Soil Constraints for Sustainable Upland Crop Production in Humid and Sub-Humid West Africa

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ABSTRACT

Major upland soils in the humid and sub-humid zones of West Africa consist of low activity clays (LAC) Alfisols, Ultisols and Oxisols. Alfisols which are less leached and have a high base saturation are more dominant in the sub-humid zone. Chemically they are more fertile, but they have a low structural stability. The Ultisols/Oxisols which are more prevalent in the humid zone, are less fertile, with major nutrient and acidity constraints. The major constraints on sustainable crop production on these soils, can be removed by proper seedbed and residue management, and by judicious fertilizer application and by liming amendments. These measures are needed to ensure the maintenance of adequate chemical, physical and biological fertility of the soils. Prototype technology research in West Africa that seeks to improve productivity and sustainability on these LAC soils has shown, that minimum tillage and/or alley-cropping are promising technologies for managing these soils. Further research is still needed to refine these systems and to identify alternative systems for the region.

Introduction

Small-scale agricultural systems, based on traditional practices, predominate in tropical Africa. They range from extensive to intensive natural fallow systems, which may or may not include some modifications, such as the inclusion of higher-yielding and disease-resistant varieties. The length of fallow periods is closely related to demogaphic pressure and land quality. These systems, characterized by low productivity and high biological sustainability, are currently undergoing various degrees of degradation, which affect their stability, durability and their contribution to food production.

Alternative high-input and mechanized farming systems have been introduced and tested, with limited success, to boost food production in lowland humid and sub-humid tropical Africa. In many instances, such innovations have led to increased land degradation. The failure of these large scale farming systems, often attributed to socio-economic factors, is also due to the use of inappropriate soil management methods, based on a lack of understanding of the soil constraints. In this paper, the constaints and potential of the dominant upland soils in lowland humid and sub-humid West Africa are discussed, with examples of management options for sustainable and productive farming.

Concept of sustainable farming

The concept of agricultural sustainability has received much attention recently, but sustainability means different things to different people. Agricultural sustainability and productivity have been a goal of the Consultative Group on International Agricultural Research (CGIAR) from its inception in the 1970s (CGIAR, 1990). Since agricultural

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sustainability, is a dynamic concept, the CGIAR has defined sustainable agriculture as: "The successful management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the quality of the environment and conserving natural resources". A comprehensive definition reached by the American Society of Agronomy describes sustainable agriculture as one: "that over the long term enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs, is economically viable, and enhances the quality of life of farmers and society as a whole" (Anon., 1989).

In the simplest sense, sustainability is the ability of a production (cropping) system to produce a stable annual yield of the desired crop over a long period of time. The length of time that would be acceptable as a measure of sustainability is undefined and could be set arbitrarily for each particular environment and set of socio-economic circumstances. Pragmatic boundaries could be set for the fluctuation of yield around the long-term mean [e. g. by utilizing the reciprocal of the coefficient of variance of the annual mean fluctuation (Conway, 1985)] . This type of restricted definition is useful to the biophysical scientist, as it sets a recognizable production goal (stable yield of diverse high quality crops over a long term) and at the same time, it establishes a definable boundary (the cropping system) for examining the quality and maintenance of renewable and non-renewable resources particularly those of soil. Non-renewable loss includes physical loss of soil by erosion. Nutrient depletion may or may not be renewable within the physico-chemical and biological capacity of the soil. Measurement of soil resource sustainability and degradation may thus include assessments of processes affecting erosion, compaction, depletion of nutrients and acidification, as well as their alleviation. This is the sustainability concept used in this paper.

Soil constraints for crop production

The combination of growing periods and the soil resource base differentiates the major agro-ecological zones and their land use potential for crop production. The humid forest zone, with perudic and udic moisture regimes, covers areas with a growing period of $\geqq$ 270 days, while the sub-humid wooded savanna zone, with udic-ustic moisture regimes, covers areas with a growing period of 160 to 269 days. These two agro-ecological zones cover about 87.8% of West Africa, stretching from Cameroon to Senegal, with a total area of 280 million hectares. Major upland soils in these zones consist mainly of Oxisols (Ferralsols), Ultisols (Acrisols), Alfisols (Luvisols, Nitosols) and Psamments (Regosols). Oxisols and Ultisols (24%) occupy a large part of the humid zone, whereas Alfisols (73%) are more extensive in the sub-humid zone (Fig.1).

Although the low activity clays (LAC) soils are defined as soils with an effective cation exchange capacity (ECEC) of $<$ 16 meq/100g clay in the subsoil (i. e. B horizon) (Juo and Adams, 1986), observations in West Africa have shown that the majority of the LAC soils have ECEC $<$ 8meq/100g. The clay fraction is composed mainly of kaolinite and halloysite, with oxides and hydrous oxides of Fe and Al. Within the commonly observed soil pH-H_2O range of 4.0 to 6.0, these inorganic soil components contribute little to the soil cation exchange capacity (CEC) (Juo and Adams, 1986). Soil organic matter contributes a major portion of CEC in the surface soil of Alfisols with pH-$H_2O > 5.0$, with lesser effect in the acidic Ultisols and Oxisols with pH-$H_2O < 5.0$. Because of the presence of variable charge clays in the LAC soils, the ECEC of the particularly acid soils can be raised by liming and or the addition of P or silicates. The soil CEC plays an important role in nutrient retention and soil aggregation in these LAC soils.

Alfisols and associated soils

The Alfisols that are less leached have a lower acidity but high base saturation (>35%

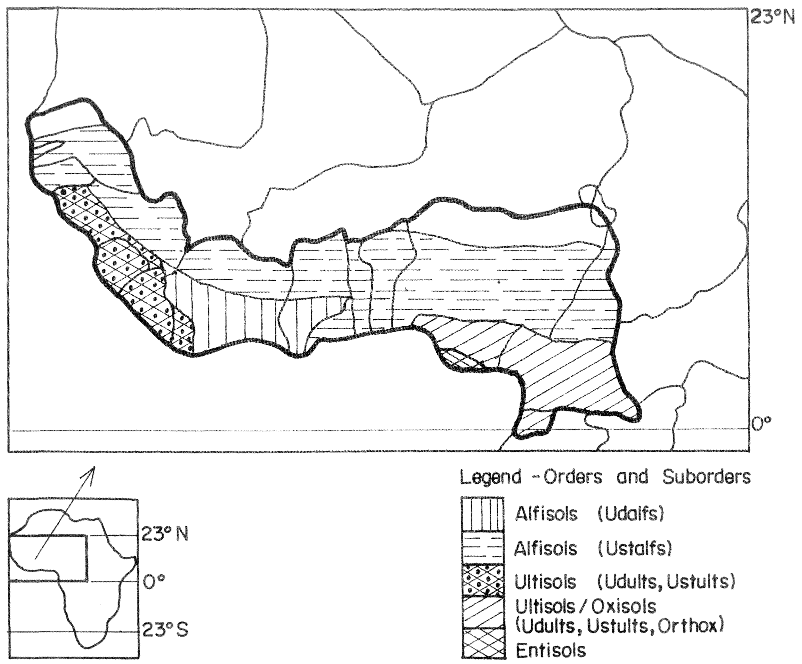

Fig. 1 Distibution of major soils in humid and subhumid tropical West Africa.

Table 1 Some chemical characteristice of surface soils of Alfisols and Ultisols from southern Nigeria

pH-H_2O	Org. C (%)	Exchangeable cations Ca	Mg	K	Na	Total acidity	ECEC	Base saturation	Bray-P	Hws-B	DTPA-Extr. Cu	Fe	Mn	0.1N HCL Extr. Zn
		meq/100g						(%)	ppm					
		*Egbeda soil (Oxic Paleustalf), Ibadan												
6.4	1.82	3.80	1.63	0.27	0.04	0.04	5.78	99.1	7.35	0.86	1.20	24.0	36.0	68.0
		**Alagba soil (Oxic Paleustalf), Ikenne												
6.1	1.82	3.90	1.87	0.14	0.04	0.12	6.07	98.0	8.40	0.47	0.06	20.0	30.0	2.40
		*Nkpologu soil (Oxic Palgustult), Nsukka												
4.5	1.02	0.40	0.32	0.08	0.08	1.44	2.32	37.9	9.10	0.24	0.20	32.0	3.3	0.70
		***Onne soil (Typic Paleudult), Onne												
4.3	1.04	0.26	0.09	0.07	0.02	2.08	2.52	17.5	141.0	1.20	0.62	174.2	2.8	1.50

*Derived from basement complex rocks.
**Derived from sedimentary material.
***Derived from marine sediments.

of ECEC in the subsoil) and their fertility is low to moderate (Table 1). Benefits from N, P, and K application on the Alfisols have been well-documented for continuous crop production (Kang, 1989). With intensive cropping, N is the primary limiting nutrient, followed by P. Potassium is generally needed with long-term continuous cropping, particularly on soils derived from sedimentary rocks. The Alfisols and associated soils have low P fixation and high residual effects from applied P. In addition the presence of mycorrhiza is common and effective on these soils, resulting in a low P reqirement for crop production.

Continuous cultivation and fertilizer application can also significantly affect the properties of Alfisols and associated soils. Cropping, and in particular continuous fertilizer application, reduces soil pH, soil organic matter, and extractable cations. Lowering of soil pH on the Alfisols can result in increased toxic levels of Al and Mn (Kang, 1989).

The Alfisols show a significant clay increase with depth, and part of the clay fraction is readily dispersible in oxic Alfisols. The Alfisols (with the exception of Nitosols, which have a high structural stability) with coarse-to medium-textured surface horizons, and a sharp transition to clay B horizons, have a less stable structure, and are subject to soil compaction and erosion.

Ultisols and Oxisols and associated soils

The highly weathered and leached Oxisols and particularly Ultisols are acidic, with low base saturation (<35% of ECEC in the subsoil). Both soils have very low nutrient levels in the soil solution and consequently a low capacity to provide nutrients to crops. The low productivity of these acid soils has in addition been attributed to Al and Mn toxicity. In many earlier studies, acid soils in the humid tropics were limed to neutral pH, with generally poor results due to nutrient imbalance. Following the findings of the 1950s that acid soils contain more exchangeable Al^{3+} than H^{+}, primary consideration has been given to the removal of toxic factors which limit plant growth (Kamprath, 1984). Research on acid soils in West Africa has confirmed these findings. Low lime rates are needed to reduce toxic levels of Al^{3+} and Mn^{2+}, and application of 0.5 to 1.0 t lime per hectare was found to be adequate for highly acid soils (IITA, 1985). These soils are usually also deficient in P. Rock phosphates can be used on unlimed acid soil as an inexpensive and efficient way of supplying P to acid tolerant crops (Juo and Kang, 1979).

The physical properties of Ultisols are similar to those of Alfisols, but djfferent from Oxisols. In the Oxisols, the clay is highly resistant to dispersion. The Oxisols have more stable aggregation, throughout the soil profile, which results in good infiltration and water transmission and low erodibility (Lal and Greenland, 1986).

Soil biological factors

Soil biological activities have a pronounced effect on the productivity of these LAC soils. Soil biological processes contribute to fertility by increasing the amount and efficiency of nutrient acquisition (and recyling) by vegetation, by the synthesis and breakdown of soil organic matter, by regulation of the retention and flow of nutrients, and by the maintenance of a good soil physical structure and water regimes (particularly through the action of the soil fauna). There is however only limited information on any of these processes for the LAC soils of West Africa.

Soil organic matter levels may under natural vagetation be comparable with those for the same soil type in temperate region, but the rate of decline under cultivation is higher in the tropics. There is no fundamental reason to believe, however, that the balance between plant residue decomposition and soil organic matter synthesis is any different in tropical soils than in the temperate zone (Ayanaba *et al.,* 1976), which offers the potential for managing soil organic matter levels through organic inputs. This is the basis of the fertility control systems described in the next chapters

Among the soil macro-fauna, the activities and effects of termites and, especially, earthworms, which show a high activity on the Alfisols, are the most studied. The mound-building termites are known to play an important role in the recycling of fine soil particles from deeper soil layers. This creates a high degree of soil variability at the surface, which results in infertile spots mainly due to the higher clay content and poorer structure (Kang, 1978). In contrast, earthworm activities show more beneficial effects on soil productivitv and crop performance. Earthworms play an important role in litter decomposition, and through their casting activity can contribute to biological tilling of the soil. It was estimated that the annual rate of soil turnover due to earthworm activity can reach a value as high as 50 t/ha per year (Nye, 1955). In addition, the wormcasts show a higher nutrient content, soil aggregation, and microbial content than the corresponding surface soil. But continuous cultivation can result in a drastic decline of earthworm activity, particularly with the removal of crop residues (Kang and Juo, 1986). Perfect *et al.* (1981) also observed marked changes in the soil faunal population and microbial activities following forest clearing and subsequent cultivation in southern Nigeria. They reported that the application of pesticides, such as DDT, caused a significant reduction in the populations of microarthropods, and the effect became more pronounced with successive years of cropping.

Although most of the LAC soils are well-endowed with a wide range of rhizobia, inoculation with appropriate strains can sometimes be beneficial for some annual and perennial legume species, such as soybeans or *Leucaena leucocephala.* On the Ultisols and Oxisols, liming and P application also promote nodulation and N_2 fixation.

Alleviation of soil constraints for crop production

Both the LAC Alfisols and Ultisols, as well as associated soils which have a low structural stability, are prone to physical degradation (or compaction). This condition is thought to occur where the soil has<10% of soil volume occupied by pores>50 μm in diameter (transmission pores) and <10% of soil volume occupied by pores 0.5-50 μm in diameter (retention pores) (Greenland, 1979). Thus, a compacted soil has high values of bulk density and soil temperature, and low values of infiltration rate, total porosity, soil water retention, hydraulic conductivity (Table 2) and mean weight diameter of aggregates (Lal, 1987).

Table 2 Effect of tillage method on soil physical properties of an Alfisol in western Nigeria

Tillage treatment	Bulk density	Porosity (%)	Water stable aggregates>2.36mm (%)	Saturated hydraulic conductivivy (mm/h^{-1})
Uncultivated control	1.15	55.9	79	1,150
No till age	1.42	49.2	48	440
Plow	1.48	46.0	23	200
Plow+harrow	1.51	44.1	15	150
LSD (0.05)	0.03	2.3	5	40

Source: Aina, 1979.

Soil compaction is caused by raindrop impact and by human, animal, and mechanical traffic. Raindrop impact also results in the breakdown of surface soil aggregates, leading to the formation of surface crusts. Both soil compaction and surface crusting, observed on cropped land, reduce the infiltration rate, which in turn increases water runoff and soil erosion during the high intensity rainstorms characteristic of the West African region. Water runoff and erosion may also be increased through saturated overland flow due to the reduction in the total soil porosity brought about by soil compaction (Lal, 1987). The eventual result is, therefore, a highly degraded soil. Past research has indicated that such physically degraded soils may be ameliorated by fallowing with an approp riate herbaceous or perennial shrub species, as illustrated in Tables 3 and 4.

Sustainable crop production is dependent upon the elimination or minimization of soil erosion and compaction. Results of investigations in West Africa have shown two possible alternatives for minimizing the soil structural deterioration under long-term cropping: (1)

Table 3 Effect of 2 year fallow, using herbaceous species, on selected soil physical properties in the 0-0.1m depth of an Alfisol in western Nigeria

Fallow	Bulk density	Infiltration rata (mm/h)	Soil water retention (%) at	
			−10kPa	−30kPa
Brachiaria ruziziensis	1.34	190	18.7	12.6
Paspalum notatum	1.35	140	19.5	14.3
Cynodon nlemfuensis	1.30	180	19.7	13.5
Pueraria phaseoloides	1.32	160	18.4	14.4
Stylosanthes guianensis	1.33	160	19.1	14.6
Stizolobium deerangium	1.33	210	19.0	14.2
Centrosema pubescens	1.33	180	18.4	15.2
Psophocarpus palustris	1.14	420	18.8	14.9
Weed fallow	1.42	130	15.7	14.5
Preseeding	1.50	90	17.1	14.5
LSD (0.05)	0.04	170	2.7	2.8

Source: Lat *et al.*, 1979.

Table 4 Effect of shrub species planted in hedgerows on selected soil physical properties of the 0-0.05m depth of the inter-hedegrow space

Shrub species	Bulk density	Infiltration (mm/min)	Soil water content at saturation (%)
Gliricidia sepium	1.33	2.53(0.93)*	47.5
Leucaena leucocephala	1.31	1.59(0.46)	46.5
Alchornea cordifolia	1.37	1.96(0.67)	4.14
Acioa barteri	1.34	2.87(1.05)	40.0
Control	1.41	0.79(−0.23)	39.4
SE±	0.031	(0.20)	1.81

*Values in parentheses are log transformed values.
Source: Hulugalle and Kang, 1990.

applying adequate external or an *in situ* mulch on the soil surface to protect it from the erosive and compactive effects of high-intensity rainfall, and (2) eliminating or minimizing soil disturbance over the crop area (Lal, 1987). A major disadvantage of using external mulch is the difficulty in obtaining sufficient quantities and the cost involved. Both of the above interventions may be achieved with the use of production systems where mulch production occurs *in situ*, such as in reduced tillage (Lal, 1983) or alley-cropping systems (Kang and Wilson, 1987).

Although soill fertility problems on the LAC soils can be corrected by liming and appropriate fertilization, socio-economic constraints often limit the application of these crop production technologies in many areas in West Africa. Use of low chemical input systems, based on one or more of the fallowing practices, has shown varying degrees of success: use of acid-tolerant cultivars cropping systems promoting maximum recycling of nutrients and maintenance of organic matter. Long-term research results on Alfisols have also shown that chemical soil degradation, resulting from continuous cultivation and fertilizer use, can best be controlled by the application of adequate amounts of organic material (Kang and Balasubramanian, 1990).

Fallowing and the addition of organic mulches, vhich affect the soil temperature and light intensity, are also known to influence the casting activity of earthworms and physico-chemical properties of the wormcasts on Alfisols. Figure 2 illustrates the differential effect

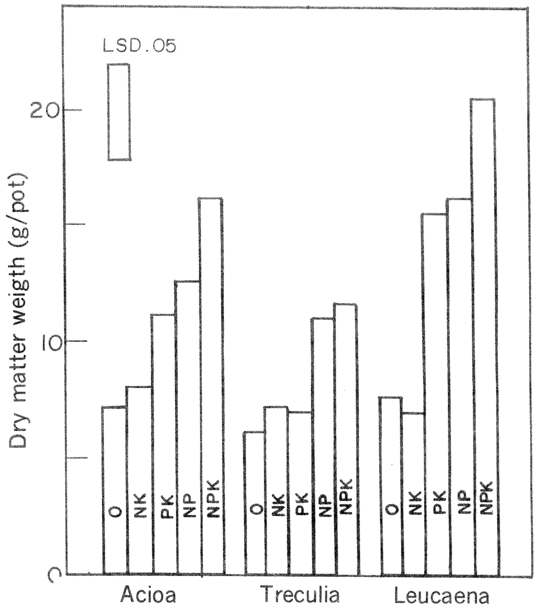

Fig. 2 **Day weight of maize in pot trial grown on wormcasts collected from plots (> 10 years old) of** *Acioa barteri, Treculia africana,* **and** *Leucaena leucocephala,* **as affected by fertilizer application. Plants harvested 4 weeks after planting (B. T. Kang and K. Akinnifesi, unpublished data).**

on maize in a greenhouse trial, grown in wormcasts collected from under three woody species. Wormcasts collected from under *Leucaena* show a higher fertility than those collected from *Acioa barteri* and *Treculia africana* plots with N and P applications. Response of maize to N was less pronounced when the plants were grown in wormcasts collected from under *Leucaena*. Thus, with proper selection of the fallow vegetation, soil biological factors can be manipulated for higher soil productivity.

Prototype production systems

Research results in the tropics have shown that there are a number of processes by which fallow vegetation sustains the productivity of these LAC soils. These are processes that contribute to the production and maintenance of adequate *in situ* mulch, soil protection, and recycling of nutrients. The prototype technology research at IITA seeks to couple biological processes with improved cropping systems, which will enhance stability and increase the efficiency of resource use. Following are two examples of potential prototype production systems.

Reduced-tillage system

In this system, preplanting land preparation is eliminated, except for the opening of a narrow (2-3cm) strip or hole in the ground for seed placement to ensure good seed-soil contact. The entire soil surface is covered by crop residue mulch or killed sod. Weeds are controlled either by herbicides (Lal, 1983) or by slashing immediately prior to planting (Wilson *et al.,* 1982). The system requires adequate mulch (Kang and Juo, 1986): with

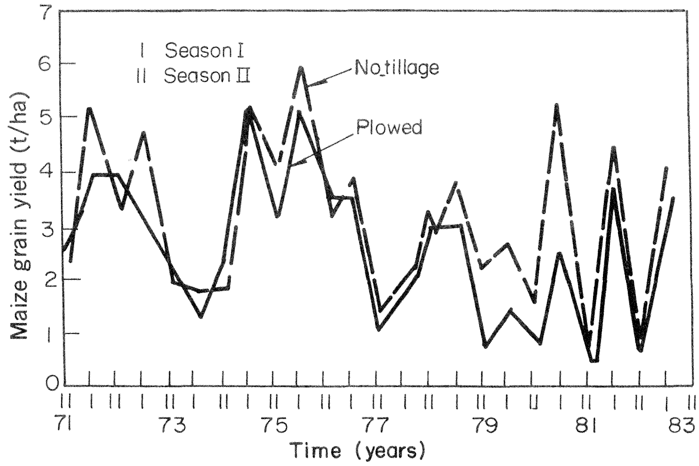

Fig. 3 Maize grain yield over 24 consecutive crops grown under a no-tillage system, compared with a conventional plough system (IITA, 1985).

sufficient mulch in a no-tillage system, maize yields can be sustained for a considerable period (Fig. 3).

Alley-cropping system

This agroforestry system involves the growing of food crops in alleys formed by hedgerows of trees and shrubs, preferably N_2-fixing leguminous species, that are periodically pruned during the crop growing season to minimize shading of the food crops. The pruning is used as mulch and green manure (Kang and Wilson, 1987). This system, which has most of the elements of the natural bush fallow system, can be practiced as a low chemical input and conservation farming technique. It has high potential for nutrient cycling that may reduce nutrient leaching losses. In addition, the system can provide much needed browse, staking material, and fuelwood (Kang and Wilson, 1987). Results of investigations on sloping land showed that alley-cropping gave a higher maize yield than no-tillage and tilled control treatments (Fig. 4). Long-term observation also showed that sustained and high crop yields can be obtained with alley-cropping (Fig. 4 and 5). Some elements of the alley-cropping system have been practiced by traditional farmers for generations in southeastern Nigeria. The alley-cropping and farming (which incorporate an animal production component) systems are currently being used in various parts of West Africa and elsewhere in the humid and sub-humid tropics. Further research is under way to refine the technology, particularly to identify a wider range of woody species and management options.

Preliminary results also show that the system has a potential for acid Ultisols if appropriate hedgerow species are used (Table 5). Alley-cropping with *Flemingia congesta, Cassia siamea* and *Acioa barteri* on an Ultisol in southern Nigeria has resulted in a higher cassava tuber yield than in the control treatment during the 1988/1989 cropping. Despite lower cassave population in the 1985/1986 cropping seasoe, there was no difference in the cassava yield between the control and the *Acioa* and *Cassia* treatments.

Conclusions and recommendations

The LAC soils, due to their inherent characteristice, have unique potentials, constraints,

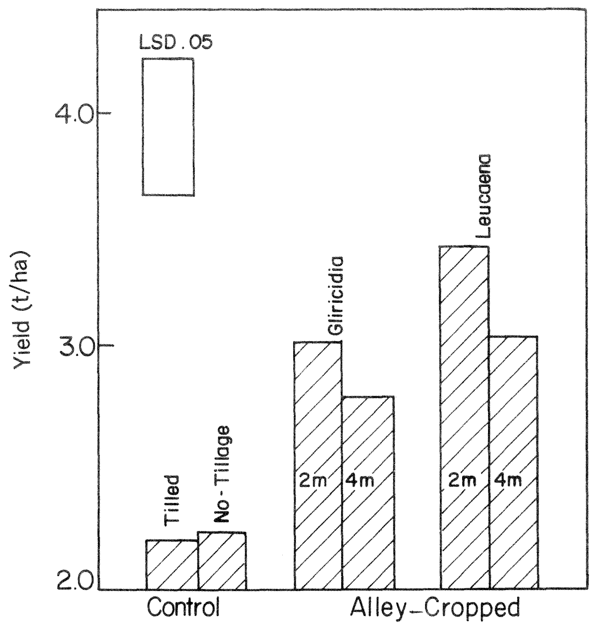

Fig. 4 Grain yield of maize on an Alfisol in the seventh cropping year as affected by tillage and alley cropping with *Leucaena leucocephala* and *Gliricidia sepium*. Alley-cropped plots were tilled with two inter hedgerow spacings of 2m and 4m (Kang and Ghuman, 1989).

Table 5 Effect of hedgerow species and fertilizer application on fresh cassava tuber yield (t/ha) at Onne, southeastern Nigeria

Hedgerow species	Fertilizer rate (N and K in kg/ha) 0	45	Mean
1985/86*			
Acioa barteri	15.0	16.0	15.5
Cassia siamea	13.2	17.2	15.2
Gmelina arborea	5.4	6.9	6.2
No tree control 14.2		16.0	15.1
Mean		11.9	14.0
1988/89**			
Acioa barteri	11.7	15.5	13.6
Cassia siamea	14.5	18.3	16.4
Flemingia congesta	19.0	18.2	18.7
Gmelina arborea	11.0	11.3	11.2
No tree control	9.6	13.7	11.7
Mean		13.2	15.4

*For this cropping year, control cassava stand 10,000 plants/ha; other treatments 6,667 plants/ha. Source: B. T. Kang, M. van der Kruijs, A. C. B. M. and Austin, P. D. unpublished data.
**Source: M. Gichuru, unpublished data.

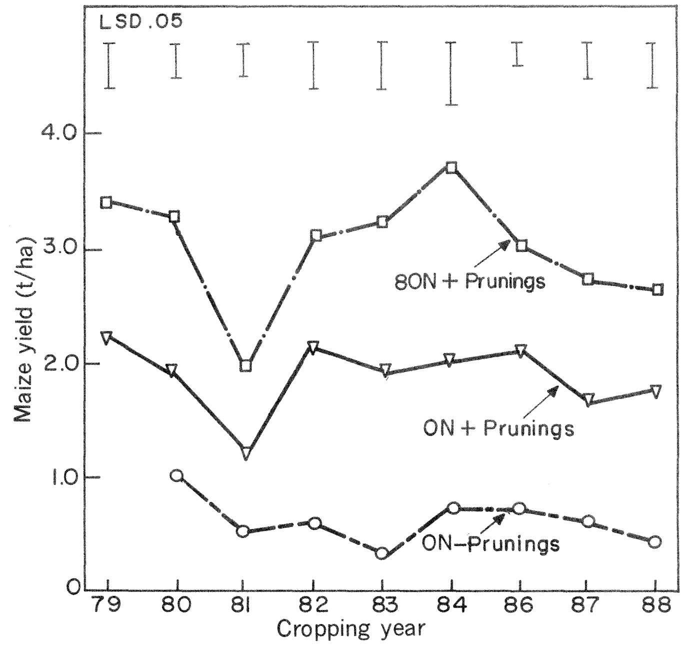

Fig. 5 Grain yield of first season maize in maize-cowpea sequential cropping on a Psammentic ustorthent in alley-cropping with *Leucaena leucocephala* at Ibadan, southern Nigeria, as affected by N application and prunings of hedgerows. (B. T. Kang, unublished data). (N-rates, 0 and 80kg N/ha ; +Prunings, hedgerow prunings retained ; − Prunings, hedgerow prunings removed from plot).

and management requirements for crop production.

Results of investigations on LAC Alfisols and Ultisols in West Africa have shown that the following three elements are desirable for sustained crop production : (1) production of adequate *in situ* mulch to protect the soil from erosive rains, (2) reduce tillage to minimize soil disturbance, traffic and compaction effects, and (3) judicious fertilizer and lime use to minimize soil acidification and chemical soil degradation. These desired conditions can be obtained by combining reduced tillage and a variant of the alley-cropping system. Recent data show that the combined system may result in more sustainable production (Lal, 1987 ; Celestino, 1985 ; Hulugalle and Kang, unpublished data).

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Discussion

Woo Yin Chow (Singapore) : In one of your slides, runoff losses where the alley crops *Gliricidia* and *Leucaena* were planted at 4m apart were greater than in the control plots with tillage and no-tillage. Can you explain why this occurred?

Also since *Gliricidia* is a fast-growing legume tree it sometimes competes for plant nutrients with the economic crop. Did you observe such a phenomenon?

Answer : Runoff and erosion were less pronounced in the plots with tillage and alley-cropping (*Gliricidia* and *Leucaena*) than in the tilled control plot. In the humid and sub-humid zones, there is no water and nutrient competition between *Gliricidia* and the economic crop on non-acid soils.

Aubert, G. (France) : You mentioned that "minimum tillage" is the best method for land cultivation in tropical countries. This is true if you deal with Ferralitic soils (French classification). However, in the case of Ferruginous tropical soils, reasonable tillage is necessary because this type of soil shows compacted layers under the well-structured and well-aggregated superficial horizons (15 to 20cm).