Soil Acidification and Its Impact on Nutrient Deficiency with Emphasis on Red Soils and Pine Litter Additions

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1. INTRODUCTION

The optimum soil pH for the majority of agricultural crops is between 5.5 and 6.5. When we examine the soil acidity data from all the recent surveys and experiments in the Middle Mountains (Sherchan and Gurung, 1995), it is clearly evident that only a few soils in the region meet these requirements. There are a number of reasons why soils are acidic in the Middle Mountains. First, the dominant bedrock is sandstone, siltstone and quartzite, all of which produce acidic soil material. A second and very important reason is that with the introduction of double and triple annual crop production, chemical fertilizers are widely used.Nepal has no fertilizer plants and the farmers are entirely dependant on external supplies, so the most appropriate fertilizer if often unavailable at the time and location where it is most needed. As noted by Chitrakar (1990), Sherchan and Baniya (1991) and Suwal et al. (1991), ammonium sulphate and urea are the most commonly used fertilizers in Nepal and both of these fertilizers acidify the soils. As manure is in short supply and no lime is currently being applied in the farming system, the concern has been raised that soil acidification is reaching considerable proportions. This has serious implications because base cations, which are needed in large quantities for crop production, will be in short supply and available phosphorus, which has an optimum solubility in the 6.2-7.0 pH range, will not be available at low pH because it will be tied up with Al and Fe.

A more recent threat from acidity has come from the practice of forest litter collection during the dry season, to provide animal bedding and subsequent nutrient input into agriculture. Most of the litter from broadleaf trees is relatively neutral but as shown by Schreier et al. (1994) and Shrestha and Brown (1995), the afforestation efforts carried out over the past 15 years have been dominated by creating Chir pine plantations. Chir pines (*Pinus roxburghii*) are native to the Middle Mountains, they germinate easily in nurseries, need little maintenance and have a high survival rate once transplanted into degraded sites and soils with poor nutrient conditions. Pine can be considered a pioneer species that can stabilize the soil in very degraded areas. One of the reasons for its high rate of survival is that pine litter cannot be used as animal feed. As well, its use as a firewood is limited because of its undesirable burning properties. The planting of pine plantations has become a national tradition in Nepal, and as the forests become more pine-dominated, the forest litter collected by farmers during the dry season is becoming dominated by pine. Pine and pine litter have a tendency to acidify the soils and, in 1991, we expressed concern regarding the long term consequences of this forest transformation on soil acidity and agricultural productivity. Little research has been done to determine the effect of these management practices on the overall soil fertility and it is the aim of this paper to determine the extent of the acid problem, address the processes that lead to acidification, and present possible alternatives to resolve the problem

2. EXTENT OF SOIL ACIDITY IN THE JHIKHU KHOLA WATERSHED

Soil pH values were measured in 0.01 M $CaCl_2$ solutions and from all the surveys carried out in the project the average values are in the 4.8-5.4 range. The factors that have the greatest influence on soil fertility are land use and soil type, and when all samples were stratified by these two factors it became evident that the irrigated agricultural fields had the higher pH values while almost all dryland agricultural soils, grazing lands and forest soils were acidic to very acidic (average values between 4.2-4.8 pH).

A soil acidity map was produced for the entire watershed by grouping all measured soil samples into three acidity categories: pH > 4.8, pH between 4.3 and 4.8, and a very acidic class with pH < 4.3. Then all soil samples collected during the soil survey and the Dhulikhel survey were displayed by their proper spatial location and assigned to each of the representative soil acidity classes. The results provided in Plate 4 (Appendix I) revealed that 18% of all samples were in the very acidic range, 52% in the acidic range and only 30% were in the category considered adequate for agriculture. This clearly suggests that the soil acidity problem is widespread, encompassing almost the entire watershed.

The detailed information on soil fertility in the Bela-Bhimsenthan sub-watershed, described in the previous paper, showed that there are significant differences in soil pH and selective nutrients in different soil types,land use practices, and elevation/aspects. Using the geo-referenced information in the Geographic Information System (GIS), a digital overlay technique was used to display the combination of land use (khet, bari, grazing, forests), soil type (red vs. non-red) and topography (high and low elevation, above or below 1200 m, and north vs. south facing slopes). Of the 32 types of possible combinations only 24 existed in the study area. A minimum of 10 soil samples were available for each of the 24 identified types of polygons and the average value for each known polygon was used as a basis to produce a pH map for the sub-watershed. The resulting pH map (Plate 7, Appendix I) is unique as it is based on more than 200 soil samples and takes into consideration differences in land use, soil type and topographic position.

Based on this analysis, 48% of all land has pH values in the acid range (< 4.8), 33% were in the intermediate range, and only 19% of the land in the sub-watershed is considered to have acceptable pH values for agricultural production. It is obvious that forests can tolerate acidic conditions better than agricultural crops, hence the concern is more for the agricultural area. However, soil acidity affects essential nutrients such as Ca, Mg, P, K, and base saturation.

3. CAUSES OF ACIDITY AND THE EFFECTS OF ACIDITY ON OTHER NUTRIENTS

Given the variability, it is not easy to partition the causes of soil acidity. It is evident that soil type hassome influence, as the red soils are 0.15 pH units higher than the non-red soils. These differences likely influence other nutrients as can be seen in Table 1. From this data it is clear that red soils have slightly higher pH and significantly higher exchangeable cations (K, Mg, and Ca). In contrast, red soil base saturation is lower because the differences in cation exchange capacity is due to textural differences between these soils.

The data in Table 1 shows that red soils have on average a 0.15 pH value higher than non-red soils. This has indirect effects on the nutrient supplying capabilities of the soils. From Table 1, it can be noted that available phosphorus and percent base saturation are higher for the non-red soils than for the red soils. The salient point to consider, however, is not the absolute values of these parameters, but their contribution to crop productivity. Although the non-red soils may have higher available P, the lower pH makes the P very slowly available to crops, and thus the rate by which the soil supplies P to the plant may be insufficient to meet the seasonal requirements, or even the daily requirements, of crops. Cation exchange capacity measurements are more dynamic and exchange reactions are believed to occur instantaneously. It can be seen that although the two soil types have almost the same organic carbon (organic matter) contents, the red soils have the higher capacity by over 45 %. The exchangeable cations are higher in the red soils, but a better relationship may be seen when the ratio of the exchangeable ions is compared to percent base saturation. These values show that

more of the basic exchangeable ions that are on the exchange complex are available to crops growing on the red soils, even though their percent base saturation is lower (46.8 vs. 55.7).

Table 1. Differences in soil fertility between red and non-red soils.

Variables	Red Soils (mean values, n = 90)	Non-red Soils (mean values, n = 110)
pH	4.94	4.78
Avail. P (mg/kg)	9.8	22.1
Carbon (%)	0.99	1
Cation Exchange Capacity (cmol(+)/kg)	13.1	8.9
Exch. K (cmol(+)/kg)	0.37	0.21
Exch. Mg (cmol(+)/kg)	1.77	1.09
Exch. Ca (cmol(+)/kg)	3.97	3.54
Base Saturation (%)	46.8	55.7
K: Base Saturation	0.8	0.4
Mg: Base Saturation	3.8	1.9
Ca: Base Saturation	8.5	6.3

From this data, it is clear that the red soils with their slightly higher pH have significantly higher available base cations (K, Mg and Ca) than the non-red soils. Thus, even though the red soils have a lower base saturation value as a percentage, the amount of total base cations available is higher than in the non-red soils.

The higher exchange capacity in the red soils is due to their higher clay contentwhich allows them to hold more cations within their structure. They are therefore slightly less vulnerable to cation losses and acidification than are the non-red soils, which are dominated by quartzite and sandstone. The latter are lower in exchange sites and tend to be more sensitive to acidification and leaching. These trends were fairly consistent even after all samples were stratified by land use (irrigated agriculture, rain fed agriculture and grazing).

However, acidification of the red soils is of particular concern in relation to phosphorus availability, as phosphorusis one of the key nutrients that are deficient in all parts of the watershed. Red soils have significantly lower available phosphorus content and this is in part related to soil acidity. The red soils have relatively high Fe and Al contents and the solubility of Al is particularly sensitive to soil acidity. As is shown in Figure 1, aluminum is insoluble between pH 4.3 and 6.5, but its solubility changes drastically below pH 4.3. Aluminum can readily interact with phosphorus creating occluded phosphate which will precipitate and no longer be available to plants. Since phosphorus is already one of the most limiting nutrients in the soils of the Middle Mountains, this acidity effect is considered to have serious consequences. The exchangeable Al content of a selected number of red soils was displayed in relation to pH and the results clearly indicate that exchangeable Al increases dramatically in the red soils at pH < 4.3.

The implications of these results are two-fold. First, the non-red soils have low buffer capacities and are generally of low pH. They are therefore vulnerable to leaching and acidification. In contrast, the red soils have more buffer capacity and higher cation content but their Al and Fe content also is high. This means that at low pH phosphorus deficiencies will occur.

To document these deficiencies, we first produced a soil phosphorus map for the Bela-Bhimsenthan sub-watershed. The same overlay and sampling stratification methods were used as before. The resulting phosphorus map is provided in Plate 8 (Appendix I) and as can be seen in Table 2, the results are not encouraging. Almost two thirds of all land in the sub-watershed has poor to very poor phosphorus conditions.

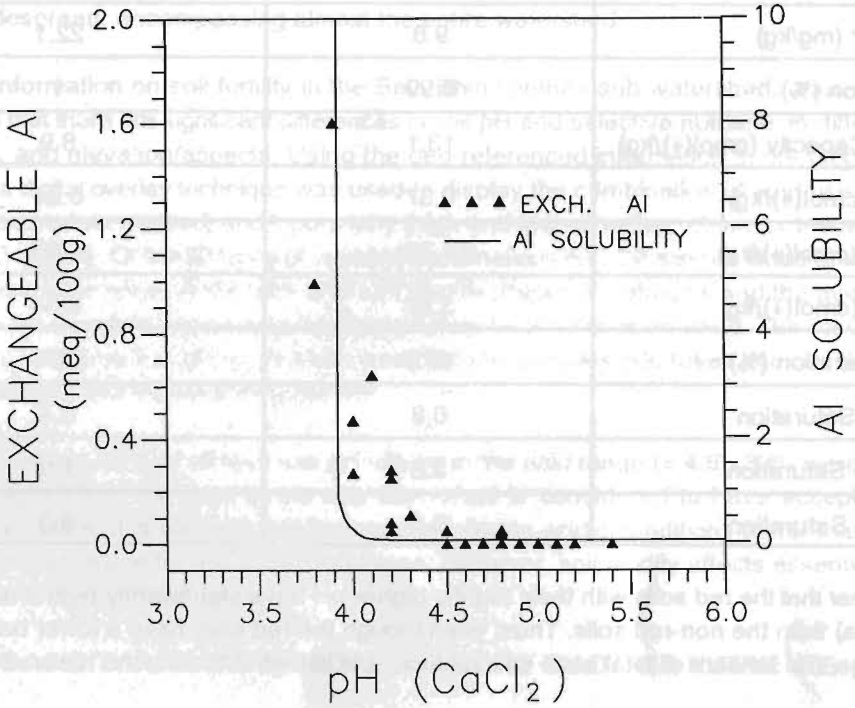

Figure 1. Aluminum solubility and exchangeable Al in relation to soil pH.

With the GIS technique it was also possible to produce a combination pH / phosphorus map, the results of which are provided in Plate 9 (Appendix I) and Table 3. It is evident that 40% of all soils in the watershed have both low pH and low available phosphorus and these areas require special attention.

Table 2. Extent of available Phosphorus in the Bela-Bhimsenthan sub-watershed.

Available Phosphorus (mg/kg)	Area in ha	Percent of Sub-Watershed
Very poor < 5	639	36
Poor 5 - 10	433	25
Fair 10-15	201	11
Moderate > 15	501	28

Table 3. Classification of combined soil acidity and available Phosphorus.

pH	Available P (mg/kg)	Area in ha	Percent of Sub-watershed
< 4.8	< 10	712	40
< 4.8	> 10	145	8
4.8 - 5.0	< 10	119	7
4.8 - 5.0	> 10	472	27
> 5.0	< 10	242	13
> 5.0	> 10	84	5
		Total : 1774 ha	1

We can now examine the 200 soil samples analyzed in the test area and document the number of samples under different land uses and soil types that fall into a high acidity and low phosphorus category. As is shown in Figure 2, 75 % of all grazing lands and 23 % of the dryland agricultural lands are very acidic (<4.8) and have P values below 10 mg/kg. In the red soils this percentage increases to 80% for grazing and 40% for dryland agriculture. This suggests that red soils have slightly more problems with acidity and phosphorus deficiencies than the non-red soils. In addition to the three land uses, we also analyzed 12 forest plots on red soils and all of them fall into this very acidic category.

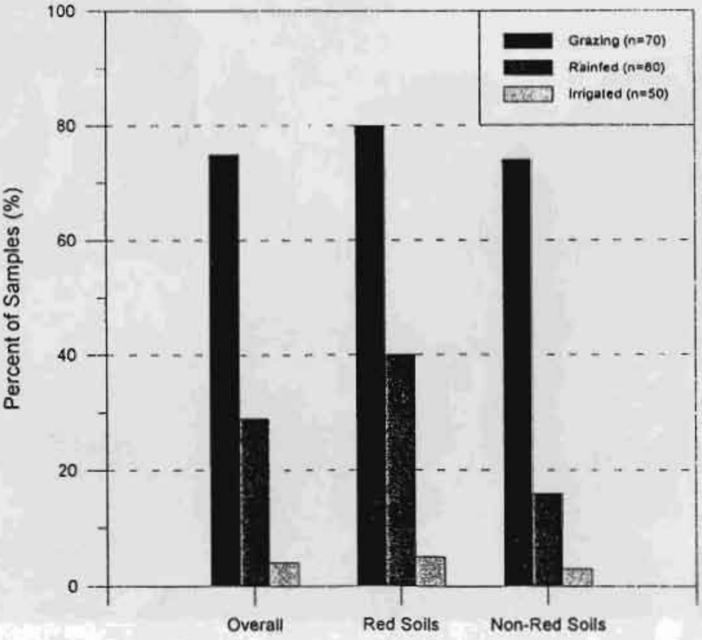

Figure 2. Distribution of acidic soils, with low phosphorus content in relation to land use and soil type.

As most of the grazing lands and forests are over-utilized and degraded, it is likely that leaching, soil losses by erosion and a lack of inputs (cations) have caused these difficult conditions. However, acidic bari land with low P content on red soils are almost three times as common as on non-red bari land. Since both of these soil ypes receive significant inputs from manure and fertilizers, other factors are likely to play a role. Shrestha and Brown (1995) have demonstrated that the forest cover has changed significantly from a mixed stand to one dominated by chir pine plantations. In contrast, khet land, which receives sediments and nutrient via irrigation water, is significantly enriched and, with the exception of a few samples, all soils under irrigation agriculture do not have an acidity problem. This enrichment effect was described in more detail in the previous paper (Shah and Schreier, 1995) and leads to significant increases in soil pH, Ca, Mg and base saturation.

4. PINE LITTER , TERMITES AND SOIL ACIDIFICATION

Traditionally, poor farmers collect forest litter during the dry season for use as animal bedding and subsequent input into agricultural soils in the form of compost. This practice has increased significantly over the past 10 years because of crop intensification (double and triple crop rotations), a lack of access to fertilizers at certain times of the year, and the farmers' belief that organic inputs are essential in maintaining the soil structure and nutrient pool under agriculture. Since the forests are becoming dominated by pine (70% of all trees planted in the watershed over the past 5 years have been pine) the proportion of pine litter collected during the dry season has gone up dramatically. Also, under temperate conditions, the decomposition of pine litter can take several years and can lead to soil acidification. As is shown in Figure 3, massive quantities of pine litter are transported and transferred from the forest into agriculture. The following questions must therefore be asked:

1. Is pine litter a good source of fertilizer?
2. Is the pine litter decomposition sufficiently rapid to benefit nutrient cycling in agriculture?
3. Is pine litter decomposition increasing soil acidity and what are the implications under agriculture? Since most of the fertilizers used in the watershed are acidifying soils and pine litter is inherently acidic, is the addition of pine litter adversely affecting the nutrient regime?

Figure 3. Forest litter collection during the dry season.

Two experiments were carried out to examine the effect of pine litter on soil acidity and nutrient conditions. In the first, two sets of 25 litter bags were used to document the pine needle decomposition process. The bags were constructed from fine mesh nylon, which allowed air and water to freely penetrate the bags. They were cut to 20x20 cm size, 10 grams of dry pine needles were added to each bag and nylon thread was used to sow the bags closed. Twenty-five bags were buried in red bari soils and 25 in non-red bari soils near the erosion plot site in a 10 metre strip at 15 cm depth. Five of the 25 bags were removed after every 4-6 month period to determine the amount and quality of the litter remaining. A similar experiment was carried out using metal mesh bags to provide information on the rate of decomposition of the litter.

The aim of the second experiment was to document whether pine litter is indeed acidifying the soils. Two five metre long trenches, 30 cm wide and 20 cm deep were dug in red and non-red bari soils at the same sites, and a layer of 15 cm of dry pine litter was added to the trench. The excavated soil was used to cover the litter. Ten soil samples were collected for pH and nutrient analysis from the excavated surface before the litter was applied. The remaining residue was examined after intervals of between 4-8 months over a time period of 2 years and the soil underlying the litter was analyzed each time to document the extent of acidification.

The results of these two experiments produced some unexpected findings. Termites play a very active role in the decomposition of the pine litter. Termites make holes into the nylon bags, break up the needles into small pieces and remove them from the site. The attack and removal rate is extremely variable and we suspect is dependant on soil type and moisture conditions. A much lower rate of removal was observed in the non-red soils, which were sandier in texture and drier than the red soils which contain significant portions of kaolinite. The rate of decomposition is shown in Figure 4, and indicates that almost all litter disintegrated and disappeared in the red soils within 7 months. In contrast, 30 months after the initiation of the experiment in the non-red soils, 2% residue still remained in the bag.

The experiment with a metal mesh bag indicated that 2/3 of the litter remained after 10 months. The termites apparently were unable to penetrate this structure. This suggests that in the absence of termites microbial decomposition of pine litter is slow, a fact that is well known from many studies in the northern latitudes.

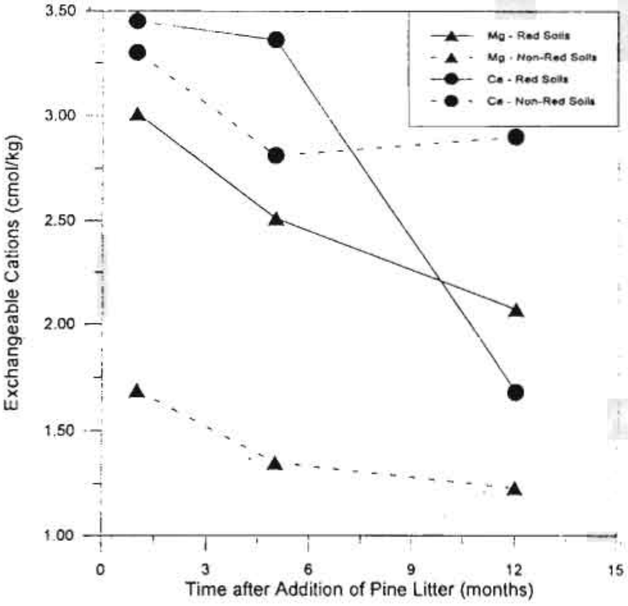

Figure 4. Rate of pine litter decomposition in different soils.

The results from the acid monitoring program are more complex. We were unable to show a pH change between the sample and the control after 12 months started in both the red and non-red soils. This was long after the pine litter had disappeared by termite and microbial action. However, the cations, particularly exchangeable Ca and Mg, decreased significantly over the 12 month monitoring period in both the red and non-red soils (Figure 5). This suggests that the soils might be buffered, but this buffer capacity may not be maintained if additions of pine litter were to continue.

Exchangeable Mg and Ca in the two soils decreased over time and the percent decrease in red soils was larger than for the non-red soils. This may indicate that the red soils had better soil structure which promoted infiltration of water, causing more leaching and potentially less surface erosion. However, it is more likely that, because termites were more active in the inherently more fertile red soils and incorporated much of the exchangeable Mg and Ca (exchangeable = more readily available) as they fed on the litter, they caused more rapid decomposition of the organic material. Since the termites are mobile, they exported much of the exchangeable cations, notably Ca, from the site and deposited these constituents elsewhere (e.g. termite mounds or termilaria, as it is known that Ca is a constituent of these structures).

The data also indicates that there is some buffering capacity in the two soils. This, however, may be of short duration. The presence of aluminum, which changes form at different pH levels, may be responsible in part for this buffering, hence temporarily limiting changes in pH. As the pH drops or the acidity increases, compounds in the soil begin to dissolve, freeing soluble silicic acid, which leaches and liberates Al and its various forms (e.g. H^+ + mineral-Al-OH ---> Al^{3+} + H_2O + residue). At pH equal to five, aluminum occurs in three different forms: Al^{3+}, $AlOH^{2+}$ and $Al(OH)_2^+$. The Al^{3+} increases in proportion as the pH drops below 5 and it is this form of aluminum which is most deleterious, or even toxic, to crops. Also, as the pH drops from 5 to 4, the amount of soluble aluminum increases about 1,000 times. Thus, in addition to the potential toxic effects of the aluminum on crops, this aluminum can polymerize with a gel and acts as a cement among sand, silt and clay particles when the soil dries (e.g. the dry season). These aluminum materials may form hardened layers (incipient pans) in the soils and affect both management and the rates of water infiltration. If acid inputs continue, this would remove basic cations and change the $Al(OH)_x$ forms, or the $Al(PO_4)_x$ forms, with largely unknown consequences in soil structure, fertility considerations and impacts on surface run-off and erosion.

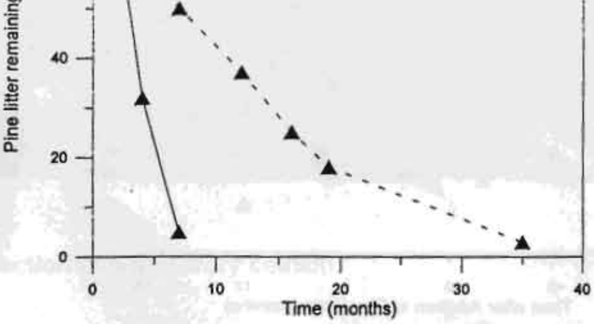

Figure 5. Leaching of cations under decomposing pine litter layer.

5. REMEDIATION OF SOIL ACIDITY

The application of lime and manure is one possible solution to avoiding further increases in soil acidity. To document this, a small experiment was carried out in a very degraded red soil site in the Bela sub-watershed. A 3x4 block treatment of lime and manure was applied to this site in 1992. Several nitrogen fixing tree species and native grasses were planted on bare soils in 10 by 1 metre strips, leaving a control site with no treatment. Lime, manure and a combination of lime and manure were applied at rates equivalent to 20 tonnes/ha at the beginning of the experiment and plant response is being monitored on a continuous basis. Two years were required to establish good plant growth (due to insect and disease attack) but in the third year we noted significant responses from the treated soils over the control. The combined lime/manure application did significantly better in term of biomass production than either the single lime or manure treatment. The plant response to the lime treatment was slightly better than to the manure treatment alone. The treatment was only applied once and consisted of 20 tonnes/ha of lime/ha and 20 tonnes/ha of manure/ha and after one year there were slight improvements in pH (0.2 pH units) in most plots that received treatment. Since local limestone sources are available in the watershed, additional tests are underway to document if such a treatment could be used to reverse the present soil acidification trend and to returnproductive capacity to the soils. A more extensive lime response test is needed using locally available sources before this management option is extended to the entire watershed. As part of this evaluation, emphasis should be directed toward documenting how the phosphorus availability changes as a result of the lime and manure treatment. The results obtained to date are encouraging.

6. CONCLUSIONS

A number of conclusions can be reached from this analysis.

1. The soils in the watershed are very acidic with approximately 70% of all surveyed samples below the 4.8 pH level (in $CaCl_2$). This was confirmed in a more detailed study in a sub-watershed where the soils were stratified into red and non red soils and four different land use classes. Significantly lower pH values were found in non-red soils. These soils are mostly developed over sandstone, siltstone and quartzite materials and hence have lower levels of base cations, lower CEC and higher base saturation than do their red soil counterparts which contain significant portions of clay minerals.

2. Soil acidity influences Al solubility and can cause Phosphorus deficiency. About 61% of all the soils analyzed were in the poor and deficient range and 40 % of all soils were found to have a combination of low pH (<4.8)and low phosphorus (< 10mg/kg) values.

3. Seventy-five percent of all grassland sites and 23% of dryland agricultural sites fell into the combined low pH and low P class. In contrast very few irrigated soils are low in pH or P because the annual input of irrigation water and sediments significantly enriches these soils.

4. Eighty percent of all red soil samples under grazing land and 40% of all red soils under dryland agriculture have high acidity and correspondingly low phosphorus. Aluminum solubility at low pH was shown to be at least in part responsible for making phosphorus unavailable to plants in these soils.

5. The addition of pine litter to agricultural soils is been viewed with concern because pine needles decompose very slowly and are known to acidify soils. In a litter bag experiment is was shown that termites play a significant part in the decomposition of pine litter. However, their activity is significantly

curtailed in the sandy non-red soils where decomposition took more than 32 months. In the red soils where termites are very active the same amount of litter was completely removed within 7 months.

6. **Experiments with pine litter layers show no soil pH decrease under decomposing litter over a 12 month period, but the amount of exchangeable Ca and Mg was significantly reduced. It is postulated that Al hydrolysis is buffering soil acidity but that the leaching losses of cations will eventually lead to Al alteration and acidification.**

7. **Lime applications from local sources appear to be beneficial to plant growth on red soils but a combination of lime and manure showed the best biomass production results. The application of lime ameliorated the pH of the red soils and improved the cation content, hence red soil degradation might be reduced by such treatment.**

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