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Grassland improvement in subtropical Guangdong Province, China.
3. Strategy for improvement of acid soils

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Abstract

This paper reports a strategy for improvement of the acid Hapludult soils found in north Guangdong Province, China. These soils are so infertile that productive pastures cannot be developed without first improving the soil. Rebuilding soil fertility is a slow and costly process which requires manipulation of pasture species and fertiliser inputs to raise the soil organic matter level and thereby increase the cation exchange capacity. Three stages of soil improvement-pasture development are described through which individual paddocks may advance before high beef production can be realised. A molasses grass — round-leafed cassia mixture which responds to low rates of P and K is recommended for Stage 1 improvement on unlimed soil. This combination has low palatability to cattle, but the yields of above 11 000 kg/ha DM top and root growth should significantly increase the level of soil organic matter. With moderate P and K inputs and some soil improvement in Stage 1, better quality species such as setaria sown with lotononis or Oxley stylo show promise for summer grazing by cattle on unlimed soil in Stage 2 improvement. Lime application may further increase the range of quality summer grasses and some temperate species during Stage 2. However, only after several years of rebuilding soil fertility and nutrient recycling under grazing can high producing Stage 3 subtropical and temperate species be sustained without high annual fertiliser and lime inputs. Cash crops and forage crops can be used in rotation with permanent pasture and strategic use of lime to diversify income, provide more cattle feed at critical periods, stop weed invasion and break insect and disease cycles. Changes in pasture composition (succession or retrogression) provide a useful guide to changes in soil fertility. While further research is required to refine the low-input, soil-improvement strategy described, this approach appears most likely to lead to sustained pasture development on the red soils in south China.

Introduction

Concentrating on the weakest links in the production process most often produces the highest net return for the physical effort and capital invested (Whiteman 1980). The analyses of climate and soils in Shaoguan Prefecture in north Guangdong Province, China, identified 3 fundamental constraints to pasture development: (1) low temperatures and frosting; (2) impoverished nutrient status (e.g. deficiencies of P, K, Mg, Ca, B and Zn); and (3) high levels of exchangeable aluminium. All 3 factors limit the choice of species (Michalk *et al.* 1988, Michalk and Ryan 1989; Michalk and Huang 1994a).

In fact, the Hapludult soils of Shaoguan Prefecture are so infertile that productive pastures cannot be developed rapidly without excessively high fertiliser inputs. To achieve sustained production on these soils, several stages of soil improvement and pasture development must be undertaken to raise soil fertility. Only when the soil is improved can the production system be intensified to take full advantage of the favourable climatic conditions (Michalk and Huang 1994a).

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Rebuilding soil fertility is a slow and costly process which requires manipulation of pasture species and fertiliser inputs to raise soil organic nitrogen and carbon levels (Sanchez 1976). Attempts to quickly build a bank of readily available nutrients are of little use in well structured kaolonitic soils like those found in Shaoguan Prefecture which react with fertiliser to render nutrients unavailable (e.g. fixing of phosphatic fertiliser by aluminium and iron oxide) and which are highly leached.

Since high levels of exchangeable aluminium inhibit uptake and translocation of P by plants (Haynes and Ludecke 1981), it is often difficult to separate the effects of Al toxicity and P deficiency on acid soils (Haynes 1984). For this reason, application of lime and P fertiliser is essential for the development of pasture systems. Understanding the effects and interactions of these inputs is central to the sustainable management of infertile, acid soils.

However, the application of the amounts of fertilisers and soil modifiers required by moderate- to high-producing pastures is beyond the limited resources of peasants in subtropical China. This inability of farmers to pay for high fertiliser inputs in marginal lands has also led to the development of low-input alternatives in South America (Sanchez and Salinas 1981).

Low-input technology: the basis for soil improvement

The basic concept of low-input soil management technology is not to eliminate the use of fertilisers or soil modifiers, but rather to make the most efficient use of scarce purchased resources by selecting pasture and crop species with tolerance to existing soil constraints, thereby reducing the fertiliser inputs necessary to obtain reasonable but not necessarily maximum yields.

Sanchez and Salinas (1981) outline 3 basic principles which underpin low-input soil management technology: (1) adaptation of plants to the soil constraints, rather than elimination of all soil constraints to meet the plant's requirements; (2) maximisation of the output per unit of added chemical input; and (3) advantageous use of favourable attributes of acid, infertile soils.

Use of adapted pasture species

Studies conducted at Lechang Farm provide an indication of the relative tolerance of species to the acid conditions which exist on the red soils in subtropical China (Table 1). Species which responded to low rates of P (<18 kg/ha P) and K (0–50 kg/ha K) on unlimed soils were classified as "tolerant", whereas "susceptible" species required the level of aluminium saturation to be lowered significantly by lime application and the available P and K status to be raised before they produced acceptable yield.

Of the species tested, molasses grass (*Melinis minutiflora*) and round-leafed cassia (*Chamaecrista rotundifolia*) were the most tolerant of the acid soil conditions and were productive with minimal P and K inputs. These species are recommended for initial development of pastures (Michalk and Huang 1994a; 1994b). While these species are not particularly palatable to cattle (CIAT 1973; Valdes *et al.* 1987), when sown together they make a significant contribution to the organic matter levels of the low cation exchange capacity (CEC) Hapludult soils at Lechang Farm. It may be useful to sow a light rate of setaria to invade such pastures as the soil improves in Stage 1.

With moderate P and K inputs, better quality grasses (e.g. setaria, rhodes grass, signal grass, guinea grass) and legumes (lotononis, fine-stem stylo) can produce higher yields of higher quality dry matter which is more suitable for cattle production (Michalk and Huang 1994a; 1994b).

Maximisation of output per unit of fertiliser input

Nutrient deficiencies are the main cause of the low productivity of red soils in south China (He *et al.* 1990). At the initial stage of improving Hapludult wastelands, application of N, P, K, Ca, Mg and B substantially increases the yield of most crops and grass-based pastures. On unlimed soil, P and K are the nutrients which most limit production of acid-tolerant pastures and attention must be paid to applying appropriate quantities consistent with low-input technology.

For example, economic analyses of a significant P x K interaction for setaria-based pastures at Lechang Farm showed that application of 37 kg/ha P and 133 kg/ha K at sowing, which produced an estimated cumulative yield of 17 t/ha

Table 1. Adaptability to soil conditions of grasses and legumes recommended for grassland improvement in north Guangdong Province.

Botanical name	Common name	Expected yield[1]	Tolerance to[2]:					
			High Al	High Mn	Low Ca + Mg	Low P	Low K	Fire
		(kg/ha DM)						
GRASSES								
Brachiaria decumbens	Signal grass	2580	M[3]	?	?	M	S	T
Cenchrus ciliaris	Buffel grass	320	S	S	S	S	S	T
Chloris gayana	Rhodes grass	1460	S	?	?	S	?	T
Melinis minutiflora	Molasses gras	4800	T	T	T	T	M	S
Panicum maximum	Guinea grass	1670	T	T	?	S	S	T
Paspalum dilatatum	Common paspalum	900	T	T	T	S	S	T
P. plicatulum	Brownseed grass	2720	T	T	T	T	?	T
P. notatum	Bahia grass	680	T	T	T	T	T	?
Pennisetum clandestinum	Kikuyu	340	?	?	?	S	?	?
Setaria sphacelata	Setaria, bristle grass	2710	T	?	T	T	S	?
LEGUMES								
Aeschynomene falcata	Jointvetch	2120	T	?	?	T	T	?
Arachis pintoi	Forage peanut	1080	T	?	T	M	M	?
Chamaecrista rotundifolia	Round-leafed cassia	2240	T	?	T	T	S	?
Lotononis bainseii	Lotononis	1050	T	T	T	T	S	?
Lotus pedunculatus	Lotus trefoil	1960	T	?	T	M	?	?
Macroptilium atropurpureum	Siratro	310	T	S	S	T	T	M
M. lathyroides	Phasey bean	540	T	M	S	S	T	?
Ornithopus compressus	Yellow serradella	840	T	T	?	T	?	?
Stylosanthes guianensis	Common stylo	1120	T	T	T	T	T	S
S. guianensis var. *intermedia*	Fine-stemmed stylo	1620	T	T	T	T	T	T
Trifolium repens	White clover	420	S	S	S	S	S	?
T. subterraneum	Subclover	620	S	S	S	S	S	?

[1] Mean of evaluations conducted at Lechang Farm with variable fertiliser regimes and with and without companion legume (or grass) on unamended Hapludult soil (Michalk and Huang 1994a; 1994b).

[2] Based on Andrew and Robins (1969; 1971); Andrew and Hegarty (1969); Andrew *et al.* (1973); Andrew and Vanden Berg (1973); Spain *et al.* (1975); Sanchez (1976); Michalk and Huang (1992; 1993; 1994a; 1994b); and personal observation.

[3] T = tolerant; S = susceptible; M = moderately tolerant; and ? = tolerance unknown.

DM over 3 years, was the most profitable combination, but it was also the most risky (D.L. Michalk, unpublished data). If the rule for low-input technology of only recommending fertiliser rates which return more than $1.5/$1 invested is adopted (Sanchez 1976), the recommendation is to apply 7 kg/ha P and 50 kg/ha K which would produce 75% of maximum yield and return yuan 2.9 for each yuan invested in fertiliser ($A1 = 4 yuan).

However, while the P_7K_{50} combination may be economically attractive, higher rates of both nutrients may be required to sustain pasture yields in the medium term, and to ensure that soil improvement proceeds as quickly as possible. In severely P-deficient soils, for example, available P may so limit microbial growth that application of P fertiliser can significantly increase the quantity of N mineralised (Munevar and Wallum 1977) and increase the rate of organic matter accumulation due to higher pasture production. Microbial activity of the soil is also increased by liming acid soils, as is the CEC of these variably charged Hapludults (Table 2).

Making use of favourable soil attributes

Despite their acidity and low nutrient levels, many Oxisols and Ultisols have desirable features. For example, by keeping the soils acid, the solubility of slowly available but cheaper P fertiliser (e.g. rock phosphate) is higher than if the soil is limed, and weed growth may be decreased considerably compared with a limed and well fertilised soil (Sanchez and Salinas 1981).

More importantly, the low CEC and good structure of these soils assist the downward movement of calcium and magnesium to the subsoil (Sanchez 1976). The subsoil of most Oxisols and Ultisols is usually quite acid and can present a chemical barrier to root development either because of Al toxicity, extreme Ca and Mg deficiencies, or both. It is common to observe roots confined to the topsoil and for plants to suffer water stress when drought periods occur even though there is ample subsoil moisture (Sanchez and Salinas 1981).

The effect of limited rooting depth was examined at Lechang Farm using moisture and growth indices of the type described by Fitzpatrick and Nix (1970). Over a 6-year period (1981-1986), the soil moisture budget indicated that moisture would limit growth for less than 5% of the time when plant roots were assumed to be using the top 70 cm of the profile (unrestricted root depth — Figure 1). However, field observations indicated that most roots were restricted to the top 10 cm of the profile, and when the model was run using this root depth restriction, plants were stressed for more than 30% of the time and, for approximately 13 weeks/year, the moisture index was zero (Figure 1). The growth index averaged over the 6 years showed that water stress reduced potential growth by about 44% (Figure 1).

Al toxicity in the subsoil of Lechang soils was reduced by rapid downward movement of Ca and Mg. Fourteen months after liming with 4 t/ha, soil monitoring detected substantial movement of Ca and Mg from the topsoil down to 40 cm (Table 2). The rapid movement is related to the

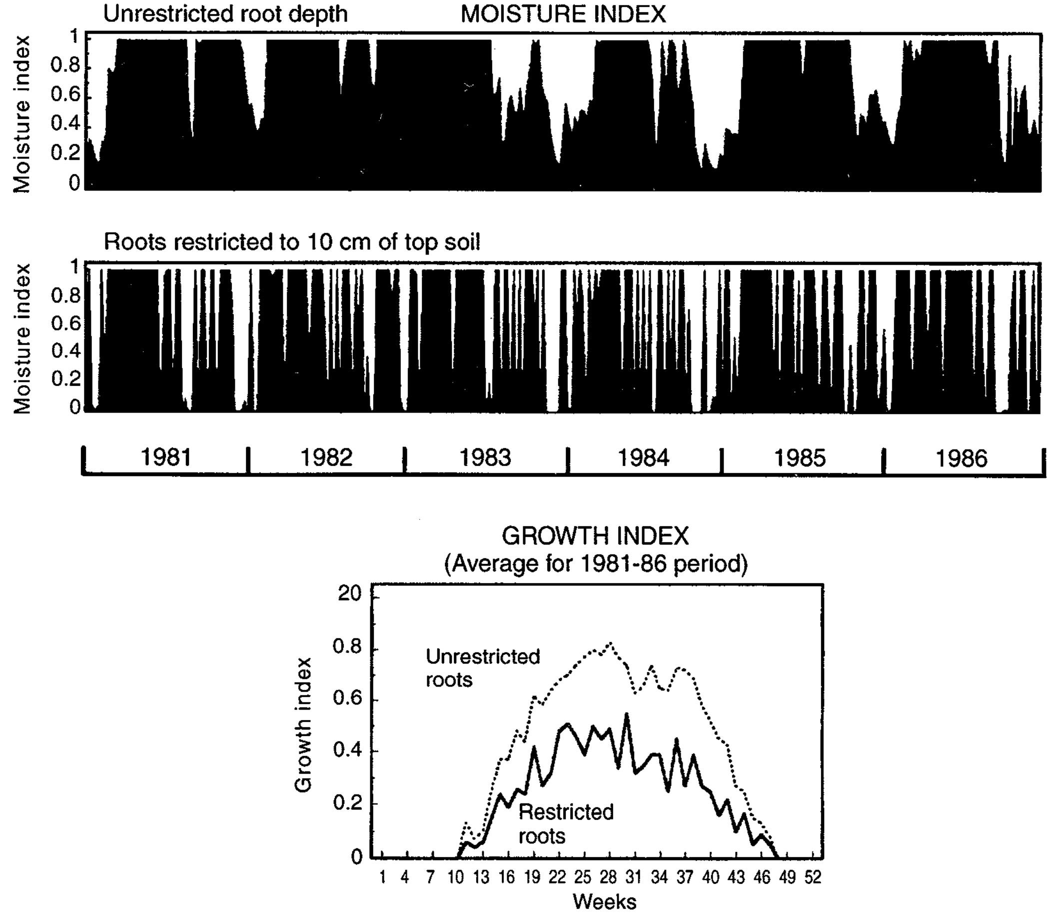

Figure 1. Effect of plant rooting depth on moisture and growth indices for tropical legume-based pastures at Lechang Farm.

high annual rainfall, the porous nature of the well aggregated soils, and their low permanent charge (8 meq/100 g clay at pH 7.7) (Yu and Zhang 1986). Once the permanent charge sites are saturated, exchangeable Ca and Mg held on the pH-dependent charge sites are likely to move down the profile fairly easily (Sanchez 1976).

However, the rapid downward movement also has a major influence on the residual effect of lime. At Lechang Farm, exchangeable Ca and Mg in the top 10 cm of the profile decreased by 5 meq/100 g over the 14 months (Table 2), and Al saturation increased from 0 to 20% (Michalk and Ryan 1989). Based on this re-acidification rate, an annual maintenance application of about 500 kg/ha lime is needed to ensure an adequate supply of Ca and Mg in the top soil and to keep Al saturation below 10%.

Table 2. Downward movement of Ca and Mg 14 months after lime treatment of Lechang soil (Michalk *et al.* 1988).

Depth	pH (NaCl)			Exchangeable cations					
				Ca & Mg			Al		
	0[1]	7	14	0	7	14	0	7	14
(cm)				(meq/100 g)					
0-10	4.1	5.9	4.7	0.26	8.0	2.9	2.2	0.0	0.8
10-20	4.3	4.4	4.3	0.20	0.9	0.7	2.1	1.5	1.6
20-30	4.3	4.4	4.4	0.14	0.4	0.8	2.1	1.6	1.6
30-40	4.3	—	4.3	0.08	—	0.3	1.9	—	2.0
40-50	4.2	—	4.3	0.11	—	0.1	2.0	—	2.0

[1] Months after 4 t/ha lime was incorporated.

This maintenance rate is consistent with those recommended for similar soils in South America (Sanchez and Salinas 1981). Over time, however, less frequent lime application may be required as the loss of exchangeable cations is reduced due to higher levels of organic matter.

Importance of soil organic matter

For sustained soil improvement, soil organic matter must first be increased from the present levels. A soil survey undertaken in 1986 indicated that the 2.5 million hectares of acid soils in the 12 counties in Shaoguan Prefecture have an average organic matter content of 3.4%. However, the 30% of this area occupied by the soils coded in the Chinese classification as groups 4-1-5 and 4-1-7, averaged less than 3.0% with a range of 0.8–4.0% in the top 25 cm of soil (Anon. 1985).

Soil organic matter is important because it: (1) starts the recycling process of plant nutrients; (2) improves the water-holding capacity of the soil surface layers; and (3) improves the ability of the soil to retain plant nutrients in the root zone. Figure 2 shows that when soil organic matter of Hapludult soils at Lechang Farm was increased from 2 to 5%, the CEC increased by more than 50%.

Grazing strategies (particularly grazing pressure) are the key to management of the organic matter and nutrient condition of tropical

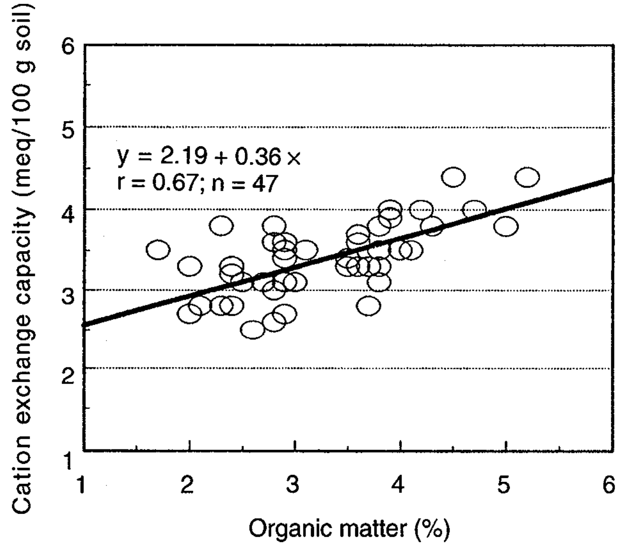

Figure 2. Effect of soil organic matter level on cation exchange capacity of Hapludult soils at Lechang Farm.

soils (Williams and Chartres 1991). Since soil improvement is not taking place under current traditional grazing practices, changes in management are required. Appropriate management may require acceptance of short-term losses in livestock production to guarantee long-term soil improvement. This approach should be acceptable to Chinese farmers since livestock production levels on unimproved soils are much lower than those possible with conservative management on pioneer pastures.

Strategy for soil improvement

Depending on the base fertility level, there are several stages of soil improvement through which individual paddocks must advance before high beef production can be realised, or before alternative cropping enterprises can be considered.

A strategy for improvement of soils, identified by a survey undertaken in 1981 as belonging to the Lechang groups (4-1-5 and 4-1-7), was developed using research data collected at Lechang Farm between 1986 and 1989. Details of the objectives and methods used in each stage of improvement are provided in the following sections.

Stage 1: Initial improvement with pioneer pasture species

Legume-grass combinations are required for initial improvement. For example, in acid infertile Oxisols of the Llanos in Colombia, a mixture of molasses grass and common stylo is the most successful combination (Spain 1975). In north Guangdong Province, molasses grass-cassia was recommended for Stage 1 improvement (Table 3). A low rate of setaria may also be included to take advantage of initial improvement of soil and lift the quality of the pasture for cattle.

Pioneer pasture species must be adapted to low fertility, acid soils. Cassia stands out as the favoured pioneer legume for use on red soils in subtropical China for the following reasons: (1) high dry matter production with minimal fertilisation; (2) ease of establishment; (3) quick ground cover to prevent soil loss; (4) good regeneration from seed; (5) high survival of established plants over winter; (6) high production of seed which is readily harvested by hand; and (7) no observed insect or disease damage. Molasses grass also rapidly formed thick swards in the establishment year with minimal fertiliser inputs. Further, unlike other acid soil-tolerant grasses (e.g. signal grass), molasses grass is susceptible to fire (Table 1) and can easily be removed by strategic burning (Sanchez 1976) to make way for more palatable species.

In addition to the 5000 kg/ha/yr DM of top-growth produced by molasses grass-Wynn cassia pastures, a large amount (>6000 kg/ha/yr DM) of root material is left in the soil. The effect of residual dry matter on the rate of accumulation of organic matter in soil carrying dense molasses grass-cassia pastures is yet to be determined. However, experiments in Jiangxi Province showed that 6 consecutive years of green manure crops doubled soil N (0.04 to 0.09%) and P (0.03 to 0.08%), and increased soil organic matter from 0.6 to 1.6% (He *et al.* 1990). It is also expected that organic matter will increase under molasses grass-cassia pastures with medium-term improvement leading to higher total herbage production due in part to increases in the CEC and nutrient cycling.

Table 3. Proposed strategy for soil improvement and pasture development for Shaoguan Prefecture.

Stage	Time (years)	Pasture-crop program
Stage 1	1-3	Sow cassia-molasses-setaria mixture.
Stage 2		**Option 1**
	4-8	Oversow with Oxley stylo
		Option 2
	4	Lime, plough, sow winter forage.
	5-9	Then:
		(1) Re-sow lotononis-setaria in spring
		OR
	5	(2a) Cash crop in spring with beans or peanuts;
	5	(2b) Forage (oats-vetch) in winter;
	6-10	(2c) Sow to lotononis-setaria in following spring. (**Note:** Oxley stylo can be sown with or as an alternative to lotononis).
	9-13	Paddocks treated as Option 1 must be treated as Option 2 before proceeding to Stage 3.
Stage 3	11-?	Soil fertility improved enough to grow more productive and better quality tropical legumes, tropical grasses and temperate species.

1. This program is based on limited observations over 3 years at Lechang Farm, and experience of pasture development in tropical-subtropical areas elsewhere.

2. To achieve the anticipated soil improvement, it is assumed that all pastures and crops are adequately supplied with initial and maintenance fertiliser inputs.

Since cassia-molasses grass pastures are poorly utilised by cattle, the criterion of $1.5/$1 invested in fertiliser may need to be modified for Stage 1 to take into account the value of soil improvement rather than direct benefits from livestock production.

Stage 2: Replacement of pioneers with better species

In general, pioneer species which are tolerant of soil acidity and low levels of P and K, also have low palatability to livestock. Since pasture production has no direct value until converted into a saleable product, it is necessary to replace pioneer species with more nutritious grasses and legumes as quickly as possible. Two options are available to achieve this transition.

Option 1. As soil improves with minimal fertiliser inputs and soil organic matter is increased during Stage 1, pioneer species can be replaced with acid-tolerant species better suited to cattle production, but which require higher fertiliser inputs for sustained production. Of the species tested, the combination of setaria (particularly cv. Narok) with lotononis or Oxley stylo shows promise for summer grazing on unlimed soil when adequately fertilised with P and K. These species require higher soil fertility to establish and persist, and although dry matter yields may not be greater than for Stage 1 species, their quality and acceptability to cattle are superior. Good management, which is also important to the maintenance of stable swards of these species, is described by Michalk *et al.* (1994).

Option 2: Further flexibility in species selection may be possible in Stage 2 development if lime is used to reduce the Al-saturation level. Studies show that production of grasses with higher protein and digestibility such as green panic improves with lime application, but suitable companion legumes other than lotononis cannot be recommended on the basis of present data (Michalk and Huang 1994a). However, based on research elsewhere, it is anticipated that the yield of siratro, greenleaf desmodium and centro will increase when grown under higher fertiliser regimes on soils improved by Stage 1 treatment or with lime application.

Lime application also provides the opportunity for cash crops (beans or peanuts) and winter forage crops (oats-vetch) to be grown prior to establishment of Stage 2 pastures. In addition to generating income and providing more feed for cattle in winter, annual grain and fodder crops also provide a break in the pasture sequence to assist with control of weeds, pests and diseases.

Stage 3: High production pastures

Only after several years of rebuilding soil fertility and nutrient cycling under grazed permanent pasture is the establishment of higher quality species likely to be a feasible option. The importance of the prior improvement phases was demonstrated at Lechang Farm by the failure of temperate species sown on “unimproved” soil to reach expected potential even with high fertiliser inputs (600 kg/ha superphosphate; 300 kg/ha potash; 4 t/ha lime). Similarly, the production of subtropical species such as green panic, kikuyu and common paspalum, which have the capacity to grow under cool conditions, was limited by soil fertility (Michalk and Huang 1994b).

These examples highlight the importance of soil improvement in the development of pasture systems to alleviate the winter feed shortage, and the inability of inorganic fertilisers alone to solve fertility problems in these soils.

Succession and degradation in pastures

The strategy for soil improvement outlined in Table 3 is an example of succession created by manipulating soil fertility through fertiliser inputs and species introductions. Succession is the process of community change in which one group of species is replaced by another when the environment or management is changed. Such change in pasture composition may provide a useful guide to soil improvement produced by planned improvement strategies. For example, a change from legume to grass dominance under a management strategy known to maintain legumes may signal an increase in soil nitrogen resulting from legume-fixed N or N release from accumulated organic matter.

Changes in species dominance were observed in Stage 1 pastures at Lechang Farm over a 3-year period with molasses grass being replaced by cassia in Year 2, and setaria (sown at a low rate in Year 1) becoming a co-dominant in Year 3. The inability of cassia to compete with setaria may be due to both the ability of setaria to absorb K at a greater rate from low K soils (Whelan and

Edwards 1975) and the high density of grass roots compared with the legume (Kerridge *et al.* 1986).

Degradation is the reverse process in which less desirable species invade pastures as soil fertility declines, or where sown pasture species cannot compete and persist under the management imposed to take advantage of the existing or improved soil fertility. For example, slow regrowth of perennial ryegrass in temperate-based pastures at Lechang Farm enabled native grasses and weeds to invade and utilise the N fixed by white clover grown on limed soil.

Such observations of succession or degradation may indicate whether the correct grazing management, fertiliser and soil improvement strategies have been used.

Soil improvement with crops

Soil can also be improved through cropping. Research conducted on red soils in Jiangxi Province has identified sweet potato, some peanut cultivars, mung beans, radish, rye, buckwheat, vetch and cassava as crops which are adapted to acid soils with minimal or no fertiliser inputs (He *et al.* 1990). Like pastures, crops which require high fertility completely fail or produce only low yield unless extremely high rates of multi-nutrient fertiliser are applied.

The breakdown of residues of acid-tolerant crops may also improve soil sufficiently over time to enable soybeans, sorghum, corn and sesame to be planted in spring and summer, and rape, vetch, wheat, radish and cabbage to be planted in autumn and winter to provide further crop residues. Only when the soil is improved still further, usually through the application of large amounts of barnyard manure, can cotton, sugar cane and ginger be planted to obtain economic yields.

Discussion

It was once thought that Oxisols and Ultisols could not support productive and sustained agricultural activities in the tropics and subtropics, but there is now ample evidence to indicate that they can be used for crop and pasture production provided the general principles of low-input soil management technology are applied (Sanchez and Salinas 1981). Using the limited data and observations from Lechang Farm, we have suggested in this paper a model on which to build a program to improve soil through conservation of organic matter, nutrient recycling and fertiliser application at minimum cost and risk.

Concerns have been expressed that the use of plants tolerant of acid soil constraints and minimal fertiliser inputs may completely deplete the low nutrient reserves of soils like the Hapludults in north Guangdong and render them totally useless in the medium to long term (Sanchez and Salinas 1981). However, analysis of nutrient status of such low-input systems provides no evidence of depletion of soil reserves, but rather a gradual increase, particularly in grazed pasture systems, where approximately 80% of the major nutrients (except nitrogen) consumed by cattle are returned to the soil via excreta (Mott 1974).

While further research is required to refine the low-input, soil-improvement strategy described, we are certain that it is the approach most likely to lead to sustained pasture development on the red soils in south China. The alternative approach of trying to eliminate the major soil constraints by applying massive inputs of fertilisers and soil modifiers is beyond the resources of both peasant farmers and larger commercial enterprises.

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References

ANON. (1985) *Shaoguan Soils.* (Shaoguan Soil Testing Office: Shaoguan Prefecture, Guangdong Province, China).

ANDREW, C.S. and HEGARTY, M.P. (1969) Comparative responses to manganese excess of eight tropical and four temperate pasture species. *Australian Journal of Agricultural Research,* **20,** 687-696.

ANDREW, C.S. and ROBINS, M.F. (1969) The effect of potassium on the growth and chemical composition of some tropical and temperate pasture species. *Australian Journal of Agricultural Research,* **20,** 999-1021.

ANDREW, C.S. and ROBINS, M.F. (1971) Effects of phosphorus on the growth, chemical composition and critical phosphorus percentages of some tropical pasture grasses. *Australian Journal of Agricultural Research*, **22,** 693-706.

ANDREW, C.S., JOHNSON, A.D. and SANDLAND, R.L. (1973) Effect of aluminium on the growth and chemical composition of some tropical and temperate pasture legumes. *Australian Journal of Agricultural Research*, **24,** 693-706.

ANDREW, C.S. and VANDEN BERG, P.J. (1973) The influence of aluminium on phosphate sorption by whole plants and excised roots of some pasture legumes. *Australian Journal of Agricultural Research*, **24**, 341-351.

CIAT (1973) Annual report, Centro Internacional de Agricultura Tropical, Palmira, Colombia [cited by P.A. Sanchez (1976), *Properties and Management of Soils in the Tropics*, (John Wiley and Sons: New York)].

FITZPATRICK, E.A. and NIX, H.A. (1970) The climatic factor in Australian grassland ecology. In: Moore. R.M. (ed.) *Australian Grasslands*. pp. 5-26. (Australian National University Press: Canberra).

HAYNES, R.J. (1984) Lime and phosphate in the soil-plant system. *Advances in Agronomy*, **37,** 249-315.

HAYNES, R.J. and LUDECKE, T.E. (1981) Yield, root morphology and chemical composition of two pasture legumes as affected by lime and phosphorus applications to an acid soil. *Plant and Soil*, **62,** 241-254.

HE, DIAN-YUAN, LIU, CHONG-QUN and XIAO, KE-QIAN (1990) Utilisation and improvement of red earths in hilly regions. In: Institute of Soil Science, Academic Sinicia (ed.) *Soils of China*. pp. 705-723. (Science Press: Beijing).

KERRIDGE, P.C., EDWARDS, D.G. and SALE, P.W.G. (1986) Soil fertility constraints - Amelioration and plant adaptation. In: Blair, G.J., Ivory, D.A. and Evans, T.R. (eds) *Forages in Southeast Asia and South Pacific Agriculture. ACIAR Proceedings Series No. 12*. pp. 179-187.

MICHALK, D.L., SCHUHKRAFT, G.R. and KUANG, SHAO-JUN (1988) Range improvement on acid infertile soils in north Guangdong Province, China. *Proceedings of the Third International Rangeland Congress, New Delhi, India*. pp. 307-309.

MICHALK, D.L. and RYAN, W.J. (1989) A programme for soil improvement, pasture development, and cattle management for acid infertile soils in Shaoguan Prefecture. Final Report to the Animal Husbandry Bureau of Guangdong Province, Overseas Project Section, NSW Agriculture, 143 p.

MICHALK, D.L. and HUANG, ZHI-KAI (1992) Response of subterranean clover (*Trifolium subterraneum*) to lime, magnesium, and boron on acid infertile soil in subtropical China. *Fertilizer Research*, **32,** 249-257.

MICHALK, D.L. and HUANG, ZHI-KAI (1993) Response of white clover (*Trifolium repens*) to lime and magnesium on infertile acid soil in subtropical China. *Proceedings of the XVII International Grassland Congress, Palmerston North, Hamilton, Lincoln and Rockhampton*. pp. 1562-1563.

MICHALK, D.L. and HUANG, ZHI-KAI (1994a) Improvement of grasslands in subtropical Guangdong Province, China. 1. Evaluation of pasture legumes. *Tropical Grasslands*, **28,** 129-138.

MICHALK, D.L. and HUANG, ZHI-KAI (1994b) Improvement of grasslands in subtropical Guangdong Province, China. 2. Evaluation of pasture grasses. *Tropical Grasslands*, **28**, 139-145.

MICHALK, D.L., RYAN, W.J. and HUANG, ZHI-KAI (1994) Improvement of grasslands in subtropical Guangdong Province, China. 4. Development of a whole-farm grazing system. *Tropical Grasslands*, **28**, 155-163.

MOTT, G.O. (1974) Nutrient recycling in pastures. In: Mays, D.A. (ed.) *Forage Fertilization*. pp. 323-339. (American Society for Agronomy: Madison, Wisconsin).

MUNEVAR, F. and WALLUM, A.G. (1977) Effects of the addition of phosphorus and inorganic N on carbon and nitrogen mineralisation in andepts from Colombia. *Soil Science Society of America Journal*, **41,** 540-545.

SANCHEZ, P.A. (1976) *Properties and Management of Soils in the Tropics*. (John Wiley and Sons: New York).

SANCHEZ, P.A. and SALINAS, J.G. (1981) Low-input technology for managing oxisols and ultisols in tropical America. *Advances in Agronomy*, **34,** 279-406.

SPAIN, J.M. (1975) The forage potential of allic soils of the humid lowland tropics of Latin America. In: Doll, E.C. and Mott, G.O. (eds) *Tropical Forages in Livestock Production Systems. ASA Special Publication 24*. pp. 1-8. (American Society of Agronomy: Madison, Wisconsin).

SPAIN, J.M., FRANCIS, C.A., HOWELER, R.H. and CALVO, F. (1975) Diferencias entre especies y variedades de cultivos y pastos tropicales en su tolerancia a la acidez del suelo. In: Bornemisza, E. and Alvarado, A. (eds) *Manejo de Suelos en la America Tropical*. pp. 313-335. (North Carolina State University: Raleigh, North Carolina).

YU, TIAN-REN and ZHANG, XIAO-NIAN (1986) Physio-chemical properties of red soils of China. In: Li, C.K. *et al.* (eds) *Proceedings of the International Symposium on Red Soil*. pp. 409-441. (Science Press: Beijing).

VALDES, L.R., CLEMENTS, R.J. and JONES, R.M. (1987) Acceptability of *Cassia rotundifolia* to grazing cattle. *Annual Report 1986-87, Division of Tropical Crops and Pastures, CSIRO, Australia*. pp. 20-21.

WHELAN, B.R. and EDWARDS, D.G. (1975) Uptake of potassium by *Setaria anceps* and *Macroptilium atropurpureum* from the same standard solution culture. *Australian Journal of Agricultural Research*, **26,** 819-829.

WHITEMAN, P.C. (1980) *Tropical Pasture Science*. (Oxford University Press: Oxford, United Kingdom).

WILLIAMS, J. and CHARTRES, C.J. (1991) Sustaining productive pastures in the tropics. 1. Managing the soil resources. *Tropical Grasslands*, **25,** 73-84.

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