *Agric. Ecosyst. Environ*. 71: 115-129.

WRI/UNEP/UNDP/WB. 1996. *World Resources: A Guide to the Global Environment, 1996-97*. Oxford University Press, UK.

Xie, J.C., W.Y. Xing and J.M. Zhou. 1998. Current use of and requirement for nutrients for sustainable food production in China. Pp. 267-277. In A.E. Johnston and J.K. Syers (eds.) *Nutrient Management for Sustainable Crop Production in Asia*. CAB International, Wallingford, UK.

RECEIVED: 10/30/03
REVISED: 03/15/04
ACCEPTED: 03/31/04