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# INCREASING NUTRIENT UTILIZATION AND CROP PRODUCTION IN THE RED SOIL REGIONS OF CHINA

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**ABSTRACT**

Red soils belong to Oxisols, Ultisols, and some of the Alfisols in the soil order of the United States soil taxonomy. These soils had and continue to play an important role in the economic development of China. Non-judicious use of red soil resources, particularly deforestation, has caused severe soil erosion, resulting in the degradation of the environment and reduced agricultural production in the red soil regions. Various approaches have been developed to restore the fertility of degraded red soils. These include: 1) reclamation of the surface and subsurface soil by a mixture of lime, manures, and chemical fertilizers; 2) improvement of the entire rooting depth of citrus and other deeply-rooting crops using trench-planting and soil chiseling techniques; 3) increased input of organic materials applied alone or together with chemical fertilizers or lime; 4) integrated utilization of red soil resources to minimize soil erosion and water losses; and 5) diversified crop production systems to increase economic return. These efforts have proved to be effective in sustaining agricultural production and further improving nutrient utilization efficiency and environmental quality in the red soil regions of China.

## INTRODUCTION

The term ‘red soils’ used in this article covers all of the red soil sequences including laterite, lateritic soils, red soils, yellow soils and other soil groups of similar properties in the tropical and subtropical regions of China. They are equivalent to Oxisols, Ultisols and some of the Alfisols in the soil taxonomy of the United States. The red soil regions cover an area of 260 million ha, embracing 15 provinces and autonomous regions in China and accounting for 27% of the country’s total land. The distribution patterns of land use in these regions include arable 13.6%, forestry 44%, grassland 3.7%, wasteland 24%, and others 14.7% (Table 1). Red soils are widely distributed in tropical and subtropical regions and constitute the most important soil resources for food production in the world (Von Uexkull and Mutert, 1995).

China red soil regions have favorable climate and biological resources, including annual mean temperatures of 17–20°C, mean annual solar irradiation of 420–460 Mjm$^{-2}$, and annual rainfall ranges from 1300 to 1700 mm with a distinct peak in spring (March–May) and early summer (June–July) followed by a late summer drought. These regions account for only 27% of the nation’s

***Table 1.*** Land Use Distribution of Red Soils in China

| Type of Land Use | Sub-type of Land Use | % |
|---|---|---|
| Arable land | Paddy field | 8.5 |
| | Upland | 5.1 |
| Forestry | Forests | 26.9 |
| | Shrubs | 8.2 |
| | Sparse forests | 4.0 |
| | Others | 5.0 |
| All others | Grassland | 3.7 |
| | Barren land | 23.5 |
| | Coastal land | 0.3 |
| | Water surface | 4.0 |
| | Others | 10.8 |
| Total | | 100.0 |

Data from Gong and Shi (1992).

total cultivated land, yet contribute 42.7% of the grain and 75% of the rice (*Oriza sativa L*) produced in China and support 43% of the country's population.

## NUTRIENT LOSS AND SOIL DEGRADATION IN RELATION TO SOIL EROSION

The red soil regions are dominated by low mountains and hills. The unique landscape along with an uneven distribution of rainfall makes the agroecosystem very vulnerable to erosion. These regions are also densely populated and under a great pressure to increase arable land to meet an increasing demand for food and fibre, which is often achieved by deforestation. Control of erosion is the most critical challenge since it has resulted in a tremendous loss of nutrients and the decline of soil fertility. Of the 106 million ha of hilly and mountainous areas, 48 million ha have been severely eroded as a result of excessive deforestation and inappropriate land use. The eroded land area (62 million ha) accounts for nearly a quarter of the total area of the red soil regions. In the Zhejiang Province alone, about 30% of the total area has been subjected to severe soil erosion (Yu et al., 1998).

Soil erosion to the Yangtze and Zhujiang rivers is approximately 25 billion tons of soil per year (Zhang and Zhao, 1994). Large amounts of organic matter and nutrients are also lost from the cultivated land (Luo et al., 1995). Annual loss of N, P, and K in southern China due to soil erosion amounts to 3.1 million tons, about twice the amount of fertilizers applied yearly in these regions. Approximately 1.2 million tons of N, P, and K were lost from the Jiangxi and Hunan Provinces in the Southeast China (Table 2). The losses of surface soil and nutrients not only substantially decreases nutrient status and utilization efficiency, but also has a great impact on degradation of the environment. Lakes, rivers, and reservoirs are silted and their storage capacity is greatly reduced. At the same time they are susceptible to eutrophication and vulnerable to natural catastrophes such as flooding. Drought has become more and more frequent and intensive in these regions (Gong and Shi, 1992; Sun, 1995; Zhang and Zhao, 1994).

***Table 2.*** Nutrient Losses as a Result of Soil Erosion in the Red Soil Regions

| | Nitrogen | Phosphorus | Potassium | Total |
|---|---|---|---|---|
| Regions | Million Tons per Year | | | |
| Southern China | 1.12 | 0.93 | 1.05 | 3.10 |
| Jiangxi Province | 0.27 | 0.23 | 0.26 | 0.76 |
| Hunan Province | 0.16 | 0.12 | 0.15 | 0.43 |

Data from Luo et al. (1995).

*Table 3.* Impact of Soil Erosion on Soil Properties

| Parent Materials | Soils | Bulk Density ($g\ cm^{-3}$) | Porosity (%) | Hydro-lysable N ($mg\ kg^{-1}$) | Bray 1-P ($mg\ kg^{-1}$) | N $NH_4Ac$ Extract-able K ($mg\ kg^{-1}$) |
|---|---|---|---|---|---|---|
| Granite | Original | 1.38 | 48.3 | 120 | 5.4 | 201 |
| | Eroded | 1.55 | 42.8 | 28 | 1.0 | 39 |
| The Quaternary red earths | Original | 1.34 | 49.2 | 88 | 4.0 | 79 |
| | Eroded | 1.53 | 42.3 | 36 | 2.0 | 28 |
| Sandstone | Original | 1.44 | 44.7 | 48 | Trace | 46 |
| | Eroded | 1.62 | 40.2 | 27 | Trace | 5 |

Data from Luo et al., 1995.

Soil degradation is one of the most severe consequences of soil erosion which considerably increased bulk density of the soil, and decreased soil porosity and plant-available N, P, K in the rooting zone (Table 3). Zhang and Zhao (1994) showed that 25.9, 40.8, and 33.3% of the soils in the hilly red soil regions were at slight, medium, and severe levels of soil degradation, respectively. Lateritic red soils were usually among the most highly degraded. Erosion is posing great constraints to the sustainability of agricultural production in these regions.

## SOIL RECLAMATION TO INCREASE NUTRIENT UTILIZATION AND CROP PRODUCTION

Eroded red soils are characterized by low pH, low organic matter, low nutrient availability and a lower water holding capacity. Nutrient utilization efficiency is generally less than 10% for P, less than 30% for N and K (Lin, 1995). These factors plus aluminum toxicity and poor soil structure are the major constraints responsible for the low nutrient utilization efficiency and productivity levels. Soil reclamation is critical for restoring fertility, increasing nutrient utilization efficiency, and increasing the productivity of those eroded soils.

### Liming to Alleviate Soil Acidity and Improve Water Use and Crop Growth

In a study by Zhang et al. (1991), application of liming materials such as $Ca(OH)_2$ and limestone was shown to be one of the most effective measures used

***Table 4.*** Liming Effects on Soil pH and Dry Matter Yield (DMY, % of the Maximum) of White Clover

| Soil or Plant Parameters | | Amounts of Lime Added ($g\ kg^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
| pH | Topsoil | 4.8 | 5.5 | 5.8 | 6.3 | 6.6 | 6.8 | 7.3 |
| | Subsoil | 4.5 | 5.3 | 5.5 | 5.6 | 6.1 | 6.4 | 7.0 |
| DMY | Topsoil | 24 | 49 | 69 | 83 | 100 | 68 | 33 |
| | Subsoil | 4 | 9 | 2 | 47 | 100 | 56 | 64 |

Data from Zhang et al. (1991).

for increasing nutrient utilization and crop yields in the eroded acidic red soils, while overliming was found to decrease crop yields due to its causing deficiencies of some micronutrients such as Zn, Fe, Mn, and Cu. Maximum yields of most crops [eg., rice, wheat (*Triticum aestivum L*), soybean (*Glycine soja*), corn (*Zea mays L*), and oil rapeseed (*Brassica napus*)] were obtained with a soil pH around 6.0–6.5. The effect of liming on soil pH and yield of white clover (*Trifolium repense*) from this study is shown in Table 4. The soil was an Ultisol (Typic Plinthaquult), a typical type of red soil in China. The maximum yield of white clover was obtained at 2.0 g lime $kg^{-1}$ soil (2600 kg lime $ha^{-1}$), which raised soil pH to 6.1 for the subsoil and 6.6 for the top soil.

Soil pH increase by surface application of lime is often limited to the top of 20 cm soil profile (Wang and Kong, 1992). Soil acidity and Al toxicity in subsoil are the two most important constraints for the crops with a deep rooting system such as cotton and citrus. Application of gypsum has been found to increase crop yield by alleviating Al toxicity and improving Ca availability in subsoils (Farina and Channon, 1988). Recent research by Shui and Chen (1995) indicated that application of limestone, manure, and chemical fertilizers to an acidic subsoil significantly enhanced root growth of cotton (*Gossypium hirsutum* L) (Table 5). Application of limestone, organic manure, and chemical fertilizers to subsoil increased the use of soil moisture in deeper layers by cotton (Table 5). The water use from subsurface layers (30–50 cm depth) by the cotton plants was increased by 2–4 times by these treatments. Manure was the most effective amendment in enhancing root growth and water use. Increasing the use of soil water in the subsurface soil layers in this region is very important for increasing yield and for the sustainability of the system because drought during the late summer and autumn season is very often the limiting factor.

***Table 5.*** Effects of Application of Chemical Fertilizers, Manure, or Limestone to Subsoil on Cotton Root Growth and Water Uptake of Cotton from Subsoil During the Dry Season on a Red Soil from China

| Treatments | Lateral Root Numbers per Plant cm Depths | | | Length of Primary Root | Root DMY | Water Use in 30–50 cm Soil Layer |
|---|---|---|---|---|---|---|
| kg $ha^{-1}$ | 0–18 | 18–28 | 0–28 | cm | g $plant^{-1}$ | $m^3$ $ha^{-1}$ |
| Control | 12.1 | 0 | 12.1c† | 32.2d | 14.6c | 147d |
| Borax, 15 | 12.4 | 5.0 | 17.4b | 38.6c | 16.4b | 381c |
| KCl, 450 | 12.3 | 6.2 | 18.5b | 42.1ab | 16.8b | 404c |
| Blended fertilizers | | | | | | |
| (15N-15P-15K, 450) | 12.7 | 6.0 | 18.7b | 40.5b | 17.1ab | 561b |
| Manure, 1 5000 | 13.0 | 8.0 | 21.0a | 41.2ab | 17.8a | 706a |
| Limestone, 3750 | 13.8 | 7.0 | 20.8a | 45.8a | 17.5ab | 684a |

Data from Shui and Chen (1995).
†The same letter following mean within the same column indicate insignificant difference between treatments ($p<0.05$)
Based on Duncan Multiple-Range Test.

## Trench-Planting and Soil Chiseling to Increase Rooting Depth and Crop Production

Soil acidity, compactness, low fertility, and seasonal drought largely reduced production of citrus (*Citrus*), food bamboo (*Bambusa*), and trees in the hilly red soil regions. Growing citrus or trees on eroded red soils by means of surface application of soil amendments (0–20 cm) has not been successful. Reclamation of the entire surface and subsoil is too costly for the farmers. Therefore, special techniques called as "trench-planting" and "soil chiseling" were developed to grow deeper rooted citrus on the eroded red soils, therefore increasing nutrients and water use efficiency (Chai et al., 1995). A trench of 100 cm in width and 100 cm in depth is made and filled with a mixture of manures, chemical fertilizers, limestone and surface soil before the citrus seedlings are transplanted along the reclaimed soil. Several years later, in order to increase the rooting zone, another soil chiseling trench (80 cm in width and 80 cm in depth) is made beside the planting trench and filled with previously described soil amendments (Lu et al., 1997). These techniques allowed the reclamation of over a hundred thousand hectares of eroded red soils, where citrus crop growth was considered to be impossible by means of traditional agricultural practices. The trench planting and soil chiseling have been shown to advance fruit-bearing of citrus by at least one year and increase fruit yield by more than three times, as compared with conventional practices of red soil reclamation (Lu et al., 1997).

## Increasing Input of Organic Matter to Enhance Soil Fertility

By increasing organic matter inputs, significant improvement of chemical and biochemical properties and fertility of red soils were achieved for different cropping systems (Table 6). After restoration of crop production through soil reclamation, input of organic matter was increased by applying manures, falling litters and leaves from the standing crops, and by returning straw and leaving roots after the plants were harvested. After 38 years under forest, organic matter content in the 0–15 cm soil depth increased by 20-fold, total N by 15-fold, and total P and extractable P by 6- and over 100-fold, respectively. Microbial biomass C, N, and P, which are closely related to organic matter supply and soil quality, were significantly increased with increasing years of soil reclamation and crop restoration (Table 6). Crop productivity of the red soils was significantly increased by reclamation and the return of leaves and residues of growing crops or trees to the soil (He et al., 1997).

***Table 6.*** Changes of Soil Chemical and Biochemical Properties of Eroded Red Soils After Reclamation (0–15 cm Depth)

| Land Use History | pH ($H_2O$) | Organic C (g kg$^{-1}$) | Total N (g kg$^{-1}$) | Total P (mg kg$^{-1}$) | Extractable P (mg kg$^{-1}$) | Microbial C (mg kg$^{-1}$) | Microbial N (mg kg$^{-1}$) | Microbial P (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| Eroded-unarable | 6.0 | 1.69 | 0.19 | 300 + 10 | 0.9 ± 0.1 | 22.5 + 3 | 4.0 ± 0.3 | 2.1 ± 0.2 |
| Upland-5 yr | 4.8 | 5.10 | 0.49 | 310 ± 5 | 1.8 ± 0.3 | 89.4 ± 8 | 23.7 ± 1.5 | 6.8 ± 0.7 |
| Citrous orchard-6 yr | 6.0 | 5.25 | 0.55 | 240 ± 5 | 43.8 ± 2.1 | 185 ± 11 | 19.0 ± 1.2 | 20.2 ± 1.4 |
| Citrous orchard-9 yr | 5.0 | 15.1 | 1.79 | 860 ± 60 | 171 ± 3.7 | 274 ± 17 | 31.9 ± 2.5 | 31.5 ± 2.9 |
| Citrous orchard-14 yr | 4.6 | 18.2 | 1.93 | 1804 ± 90 | 215 ± 4.9 | 397 ± 21 | 35.2 ± 2.5 | 42.3 ± 3.7 |
| Paddy-17 yr | 5.1 | 20.5 | 1.98 | 750 ± 20 | 120 ± 6.7 | 402 ± 25 | 45.2 ± 3.0 | 30.8 ± 2.8 |
| Tea orchard-32 yr | 4.9 | 27.4 | 2.15 | 550 ± 10 | 117 ± 4.5 | 370 ± 22 | 47.9 ± 3.2 | 24.6 ± 2.1 |
| Forest-38 yr | 5.8 | 34.3 | 2.97 | 440 ± 20 | 4.1± 0.4 | 391 ± 27 | 52.6 ± 4.1 | 15.3 ± 1.1 |

Data from He et al. (1997).

### Increasing Utilization Efficiency of Nitrogen Fertilizer by Organic Matter

Application of manure is a traditional agricultural practice to sustain soil fertility and crop production in China. Application of chemical fertilizer and manure in proper proportion has been demonstrated to increase nutrient utilization efficiency (Lin, 1995; Yang et al., 1994). Recently an elaborate pot experiment with ryegrass (*Lolium perenne L. cv 'Linn'*) as an indicator plant was designed to understand the mechanisms responsible for the beneficial effects of organic material addition on nutrient transformation, availability and utilization in red soils. The results show that application of organic carbon (cellulose) along with chemical fertilizer (ammonium sulfate) greatly enhanced growth of microorganisms in the soils, which in turn, increased incorporation of the applied inorganic N that was not absorbed by the plants into microbial biomass and other organic fractions (Table 7). Organic treatments with $(NH_4)_2SO_4$ increased yields of ryegrass and nitrogen utilization efficiency by 6 and 11% respectively, for the clayey and sandy textured soils as compared with $(NH_4)_2SO_4$ application alone (Table 7).

## INTEGRATED AGRICULTURE TO INCREASE NUTRIENT USE AND PRODUCTION

Several ecological models of the integrated agricultural production systems that have been successfully developed in the red soil regions are: 1) forests inter-cropping with shrubs and grasses on the top of the mountains and/or on the hills; 2) cash crops such as citrus, peach (*Prunus persica*), food bamboo, and tea (*Thea sinensis*) plants grown on the hillsides; 3) highland crops such as wheat, corn, and oilseed grape or pastures grown on the lower and gentle slopes of hills; 4) rice and other lowland crops grown in the valleys and basins; and 5) fish raised in the ponds with forage crops growing around the peripheries of the ponds in the lowland of the red soil regions (Chai et al., 1995). This integrated agriculture provided economic and ecological benefits to the farmers (Chai et al., 1995, Zhang, and Zhao, 1994). The tea-forestry inter-cropping system had the greatest gross output (4900 US\$ $ha^{-1}$), followed by the food bamboo and fruit-forestry inter-cropping systems (4800 US\$ and 3700 US\$ $ha^{-1}$, respectively), and the single forestry had the lowest output (1000 US\$ $ha^{-1}$) (Table 8). However, net income per hectare of the six agroecosystems decreased in the order: food bamboo > upland cropping > rice-forestry > fruit-forestry > farmland-fish-poultry > forestry alone. The output/input ratio was in the order of forestry alone > food bamboo > farmland-fish-poultry > upland cropping > fruit-forestry > tea-forestry. The single forestry production system had the highest output/input ratio due to its very low input although it had the lowest output and net income. On the other hand, all of

***Table 7.*** Increase in Nitrogen Use Efficiency (NUE) by Ryegrass Grown Under Different Treatments in Sandy and Clayey Red Soil in China

| Soils | Treatments | Total N ($g\ kg^{-1}$) | Microbial C ($mg\ kg^{-1}$) | Microbial N ($mg\ kg^{-1}$) | Available N ($mg\ kg^{-1}$) | N uptake ($mg\ kg^{-1}$) | NUE (%)† |
|---|---|---|---|---|---|---|---|
| Sandy | Control | 0.36 | 84.5 ± 5.0 | 13.4 ± 1.1 | 62.8 ± 1.9 | 24.1 ± 0.6 | |
| | $(NH_4)_2SO_4$ (100 mg N $kg^{-1}$) | 0.38 | 94.3 ± 4.8 | 16.3 ± 1.3 | 67.0 ± 1.7 | 57.8 ± 1.4 | 33.7 |
| | $(NH_4)_2SO_4$ + glucose (0.5 g C $kg^{-1}$) + cellulose (1.5 g C $kg^{-1}$) | 0.38 | 160 ± 11 | 20.1 ± 1.4 | 68.6 ± 1.8 | 64.1 ± 1.4 | 40.0 |
| Clayey | Control | 0.42 | 56.6 ± 5.4 | 8.3 ± 0.9 | 65.6 ± 1.7 | 17.8 ± 0.6 | |
| | $(NH_4)_2SO_4$ (100 mg N $kg^{-1}$) | 0.45 | 75.5 ± 6.3 | 12.3 ± 1.0 | 67.6 ± 2.0 | 27.4 ± 0.9 | 9.6 |
| | $(NH_4)_2SO_4$+ glucose (0.5 g C $kg^{-1}$) + cellulose (1.5 g C $kg^{-1}$) | 0.46 | 109 ± 8.6 | 16.2 ± 1.2 | 72.8 ± 2.1 | 38.7 ± 1.5 | 20.8 |

Data from Yao et al. (1998).

†NUE (nitrogen utilization efficiency) = (N uptake by ryegrass with N fertilizer − N uptake by ryegrass without fertilizer)/applied N × 100%.

*Table 8.* Comparison of Economic Benefits of Six Major Agro-ecological Models on Red Soils

| Agro-ecological Models | Output | Net Income | Output/Input Ratio | Ecological Benefit |
|---|---|---|---|---|
| | US$ $ha^{-1}$ | | | |
| Tea-forestry | 4900 | 1600 | 1.5 | Very good |
| Food bamboo | 4800 | 4200 | 8.0 | Good |
| Fruit-forestry | 3700 | 1460 | 1.7 | Very good |
| Upland cropping | 2700 | 1600 | 2.5 | Poor |
| Farming-fishery-poultry | 2000 | 1260 | 2.6 | Good |
| Forestry alone | 1000 | 980 | 15 | Excellent |

Data from Luo et al. (1995).

the forestry, tea-forestry inter-cropping and fruit-forestry inter-cropping systems provided a favorable ecological benefit. Therefore, by implementing an integrated agriculture, agro-ecological functions of different production systems can be optimized to obtain an improved economic return and ecological benefit by taking all of the climate, topography, soil, ecological conditions, and social-economic factors into consideration in a specific area.

## CONCLUSIONS

Red soils are the most important natural resource in tropical and subtropical regions and support a large proportion of the population in China. Most red soils in these regions were degraded as a consequence of soil erosion and had low inherited fertility. Improved management practices of red soils are crucial for sustainable agricultural production in these regions. Improper use of red soil resources such as deforestation for expanding arable land for crop production on mountainous and hilly regions could cause severe soil erosion. Successful management of red soils includes integrated utilization of red soils, restoration of soil fertility by applying lime, manures, and chemical fertilizers, and increasing nutrient utilization efficiency and crop production by trench-planting and soil chiseling, subsoil reclamation, and application of chemical fertilizers and manure in a proper proportion.

Future research needs to focus on: 1) monitoring the dynamics of economic productivity, soil fertility, ecological and environmental impact of different agro-ecological models using geographic information systems; 2) using new selection and breeding methods along with molecular biology techniques to improve or breed crop varieties which can adapt to the acid infertile red soils and have high nutrient use efficiency; and 3) to increase plant-availability and subsequent use of native and applied nutrients through application of genetically-engineered microorganisms. All the research will help establish a high output, and highly efficient but sustainable agriculture in the red soil regions and minimize the degradation of ecosystems.

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