Chapter 6

Soil Fertility Issues under Irrigated and Rain-Fed Agriculture In the Middle Mountains of Nepal

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Introduction

Rapid population growth and resources' constraints are placing severe pressure on the subsistence economy in the middle mountains of Nepal. Over the past few years, an interdisciplinary research project was carried out to document the resource status, examine land-use dynamics, determine soil fertility conditions, and quantify the soil erosion, and hydro-meteorological processes affecting resource use and causing degradation. This cooperative study between ICIMOD and the University of British Columbia (UBC) has been very challenging as it contains an extensive environmental monitoring programme and data integration using GIS techniques.

Over the past few years, soil fertility conditions in relation to land use have been monitored in the Jhikhu Khola Watershed in the middle mountains of Nepal. The watershed is located 50km east of Kathmandu and covers 11,000ha of land between 700 to 1,900m in elevation. The land use within the watershed is typical of the middle mountains and land-use pressure is high. The watershed area is dominated by an elaborate system of man-made terraces. There has also been a gradual transformation from single to multiple annual crop rotations in the area, wherever irrigation water is available. Soil fertility maintenance with limited input and intensive farming systems suggest that the middle mountains of Nepal are facing serious problems.

Land-use Patterns and Cropping Intensity

The study area displays the typical land-use pattern found in densely-populated parts of the middle mountains. Agricultural crop production is carried out on *khet* (irrigated lands) and *bari* (rain-fed uplands). Rice-based farming systems are predominant on *khet* and the general cropping patterns are spring maize followed by rice, or two crops of rice followed by wheat, tomatoes, or potatoes. Under rain-fed farming systems, typical annual cropping sequences are maize intercropped with millet, followed by wheat or mustard, depending on soil moisture conditions.

Cropping intensity, as revealed through socioeconomic surveys, averages out at 2.7 crops/year grown under irrigated conditions and 2.5 crops/year under rain-fed conditions. Increases in cropping intensity over the past 10 years have resulted from increasing demand for food, availability of short-growing season crop varieties, and, most important of all, market-oriented cash crops.

Soil Inventory

Soil inventory and mapping were carried out for the study area on a scale of 1:20,000. The major soils of the watershed can be broadly divided into two main types: red soils and non-red soils. The more prevalent red soils are **Rhodustults** and **Paleustults**, developed on phyllitic parent material, and the non-red soils are mainly **Ustochrepts** and **Dystrochrepts**, formed on phyllite and schists. The red soils have developed on old river terraces and are the oldest soils in the middle mountains. They are known to be highly prone to erosion and under low organic matter input, therefore it is very difficult to maintain soil fertility. All red soils have a diagnostic clay enriched Bt horizon with higher clay content in the B horizon than in either the A or C horizons.

Soil Fertility Survey

A 1:20,000 scale soil survey was conducted in the watershed, and some 340 soil pits and auger holes were sampled for nutrient analysis and texture characterisation. Subsequently, the soils were examined in more detail and a red versus non-red soil map was produced and digitised. This allows us to display the nutrient status of the different soils in a spatial manner and will assist us in modelling production in relation to soil constraints.

In addition to the general soil survey, three detailed fertility surveys were conducted during the 1992-93 season. First, 200 sites were selected according to the major land-use types and various biophysical conditions in the watershed. Forest soil evaluations were completed by Schmidt (1992) and Schmidt et al. (1993) and dryland agriculture by Wymann (1991). As a result of these surveys, it became evident that the biophysical conditions (aspect and elevation) and the soil types are key components influencing land use and productivity. As a result a 2 x 2 x 2 x 3 factorial survey was carried out in the middle section of the watershed to cover elevation (above and below 1,200m), aspect (north versus south), red versus non-red soils, and land use (irrigated-*khet*, rain-fed-*bari*, and grazing land). The aim was to document differences in soil fertility due to land use, while keeping some of the main biophysical conditions constant.

Of the 24 combinations of the biophysical types, only 20 occurred. This was because there is little irrigated land above 1,200 metres, particularly on the south facing slopes, and insufficient grazing land occurred on high elevation, red soils on northern aspects. An overview of the combination of classes and the number of fields in which samples were collected is provided in Table 1. All sampling sites were identified on the enlarged (1:5,000 scale) aerial photographs and surface samples were collected for nutrient analysis. The samples have been duly analysed in the soil laboratory at the University of British Colombia (UBC).

Table 1: Sampling Design for Detailed Nutrient Analysis

Soil Type	Elevation	Aspect	Land Use	Sample #
Red Soils	< 1,200m	South	*bari*, grazing, *khet*	10 each
Red Soils	< 1,200m	North	*bari*, grazing, *khet*	10 each
Red Soils	> 1,200m	North	*bari*	10
Red Soils	> 1,200m	South	*bari*, grazing	10 each
Non-Red Soils	< 1,200m	South	*bari*, grazing, *khet*	10 each
Non-Red Soils	< 1,200m	North	*bari*, grazing, *khet*	10 each
Non-Red Soils	> 1,200m	South	*bari*, grazing	10 each
Non-Red Soils	> 1,200m	North	*bari*, grazing, *khet*	10 each

Two detailed soil surveys were carried out to document the changes in soil fertility over time, due to alterations in nutrient input and intensification in production. First, a site was selected consisting of a pine forest planted 17 years previously, situated adjacent to dryland agricultural fields and irrigated fields. All three originated on the same soils, and, based on the historic aerial photos and farmers' surveys, it was clear that the land uses remained the same over the 17-year period, but the inputs, use, and intensity of production had changed significantly. This was a relative comparison since we did not have historic soil samples. The differences in soil fertility between the three land uses could be attributed to the difference in management. The prime concern of this study was that the nutrients under forests had not been sustainable as a result of extensive litter collection. Similarly, irrigated and rain-fed agriculture under increasing crop intensification had also not been sustainable because of insufficient nutrient inputs. This comparison was made to provide long-term rates of change and relative degradation in soil fertility between different land uses that receive different inputs. Ten surface soil samples were collected in each of the three land-use types and profiles were analysed in each.

The second detailed survey was conducted on 12 forested sites and seven agricultural sites originally sampled in 1989. These sites were used to determine potential soil fertility changes over a five-year period. These plots were re-sampled in April 1994. Ten composite samples were gathered and combined into one bulk sample per plot during each of the two surveys. The 1994 set of samples was sent for analysis in the soil laboratory at UBC. The samples were representative of typical pine and *sal* forests and *bari* agricultural fields.

Analysis of variance, t-tests, and Mann Whitney U-tests were used to determine differences between soils under different land uses. The test site results were extrapolated for the entire watershed by comparing the mean values of key soil fertility variables collected from different soil and land use surveys.

Results and Discussion

Soil Profile Comparison

Our basic assumptions are that all red soils in the test area are of similar origin and original composition, and that differences in surface horizons result from recent changes in land management. Results for soil profiles in the forest and agricultural fields (Table 2) support these assumptions. The sequences of horizons are the same, and the overall chemical composition of the Bt and BC horizons are also similar. The forested site has slightly greater pH, greater base saturation, and total Fe and Al and clay contents than the agricultural site. The differences, however, are small and do not contradict the suggestion that the soils have a common origin. About two-thirds of the total iron is in the active CBD extractable form. This has implications for phosphorus availability. In addition, 16 per cent of the total iron is in the amorphous (ammonium oxalate extractable) form, this is more than 25 per cent of the active iron.

Table 2 also shows that these strongly weathered and oldest soils in Nepal have very low nutrient status. They have large amounts of clay (<2um), and mineralogical analysis of the B and BC horizons (Schreier et al. 1990) indicates a predominance of illite and kaolinite. The illite is a result of the weathering of mica, a mineral that is most prevalent in the parent materials of the watershed. The kaolinite results from rapid weathering on acid, freely-drained sites; it influences soil fertility because of its small cation exchange capacity.

Long-term Land Use Effects on Soil Fertility Differences

Soil fertility differences were compared for three land uses (Tables 3 and 4). The forested soils had significantly less ($P = 0.05$) exchangeable Ca, Mg, base saturation, available P, total N, and organic C than those under the other land uses, and CBD-extractable Fe in the surface horizons was significantly greater. Nutrient removal by biomass collection in the forest plantation over the past 17 years helps explain the low nutrient status of its soils. By contrast, the agricultural sites receive nutrient inputs from manure and chemical fertilisers. The differences between dryland and irrigated agriculture are smaller: P is significantly greater ($P = 0.05$) on the irrigated sites than on the rain-fed sites, but the differences in Ca and Mg are significant at only $P = 0.20$ and $P = 0.10$, respectively. These differences suggest that the irrigated fields receive nutrients and cations from irrigation water and sediment suspended in the water in addition to the nutrient inputs in manure and chemical fertilisers (Schreier et al. 1990).

Table 2: Comparison of Profile Characteristics between Forested and Agricultural Sites

	Agricultural sites			Forested sites		
	AB (0-20)	Bt (20-50)	BC (50-100)	AB (0-20)	Bt (20-50)	BC (50-100)
pH ($CaCl_2$)	4.8	4.6	4.7	4.3	5.1	5.4
P (mg/kg)	1.9	1.9	0.3	0.8	1.9	0.5
N (g/kg)	0.76	0.43	0.21	0.62	0.43	0.32
C (g/kg)	7.5	4.5	1.9	7.9	4.5	3.4
Ca (cmol/kg)	1.72	1.59	1.04	1.47	1.45	1.48
Mg (cmol/kg)	1.99	2.00	1.48	0.82	1.25	1.54
K (cmol/kg)	0.30	0.31	0.09	0.26	0.09	0.20
CEC (cmol/kg)	15.7	16.6	12.8	15.8	14.9	10.9
BS (%)	25.8	23.7	20.6	16.4	18.9	29.7
CBD %Fe	2.91	3.25	3.39	3.01	3.34	3.53
CBD %Al	0.4	0.43	0.47	0.48	0.56	0.53
PYR %Fe	0.08	0.02	0.01	0.15	0.06	0.01
PYR %Al	0.08	0.07	0.05	0.13	0.05	0.04
AAO %Fe	0.79	0.88	0.39	0.75	0.99	0.93
AAO %Al	0.21	0.22	0.13	0.21	0.24	0.20
Clay (%)	47.5	52.6	42.7	43.9	56.2	53.8
Silt (%)	30.2	25.6	28.8	28.8	22.3	24.2
Sand (%)	22.3	218	28.5	27.3	21.5	22.0
Ca (% total)	0.09	0.08	0.08	0.06	0.06	0.05
K (% total)	1.65	1.60	1.60	1.30	1.40	1.50
Mg (% total)	0.36	0.34	0.34	0.30	0.35	0.34
Fe (% total)	4.67	4.77	4.77	4.69	5.90	5.72
Al (% total)	8.54	8.62	8.62	8.27	10.20	9.98
P (% total)	0.03	0.03	0.03	0.03	0.03	0.02
% Active Fe/total	62.3	68.2	71.0	64.1	56.6	61.7
% Active Al/total	4.7	4.9	5.4	5.8	5.5	5.3
% Amorphous Fe/total	16.9	18.5	8.2	16.0	16.7	16.3
% Amorphous Al/total	2.5	2.6	1.6	2.5	2.3	2.

CEC = Cation exchange capacity
BS = Base saturation
CBD = Citrate-bicarbonate-dithionite extractable (=active)
PYR = Pyrophosphate extractable
AAO = Ammonium oxalate extractable
Amorphous = CBD-AAO

Table 3: **Mean Values of Fertility Characteristics of Soils under Forests, Rain-fed, and Irrigated Agriculture**

	Forested (n = 10)	Rain-fed Agriculture (n = 10)	Irrigated Agriculture (n = 10)
pH	4.2	4.5	4.9
C (g/kg)	4.5	11.4	10.9
N (g/kg)	0.45	1.21	0.98
Ca (cmol/kg)	1.47	2.63	2.79
Mg (cmol/kg)	0.55	1.28	1.77
K (cmol/kg)	0.25	0.52	0.3
P (cmol/kg)	1.4	6.4	8.6
CEC (cmol/kg)	15.18	12.03	11.94
BS (%)	16.1	37.6	40.3
CBD Fe (%)	3.28	2.48	2.5
CBD Al (%)	0.36	0.23	0.33
AAO Fe (%)	0.37	0.35	0.59
AAO Al (%)	0.32	0.19	0.03

Table 4: Variables Found to be Significantly Different between the Three Land Uses Using the t and U Test ($P < 0.05$)

	Rain-fed Agriculture	Irrigated Agriculture
Forested	C, P, Ca, Mg, BS, N Fe(CBD), Al(CBD), pH, Al(AAO)	C, P, Ca, Mg, BS, N, Fe (CBD), pH, Fe(AAO), Al(AAO)
Rain-fed Agriculture		P, N, Al(CBD), Fe(AAO), Al(AAO),pH

To assess nutrient input from irrigation, water sampled from the nearby spring and stream during the dry season of 1990 was analysed (Table 5). The water is alkaline and contains moderate quantities of Ca, Mg, and PO_4; it also contains some Na, K, and nitrate. Non-irrigated fields receive several times more organic matter and chemical fertiliser than irrigated fields (Riley 1991), and this results in significantly greater organic carbon (P + 0.10) and total nitrogen (P + 0.05) in the soils of rain-fed systems. Overall, the nutrient status is best on irrigated land (Shah et al. 1991). Nutrient addition through irrigation water, possibly supplemented by nitrogen enrichment through blue-green algal fixation (Sanchez 1976), and reducing conditions, with slow organic matter decomposition, are thought to be the main reasons for the differences. Also, the rice grown by irrigation seems to be less nutrient demanding than maize or wheat.

Table 5: Chemical Composition of Irrigation Waters, April 27, 1990

	Spring	Stream
Ca (mg/l)	20.1	20.0
K (mg/l)	1.9	1.8
Mg (mg/l)	3.3	1.4
Na (mg/l)	9.8	9.6
NO_3(mg/l)	1.7	1.9
PO_4(mg/l)	0.25	0.26
pH	8.2	8.7

Nutrient losses by harvesting and erosion are significant in the middle mountains. The forested and rain-fed sites are clearly affected by erosion. Runoff losses from irrigated fields are smaller than from rain-fed sites, and this might contribute to the differences in nutrient conditions between the two agricultural uses.

Detailed Soil Fertility Survey

The soil fertility survey included the sampling and analysis of 200 sites with special reference to red versus non-red soils, north versus south-facing slopes, high elevation versus low elevation sites, and irrigated versus non-irrigated agriculture and grazing. The 2 x 2 x 2 x 3 factorial survey was carried out in the middle section of the watershed and the analysis of the soil samples was completed by June 1994. An overall summary table of mean values per factorial combination is provided in Table 6. It is apparent that low elevation sites are clearly enriched, except in the case of north-facing red soil sites which show no difference between elevations. Irrigated fields were generally found to have more cations and base saturation than their non-irrigated counterparts and grazing lands. Grazing lands are generally lowest in cations P and pH. The explanation for this is that the soil fertility of dryland agricultural fields is declining, whereas the irrigated fields, which receive more fertilisers, water, and sediments, are being enriched. A more comprehensive statistical analysis of the data is underway.

Rates of Soil Fertility Decline

These data do not allow us to determine the exact rate of soil fertility decline because: (1) we do not know the initial soil fertility of the agricultural and forestry sites at the time the forest was established; and (2) we do not know the actual inputs and outputs of each land-use system without monitoring nutrient cycling over several years. However, we believe that the differences in nutrient status are induced by land-use management, leading to poor overall soil fertility conditions even in those fields receiving the largest inputs. This is particularly true for N, P cations and pH, all of which are in the low to deficient range in the case of most of the basic crops grown in the area (Landon 1984; Sherchan et al. 1991).

Extrapolation of Results to Adjacent Areas

Comparison of the soil survey data with our results (Table 7) shows that the differences between rain-fed and forested sites are similar, though the organic carbon content is not significantly different between these two land uses. No comparison can be made between irrigated and non-irrigated uses, because irrigation of red soils is rare and no data were available for the test area.

A fuller comparison is possible between our data and those from the surveys by Schmidt (1992) and Wymann (1991), both of which included many forested, irrigated, and rain-fed agricultural sites. The differences between and uses shown in Table 7 are not as pronounced in the Dhulikhel watershed survey because of additional variability introduced by differences in parent material, topography, and micro-climate. Nevertheless, the soils of irrigated fields are less acidic than under rain-fed agriculture or forests, and exchangeable Ca and available P are found least in forested sites. The organic carbon and nitrogen trends are less consistent, carbon being most abundant under rain-fed agriculture and nitrogen under forests. These comparisons suggest that the conclusions from the test site are representative of most conditions in the middle mountain region east of Kathmandu and confirm that the long-term soil productive capacity is not being sustained.

It is also significant that soil nutrients are in the low to deficient range for almost all the major crops (wheat, maize, mustard, rice) grown in the rotations on the study site. The conditions are adequate only for millet, which has especially small nutrient requirements. We suggest that in the absence of sufficient fertilisers, incorporation of green manures into the soil or the addition of nitrogen-fixing crops in the rotation system, are the only effective ways of limiting further deterioration.

Table 6: Summary of Nutrient Analysis for the Detailed Survey of 200 Sites

South facing slopes/red soils

Land use	ph	p ppm	C %	CEC cmol +/kg	K cmol +/kg	Mg cmol +/kg	Ca cmol +/kg	Base Sat %	
Khet	5.5	6.8	1	14.4	0.27	2.94	5.49	61.6	Low elevation
Bari	5.1	8.5	1.1	13.1	0.33	2.18	4.23	51.7	below 1200
Grass	4.9	8.5	1.7	15.6	0.35	1.71	4.33	39.7	
Khet	No khet fields on red soils								High elevation
Bari	4.8	9.8	1.1	12.5	0.3	1.77	3.14	40.1	Above 1200
Grass	4.6	4.7	1	11.4	0.21	1.35	2.15	32.5	

North facing slopes/red soils

Land use	ph	P ppm	C %	CEC cmol +/kg	K cmol +/kg	Mg cmol +/kg	Ca cmol +/kg	Base Sat %	
Khet	5.2	10.3	0.8	12	0.28	1.09	5.74	60.3	Low elevation
Bari	4.8	13.8	0.9	13.9	0.58	1.59	3.96	44.7	below 1200
Grass	4.7	4.5	0.5	12.3	0.38	1.81	2.76	40.1	
Khet	No khet fields on red soilsh								High elevation
Bari	4.7	21.5	0.9	12.3	0.59	1.52	3.55	49.3	Above 1200
Grass	No grazing land on red soils								

South facing slopes/non-red soils

Land use	ph	P ppm	C %	CEC cmol +/kg	K cmol +/kg	Mg cmol +/kg	Ca cmol +/kg	Base Sat %	
Khet	5.3	22.5	1.1	9.8	0.14	2.06	4.91	70.7	Low elevation
Bari	5	21.4	1.2	8.7	0.24	1.45	3.74	63.2	below 1200
Grass	4.6	10.3	1.1	7	0.14	0.83	1.68	43.1	
Khet	No khet fields on non-red								High elevation
Bari	4.7	19	0.9	6.5	0.15	0.88	2.71	58.7	Above 1200
Grass	4.7	8.1	1	6.5	0.17	0.87	1.65	41.1	

North facing slopes/non-red soils

Land use	ph	P ppm	C %	CEC cmol +/kg	K cmol +/kg	Mg cmol +/kg	Ca cmol +/kg	Base Sat %	
Khet	5	39	0.8	9.6	0.29	0.79	5.48	59.4	Low elevation
Bari	4.7	18.8	0.8	8.6	0.23	1.18	3.56	58.6	below 1200
Grass	4.6	9.9	1	9.9	0.23	1.14	4.25	59.1	
Khet	4.8	29.6	0.9	10	0.23	0.73	4.83	59.8	High elevation
Bari	4.8	50	1	9.1	0.39	1.19	3.56	76.5	Above 1200
Grass	4.6	10.3	1.4	11.8	0.19	0.81	2.85	37.2	

Table 7: **Comparison of Soil Fertility Conditions between Agriculture and Forestry from Soil and Land Use Surveys in the Jhikhu Khola Watershed**

Land Use	Source	No. of Samples	pH	C g/kg	N g/kg	Ca cmol/kg	Mg cmol/kg	K cmol/kg	P mg/kg
Rain-fed	(1)	7	4.8	6.9	0.68	2.15	1.31	0.27	2
Forested	(1)	5	4.6	6.6	0.54	1.54	1.08	0.30	0.6
Rain-fed	(2)	60	4.3	7	0.70	2.16	0.69	0.14	22.3
Irrigated	(2)	37	4.8	5.4	0.58	3.46	0.44	0.18	21.1
Forested	(3)	136	4.3	6.0	0.90	1.80	0.65	0.28	3.5

(1) Shah and Shreier (1991), Soil survey data
(2) Wymann (1991), Agricultural land use survey
(3) Schmidt (1992), Forestry survey data

Conclusions

The increasing demands for food, animal feed, and fuelwood by the expanding hill population in the middle mountains of Nepal have resulted in a serious depletion of soil nutrients in both agriculture and forestry systems.

The overall soil fertility conditions on the test site are generally poor under all three land uses (rain-fed, irrigated, and forested). Soil carbon, nitrogen, and available phosphorus are particularly depleted, and the soils are acidic and have low base saturation.

As the soils have a common origin and were probably similar in nutrient composition originally, the different surface soil conditions result from the dominant land use practices over the past 17 years. Because of massive litter removal and no inputs, the soils of the forested sites have the least, N, P exchangeable bases and pH values. The rain-fed sites have the most C and N because they receive the largest amount of organic matter. The irrigated sites have the most P, Ca, and Mg, because of enrichment of irrigation water and suspended sediments.

The rate of soil fertility depletion can only be estimated when the original soil fertility status is known. However, it was found that, because of nutrient removal by litter collection and crop harvesting, N and P are being strongly depleted.

When compared with other subsets of survey data collected within the 11,000ha watershed, it is evident that the results are representative of the entire area, suggesting that declining soil fertility is a widespread problem.

Fundamental changes in management are needed to sustain soil nutrients and biomass in the long run. This will require a decrease in biomass removal and additional inputs such as incorporation of green manure into the crop rotation. A short-term option is to plant nitrogen-fixing trees and to introduce nitrogen-fixing arable crops into the annual rotation. Without additional nutrient input, further decreases in biomass production are inevitable.

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