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Soil-sediment nutrient transport dynamics in a Himalayan watershed

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Abstract Nutrient dynamics in the Bela watershed, Nepal were examined using a range of GIS budget modelling and field analysis techniques. The fertility status analysis showed that soil acidity, phosphorus availability, and lack of base cations were the key soil fertility issues. Nutrient budget calculations revealed significant annual phosphorus deficits for maize rotations, but only minor deficits in rice rotations. The effect of biophysical conditions and management inputs were analysed and the link between poor soil fertility, annual deficits, soil erosion and degradation was made. The erosion and sediment transport rates from degraded sites (rilled and gullied, with $<25\%$ vegetation cover), were found to be twice those from non-irrigated agricultural sites. The nutrient content in these sediments was very low and of little benefit to farmers who re-capture sediments in their irrigated fields. In contrast, re-deposition of sediments from non-irrigated agriculture was found to enrich irrigated fields significantly. Rehabilitation of degraded areas is needed to prevent negative effects downstream.

INTRODUCTION

Phosphorus (P) problems in agriculture are rapidly emerging as major environmental and production issues (Caraco, 1995; Edwards *et al.*, 1997). In intensive agriculture, phosphorus surplus applications are leading to widespread eutrophication in streams and lakes (Sharpley *et al.*, 1994; Edwards & Withers, 1998). At the same time, soil degradation and insufficient inputs in marginal agriculture are leading to widespread P deficiencies and low productivity (Brown *et al.*, 1999). Phosphorus deficiencies are widespread in the Middle Mountains of the Himalayas, because the bedrock is generally low in P and the acidic nature of the bedrock (sandstone, siltstone, quartzite, schist) limits P availability to plants. This is made worse by the commonly available fertilizers (ammonium sulphate and urea), which acidify soils and thus further reduce the plant available P. Gaining a better understanding of the soil P dynamics is critical in determining the long-term sustainability of the land-use systems (Sharpley & Halvorson, 1994) and requires research into nutrient balances. Understanding the soil–sediment–water interactions (House *et al.*, 1998) is the main goal of this paper and the objectives are to document the P status of the soils under different biophysical and management conditions, and determine the rates of change in P movement in erosion and sedimentation processes in a watershed.

The research was conducted in the Bela catchment, a 1930 ha sub-watershed of the Jhikhu Khola basin, located 40 km east of Kathmandu, Nepal. Over the past 17 years, agriculture has expanded to marginal land at a rate of 5%, and agricultural intensification has increased from an average of 1.8 annual crop rotations to 2.6 (Schreier *et al.*, 1995; Brown, 1997). Sustaining soil fertility in both intensive and marginal agriculture is critical if we hope to sustain productivity, but nutrient inputs in the Himalayas are usually insufficient and erosion rates are high.

METHODS AND TECHNIQUES

The key factors that affect soil development in Nepal include climate, topography, parent material, length of weathering processes and management practices. A GIS approach was used to design the sampling programme so that the effect of these factors could be isolated. The watershed was divided into two elevation classes (800–1200 m and > 1200 m), two aspect classes (dominantly north *vs* south facing), two soil types (red *vs* non-red, which reflect different length of weathering and source rock: phyllite and metamorphosed schist *vs* Si-rich rocks such as quartzite, sandstone, and siltstone; see Schreier & Shah, 1995), and four land-use classes. The four land-use categories were irrigated and non-irrigated agriculture, rangeland and forests. These were differentiated as they reflect very different inputs and management practices. The owners and users of each site where samples were collected were interviewed to obtain input, production and management information. The 1200 m elevation classes break was chosen because it reflects a natural vegetation change between indigenous Sal dominated forests (*Shorea robusta*) and Chir Pine dominated forests (*Pinus roxburghii*).

The GIS (MapInfo) enabled us to stratify the watershed into a 2 × 2 × 2 × 4 factorial classification, which resulted in 32 unique factor polygons. Since forests are limited to a few selected areas, irrigation is feasible only in lower elevations, and red soils are also restricted to lower elevations, only 22 of the possible 32 combinations were observed. For each of the 22 combinations, 10 samples were selected randomly to characterize soil conditions in the watershed. The analysis of variance (Anova) and Mann-Whitney U test were used to determine the effect and contribution of each factor to the overall variability.

Well-mixed bulk soil samples were collected from 220 field, grass and forest sites. The 0–15 cm soil depth layer was analysed for pH, exchangeable P (Bray-1 method), CEC and base saturation using standard methods (Page *et al.*, 1982). GIS-based soil fertility maps were produced by combining factor maps and soil chemical data. The mean of each factor type was used to determine the soil fertility status and a nutrient budget model described by Brown (1997) and Brown *et al.* (1999) was used to determine the extent of nutrient deficiency for the common crops in the watershed.

Soil erosion was measured in five agricultural field plots from 1992 to 1998 and in two plots on degraded sites from 1997 to 1998. The plots are 85–100 m^2 in size and the runoff and soil loss was collected in storage containers located below each plot after every major storm. Annually an average of 20+ storms produced runoff with measurable sediments. Samples of the eroded soils, as well as sediments accumulated on 22 rice fields during the monsoon season, were analysed for nutrient content. Nutrient characteristics of freshly accumulated sediments in the rice fields were compared with the underlying soils, which formed the nutrient pool for the monsoon crop.

Two sediment sampling stations in two sub-watersheds were used to compare different sediment loads from a well managed and a degraded sub-watershed of similar size. A sediment-rating curve was established for the Andheri (570 ha) and Dhap Khola (539 ha) sub-watersheds for both the pre-monsoon and the monsoon seasons. In addition, analysing the Bray extractable P in the different sediment samples allowed the linkages to be made between soil fertility decline, erosion, sediment transport and deposition.

RESULTS

Soil fertility status

Soil fertility characteristics are listed in Table 1 and the results show that soil acidity, Bray extractable phosphorus and base saturation are at very low levels for agricultural production. Elevation, aspect and soil type all have significant effects on soil conditions with forested sites showing the lowest nutrient content followed by grassland and non-irrigated agriculture. Only irrigated fields showed values that are considered moderately adequate for crop production.

Differences between the 22 combinations of factors were determined using the Mann-Whitney U test and the analysis of variance. The mean values were then assigned to each factor combination class and these were then grouped into low, medium and high pH, extractable P and base saturation maps. Using the GIS overlay technique a combined pH-extractable P-base saturation map was produced. The results showed that 39% of the watershed fell into the low fertility class (low in all three variables) and only 13% of the watershed has conditions considered adequate for agriculture for all three variables.

Table 1 Soil fertility status stratified by soil factors (average class values).

	Elevation:		Aspect:		Soil type:		Land use:			
	< 1200 m	≥1200 m	North	South	Red	Non-red	Irrigated	Non- irrigated	Range	Forest
pH	4.9	4.7	4.8	4.9	4.9	4.8	5.2	4.8	4.7	4.3
CEC (cmol kg^{-1})	11.2	10.1	11.0	10.6	13.0	8.9	11.2	10.7	10.6	9.3
Exch. Ca (cmol kg^{-1})	4.18	3.10	4.09	3.40	3.97	3.56	5.29	3.60	2.82	1.15
Exch. Mg (cmol kg^{-1})	1.56	1.14	1.19	1.60	1.77	1.09	1.52	1.47	1.22	0.32
Exch. K (cmol kg^{-1})	0.28	0.28	0.33	0.23	0.37	0.21	0.23	0.35	0.24	0.63
Base saturation (%)	55.1	46.7	53.2	50.2	46.8	55.8	63.9	52.6	42.0	22.1
Carbon (%)	0.98	1.02	0.88	1.11	0.99	1.00	0.89	0.98	1.09	0.57
Avail. P (mg kg^{-1})	14.5	19.6	20.9	12.2	9.8	22.1	21.6	20.6	8.3	0.7

Soil phosphorus deficits and surpluses

The nutrient status of 114 agricultural fields was evaluated with a nutrient budget model described by Brown (1997) and Brown *et al.* (1999). Phosphorus surplus/deficit calculations made for maize and rice production are provided in Table 2. Significant P deficits were observed in maize production systems, where low inputs and high losses by erosion resulted in annual median deficit values of between 34 and 98 kg ha^{-1} year^{-1} per 15 cm soil depth. Factors such as slope, aspect, elevation and soil type have a significant impact on biomass productivity and consequently annual P deficits. Sites with higher elevation, southern exposure and red soils showed the greatest deficits. Approximately 50% of all agricultural fields were P deficient (>35 kg ha^{-1} year^{-1} per 15 cm soil depth). These sites were mostly on non-irrigated upper elevation sites where inputs were limited and erosion was more acute.

Table 2 Annual phosphorus deficits in maize and rice cropping systems depending on site factor conditions (average values).

Factors		Maize: no. farms	P deficit	Rice: no. farms	P deficits/surplus
Aspect	north	35	-48	30	-3
	south	30	$98^{\dagger}$	19	-16*
Elevation	< 1200 m	31	-41	39	-14
	≥1200 m	34	$-89^{\dagger}$	10	+5*
Soil type	red	30	-78	20	
	non-red	35	-34*	29	

$^*p = 0.1$; $^{\dagger}p = 0.05$ significance level, based on Mann-Whitney U Test between pairs.
Units: kg ha^{-1} year^{-1} per 15 cm soil depth.

Soil erosion

Agricultural erosion is of concern in non-irrigated areas with significant slopes. The results of the 7-year erosion plot study showed very large spatial and seasonal variations. Agricultural plots with similar slopes but highly different infiltration rates yielded annual erosion rates between 1 and 38 t ha^{-1} year^{-1}. Typical agricultural fields averaged 18–20 t ha^{-1} year^{-1} of soil loss with an average extractable P content of 17.8 mg kg^{-1} (range: 5.2–28.4 mg kg^{-1}). Two plots on degraded sites (gullied and rilled with less than 10% vegetation cover) were added to the monitoring programme in 1997, and the rates from the first year of monitoring were twice those from non-irrigated agricultural fields. The extractable P content in these degraded sites averaged 6.7 mg kg^{-1}, reflecting the degraded state of these sites. About 60–80% of the annual erosion occurred during two of the major storm events during the pre-monsoon season when vegetation cover was at a minimum.

Extractable P content in sediments in streams and irrigated fields

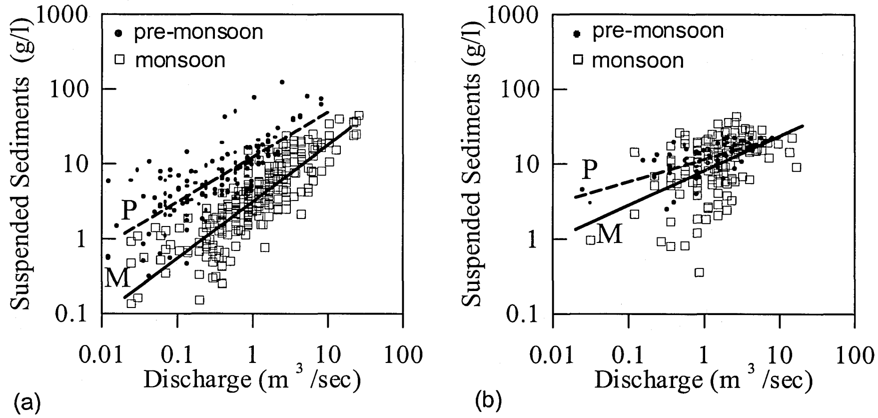
Sediments accumulated over the monsoon season in 22 irrigated rice fields showed an average extractable P content of 33.2 mg kg^{-1}. This was significantly higher than the 14.3 mg kg^{-1} of extractable P in the soils collected at the end of the rice-growing season, suggesting a significant P enrichment by sediment that is re-deposited (Schreier *et al.*, 1998). However, the source of the sediment is critical because, as shown in the erosion plot data, the extractable P content of eroded soils from agricultural fields had twice the extractable P content of the eroded material from the degraded sites. A comparison of the extractable P values in the different sediments is provided in Table 3.

The effect of degraded areas on sediment transport and quality was compared between sub-watersheds of similar size. The sediment rating curves and the extractable P content in the sediments were compared between the Andheri and the Dhap Khola sub-watersheds. The former contained 15% and the latter 24% degraded land. Suspended sediment rating curves were determined at hydrometric stations at the outlet of each watershed using hydrometric and suspended sediment data collected over two years (Carver, 1997). The data from each watershed were divided into monsoon and pre-monsoon periods (Fig. 1). The pre-monsoon season produced significantly higher suspended sediment concentrations during low streamflow than during the monsoon period. This is attributed to a lack of vegetation cover during the dry season and was corroborated by the erosion plot study (Schreier *et al.*, 1995). What is more important is that the rating curve from Dhap Khola is significantly different from that of the Andheri Khola for both seasons with higher sediment values from the watershed with more degraded areas and this despite the fact that the Dhap sub-watershed has a lower elevation range than the Andheri sub-watershed. Similarly, the average extractable P content in the suspended sediments (Table 3) was lower in the degraded watershed (8.8 mg kg^{-1}) than in the less degraded sub-watershed (15.6 mg kg^{-1}).

The data show that a link between soil fertility, erosion, landscape degradation, and sediment transport can be made by combining field measurements with GIS and

Table 3 Phosphorus content in different soils and sediments.

Source	Average P content (mg kg^{-1})	Number of samples
Eroded soils from erosion plots (non-irrigated agriculture)	17.8	75
Eroded soils from erosion plots (degraded sites)	6.7	8
Soil P content in agricultural fields	16.6	114
Sediments accumulated in rice fields (end of monsoon season)	33.2	22
Soil P content in rice fields below accumulated sediments	14.3	22
Stream suspended sediments, Andheri Khola (570 ha watershed, 15% degraded)	15.6	57
Stream suspended sediments, Dhap Khola (530 ha watershed, 24% degraded)	8.8	46



15% degraded, 570 ha size
pre-monsoon: n = 150, $r^2 = 0.59$
monsoon: n = 243, $r^2 = 0.74$

24% degraded, 530 ha size
pre-monsoon: n = 62, $r^2 = 0.30$
monsoon: n = 128, $r^2 = 0.42$

Fig. 1 Suspended sediment rating curves for (a) Andheri Khola and (b) Dhap Khola watersheds.

budget modelling techniques. The results also suggest that rehabilitation of degraded watersheds is very important because sediment transport rates increase with amount of degraded areas in the watershed. This is of little benefit to irrigation systems downstream, because it clogs the system and the extractable P content in the suspended sediment is low and of little benefit to irrigated fields. It should also be mentioned that the soil fertility–degradation–erosion–sediment transport cycles are likely restricted to micro-scale watersheds where the human impacts can be isolated. At the meso- to macro-scale of watershed, these relationships become very difficult to isolate, because cumulative effects and compounding factors influence the processes of distribution and re-deposition of sediments and nutrients.

CONCLUSIONS

The status and dynamics of soil fertility can effectively be analysed using a combination of GIS, nutrient budget modelling, and process-based field studies. The research showed that the nutrient status in a Nepal watershed was poor and the majority of non-irrigated agricultural fields had nutrient budgets that showed large phosphorus deficits ranging between 34 and 98 kg ha^{1} year^{-1} per 15 cm soil depth. Erosion rates from agricultural fields were substantial, averaging 18–20 t ha^{-1} year^{-1}, but sediment re-deposition in irrigated fields was beneficial because it enriched these sites with extractable P. Land degradation and accelerated erosion played a significant role in P cycling. Based on erosion plot data and suspended sediment analysis of two sub-watersheds of similar size, it was shown that erosion and transportation rates from degraded sites were substantially higher than from agriculture and less degraded watersheds. At the same time, the extractable P in the sediments was significantly lower from degraded sites and had little nutrient value if recaptured in lowland irrigation. Insufficient nutrient input into non-irrigated agriculture on steep slopes was likely responsible for long-term productivity decline and increased soil degradation. Nutrient balances in agriculture need to be maintained, but at the same time degraded sites, which are depleted of nutrients, need to be rehabilitated because they have negative impacts on sediment loads, create management problems in lowland irrigation systems and contribute little to the nutrient pool, if a portion of the sediments is re-captured in irrigated fields downstream.

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