Maintaining Soil Fertility in Agriculture and Forestry

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1. INTRODUCTION

The theme for the 1991 Jhikhu Khola watershed workshop (Shah et al., 1991) was "Soil Erosion and Fertility Issues in the Middle Mountains of Nepal." It was during this meeting that we became convinced that soil fertility is one of the key issues regulating future biomass production in Nepal for both agriculture and forestry. This was reinforced by Carson (1992) in his publication "The Land, the Farmer, and the Future." Despite the efforts at the agricultural research stations at Lumle and Pakribas, soil fertility has not been a priority issue in the national Agriculture and Forestry Departments. It was not until the 1995 status paper by the National Agricultural Research Council (NARC, 1995) presented to the Donors' Consortium Meeting that soil fertility became a major priority at the national level.

We identified three processes that lead to widespread soil fertility problems in the Middle Mountains of Nepal and these include: agricultural intensification, conversion of marginal lands into agriculture, and intensive use of the forests for feed, fuelwood and litter collection. The latter practice is becoming a major source of nutrient input into agriculture.

Agricultural intensification is particularly evident in the cultivated areas at the bottom of the watershed, where the introduction of short growing-season crop varieties and irrigation enabled the farmers to move from a single annual crop rotation system to triple crop rotations. In 1980, Hagen (1980) estimated 1.3 crops/year, Panth and Gautam (1987) indicated 1.6 crops/year and Riley (1991) reported averages of 2.0-2.5 crops/year. From the socio-economic surveys conducted in the Jhikhu Khola watershed (Kennedy and Dunlop, 1989; Wymann, 1991) an average figure of 2.7 crops/year was obtained in irrigated fields and 2.5 crops/year in dryland agriculture. These increases are a direct result of increasing demands for food and feed, resulting from a population growth rate which ranges between 2.7 and 3.0% per year. In spite of this intensification, there is mounting evidence that crop yields are declining (Chitrakar, 1990; Shakya et al., 1991; Sherchan and Gurung 1995; Panday et al., 1995) and soil fertility decline has been suggested as one of the main causes of reduced biomass performance by Riley (1991) and Carson (1992). Given the poor infrastructure, the unreliability of external nutrients supplies and accessability problems, we must question the sustainability of the intensive cultivation systems practiced in the watershed. With limited inputs it is not only difficult to maintain the nutrient status in the soils but soil structure, carbon content and the physical behaviour of the soils are also adversely affected.

The second issue of concern is the increasing use of marginal lands for agriculture. As shown by Schreier et al. (1994) and Shrestha and Brown (1995), up to 39% of the agricultural expansion has occurred on slopes greater than 35%. Due to land shortages and insufficient water supplies for irrigation, the poor farmers convert forest and shrub land into agricultural lands. These land conversions occur on steep slopes, where the soils are more susceptible to erosion and where the maintenance of soil fertility is even more difficult because access is more limited and the poor farmers that tend to initiate such conversions have insufficient purchasing capacity for fertilizers and other chemicals.

Forest soil fertility is also declining due to intensive fodder and fuelwood consumption and the increasing practice of collecting litter material and fodder from the forest floor. This practice is most evident during the dry season when fodder is in short supply. Forest litter is used as animal bedding and fodder, and once mixed with manure and incorporated into the agricultural system, provides a substantial nutrient input into agriculture. Given the intensity of fodder collection and litter removal, it is apparent that large amount of nutrients are removed from the forest. Since nothing is returned or recycled the only new supply of nutrients in the forest is from weathering of the bedrock. Given that many soils are deeply weathered and the dominant bedrock is inherently poor in nutrients (sandstones, siltstone, quartzite, phyllite, schist), soil nutrients in the forests are expected to decline under current forest management practices. The problem is more acute in the forest because soil erosion generally increases with slope, changes in vegetation cover, reduction in litter cover, and changes in soil structure.

The aims of this paper are to:

1. provide a status report of soil nutrients under different land uses (dryland and irrigated agriculture, grazing land and forests);
2. identify those factors that have the greatest influence on soil fertility;
3. indicate the rates of soil fertility decline; and
4. show how the cycling of nutrients can be improved.

2. STUDY SITES AND METHODS

Five different soil fertility surveys were carried out over a span of five years and they include:

a) A survey of forestry and agricultural land in the Dhulikhel watershed, in the headwater region of the Jhikhu Khola. This study included 136 forestry and shrub sites and 120 agricultural sites.
b) A general soil survey was carried out in 1990 (Maharjan, 1991) and covered the entire watershed. Samples from 350 soil pits were analyzed for basic nutrients during this survey.
c) A detailed survey of agricultural and grazing land was carried out in 1993/94 in the Bela-Bhimsenthan test area. A stratified sampling design was used to isolate slope, aspect, elevation, soil type and land use effects. Two hundred sites in irrigated and dryland agricultural fields and grazing lands were selected for this purpose.
d) A detailed comparison was made to determine the influence of land use practices on soil fertility at a site where soil type, climate and topography were held constant. Ten samples were collected in the forests, and adjacent irrigated and dryland agriculture fields.
e) A detailed forest soil fertility survey was carried out in 12 forest plots in 1989. These were selected for long term monitoring and included a detailed biomass survey of 20x20 m plots, as well as soil and foliar nutrient determinations.

Samples collected during the general soil survey (b) consisted of genetic horizons and only the first two were analyzed for nutrient content. For all other surveys, the surface layer (0-15 cm depth) was used for the analysis. Nutrients examined included % carbon (Leco), pH (in $CaCl_2$), cation exchange capacity and exchangeable cations (CEC, Ca, Mg, K, Na, in cmol/kg with ammonium acetate extraction method), % base saturation, and available phosphorus (mg/kg^{-1}, with the Bray method). All chemical analysis was carried out in the Soil Science laboratory at the University of British Columbia.

3. RESULTS

3.1. Overall Soil Fertility Status

The samples from the survey in the Dhulikhel sub-watershed (a, 1270 ha) were compared with those from the Bela-Bhimsenthan sub-watershed test area (c, 1927 ha) and the overall Soil Survey for the entire watershed (b, 11,141 ha). The Dhulikhel sub-watershed is located in the headwaters of the Jhikhu Khola watershed and was described in detail by Schmidt (1993), Schmidt et al., (1994) and Wymann (1993). The results of the three surveys are provided in Table 1 and show that the overall soil conditions are generally very poor for both agriculture and forestry. The soil acidity is at least one pH unit below optimum and the carbon, phosphorus, cation content and base saturation are very low. Only exchangeable K appears to be in adequate supply. The Bela-Bhimsenthan survey has slightly higher values because the focus was on agricultural soils while the Dhulikhel survey focused on a comparison between forests and agriculture. The soil survey included all types of land uses and thus gives a better overall representation of the conditions.

Soil acidity and available phosphorus are of major concern and will be addressed in two papers of this proceedings. The low cation exchange capacity is the result of inherited bedrock conditions (sandstone, siltstone, quartzite), and extensive weathering leaving kaolinite as the dominant clay minerals in these soils. Historic losses of organic matter due to soil erosion, crop removal and litter collection are another cause for the low exchange capacity of the soils.

Table 1. Comparison of three soil fertility surveys in the Jhikhu Khola watershed.

Variables (mean values)	Dhulikhel Survey (1,270 ha, n = 256)	Bela-Bhimsenthan (1,927 ha, n = 200)	Overall Soil Survey (11,141 ha, n =225)
pH ($CaCl_2$)	4.4	4.8	4.6
CEC (cmol/kg)	10.5	10.8	10.4
exch. Ca (cmol/kg)	2.18	3.75	2.58
exch. Mg (cmol/kg)	0.61	1.39	0.99
exch. K (cmol/kg)	0.27	0.28	0.29
Base Satur. (%)	30.9	51.7	39
avail. P (mg/kg)	11.6	16.5	2.1
Carbon (%)	0.68	1.01	1.01

3.2. Factors Influencing Soil Fertility

From the analysis of these surveys it became evident that a number of factors have contributed to the poor state of soil fertility in the Middle Mountains. They include factors of soil formation such as topography, parent material, climate, time, land use, and management. Since there is little historic information on soil conditions, it is difficult to isolate which factors are most important but the human influence must be considered to be a primary factor. The Bela-Bhimsenthan survey was carried out in 1993/94 to isolate some of the key factors that affect soil fertility. The survey included 200 sites with 10 sites each in three land use classes, two soil type, two aspect and two elevation categories. As shown in Table 2, only 20 of the 24 possible combinations could be sampled because the red soils, which are the oldest soils in Nepal, have only a limited distribution at elevations above 1200 m in the Jhikhu Khola watershed.

Table 2. Sampling design for detailed nutrient analysis.

# of Sites	Land Use	Soil Type	Aspect	Elevation
10 each	Bari, Khet, Grazing Land	Red Soils	South	< 1200 m
10 each	Bari, Khet, Grazing Land	Red Soils	North	< 1200 m
10 each	Bari	Red Soils	North	> 1200 m
10 each	Bari, Grazing Land	Red Soils	South	> 1200 m
10 each	Bari, Khet, Grazing Land	Non-Red Soils	North	< 1200 m
10 each	Bari, Khet, Grazing Land	Non-Red Soils	South	< 1200 m
10 each	Bari, Grazing Land	Non-Red Soils	South	> 1200 m
10 each	Bari, Khet, Grazing Land	Non-Red Soils	North	> 1200 m

* Bari = Dryland Agriculture, Khet = Irrigated Agriculture

The data set was analyzed using analysis of variance, T-test, and Mann-Whitney U-test. The results, provided in Table 3, indicate that overall, the soil type (red vs. non red) was most important followed by land use, and aspect. Different soil variables are influenced in different ways. For example phosphorus appears to be influence by all factors, while carbon can only be differentiated by aspect and CEC by soil type. Fortunately, factor interactions were minimal and only in the case of elevation/aspect is the validity of the analysis of variance questionable.

Table 3. Significant factors that influence soil development and soil fertility (based on analysis of variance).

Variables	Aspect	Elevation	Soil Type	Land Use
pH		2	3	1
P (mg/kg)	3	4	1	2
C (%)	1			
CEC (cmol/kg)			1	
Exch. K (cmol/kg	2		1	3
Exch. Mg (cmol/kg)	2		1	
Exch. Ca (cmol/kg)	3	2		1
Base Saturation (%)			1	2

* 1-4 = F-Values (in decreasing order of significance, cells with no number are not significant at P = 0.01)

3.2.1. ASPECT AND ELEVATION

Only pH and Ca show a consistent pattern between elevation/aspect and soil chemistry. As shown in Figure 1, the pH is about 0.3 units lower in the upper elevations on the south facing slopes and 0.15 pH units lower in the upper elevation north facing slopes.

About 95% of all upper elevation sites ranged between pH ($CaCl_2$) 4.6-4.8, while 95% of all sites below 1200 m elevation ranged between 4.7-5.2. Similarly exchangeable Ca is 1.5 cmol/kg higher at the lower elevations on south facing slopes and 0.5 cmol/kg higher at low elevations on north facing slopes. More leaching and erosion losses in the upper elevations leads to the removal of bases and hence increases soil acidity and exchangeable Ca at lower elevations. The differences on the south facing slopes are significantly higher and are attributed to the greater diurnal temperature fluctuations that occur on the south facing slopes.

Although the cation exchange capacity (CEC) is significantly lower on the south-facing, higher elevations than at lower elevations, this pattern was not observed on the north facing slopes and it is concluded that these differences are not due to the elevation/aspect component but rather due to differences in parent materials. Sandstone and siltstone are the dominant bedrock at the south facing sites above 1200 m elevation. The coarse textured soils have much higher infiltration rates and, as shown by Carver et al. (1995), the differences have resulted in significantly lower soil surface erosion on dryland agricultural lands. The presence of sandstones is significantly less at all other sites, with phyllites and quartzites being more dominant. The available phosphorus values were significantly higher in the upper elevations on the north slopes, and this is in part due to differences in parent material and land use and not considered the result of aspect or elevation.

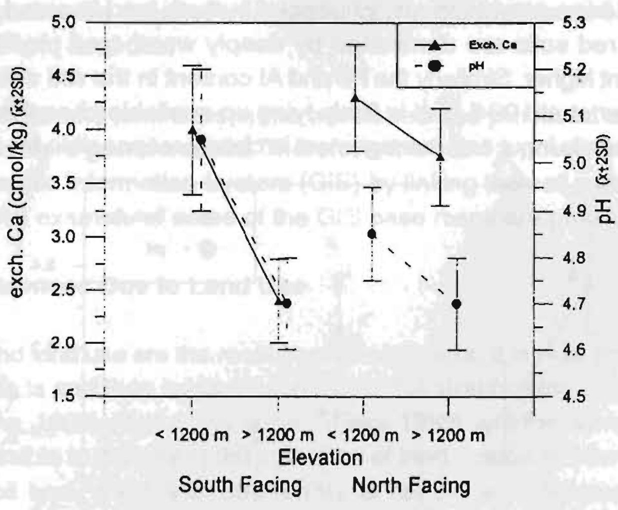

Figure 1. The impact of elevation and aspect on soil pH and exchangeable Ca.

3.2.2. LAND USE AND PARENT MATERIALS

Using the same data set, the influence of land use and soil type on soil chemistry was also examined. Differences between irrigated and non-irrigated sites and grazing lands were determine separately in red and non-red soils. As can be seen in Figure 2, CEC and exchangeable Mg values are clearly dominated by parent material. In both cases there is no difference between land use but consistent differences between soil type or parent materials.

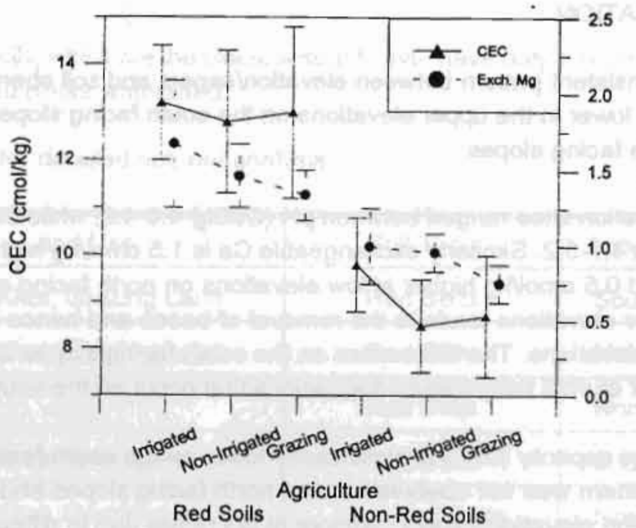

Figure 2. Differences in CEC and exchangeable Mg due to parent materials.

In contrast, land use is clearly the most dominant factor in influencing pH and exchangeable Ca (Figure 3). There are significant differences between irrigated agriculture land (khet), non irrigated agriculture land (bari) and grazing land in both red and non-red soils. The khet lands had the highest pH, Ca, and base saturation values followed by dryland agriculture and grazing land.

Available P, exchangeable K, and base saturation are influenced by both land use and parent material as can be seen in Figure 4. Since the red soils are dominated by deeply weathered phyllites, base saturation is expected to be lower and K content higher. Similarly the Fe and Al content in the red soils is significantly higher than in the non-red soils (Schreier et al 1994) and is likely tying up available phosphorus, hence the lower P content in these soils. The difference in input and management is clearly responsible for the variations between land uses.

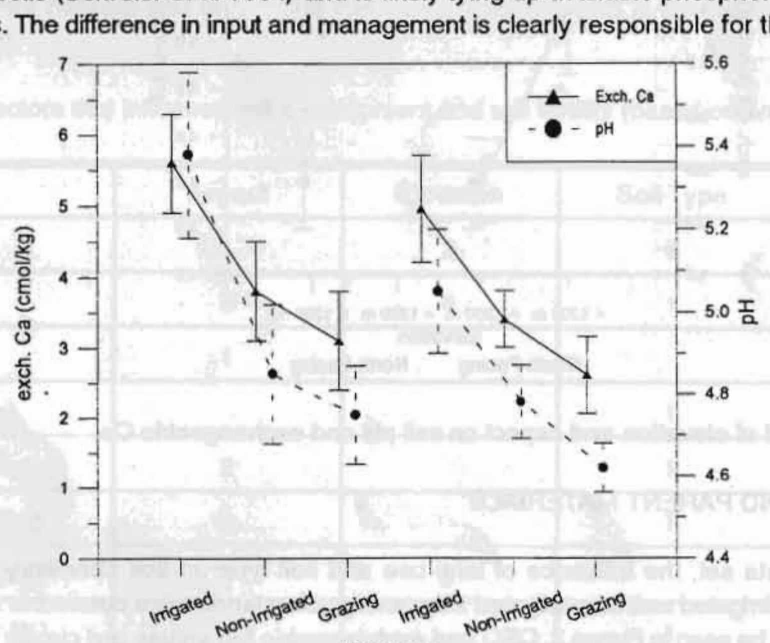

Figure 3. Land use effect on pH and exchangeable Ca.

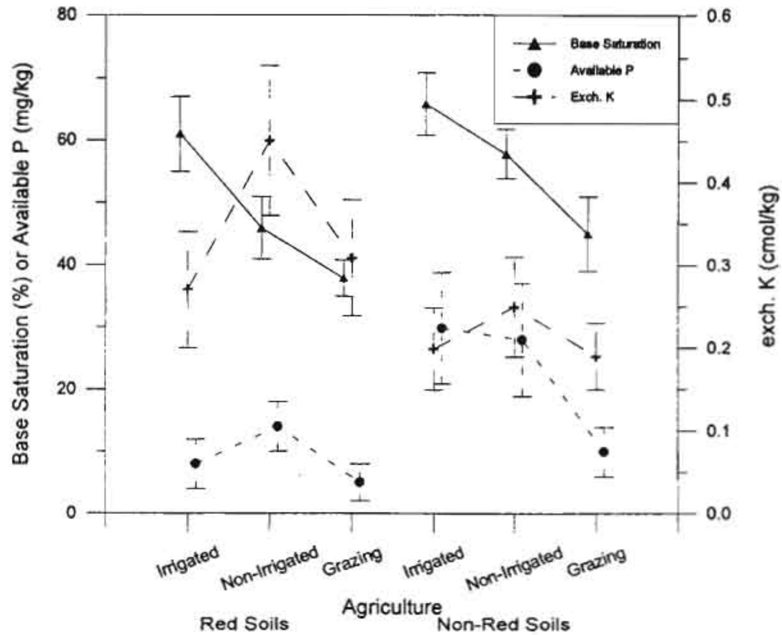

Figure 4. Land use and parent material impact on base saturation, available P and exchangeable K.

In summary, it appears that elevation and aspect influence pH, parent material differences can best be expressed using the cation exchange capacity and exchangeable Mg content, and land use is best expressed using pH and exchangeable Ca values. Available P, exchangeable K and base saturation are all influenced by both parent material and land use.

We have mapped the soils and land uses in the watershed and produced a digital topographic database to which the previous maps were georeferenced. Therefore, it is readily possible to produce selective soil fertility maps using the Geographic Information System (GIS) by linking the soil samples with the land use, soil type and elevation/aspect. An example of some of the GIS base maps are provided in Plates 1-6 (Appendix I).

3.3. Soil Fertility Differences Due to Land Use

Since parent material and land use are the most important factors, it is now possible to stratify all soil samples first by red vs. non red soils and then by land use. Using this stratification and including the Dhulikhel survey, (Schmidt, 1993; Wymann, 1993), the forestry survey (Feigl, 1989) and the controlled land use survey (Schreier et al.1994), it is then possible to document the influence of land use on soil fertility. From Figure 5, it is evident that, regardless of soil type, the forest soil fertility is the poorest, followed by grazing land and dryland agriculture.

The highest pH, exchangeable Ca and base saturation values were found in the khet lands. This is attributed to the input of cations through sediments and irrigation water. Bari land appears to have slightly higher P values and this is likely the results of more fertilizer and manure applications in dryland agriculture than in irrigated fields (Carson 1994). Grazing land, which receives minimal nutrient inputs, and the forest land, which receives no nutrient inputs, are significantly lower regardless of parent materials. These mean values are based on very large sample sizes, covering both the upper and lower portion of the watershed, and since the trends are consistent in all cases it can clearly be stated that land use management has significantly influenced soil fertility to the point were nutrient deficiencies are widespread.

3.4. Rates of Change In Soil Fertility

So far we have shown that land use and management have influenced the soil fertility status but to address the rate of changes due to management is a more challenging task as no historic data is available in the watershed. There are indirect ways to obtain data on rates of soil fertility changes over time, and two examples were used to develop more quantitative data. A 50 ha test site on red soils was selected to compare the differences in soil fertility due to irrigation, rainfed farming and forest use. Based on the 1972 aerial photos, tree coring and discussions with the farmers, it was discerned that the forest was established 17 years ago and all agricultural fields were under the current use for the past 30 years. Ten sites within each of the three land use categories were analyzed and compared. There is clear evidence that the soils originated from the same material and the climatic conditions between the sites are the same. Assuming that the soils had similar conditions before the forest was established, the differences between the forest and the agricultural conditions should be the result of management. The parent material was examined and showed no difference in nutrient conditions between the three land use activities. The soils, however, showed significant differences ($p = 0.05$) in Ca, Mg, P, C, and base saturation between the three land uses. The red soil set (number 2 in Figure 5) shows the differences between the land uses originating from the same soil unit.

It is evident that these differences were induced by management leading to poorer conditions in the forest. If we assume that the P values in dryland agriculture represent a steady state, then the forest soils would have been depleted by 0.76 g N/kg and by 3.6 mg P/kg over 17 years. This would translate into an annual loss of about 93 kg/ha of N loss and 0.5 kg P/ha. The N losses are of the same order of magnitude as the crop uptake by double crop rotation which is in the order of 60-120 kg of N /ha/year. The annual additions in the forest from pine litter fall measured 6 kg of N/ha and 0.44 kg of P/ha. The former account for about 7% of the N losses in the forest and the remainder is likely incorporated in the trees, or leached from the soil be solution, erosion and volatilization. In contrast the amount of P in the pine litter represents 73% of the annual decline and the remaining amount of loss was attributed to erosion and tree uptake. The rate of change in these nutrients between agriculture and forest land is substantial and of concern to the long term sustainability of the land use system.

The second evaluation of nutrient changes between different land uses was carried out in 24 irrigated fields. At the end of the monsoon season the soils which formed the growing media for the rice were sampled. At the same time the surface layer which represents the accumulated nutrients that were introduced as sediments in the irrigation water were also analyzed. Although, as shown by Carver (1995), the accumulation rates are highly variable, there was a significant difference in nutrient content between the residual soils and the newly accumulated soil material. As shown in Figures 6 and 7, with the exception of two samples, all newly accumulated material was higher in Ca and P than the residual that formed the nutrient pool for the rice crop. All points below the 45 degree line represent enriched conditions between residual and accumulated soils. This enrichment has a high spatial dependence and in areas with poor soil fertility the sediments show small enrichments and in more nutrient rich environments the sediments are correspondingly higher. A linear regression equation ($Ca = x+bY$) could be used to predict the rate of nutrient enrichments for all rice fields. The enrichment factor is about 1.5 at low fertility sites but can reach levels of up to 2.5 on the richer soils for soil P values. The implications of these results are two-fold. First, it is evident that irrigated agriculture is benefitting from soil erosion in the upper areas of the watershed. Since the khet lands are the most desirable fields and generally belong to the richer farmers, it can be stated that the rich farmers are getting richer by accumulating sediments and the poor farmers which predominantly own upland bari fields are getting poorer by nutrient losses from erosion. This redistribution is therefore creating a new form of poverty.

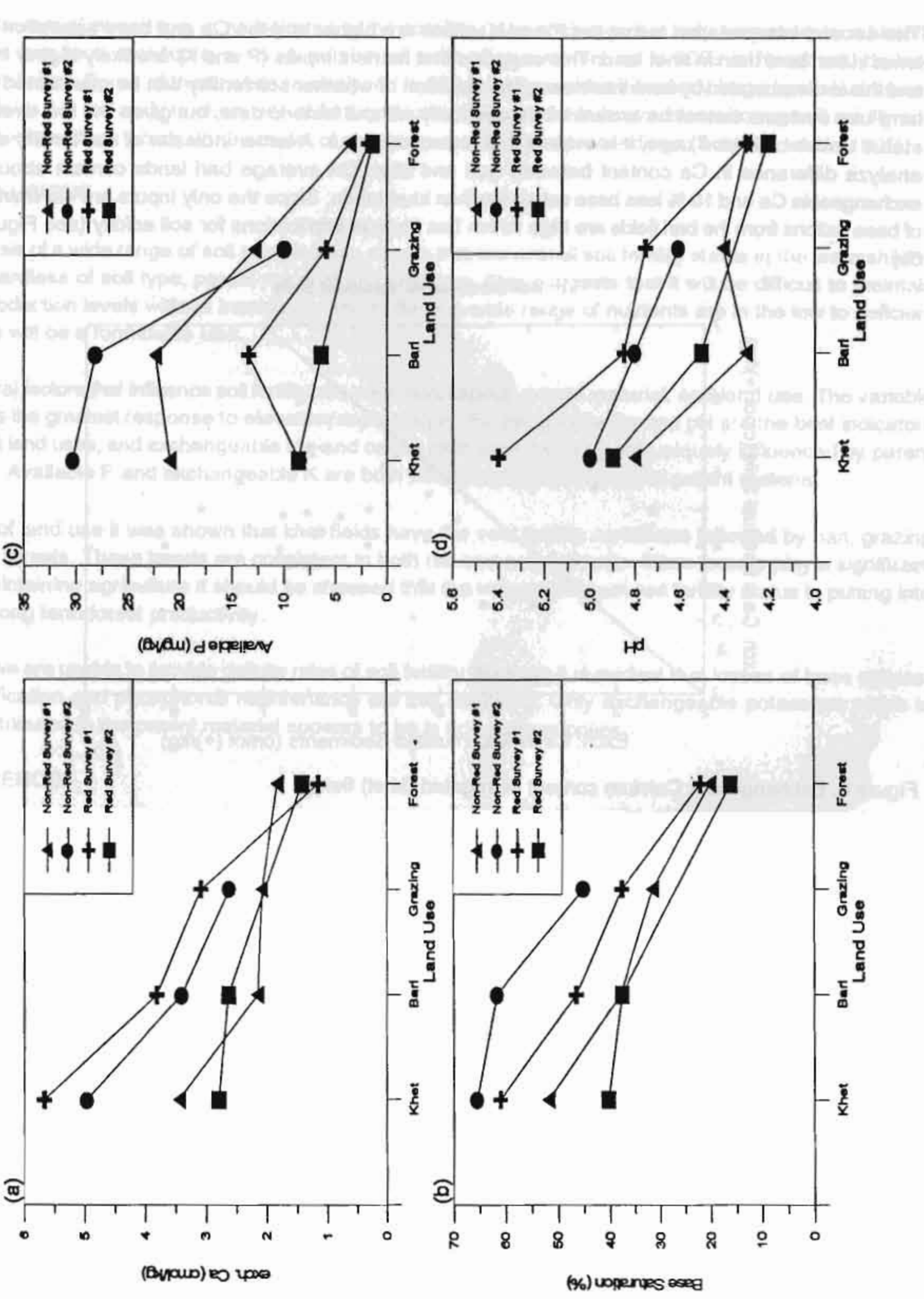

Figure 5. Land use effects on soil fertility from four comparable soil surveys.

The second interpretation is that the P and K values are higher and the Ca and base saturation values are lower in bari land than in khet land. This suggests that nutrient inputs (P and K) are likely higher in bari lands and this is corroborated by farm interviews. The question of whether soil fertility can be maintained under both land use systems cannot be answered categorically without historic data, but given the low overall nutrient status under both land uses, it is evident that losses do occur. A better indicator of soil fertility decline is to analyze difference in Ca content between bari and khet. On average bari lands contain about 33% less exchangeable Ca and 10 % less base saturation than khet lands. Since the only inputs are via manure, losses of base cations from the bari fields are high which has serious implications for soil acidity (see Figures 5a and 5b).

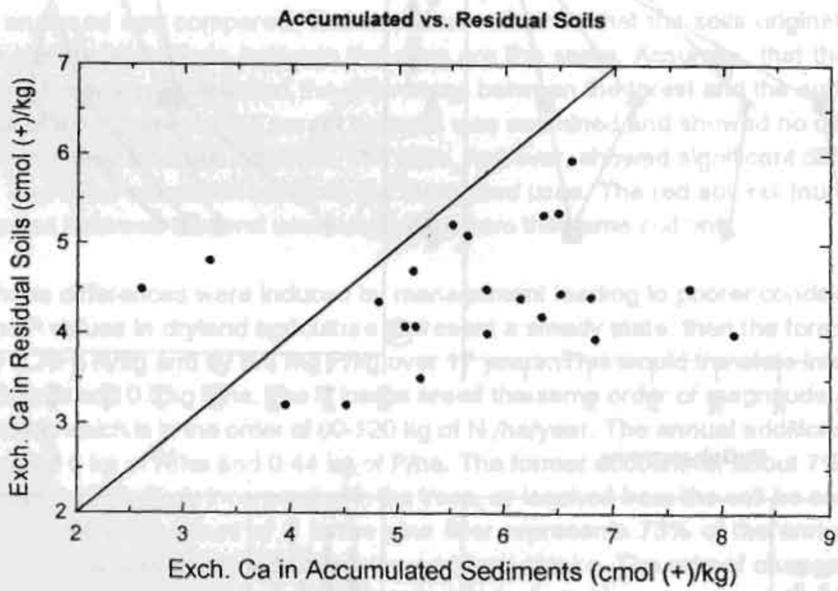

Figure 6. Exchangeable Calcium content in irrigated (khet) fields.

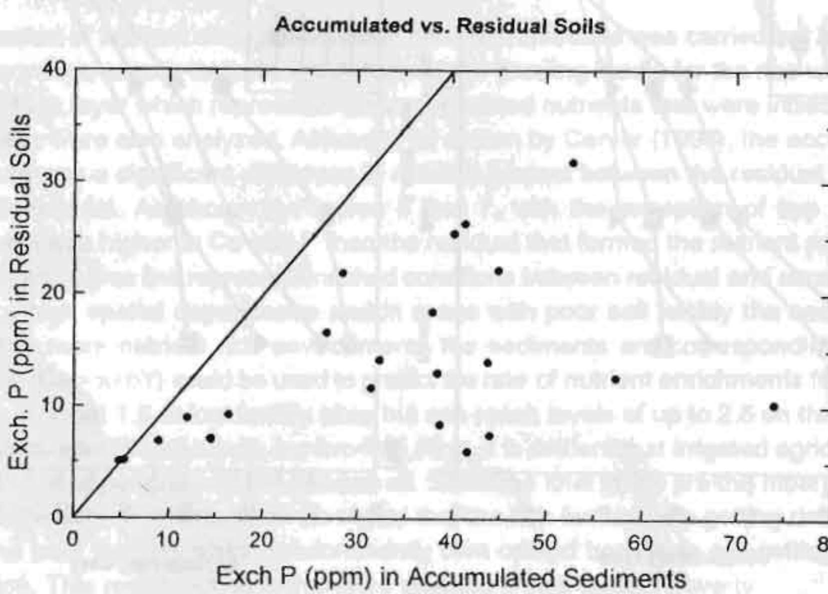

Figure 7. Exchangeable Phosphorous content in irrigated (khet) soils.

These indirect evaluations give us an indication of the possible rates of change but they cannot replace historic data from long term monitoring plots. A number of such sites were set up in 1989 in forest and dryland agricultural sites. Some of these were re-analyzed in 1994, but given the inherently large spatial variations between fields it is too early to show rate of fertility decline. One useful indicator is monitoring soil acidity and exchangeable cations which is the subject of another paper in these proceedings (Schreier, et al., 1995).

4. CONCLUSIONS

The analysis of a wide range of soil samples has shown that the overall soil fertility status in the watershed is poor, regardless of soil type, parent material and land use. This suggests that it will be difficult to maintain current production levels without increasing inputs. Since a wide range of nutrients are in the low to deficient range this will be a formidable task.

The general factors that influence soil fertility are elevation/aspect, parent material, and land use. The variable that shows the greatest response to elevation/aspect is pH. Exchangeable Ca and pH are the best indicators of different land uses, and exchangeable Mg and cation exchange capacity are uniquely influenced by parent materials. Available P and exchangeable K are both influenced by land use and parent material.

In terms of land use it was shown that khet fields have the best fertility conditions followed by bari, grazing lands and forests. These trends are consistent in both red and non-red soils. Since forests play a significant role in maintaining agriculture it should be stressed that the very poor forest soil fertility status is putting into question long term forest productivity.

Although we are unable to provide definite rates of soil fertility declines it is evident that losses of base cations, soil acidification and phosphorus maintenance are key concerns. Only exchangeable potassium which is widely distributed in the parent material appears to be in adequate supplies.

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