Nutrient Budgets: A Sustainability Index

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Abstract

The sustainability of agricultural production systems in the middle mountains of Nepal is dependent on soil and water resources, management, and market factors. However, maintaining the soil nutrient pool is the key to long-term productivity. Nutrient budgeting was used to evaluate inputs, management, and productivity, and to quantify the impact on soil fertility. Data from soil, water, and sediment analysis, and from socioeconomic farm surveys, provided inputs to the model. Soil N, P_2O_5, and Ca budgets were calculated. The results for the main cropping systems indicated substantial deficits for N and P_2O_5 under a rainfed maize-dominated rotation. Nitrogen deficits under this system were comparable to crop requirements. By comparison, nitrogen deficiencies appeared to be the only concern under triple cropping systems in a rotation dominated by irrigated rice. Nutrient budgets indicated that the soil nutrient pool is being depleted under both extensive rainfed and intensive irrigated production systems, and are an indicator of soil degradation. Prevention and rehabilitation techniques such as liming, improved composting, and integrated nutrient management must be incorporated into farm production systems if productivity is to be maintained.

Introduction

The current soil fertility status and how it is changing are strongly influenced by nutrient management. As agriculture intensifies and expands onto marginal lands, concern has been expressed that the nutrient pools in the soil cannot be sustained. There are three areas of major concern:

- double and triple crop rotations are now common where water is available;
- high yielding varieties and vegetable crops are more nutrient demanding; and
- organic matter inputs traditionally applied to upland fields are being applied to cash crops.

Chemical fertilisers and forest litter are used in an attempt to maintain production, but farmers are reporting that increased fertiliser inputs are required to maintain yields. Nutrient budgeting provides one mechanism for evaluating inputs, management, and productivity, and their impact on soil fertility.

The following nutrient budget model was developed for and then applied to the Jhikhu Khola watershed in the middle mountains of Nepal to demonstrate its application. In the model, nutrient inputs to and losses from the soil nutrient pool are estimated. The data requirements and model assumptions are outlined below. Soil samples from 130 agricultural fields were analysed. Data were collected for each field on the crops grown, inputs applied, and yields. Erosion plot, sediment accumulation, and water quality data were collected and incorporated into the model. In addition, a special study on phosphorus fixation was conducted to determine P constraints—particularly in red soils, which are known to have low P supplies (Schreier *et al.* 1999). Nutrient budgets are presented for the dominant cropping systems in the watershed and the implications for sustainability are discussed. Specific emphasis was given to rice dominated (irrigated) and maize dominated (rainfed) cropping systems.

Modelling Method

The impact of management practices on agricultural soil fertility was quantified by modelling nutrient inputs, redistribution, and losses. The approach and assumptions used to model soil N are shown diagrammatically in Figure 111. A similar framework was used to model P_2O_5 and Ca. Nutrient flows were integrated over a soil depth of 15 cm. Nutrient inputs were associated with compost, fertiliser, sediment, water, and biota; redistribution processes included erosion-sedimentation, mineralisation-immobilisation, and adsorption-desorption; and losses included leaching, denitrification, volatilisation, chemical fixation, erosion, and plant uptake. Compost additions were subjected to mineralisation and retention, and provided nutrients to subsequent crops through organic residues.

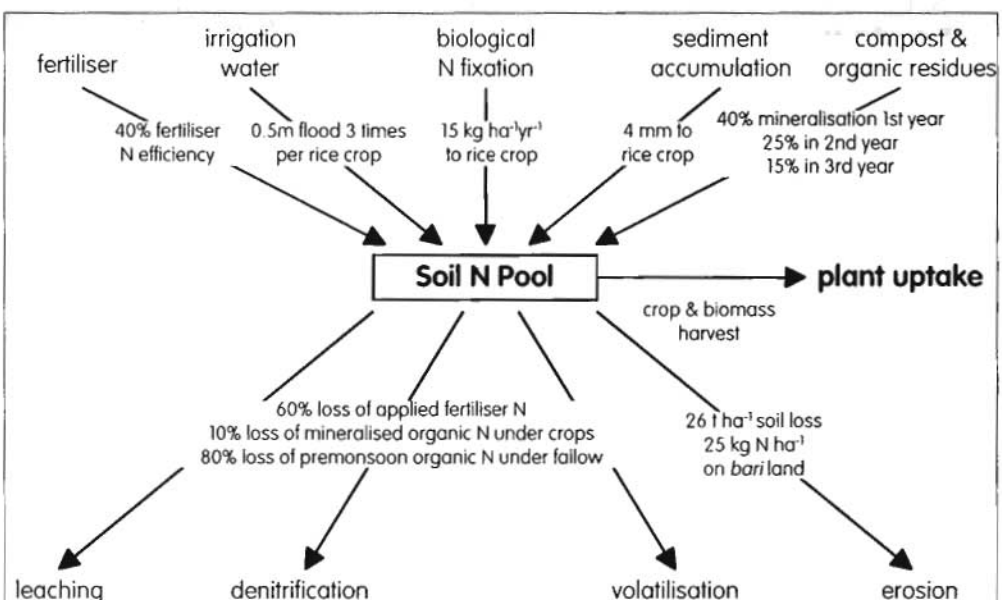

Figure 111: **Approach Used to Model Soil N Dynamics**

Data Requirements

Information from socioeconomic surveys and biophysical analyses of soil, water, and sediment samples is required in order to use such a model. Input to the nutrient budget requires data on soil fertility, biomass productivity, farm management, and soil loss from erosion plots. In addition, data from the literature are needed for verification and to fill information gaps.

Initial Soil Nutrient Pool

The initial pool of soil nutrients was calculated from the current soil fertility status for each land use category. The potentially available soil nutrient pools for N, P_2O_5, and Ca in irrigated and rainfed land were calculated from the measured soil nutrient concentration, assuming a soil bulk density of 1400 kg/m³ and a 15 cm rooting depth. An example of the calculations (for P_2O_5 in rainfed land) is shown below. The results are shown in Table 101.

$$\frac{47 \text{ mg } P_2O_5}{\text{kg soil}} \times \frac{\text{kg}}{10^6 \text{ mg}} \times \frac{1400 \text{ kg soil}}{m^3} \times \frac{100 \times 100 \text{ m}^2}{\text{ha}} \times 0.15 \text{ m} = \frac{99 \text{ kg } P_2O_5}{\text{ha 15 cm soil depth}}.$$

For each land use category, nutrient additions and/or losses will apply.

Table 101: **Initial Soil Nutrient Pool (mean values)**

Land Use	Soil Nutrient Concentration (mg/kg)			Soil Nutrient Pool (kg ha^{-1}, 15 cm soil depth)		
	N	P_2O_5	Ca	N	P_2O_5	Ca
Irrigated	854	49	2120	1793	103	4452
Rainfed	941	47	1443	1976	99	3030

Compost and Fertiliser Use

Inputs from compost and chemical fertiliser sources to cultivated land were based on the responses from the farmers surveyed. The nutrient inputs to rice, maize, and wheat crops from organic matter and chemical fertiliser sources are summarised in Table 102. The inputs from compost were calculated for traditional compost practices assuming 0.6% N, 0.06% P_2O_5, and 0.6% K_2O (Subedi *et al.* 1995), and a 25% moisture content.

The greatest amount of organic matter was applied to maize grown on rainfed lands during the monsoon. Farmers applied an average of 12 tonnes per ha, and in some cases up

Table 102: **Reported Nutrient Inputs from Organic and Chemical Fertiliser Sources (n=130)**

System	N	Med. Organic Matter Inputs (kg ha^{-1})				Med. Che. Ferti. Inp. (kg ha^{-1})		
		Amount	N	P_2O_5	Ca	Amount	N	P_2O_5
Premonsoon								
Early maize (irrigated)	12	0	0	0	0	177	35	35
Monsoon								
Rice (irrigated)	49	2,457	11	1	15	197	57	39
Maize (rainfed)	65	11,795	53	5	71	172	35	27

to 50 tonnes per ha, of organic fertiliser to rainfed lands during the monsoon season. During the winter, only 18 per cent of farmers applied organic matter to rainfed fields. Organic matter inputs to irrigated fields were lower, roughly four tonnes per ha in total, and were distributed over the premonsoon and monsoon periods. The calculated average inputs show the relatively small contributions made by organic matter to N and P_2O_5 with the exception of maize grown during the monsoon. In contrast, organic matter was the main source of Ca on rainfed fields.

The dominant chemical fertilisers used were urea (46-0-0), complex C (20-20-0), and ammonium sulphate (21-0-0), and mainly supplied inorganic N. Chemical fertiliser inputs were applied throughout the year, with monsoon rice receiving the largest N and P_2O_5 inputs. Nutrient inputs from chemical fertiliser were significantly greater than those from organic matter with the exception of maize grown during the monsoon, which received 52 per cent of N inputs and 20 per cent of P_2O_5 inputs from organic sources. At the other extreme, winter wheat typically received all N and P_2O_5 inputs from inorganic sources.

Erosion

The annual nutrient losses through erosion were estimated from the erosion rates determined in plot studies and the nutrient content of eroded sediments. The results are shown in Table 103. The erosion rates averaged 26±5 t per ha on rainfed sites (Carver 1997). Average erosion rates were used to estimate nutrient losses under farmers' practice and lower estimates of erosion rates were used to simulate best management practices. For rainfed lands, the nutrient content of sediments eroded from the plots were used to estimate annual losses. Eroded sediments commonly contain a higher nutrient content than the topsoil from which they are derived as a result of the selective erosion of organic matter and surface soil high in nutrients. Nutrient losses through erosion from rainfed fields resulted in an average annual loss of 25 kg N per ha and 23 kg Ca per ha. Available P losses were small, but the organic P losses may be high, particularly if a high intensity rainfall event occurs before compost and manure are incorporated into the soil.

Table 103: **Erosion and Associated Annual Nutrient Losses from Rainfed Lands**

	Nutrient Content ($mg\ kg^{-1}$)		Erosion		Depth Integrated Losses ($kg\ ha^{-1}$ per soil loss depth)		
	Eroded Sediment	Residual Soil	Rate ($t\ ha^{-1}$)	Soil loss (mm)	Eroded Sediment	Residual soil	Losses
Rainfed fields			26 + 5	2			
N	1882	941			49	24	25
Avail. P_2O_5	64	47			1.7	1.2	0.5
Ca	1980	1443			51	28	23
Total bases	2777	1937			72	50	43

Water Management and Sedimentation

The annual nutrient inputs to lowland irrigated fields from sediments were calculated based on the amount and nutrient content of accumulated sediment. Sediment accumulation was measured in 20 irrigated fields and the nutrient content of newly accumulated and residual soils determined. Given a median annual sediment accumulation of 4 mm, and assuming a soil bulk density of 1400 kg per cu m, an additional 11 kg N per ha and 28 kg Ca per ha were potentially available for plant uptake. Nutrients may also be gained by irrigated fields through irrigation water. Spring and stream water samples taken during the dry season of 1990 (Schreier *et al.* 1994) indicate that the water is alkaline and contains moderate quantities of Ca, Mg, NO_3, and PO_4. Assuming a 0.5m depth of water applied three times per rice crop, the irrigation water may contribute an additional 6 kg N per ha and 300 kg Ca per ha.

Phosphate Fixation

The high phosphate fixation capacity of soils in the study region has important implications for P management (Schreier *et al.* 1999). The P sorption potential for these soils is given in Table 104. The P sorption capacity averaged 6,700 kg P_2O_5 per ha for red soils and 1,500 kg P_2O_5 per ha for non-red soils, values comparable to tropical soils high in kaolinite. Given the high potential for fixation, P released to the soil solution will be governed by the chemical equilibria between soluble and insoluble mineral forms of P, the slow release of inorganic P by mycorrhizal fungi and other micro-organisms, and by mineralisation and immobilisation of organic P. Fertiliser P application, particularly on red soils, will be inefficient and crops will probably recover only 20 to 40 per cent of the P applied in organic inputs annually (Sharpley and Halvorson 1994).

Table 104: **Phosphate Sorption Potential**

Soil	Description		P Sorption Capacity	
			g P (kg soil)-1	kg P_2O_5 ha-1
Red Soils	Forest	n = 10	1.7	8200
	Cultivated	n = 20	1.2	5900
Non-red Soils	Cultivated Rangeland	n = 26	0.3	1500

Yield and Crop Nutrient Uptake

The nutrient uptake by the main staple crops grown in the region was calculated from reported yield data and average values of N, P_2O_5, and Ca uptake derived from literature sources. Reported yields for rice, maize, and wheat were compared to regional values and locally measured yields to assess the validity and variability of yields reported by farmers. Nutrient removal by rice, maize, and wheat is summarised in Table 105. The per cent nutrient composition by weight refers to the entire above ground portion of the crop. Nutrient uptake by the total biomass was utilised as crop residues are harvested and used for animal feed. Reported yield values were used to estimate total dry matter based on the ratio of grain to total biomass. For rice, maize, and wheat, grain comprises roughly 45 per cent of total dry matter (Grist 1986). The total estimated dry matter on a kg per ha basis was then multiplied by the per cent nutrient composition to calculate N, P_2O_5, and Ca uptake.

Table 105: **Nutrient Removal by the Dominant Staple Crops (median values)**								
System	Rep. Yield (kg/ha)	n	Average Composition			Nutrient Uptake (kg/ha)		
			% N	% P_2O_5	% Ca	N	P_2O_5	Ca
Premonsoon								
early maize (irrigated)	1054-6389	12	1.4	0.6	0.3	67	29	14
Monsoon								
rice (irrigated)	959-7669	49	1.0	0.4	0.1	75	30	8
maize (rainfed)	688-8256	66	1.4	0.6	0.3	128	55	27
Winter								
wheat	334-5351	53	1.2	0.5	0.1	36	15	3
wheat (irrigated)	669-5351	31	1.2	0.5	0.1	45	19	4
wheat (rainfed)	334-2675	22	1.2	0.5	0.1	36	15	3

Nutrient uptake was greatest for maize grown during the monsoon with a median value of 128 kg N, 55 kg P_2O_5, and 27 kg Ca removed per ha. Monsoon rice removed roughly 75 kg N, 30 kg P_2O_5, and 8 kg Ca per ha, while premonsoon maize and rice removed intermediate levels of N, P_2O_5, and Ca. Wheat, the main crop grown during the winter, removed the least nutrients with a median uptake for irrigated and rainfed sites of 36 kg N and 15 kg P_2O_5 per ha. These values cannot be taken as precise since the nutrient composition of crops varies substantially with differences in soil nutrient availability, plant genotype, and local environmental conditions. However, these estimates of nutrient uptake for specific fields provide an indication of the level of nutrient inputs required to maintain the soil nutrient pool.

Model Assumptions

Organic matter mineralisation was assumed to be 40 per cent in the first year, 25 per cent in the second year, and 15 per cent in the third year (Kirchman 1994). Inputs from traditional compost are subjected to storage and handling losses prior to incorporation and further N losses under crops are likely be small. N losses under fallow, however, may be substantial and were assumed to be 70 per cent. Crop recovery of applied fertiliser N was taken to be 40 per cent, that is 60 per cent losses were assumed due to leaching, volatilisation, and denitrification (Stevenson 1986). Phosphate fixation by Fe and Al oxides was assumed to be 73 per cent of applied fertiliser P and 10 per cent of mineralised organic P on red soils and 53 per cent of applied fertiliser P on non-red soils, with a subsequent slow release of 15 per cent per annum by chemical and microbial processes (Sharpley and Halvorson 1994). Ca losses by leaching were taken to be 40 per cent for all sources, and 30 per cent Ca fixation was assumed under rice production (Cook 1981). The Ca required to neutralise the acidifying effects of chemical fertilisers (dominantly urea) was taken to be 1 kg CaO per kg N applied.

Results of Nutrient Budget Calculations for the Dominant Cropping Systems

The nutrient budgets were calculated for a rainfed maize-wheat rotation and an irrigated early maize-rice-wheat rotation. The results are shown in Figures 112a-f. The calculated N, P_2O_5, and Ca inputs and withdrawals are shown in the upper and lower portions of the pie charts, respectively. The 'inputs from compost' indicate the total nutrients contained in the

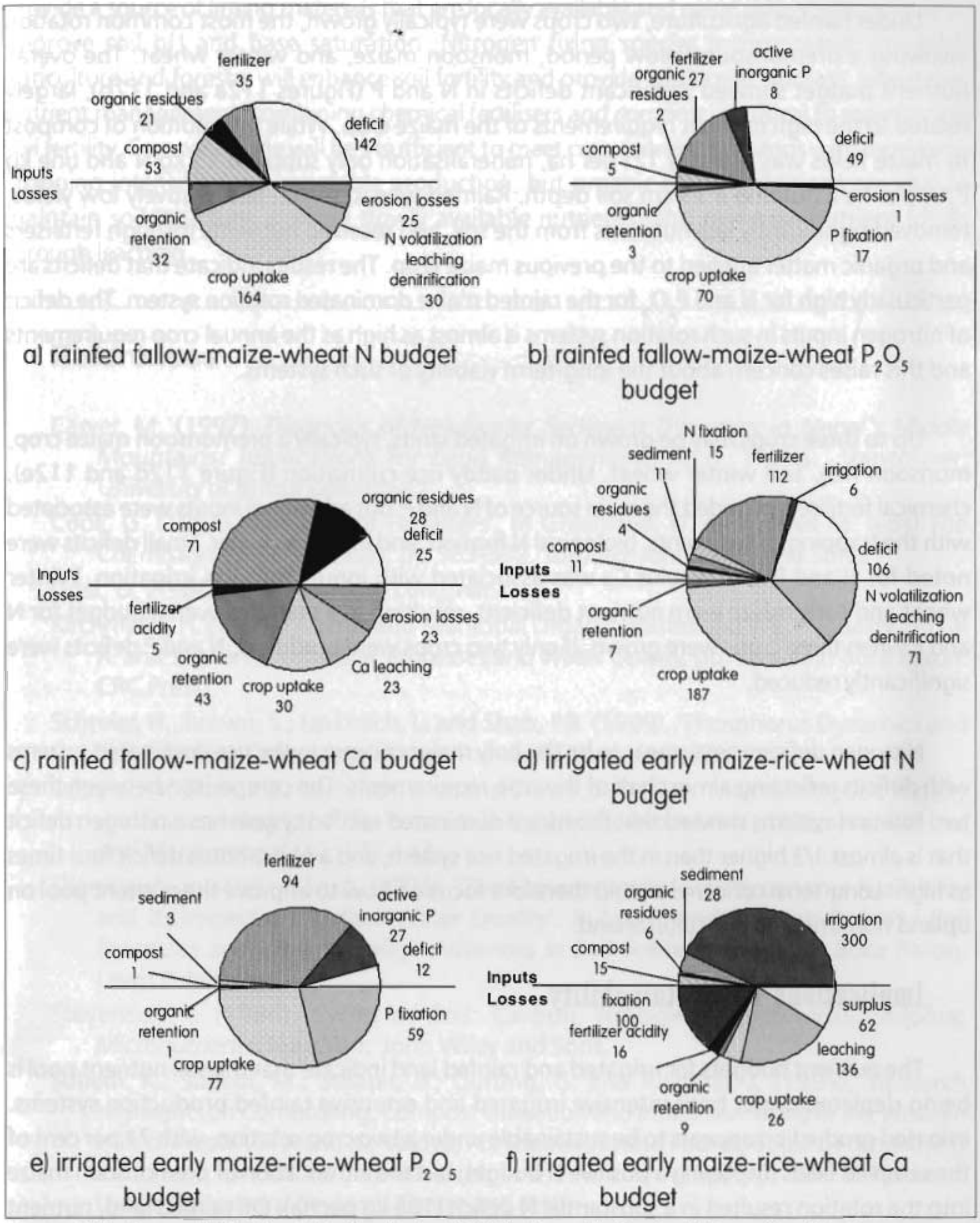

Figure 112: **Annual Nutrient Budgets for Rainfed and Irrigated Cropping Systems (numbers refer to kg per ha per 15 cm soil depth)**

organic matter applied to the crop, the 'organic residues' show the nutrient supply from prior compost applications, and the 'organic retention' refers to compost which is not decomposed during the growing season. 'Phosphorus fixation' indicates the absorption of P by Al and Fe oxides, and 'active inorganic P' refers to the slow release of inorganic P from prior inputs. Median values of compost, fertiliser, and crop uptake for households growing each crop were used.

Under rainfed agriculture, two crops were typically grown, the most common rotation involving a premonsoon fallow period, monsoon maize, and winter wheat. The overall nutrient budget showed significant deficits in N and P (Figures 112a and 112b), largely related to the high nutrient requirements of the maize crop. While the addition of compost to maize fields was typically 12t per ha, mineralisation only supplied 13 kg N and one kg P_2O_5 per ha assuming a 15 cm soil depth. Rainfed wheat, which has relatively low yields, removed significantly less nutrients from the soil, and received nutrients through fertilisers and organic matter applied to the previous maize crop. The results indicate that deficits are particularly high for N and P_2O_5 for the rainfed maize dominated rotation system. The deficit of nitrogen inputs in such rotation systems is almost as high as the annual crop requirements and this raises concern about the long-term viability of such systems.

Up to three crops may be grown on irrigated lands, typically a premonsoon maize crop, monsoon rice, and winter wheat. Under paddy rice cultivation (Figure 112d and 112e), chemical fertilisers provided the main source of N and P, but additional inputs were associated with the trapping of sediments, biological N fixation, and irrigation water. Small deficits were noted for N and P, and surplus Ca was associated with inputs through irrigation. Winter wheat and early maize were nutrient deficient, resulting in a negative overall budget for N and P when three crops were grown. If only two crops were produced, N and P deficits were significantly reduced.

Nitrogen deficiencies appear to be the only major concern in the rice dominated systems with deficits reflecting almost half of the crop requirements. The comparison between these two rotation systems showed that the maize dominated rainfed system has a nitrogen deficit that is almost 1/3 higher than in the irrigated rice system, and a phosphorus deficit four times as high. Long-term concerns should therefore focus on how to improve the nutrient pool on upland non-irrigated agricultural land.

Implications for Sustainability

The nutrient budgets for irrigated and rainfed land indicate that the soil nutrient pool is being depleted under both intensive irrigated and extensive rainfed production systems. Irrigated production appears to be sustainable under a two crop rotation, with 71 per cent of the sampled fields displaying a positive N budget, but the introduction of premonsoon maize into the rotation resulted in a substantial N deficit (106 kg per ha). On rainfed land, nutrient inputs were insufficient to meet crop requirements and the negative nutrient budgets are an indicator of soil degradation.

Prevention of further soil fertility degradation and rehabilitation of already degraded lands are challenges that must be addressed if productivity is to be maintained in the middle mountains of Nepal. Improved composting is one practical option for improving nutrient budgets under rainfed cultivation. Acidification is a concern because of the inherent acid bedrock, and the increasing use of chemical fertilisers. Calcium and magnesium based rocks provide a source of liming materials that are locally available and could potentially be used to improve soil pH and base saturation. Nitrogen fixing species incorporated into both agriculture and forestry will enhance soil fertility and provide additional biomass. Integrated nutrient management, combining chemical fertilisers and compost, is critical to maintaining soil fertility. Compost alone will be insufficient to meet crop nutrient demands with increasing cropping intensities and vegetable production, but organic matter additions are vital to maintain soil structure, provide slowly available nutrients, and minimise nutrient losses through leaching.

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