PIMAK 250

Role of Mulching Techniques in Tropical Soil and Water Management

by

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Summary

Surface mulching with crop residue at the rate of 4 to 6 tons/ha decreases soil temperature and maintains favorable soil structure through enhanced biological activity. Continuous surface cover can be maintained by growing crops exclusively for use as a mulch, by live mulch from low growing and least competitive cover crops or by the use of crop residue through rotation and tillage techniques. Mulch tillage, such as minimum tillage based on the zonal tillage concept of maintaining crop residue in the inter-row zone and simultaneously providing a good seed bed, meets most soil management requirements for many upland crops. Yields of maize, cowpeas, pigeon peas, soybeans and sweet potatoes on mulch tillage plots equal yields from plowed plots. At the same time the soil erosion is minimal and soil structure is maintained by more intensive soil flora and fauna activity.

Introduction

Mulch farming techniques offer a tremendous potential in evolutionizing a permanently viable system of land use in the humid tropics, which is now predominantly under a traditional bush – or grass – fallow system. In addition to overcoming the problems caused by conventional method of soil management, there is a definite saving in time and power resources of the farmer. Though the possibilities of such farming systems are promising, the adaptation of this system to specific conditions depends on the soil types, the nature of the crop and financial resources of the farmer.

When continuous farming replaces traditional cultivation in the tropics there is:

- Degradation of soil structure and accelerated soil erosion.
- Increased fluctuation in soil temperature.
- Decrease of soil organic matter, nutrients and moisture holding capacity.
- Change in soil physical properties and formation of compacted layers near the soil surface.

Productivity of tropical soils for arable crops can only be maintained by evolving farming systems suited for the specific soil conditions. The use of plow as a means of weed control appears unrealistic for tropical soils where the serious limiting factors are soil and water conservation and high soil temperature. Weeds can be controlled either manually, by chemicals, and by surface cover of organic mulches from crop residues. This bulletin details the potential of mulch farming techniques as a system for maintaining favorable physical conditions of the soil in the humid tropics.

Soil Physical Characteristics

One of the toposequences of soils derived from basement complex rocks in western Nigeria consists of soil series Ekiti, Egbeda, Iwo, Ibadan and Gambari as upland and Apomu, Iregun and Matako as lowland soils. The majority of upland soils derived from basement complex and sandstone parent materials are of coarse to intermediate in particle size distribution in the surface horizon. These soils are also characterized by a low silt fraction (Fig. 1). The surface horizons have a sand content of 56-80%, silt content from 11-19% and clay content of 9-25%. The individual particles of such soils are easily detached by the beating action of rain, and finer particles are washed off the field with the runoff water.

A gravelly horizon, immediately below the surface horizon is a characteristic feature of most soils on basement complex. In addition to variation in the depth of the surface soil, the gravel content in different soils also varies from 0, for soils in the lower catena, to 75% of skeletal material imbeded in the fine earth fraction (Fig. 2). The depth and the thickness of the gravel horizon varies from series to series in the various topo-sequences. For the upper slope soils the gravel horizon is 15 cm in Ekiti, Egbeda and Iwo, 20 to 25 cm deep for Ibadan and Gambari and deeper than 50 cm for Iregun and Apomu soil series. Ekiti is, in general, a shallow soil with partially decomposed parent rocks within 30 cm of the surface. The thickness of the gravel horizon is 50 cm for Iregun, 75 cm for Gambari, 100 cm for Egbeda and 125 cm for Iwo. The penetrometer readings in the gravel horizon are generally high, ranging from 1.33 to greater than 4.5 kg cm^{-2}. The overall bulk density of the gravel horizon, depending on the gravel concentration is generally high, ranging from 1.4 to 1.7 g cm^{-3}. The rigidity of the matrix formed by this combination inhibits the root penetration of most of arable crops such as maize, rice, soybeans and yams.

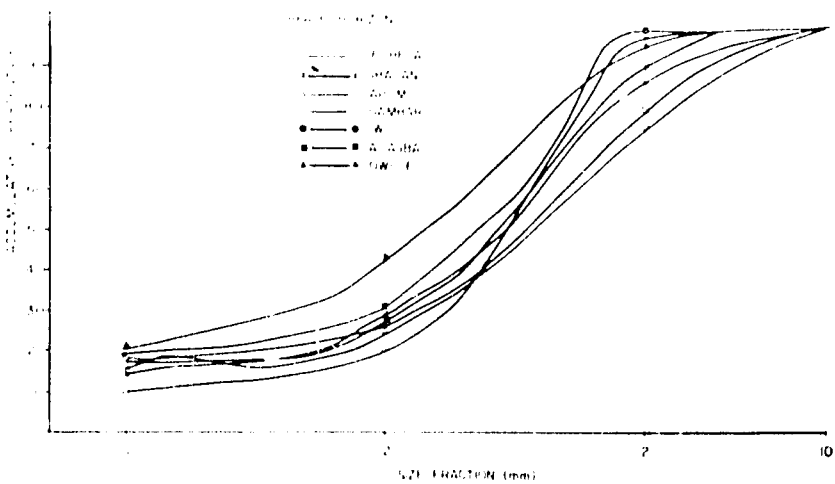

Fig. 1 Particle size distribution of the surface horizon of different soil series.

The available water holding capacity of the soil above the gravel horizon is generally low for most of the upland soils. The moisture release curves show a sharp deflection point between 0.1 and 0.3 bar suction and there is little change in moisture content beyond a suction value of 1.0 bar (Fig. 3). The available water holding capacity of the surface soil horizon ranges through 1.0, 1.2, 1.6, 2.1, 2.4 and 3.1 cm for Iwo, Egbeda, Ekiti, Gambari, Iregun and Ibadan soil series respectively.

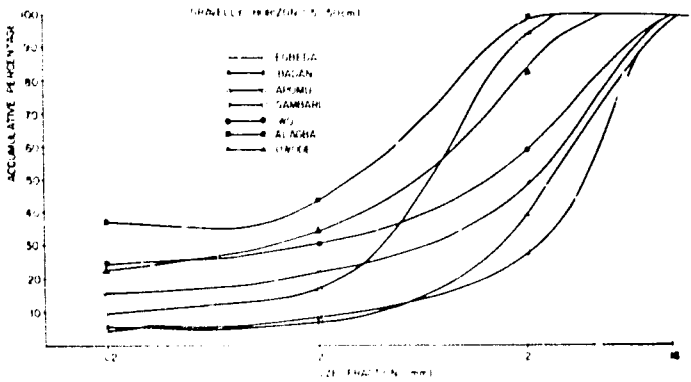

Fig. 2. Particle size distribution of the gravelly horizon for different soil series.

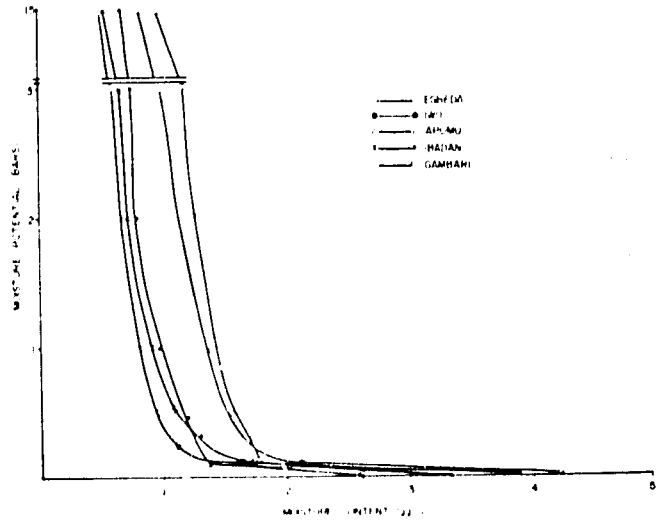

Fig. 3. Moisture release characteristics of the surface horizons of some soil series.

'nges in Soil Properties as 'sult of Forest Clearing ' Cultivation

ɔlogic Cycle:

The removal of vegetation cover ts the different components of the ɔlogic cycle. The water balance ion is P R + S + I + ∫EDt--(1)

e P Precipitation

R = Surface runoff

S Soil moisture storage

I Interflow

E Evapotranspiration

t Time

Under native vegetation cover, maintains its infiltrability and e runoff losses are low. Table 1 data of surface runoff for four ent slopes on newly cleared and tivated land under bush fallow. f losses from bush fallow plots rely 1–2% of the rains received npared to a maximum of 29% from d land. Similar results for West are reported by Dabin (1959), Nye and Greenland (1960) and Charreau (1972). Over a long period of time, soil moisture storage (S) or the equivalent rise in the ground water level for hydromorphic soils forms only a small fraction of the total precipitation. Available water storage capacity (AWC) of the soil, on the other hand, is decreased by reduction in organic matter content (Cunningham, 1963). Reduction in AWC of the surface soil may also be aggravated by a decrease in silt and clay content because of soil erosion (Lal, 1974). Removal of deep-rooted vegetation also decreases the water uptake by plants from the deeper soil stratum, thereby increasing the interflow losses of the infiltrated water (Charreau and Fauck, 1971). Forest clearing, therefore, may increase R and I and decrease S and E components of the hydrologic cycle.

Soil Infiltrability:

Infiltration capacity of many soils in the tropical forest zone is high. Infiltration rates of savannah soils are reported at 12.5 cm hr^{-1} or more (Wilkinson, 1970). Samie (1970) reported initial infiltration rates of some savannah soils as varying from 3.3 cm to 24.0 cm hr^{-1} depending on vegetation cover. The infiltration rates of some soil series from western Nigeria are shown in Figure 4. The infiltrability

1. Effect of soil slope and vegetation cover on runoff losses different times after land clearing.

%	*Freshly cleared*		*Two years after clearing*
	Bush fallow	*Bare plowed*	*Bare plowed*
	1.7	5.7	20.1
	1.3	20.0	21.4
	1.7	29.1	21.9
	2.0	12.8	17.0

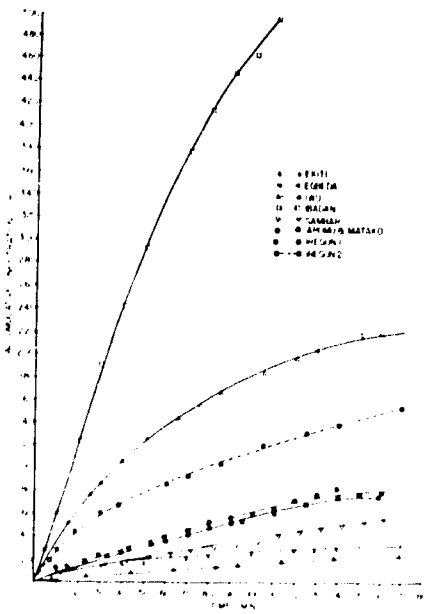

Fig. 4. Accumulative infiltration for same soil before forest clearing.

at two hours after starting the infiltration is 5.4, 6.0, 17.4, 24.0, 45.0, 66.0 and 72.0 cm hr^{-1}, for Iwo, Ekiti, Gambari,(Iregun I, Apomu and Matako), Egbeda, Iregun II and Ibadan soil series respectively.

This high initial rate indicates the predominance of macropores in the profile and a high magnitude of the horizontal component of the hydraulic conductivity of the soils under forest. The high initial infiltration rate declines rapidly after forest clearing because the exposed soil is sealed due to structural degradation by direct impact of rain drop on unprotected soil particles (Fig. 5). In two hours, the total water intake decreased from 300 cm in newly cleared land to 180 cm for land under maize, and only 80 cm for unprotected fallow, one year after clearing. If the soil has been eroded, with only stones and gravels left on the surface, the infiltration rate may again increase. The structural stability of the soils to raindrop impact is generally low (Bruce-Okine and Lal, 1975), and the surface crustation decreases the instantaneous infiltration rate tremendously.

Soil Erosion:

Vegetation removal results in accelerated soil erosion. This is demonstrated by the work of ORSTOM (Roose, 1967, 1970, 1971), IRAT (Chaminade, 1970) and IITA all in West Africa, and Hudson (1957) in Rhodesia. Soil losses of 10 tons/ha/year are normal under different crop rotations. Fournier (1967) reported erosion losses on 1.5% slope of 1420, 433 and 954 tons/km^2 under sorghum, groundnuts and rice, respectively. Kowal (1972) reported an average soil loss of 10 tons/ha/year on plots of approximately 1% slope. Experiments at IITA indicate that on a bare plot

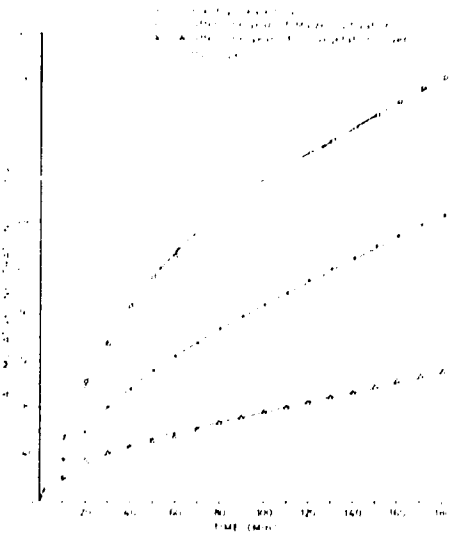

Fig. 5. Changes in soil infiltration rate after forest clearing.

annual soil loss can be as high as 115 tons/ha and 75% of the annual loss can occur in a single high intensity.

The nutrient losses in soil and runoff water caused by erosion are substantial. The nutrient losses from bare fallow plots of 1–15% slopes are given in Tables 2 and 3. The loss of nutrients in surface runoff water is negligible as compared to the loss of nutrients and organic matter in the eroded soil. In these tropical soils, the leaching losses of nutrients with percolating water are more serious than the nutrients in the runoff water (Fig. 6).

Loss of the surface soil and nutrients can result in significant yield reductions, particularly on soil with shallow surface soil horizons. The

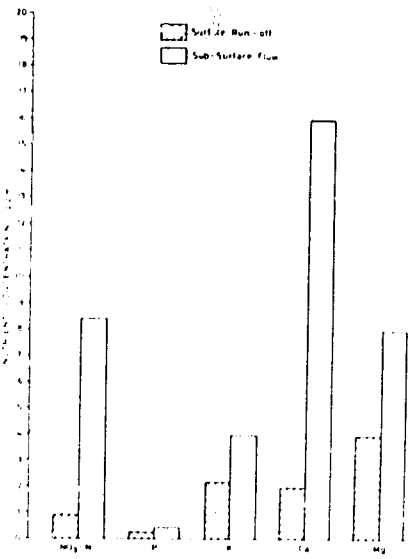

Fig. 6. Relative nutrient concentration in surface run-off and sub-surface water.

Table 2. Nutrient losses in run-off water (kg/ha/yr)

Slope %	*N*	*P*	*K*	*Ca*	*Mg*
1	3.90	0.45	4.56	11.24	24.46
5	5.51	0.54	6.17	16.99	2.53
10	5.68	0.77	5.57	14.86	3.14
15	4.51	0.72	4.14	12.53	2.96

Table 3. Nutrient losses in eroded soil (kg/ha/yr)

Slope %	*Total Organic Carbon*	*Total N*	*Available P*
1	58.3	6.2	0.2
5	865.4	99.7	1.8
10	1847.2	191.3	2.2
15	3073.4	225.6	8.1

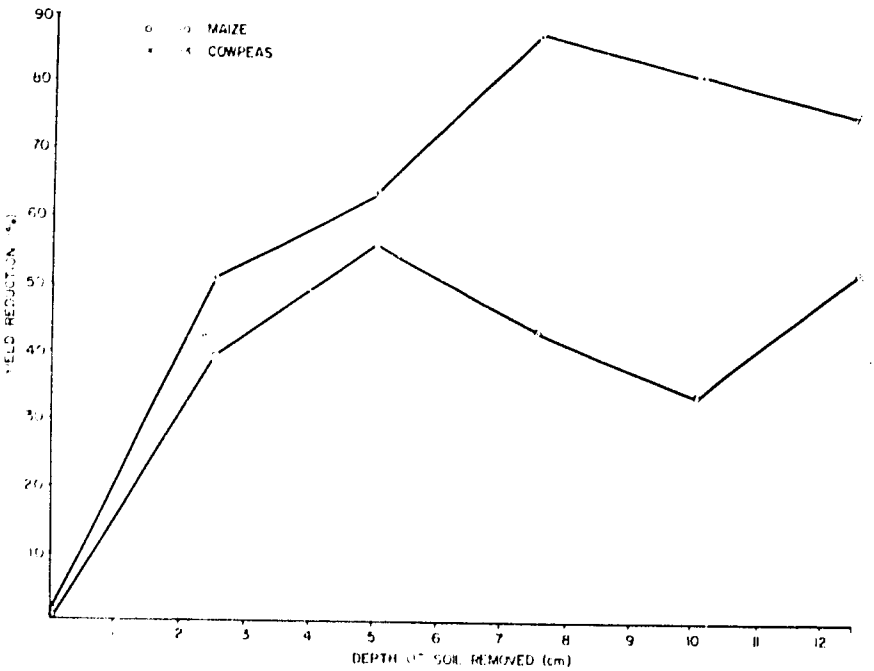

Fig. 7. Effect of surface soil removal on yield reduction.

effect of artificial removal of surface soil on yield reductions of maize and cowpeas for Egbeda soil series is shown in Figure 7. A loss of 2.5 cm of surface soil resulted in yield reductions of 40% for maize and 50% for cowpeas.

Soil Temperature

Various components of the energy balance equation are affected by vegetation removal. The energy balance equation is:

$$R_S(1-A) - R_L + G + H + LE \text{ (cal cm}^{-2}\text{ sec}^{-1}) \quad (2)$$

where R_S flux density of total short wave radiation received.

A albedo (for reflection coefficient) of ground surface.

R_L net flux density of long wave radiation emitted by the surface, the difference between that emitted and absorbed.

G Heat flux density into the ground.

H Sensible (or non-latent) heat flux density into the atmosphere.

L Latent heat of vaporization of water (cal g^{-1}).

E Evaporation rate.

Vegetation removal increases the heat flux density into the ground (G) and the L and E components of the energy balance equation. The effect of vegetation removal on soil temperature

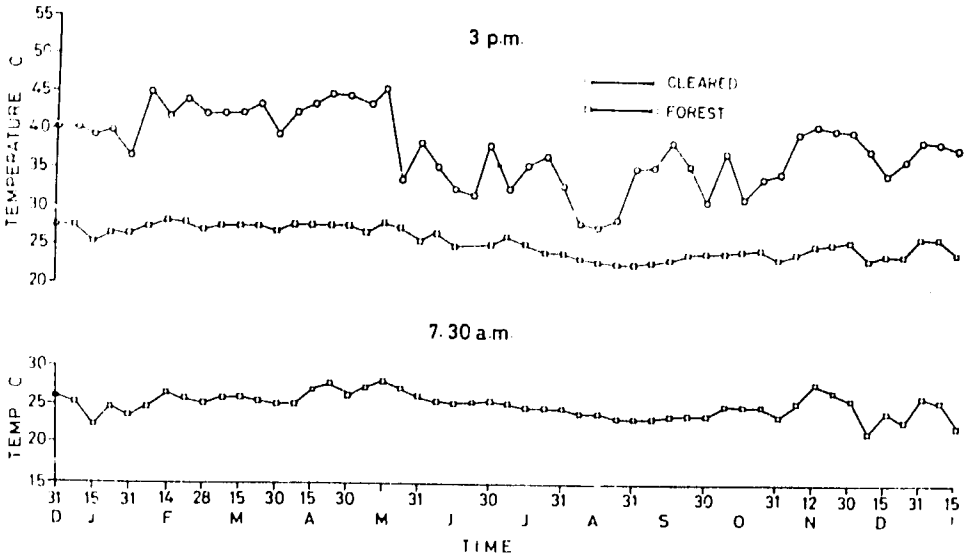

Fig. 8. Effect of forest clearing on soil temperature regime at IITA Ibadan.

measured at 5-cm depth is shown in Figure 8. The diurnal fluctuations in soil temperature of cleared land can be between 20 and 30 C.

Soil temperature above 36 C can adversely affect emergence, vigor and yield of crops such as maize, soybeans and yam. The effects of constant and fluctuating soil temperatures on maize seedlings are shown in Figures 9 and 10. On the average there was a 10% decrease in fresh and dry-shoot weight per degree increase in root zone temperature above 30 C. The shoot and root concentrations of N, P and K were also decreased while that of B increased with an increase in soil temperature. The effect of high soil temperature on soybean seedlings was similar to that of maize (Fig. 11).

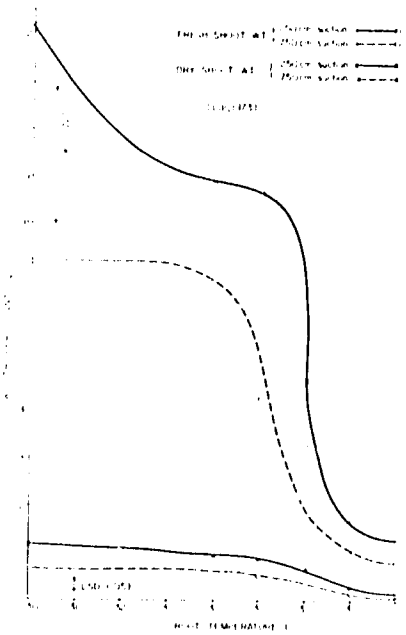

Fig. 9. Effect of constant soil temperature on shoot weight of maize for two soil moisture suctions.

Soil Structure and Biological Activity: Vegetation removal deteriorates soil structure, particularly if the soils are exposed to the vagaries of tropical

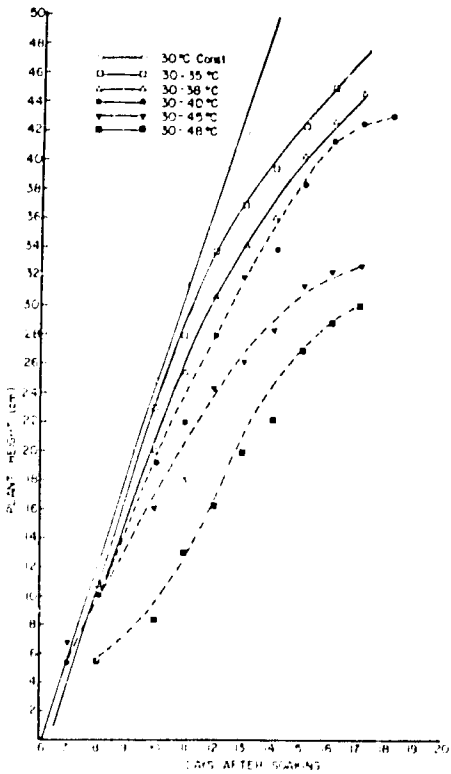

Fig.10. Effect of fluctuating soil temperature on plant height.

climate for a long time. The factors responsible for decline in soil structure are decrease in organic matter content, raindrop splash and changes in micro climate, thereby adversely affecting the flora and fauna.

Changes in Soil Properties by Tillage

Soil structure is altered by plowing due to increase in porosity and percent of macropores. This increase in porosity decreases the thermal conductivity as well as the volumetric heat capacity (Van Duin, 1956). The effect of tillage on soil thermal regime is also affected by initial soil properties such as stratification and the particle size distribution of various horizons. Tillage effects on annual variations in soil temperature are small.

In addition to plowing, various cultural practices such as planting on ridges, furrows, mounds, flat seed bed and orientation of rows significantly affect the soil temperature. Temperature variations resulting from different cultural practices are also governed by such soil properties as texture, moisture characteristics, heat capacity and thermal conductivity. For coarse-textured soils, the effect of different cultural practices on changes in soil thermal regime is shown in Figures 12 and 13. Ridges and mounds have higher maximum temperature and larger fluctuations in soil temperature than the flat seed bed. On coarse-textured soils, ridges and mounds not only have more exposed surface rea but also the lower soil moistu..e regime increases the temperature fluctuations.

Effect of Mulching on Soil Properties

Mulching affects both the physical and chemical properties of soil. The organic matter content, an important factor in maintaining the fertility status of tropical soils and cation exchange capacity, can be maintained at a high level by mulching. The effect of mulching on soil physical properties is described below:

Erosion Control: Mulching has a distinct advantage for erosion control on tropical soils. Not only is the rain drop direct impact on the soil avoided by mulching, the runoff losses also

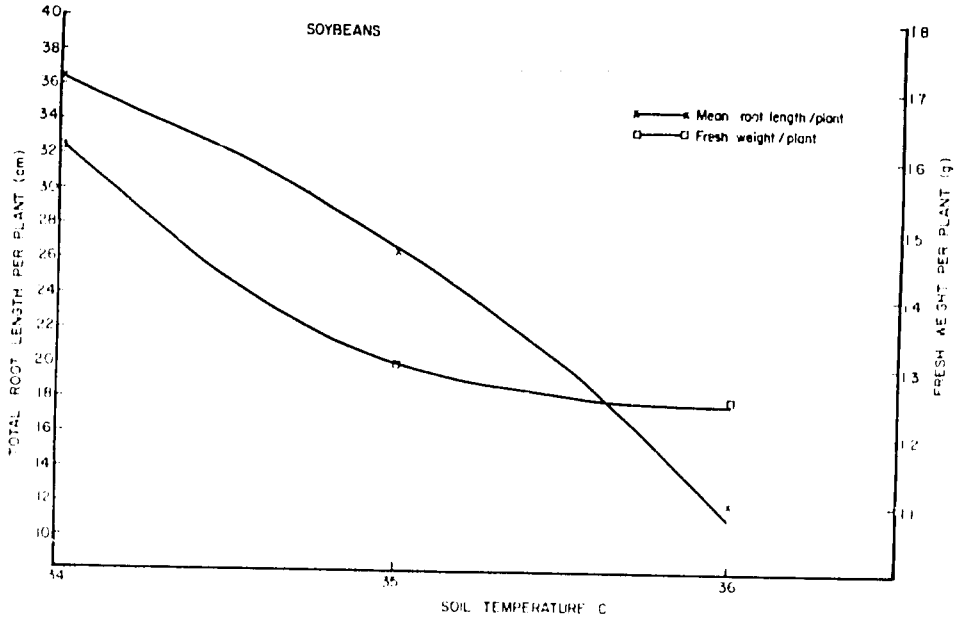

Fig. 11. Effect of constant soil temperature on shoot weight and root length of soybean seedlings.

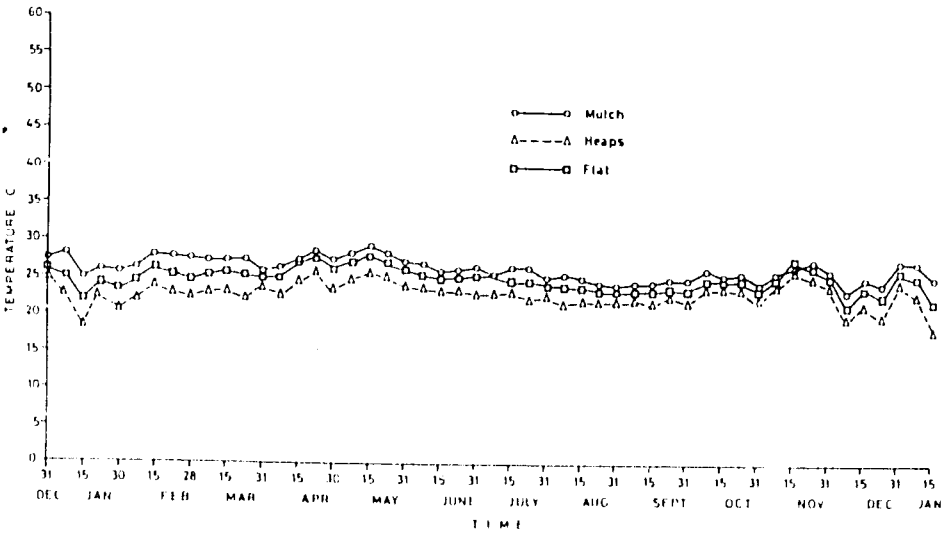

Fig. 12. Soil temperature regime at 5-cm depth and measured at 7.30 am for flat versus heaps method of seed bed preparation.

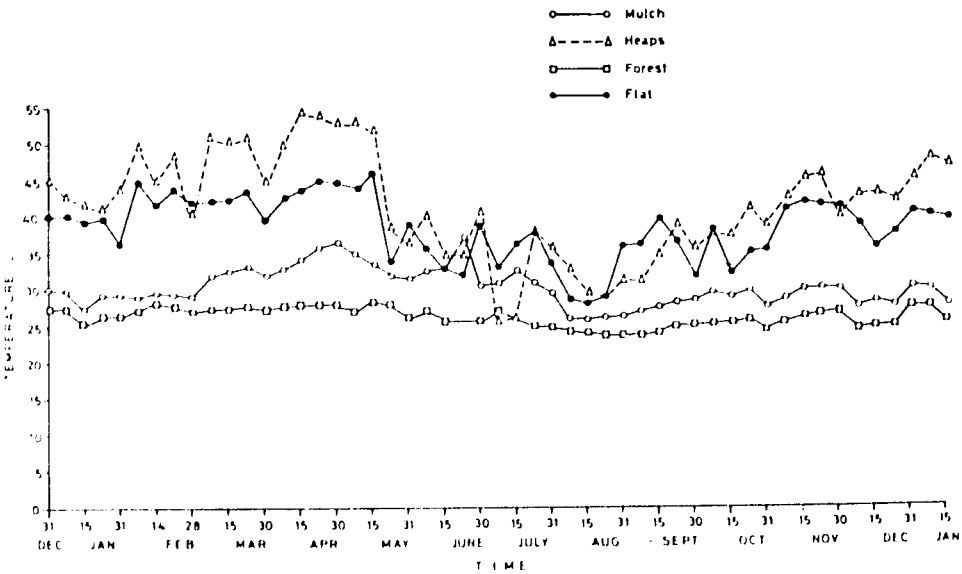

Fig. 13. Soil temperature regime at 5-cm depth and measured at 3 pm for heaps and flat seed bed as compared to that under forest.

are minimized because the soil infiltrability is maintained at its maximum level. The effect of straw mulching on runoff losses is equivalent to that of bush fallow cover for all the slope ranges of 1 to 15% (Table 4). Runoff water from the mulched plots is generally clear with a minimum of sediments (Table 5). Experiments at IITA indicate that erosion losses from mulched plots are negligible within the slope ranges of 1 to 15%. The effect of rate of mulching on runoff and soil losses is shown in Table 6. The runoff losses were 20, 8, 3 and 2% for 0, 2, 4 and 6 tons of mulch per hectare. Runoff losses for mulch rate of 2 tons/ha were only one-third of that from unmulched plots. Soil losses were in the ratio of 194: 19: 4: 1 for mulch rates of 0: 2: 4: 6 tons/ha. The plot of ratio of soil and water loss with mulch to corresponding losses with no mulch (mulch factor) indicates the effectiveness of mulch in erosion control (Fig. 14).

Table 4. Effect of mulching on runoff losses (September - December 1970)

Slope %	*Bush fallow*	*Percent runoff under maize*	
		Unmulched	*Mulched*
1	1.7	6.4	2.0
5	1.4	40.3	7.7
10	1.7	42.3	5.7
15	2.0	17.6	1.9

Table 5. Effect of mulching on the sediment density in runoff water (Storm of June 1, 1973) Total rainfall 44.2 mm

Slope %	*Sediment density g/liter under maize* *Unmulched*	*Mulched*
1	0.28	0.00
5	9.76	0.36
10	7.0	0.45
15	5.75	0.08

Table 6. Effect of rate of mulch on runoff and soil loss. Total rainfall 64 mm

Mulch rate (tons/ha)	*Slope (%)* 1	5	10	15	*Mean*	*Percentage of rainfall*
			Run-off (mm)			
0	12.0	14.8	10.4	14.8	13.0	20
2	1.3	6.2	6.0	5.7	4.8	8
4	0.4	1.5	3.6	3.3	2.2	3
6	0.0	0.7	1.9	1.8	1.1	2
			Soil loss (tons/ha)			
0	0.48	12.19	27.06	12.25	13.00	
2	0.01	3.49	0.82	0.64	1.24	
4	0.00	0.67	0.11	0.31	0.27	
6	0.00	0.16	0.03	0.08	0.07	

Soil Temperature: Soil thermal regime is a function of the contact coefficient (λC), a product of thermal conductivity and the volumetric heat capacity of the soil. A mulched plot with dry crop residue is equivalent to a two-layered profile of which the upper layer has a lower contact coefficient. The temperature variation in the soil underlying a mulched layer is thereby reduced. In a tropical climate, mulch keeps the soil temperature more uniform and decreases the amplitude of temperature wave.

The effect of mulching on soil temperature under maize and yams is shown in Figures 15 and 16. In the

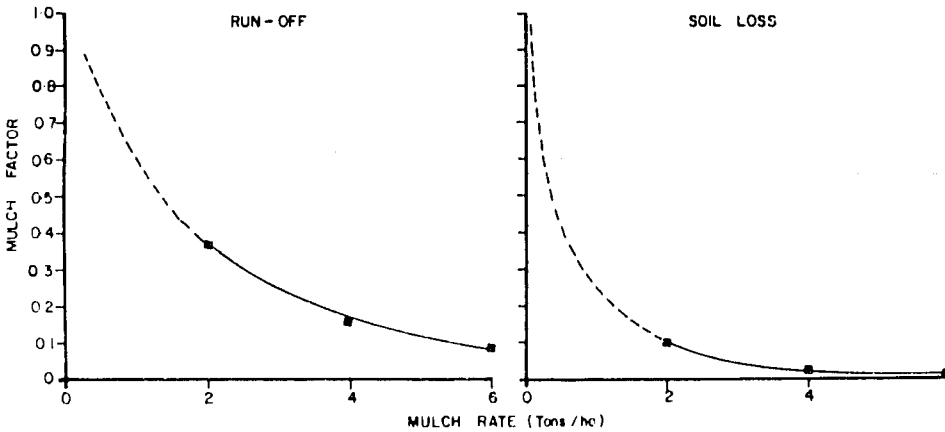

Fig. 14. Mulch factor for run-off and soil loss for soils at IITA Ibadan

initial stages of crop growth, temperature differences of as much as 8 C were observed between mulched and unmulched plots at 5-cm depth. The maximum temperature recorded for unmulched maize plots was 42 C at 5-cm depth. The minimum temperature is generally lower; hence the diurnal fluctuations are higher. Hourly observations made on soil temperature indicate that there is a phase difference of daily temperature fluctuations due to mulching. The maximum temperature on mulched plots occurs one to two hours after that of the unmulched plots.

Soil Moisture: Mulching generally improves the soil moisture regime by decreasing losses caused by surface runoff and evaporation. Evaporation of water from wet soil is characterized by three stages:

(1) a constant rate stage when the soil surface is wet and the evaporation is controlled by the external conditions (evaporation demand of the atmosphere).

(2) a stage of rapidly decreasing evaporation rate, which begins with initial drying of the surface layer.

(3) a stage of slow evaporation rate at which the water movement through soil is primarily by diffusion and therefore the evaporation is controlled by the hydrological characteristics of the soil.

Mulching may improve soil moisture storage under both stages of evaporation. The beneficial effects of mulching on soil moisture storage under maize shown in Figures 17–18 are generally more pronounced during frequent rains. Mulching also affects the soil moisture storage indirectly by controlling soil erosion. Because the unmulched plots erode severely, the loss of surface soil eventually decreases the soil moisture holding capacity.

Soil Structure and Infiltration Rate: Mulching affects the soil structure and porosity both directly and indirectly. By minimizing the direct impact of raindrops, there is a minimal crustation

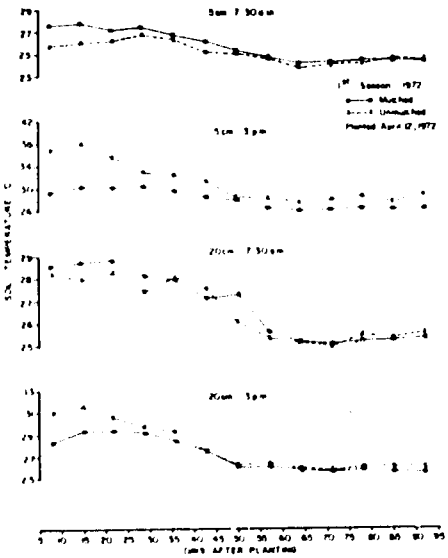

Fig.15. Effect of mulching on soil temperature under maize (Lal, 1974).

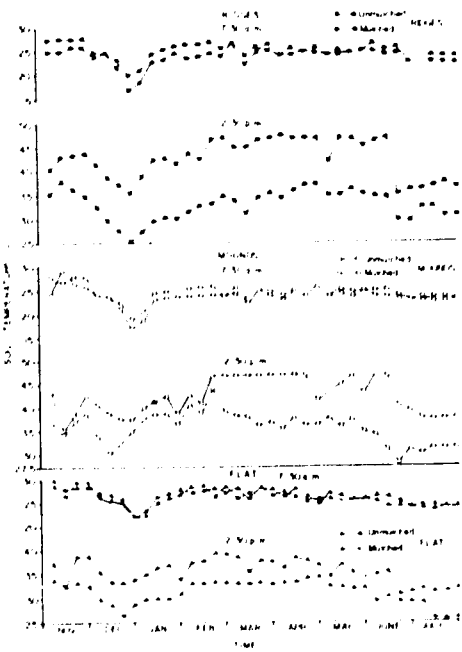

Fig. 16. Effect of mulching and methods of seed bed preparation on soil temperature under yam.

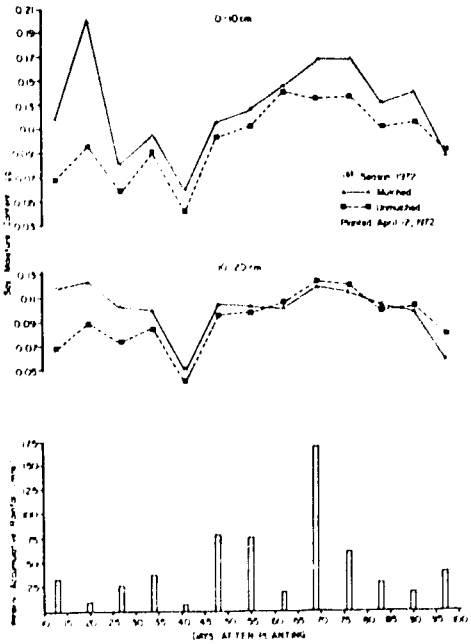

Fig.17. Mulching effect on soil moisture regime under maize (Lal, 1974).

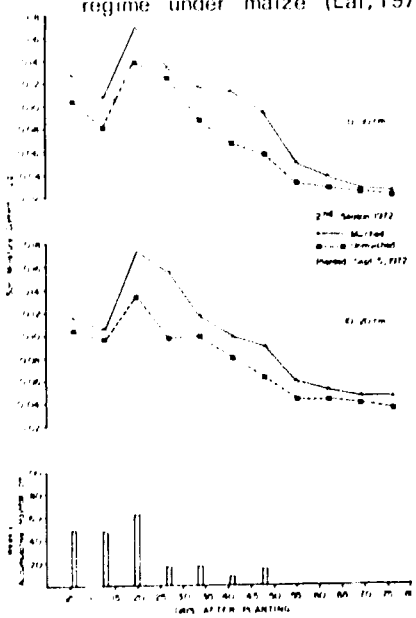

Fig.18. Mulching effects on soil moisture regime under maize (Lal, 1974)

and therefore the initial pore space is maintained. Indirectly, mulching influences the activity of micro flora and fauna and hence the soil structure. Notably in western Nigeria is the earthworm activity as influenced by mulching that stimulates worm casting. Earthworm counts on mulched and unmulched maize plots, as observed eight weeks after planting, are shown in Table 7. These data are a rough approximation and should be considered in terms of their relative values.

Mulched plots were observed to maintain their initial infiltration rate as compared to significant decline in infiltrability of the unmulched plots (Fig. 19). High earthworm activity and a minimal crust formation under mulching may in part be responsible for higher infiltration rate than on unmulched soil. Worm channels may also have an additional advantage of facilitating the root penetration in soils with otherwise restricted root penetrability.

Mulching Effects on Crop Yields

Crop Yield: The effect of mulching on crop yield is an integrated effect of innumerable factors and it is difficult to attribute the yield increments to any one variable. In addition to physical factors and availability of nutrients, the fertilizer response may be significantly affected by mulching due to complex physicochemical and biological factors (Jack et al 1955, Jurion and Henry, 1967). The effect of three years of mulching trials on maize grain yield as shown in Tables 8 and 9 indicates significant yield increases by mulching. The effect of different kinds of mulches, with and without treatment against termite, was found to have a similar effect on grain yield. Termite damage to maize by mulching was found to be significant during only the first year after clearing (Table 9).

As pointed out earlier, cultural practices significantly influence soil thermal regime. Ridges were used in the past as a soil conservation measure on steep slopes. The usefulness and feasibility of ridges as a soil protecting device is questionable, particularly for unstable soils of coarse texture. Planting on mounds has the same drawbacks as on ridges. High soil temperature, for instance, on ridges and mounds is observed to significantly influence yam emergence. Soil temperature is observed to be a major limiting factor for yam emergence when planted in the dry season of November to March. Mulching of ridges and mounds, however, not only improves the percentage of emergence, the period

Table 7. Effect of mulching on earthworm casts in maize.

Treatment	*Worm cast/m²*	*Equivalent weight tons/ha*
Mulched	568	127
Inter-row mulch	264	59
Unmulched	56	13

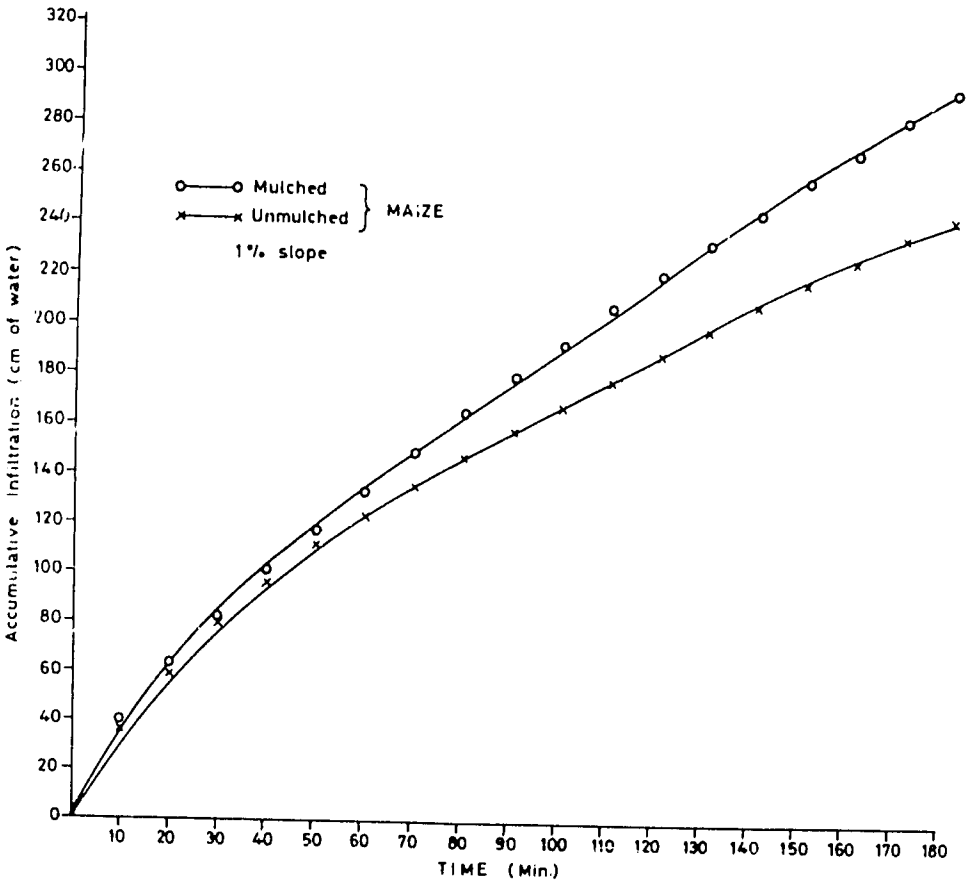

Fig. 19. Infiltration rate under mulched and unmulched plots.

Table 8. Effect of mulching on maize grain yield (1970-71)(After Lal, 1974)

Treatment	*Grain yield (tons/ha)*	
	*1970**	*1971*
Mulched	0.8	5.4
Unmulched	0.5	3.6
LSD (0.5)	0.3	0.7

* *Significantly low grain yields in 1970 were attributed to a prolonged dry spell at the flowering stage.*

Table 9. Effect of mulching on maize grain yield (1972)(After Lal, 1974)

Treatment	*Grain yield (tons/ha)* *With termite control*	*Without termite control*
Rice straw mulch	4.5	4.4
Forest litter mulch	4.4	4.3
Control	3.6	3.6
LSD (0.5)	0.7	0.7

of emergence is also significantly reduced (Figs. 20–22). Mounds and ridges, however, can be useful for root crops particularly for soils with shallow surface horizon above the ground layer.

Because length of growing season has an important influence on total yam yield and in terms of tuber formation, mulching can prolong the growth period of early and full stand establishment. The effect of mulching on tuber size,

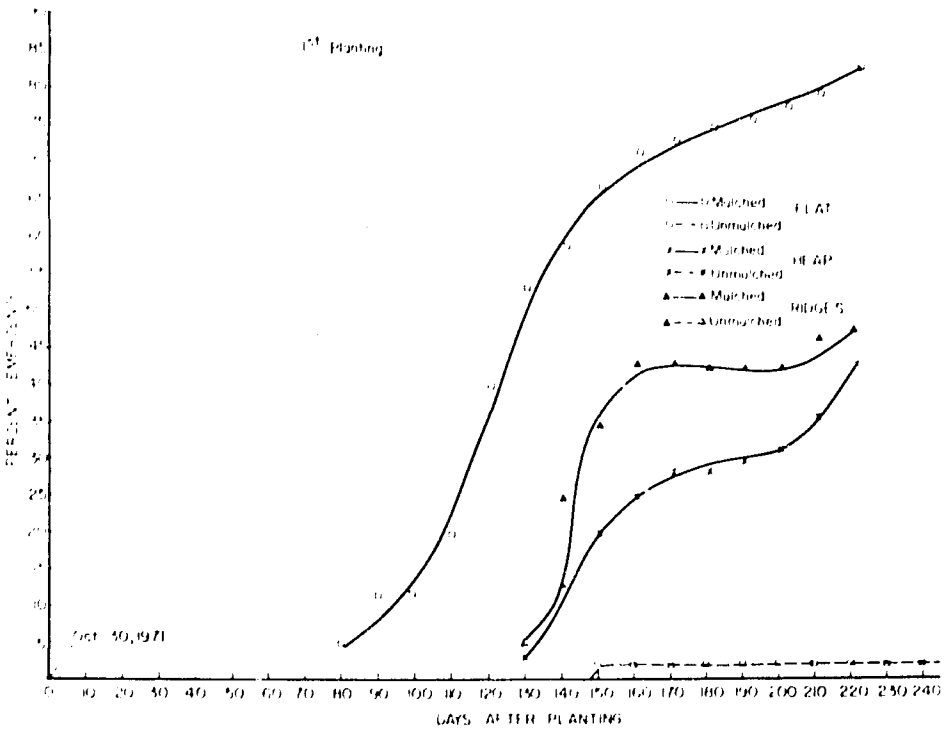

Fig. 20. Effect of mulching and methods of seed bed preparation of yam emergence for planting on 30 Oct. 1971.

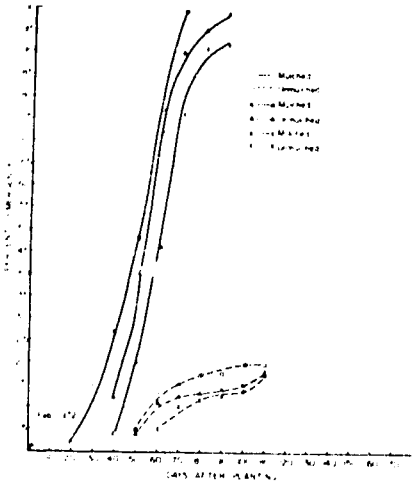

Fig.21. Effect of mulching and methods of seed bed preparation on yam emergence for planting on 1. Feb.

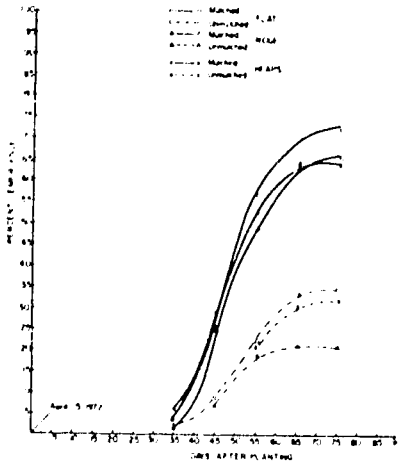

Fig.22. Effect of mulching and methods of seed bed preparation on yam emergence for April planting.

yield per hill, and total yield as affected by different times of planting is shown in Figures 23–25. Mulching can significantly improve yam yield when planted early in the season. There was an eightfold increase in yield by mulching on flat for the early planting as compared to a total failure for unmulched heaps and ridges.

Mulching and Weed Growth: Mulching is generally known to suppress weed

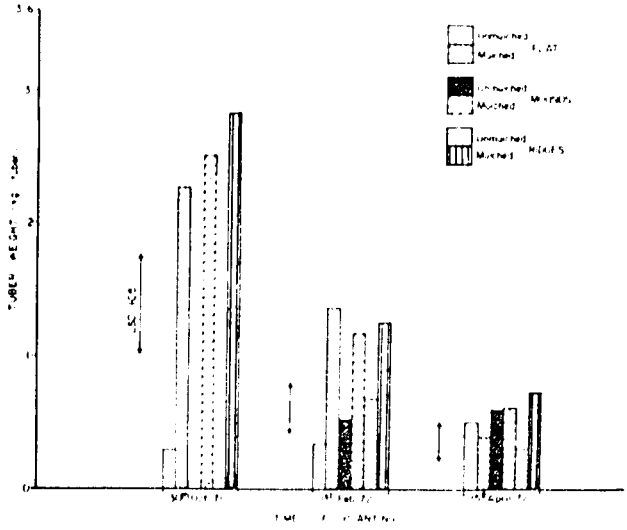

Fig. 23. Effect of methods of seed bed preparation and mulching on average tuber size.

growths. Weight of fresh weeds harvested eight weeks after planting maize in the second season of 1972 was significantly higher in the unmulched than in the mulched plots (Table 10). The lower soil moisture content in the unmulched plots could also be partly due to high weed growth.

Ways to Procure Mulch

Transported Mulch Material: Mulch material obtained from a crop, grown somewhere else either for the sole purpose of producing mulch or as a residue of a previous crop, can be used as a mulch for another crop. This process generally requires additional labor and time and often the material is not available when needed. The method is uneconomic except for high-value vegetable cash crops.

Live Mulch: This involves the principle of mixed cropping. A low growing crop, preferably a legume, is grown throughout the year. A small strip is then opened, with or without using herbicides, to plant a new crop in between. This method should work provided the host crop is not competitive for light, moisture and nutrients. Experiments conducted with *Stylosanthes gracilis* and maize were en-

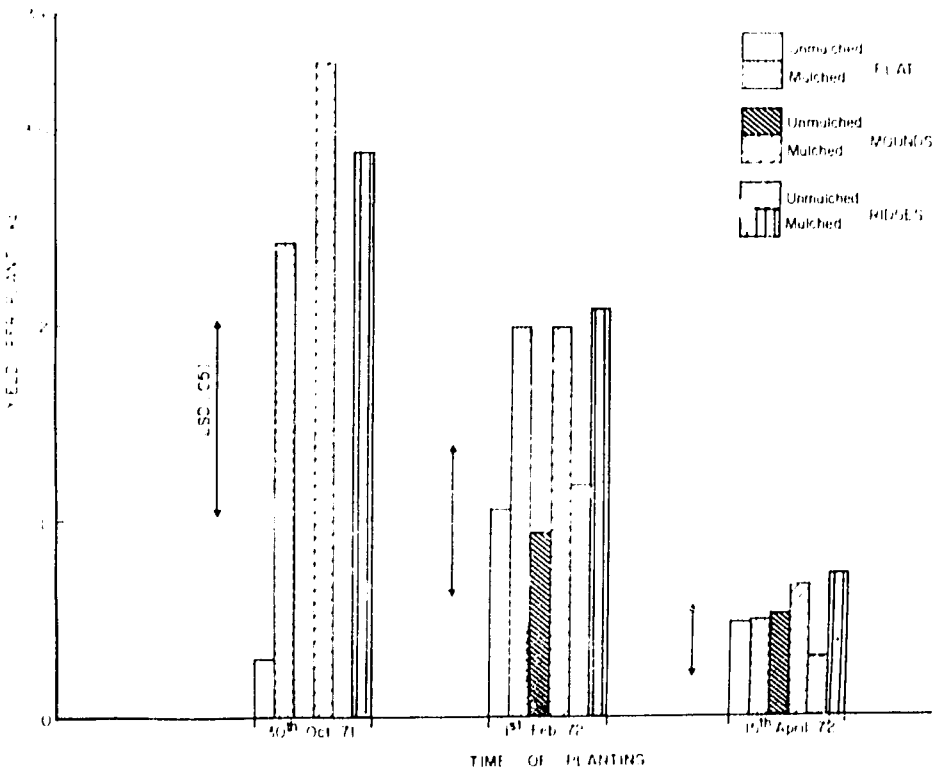

Fig.24. Effects of methods of seed bed preparation and mulching on tuber yield per plant.

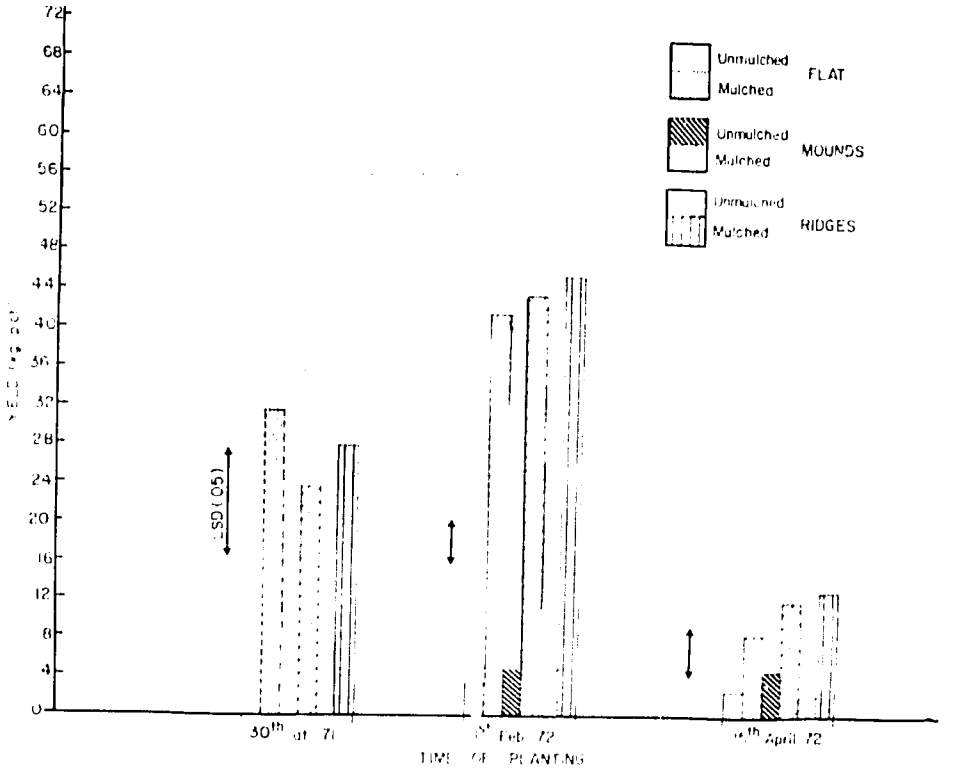

Fig. 25. Effects of methods of seed bed preparation and mulching on total tuber yield.

Table 10. Effect of mulching on weed control

Treatment	*Weed growth (kg/plot)*
Rice straw mulch	15.0
Forest litter mulch	13.0
Control	46.0
LSD (0.05)	9.0

couraging for erosion control. However, *Stylosanthes gracilis* is aggressive and competes with maize for soil moisture. Experiments with other species e.g. *Paspalum*, *S. humilus*, *Desmodium* and *Centrosema* need to be conducted.

Using Previous Crop Residue *In Situ*: The use of previous crop residue and weed regrowth in situ is another alternative. Crop residue left on the soil surface offers maximum protection against run-off and soil erosion

Tillage Techniques: The use of live mulch and crop residue in situ involves the special tillage practices, hereby referred to as mulch tillage technique. Mulch tillage techniques are based on the zonal tillage concept, whereby the seed bed is divided into a seedling zone and a soil management zone (Fig. 26). The seedling environment zone serves to provide the ideal conditions for seed germination, emergence and establishment. The inter-row soil management zone serves to conserve soil moisture, prevent runoff and erosion and optimize the soil temperature regime. According to this concept the soil is least disturbed.

Mulch Tillage Effects on Soil Conditions

Indiscrete tillage and exposing a structurally unstable soil to high intensity tropical storms result in soil crustation and increased run-off and erosion losses. Because the role of tillage as a weed control measure has diminished because of the economical availability of herbicides, conventional tillage practices need a critical appraisal regarding their effects on soil and water management in the tropics. Though mulch tillage has been widely practiced in many of the temperate

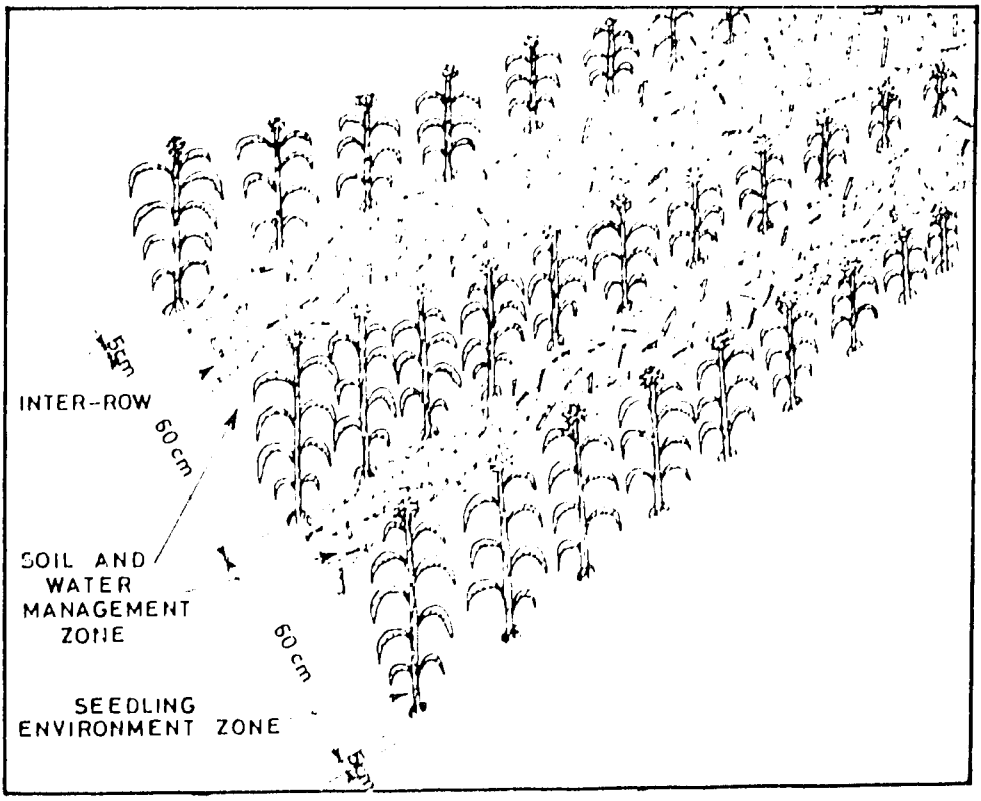

Fig. 26. Zonal tillage concept.

countries, it is yet to be known in the tropics. Muller and Bilerling (1953) reported from their work using the corridor system of land utilization in Belgian Congo (now Zaire), that upland rice yielded higher on unplowed than on plowed land.

Ospina et al. (1957) found. in Columbia that the use of plow often resulted in heavy erosion. Kannegieter (1967), (1969) reported from Ghana that a short-term Pueraria fallow combined with mulch tillage gave effective soil protection against erosion and improved soil moisture storage.

Soil Erosion and Run-Off Losses: Soil erosion increases exponentially with the increase in slope under high intensity storms. For storms of low intensity, soil physical properties have a predominant influence on soil erosion. Soil of low infiltration rate on gentle slopes can have higher erosion losses than soil of steep slopes and high infiltration rate (Fig. 27). Continuously maintained cover of partially decomposed crop residue decreases run-off and soil losses to a minimum for soil of 1 to 15% slopes (Fig. 27). This effect of mulch on soil erosion is due to decreased impact on unexposed soil as well as high infiltrability of the soil maintained at its maximum level on soil under minimum tillage (Fig.28). The practice of minimum tillage cultivation without crop residue on the soil surface, removed either by burning or grazing, results in soil crustation, decreased infiltration rate and higher losses due to run-off and erosion (Fig. 29). The maintenance of adequate vegetative cover, either from a crop residue or from a cover such as Pueraria or Stylosanthes, is crucial in erosion control. The results of minimum tillage experiments indicating higher run-off and erosion losses as compared

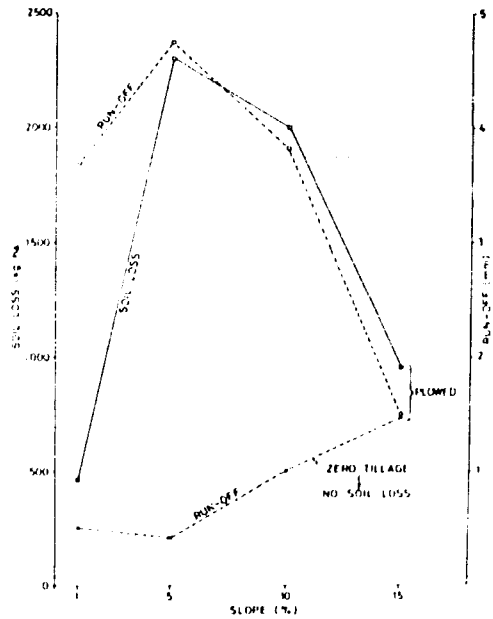

Fig.27. Run-off and erosion losses from no tillage and plowed plot.

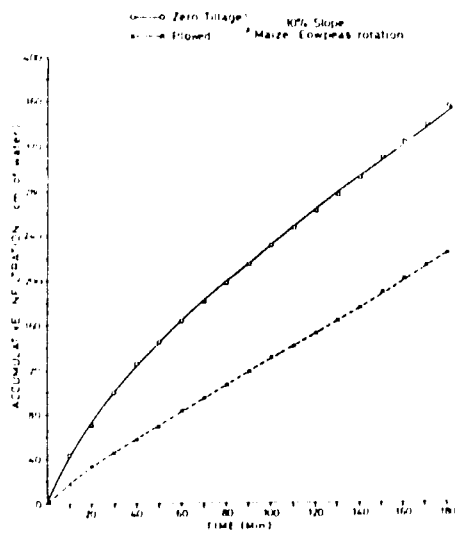

Fig.28. Comparative infiltration rate from mulch tillage and plowed plot.

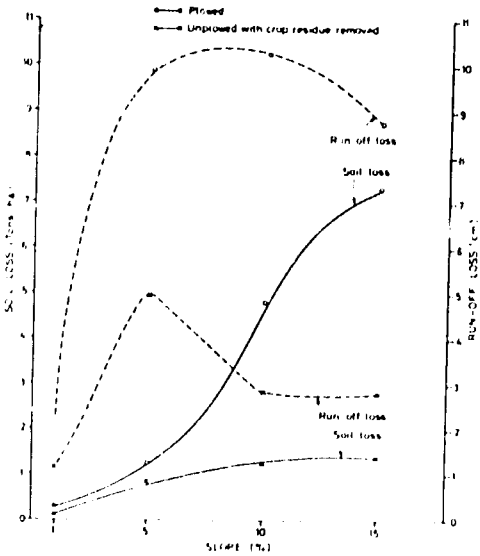

Fig.29. Run-off and erosion losses from plowed and unplowed plots with crop residue removed.

to the plowed land are due to the removal of crop residue from the unplowed plots. (Charreau and Fauck, 1971; Charreau and Nicou, 1971; and Charreau, 1968).

Soil Moisture Regime: Soil moisture reserve under mulch tillage plot is consistently higher than that under plowed (Figs. 30–33). In general, the increase in moisture storage for 0–10-cm layer was higher than 10–20-cm layer. Tillage treatments have no significant effects on improving the moisture storage capacity of the deeper horizons beyond 30-cm depth. The unirrigated plots in mulch tillage treatments showed symptoms of leaf curling less frequently than the plowed plots; thus the increased moisture reserve could carry the crop through periods of short-term drought without strong moisture stresses developing within the plants. During periods of long, dry spells there may not be a significant increase in moisture storage under

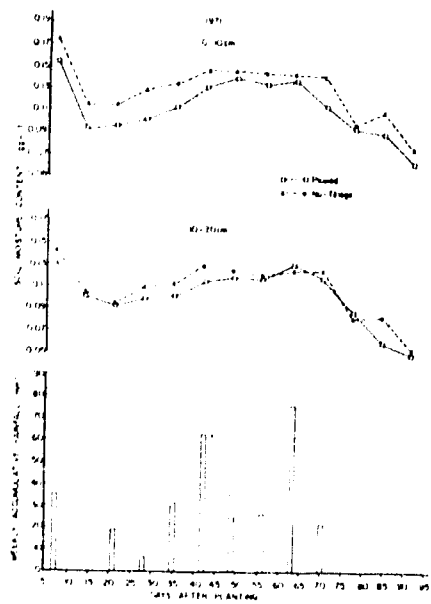

Fig.30. Soil moisture regime in plowed and unplowed plots under maize (Lal, 1974).

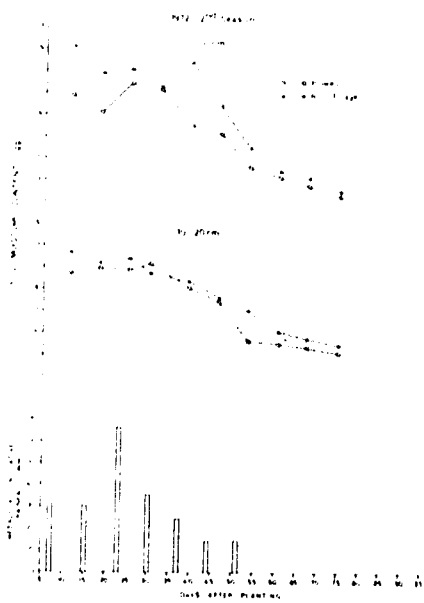

Fig.31. Soil moisture regime in plowed and unplowed plots under maize.

mulch over conventional tillage if the overall moisture holding capacity of the soil is low.

Soil Temperature: Soil temperature is significantly influenced by tillage and crop residue management (Figs. 34–36). The differences in the maximum soil temperature of the mulch tillage plots were as high as 10 and 4 C for 20-cm depths respectively. The soil temperature for the plowed plots were observed to be above the optimum level for crop growth from 11.30 a.m. to 6.30 p.m. from November to June in the Western State of Nigeria.

The effect of decreased soil temperature on time and percentage of emergence of soybeans was obvious in the mulch tillage plots. Not only did soybeans emerge faster, there was 50% more emergence in mulch tillage plots than in plowed ones.

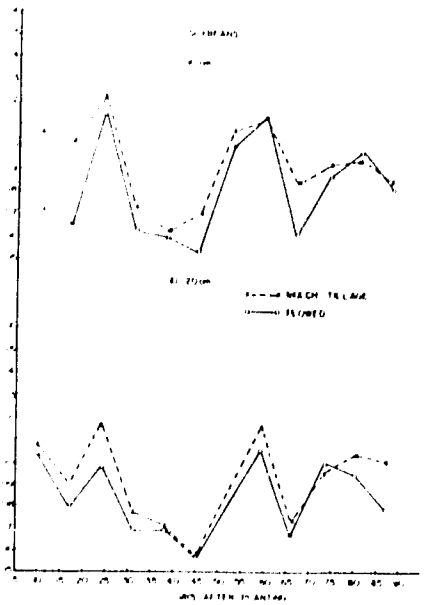

Fig.32. Soil moisture regime under plowed and unplowed soybean plots.

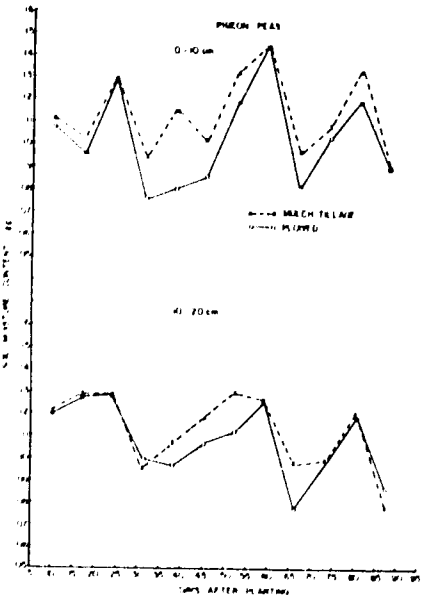

Fig.33. Soil moisture regime under plowed and unplowed pigeon pea plots.

Soil Structure: The surface soil of the plowed plots exhibits crustation after high intensity storms. A crust of approximately 2 to 5-mm thickness with peretrometer resistance of 2.5 to 2.8 kg cm^{-2} and the average force of 1.2 kg cm^{-2} is observed for the plowed plots. About 1-cm thick layer of dead crop residue on the surface of mulch tillage plots not only prevents crustation but stimulates biological activity. Earthworm casts of about 2400 m^{-2} are counted for no-tillage plots as compared with that of less than 100 m^{-2} for the plowed plots. The effect of mulch tillage on worm activity under different crop rotations is shown in Table 11. As a result of high biological activity and lack of crust formation the bulk density of the surface soil horizon under mulch tillage is generally low (Table 12). Alternation in particle size distribution of the soil due to accelerated soil erosion in the plowed and unplowed treatmeats can affect

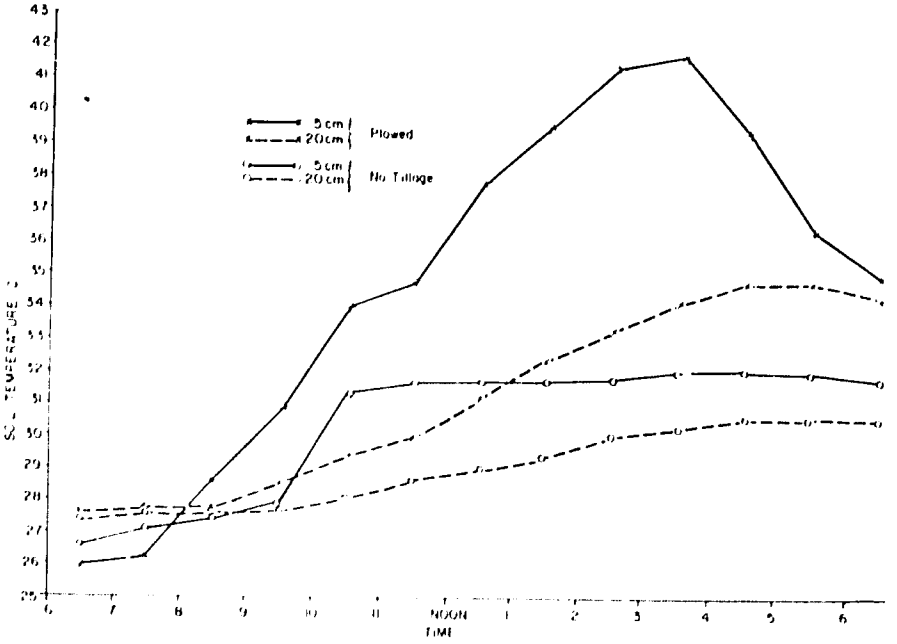

Fig. 34. Soil temperature regime under maize as affected by tillage.

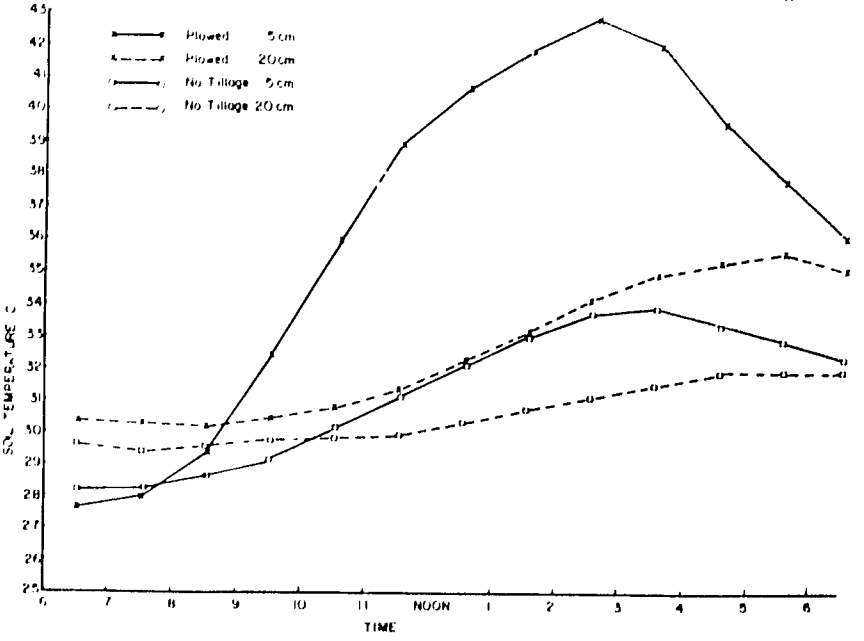

Fig. 35. Soil temperature regime under soybeans as affected by tillage.

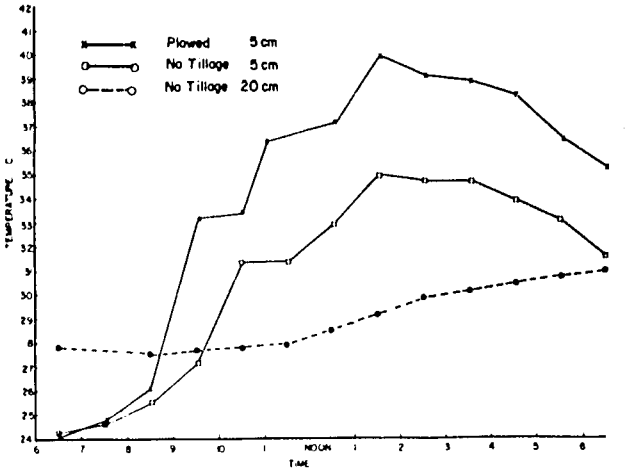

Fig. 36. Soil temperature regime under cowpeas as affected by tillage.

the pore size distribution and also the moisture release characteristics of the surface soil under different crop rotations (Figs. 37–38). Two years of continuous plowing increased the moisture content at zero suction from 31 to 34% for the no-tillage plots, while the moisture retention at the higher potential (more negative) remained the same, thereby increasing the available water capacity of the soil. Similarly the moisture equivalent values were found to be 9.45 and 9.73% for plowed and no-tillage plots respectively. The infiltration rate of the soil is maintained at its maximum by mulch tillage techniques (Fig. 39).

Changes in Chemical Properties of the Surface Soil: A continuous cover of crop residue retained in the mulch tillage plots helps maintain the ever dwindling organic matter content of the tropical soils at acceptable level. For

Table 11. Effects of tillage treatments and crop rotation on earthworm activity in the second season (Number of casts week m^{-2}).

Rotation	Number of casts per week at different times after planting							
	60 Days		67 Days		74 Days		81 Days	
	NT*	P	NT	P	NT	P	NT	P
Maize–Maize	86	12	104	0	100	0	68	0
Maize–Cowpeas	26	0	24	0	20	0	28	0
Pigeonpeas–Maize	107	18	56	8	108	0	272	0
Soybeans–Soybeans	4	1	0	0	1	0	2	0
Cowpeas–Cowpeas	8	2	0	0	4	0	2	0
Average	46	7	37	2	47	0	72	0

* NT – No tillage or mulch tillage P – Plowed

Table 12. Soil bulk density* at different times after planting as affected by tillage and crop rotations (0.10-cm depth, g cm^{-3}).

Rotation	First Season						Second Season			
	20 Days		40 Days		50 Days		20 Days		40 Days	
	NT	P	NT	P	NT	P	NT	P	NT	P
Maize–Maize	1.42	1.57	1.27	1.40	1.36	1.48	1.47	1.61	1.56	1.59
Maize–Cowpeas	1.07	1.51	1.19	1.31	1.42	1.46	1.49	1.52	1.53	1.60
Pigeonpeas–Maize	1.42	1.45	1.32	1.37	1.28	1.43	1.37	1.46	1.23	1.44
Soybeans–Soybeans	1.37	1.48	1.49	1.37	1.38	1.48	1.49	1.41	1.36	1.49
Cowpeas–Cowpeas	1.45	1.48	1.37	1.71	1.34	1.47	1.36	1.55	1.38	1.66
Average	1.34	1.50	1.32	1.43	1.41	1.46	1.44	1.51	1.41	1.56

* *The bulk density of the inter-stone material.*

instance the initial value of organic carbon content of the surface soil, immediately after clearing of 2.33% in March 1970, decreased to 1.69% for plowed and 2.26% for unplowed plots in August 1972; and to 1.4% for plowed and 1.82% for the mulch tillage plots in February 1973 (Table 13). The cation exchange capacity, the concentrations of the cations on the exchange complex and status of available nutrients can also be affected due to tillage treatments. Mulch tillage plots had higher C.E.C., a higher concentration of the divalent cations on the exchange complex, more nitrate nitrogen and available phosphorus than the plowed treatments. The effect of different crop rotations under mulch tillage on soil chemical properties is shown in Tables 14 and 15. The crop which leaves more residue on the surface maintains the organic matter content and C.E.C. at a higher level (e.g. maize) than those which have little or no residue (soybeans). The role of suitable crop rotations, therefore, is important.

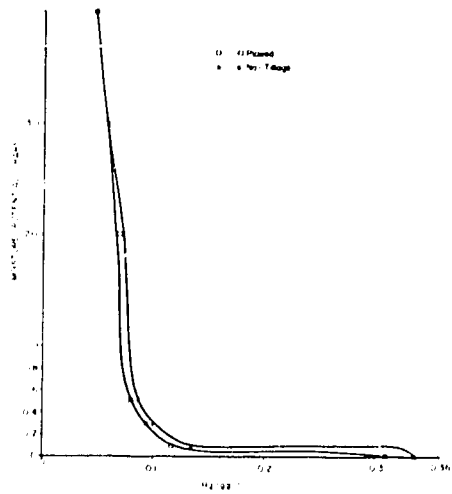

Fig.37. Soil moisture release characteristics of surface soil for plowed and mulch tillage plots (Lal, 1974).

Crop Yields: Different tillage systems affect grain yield through various prime factors and the interaction between them. Tillage effects on soil temperature, soil structure, nutrient availability and root development influence crop performance. The effect of two levels of each of irrigation and fertilizer ap-

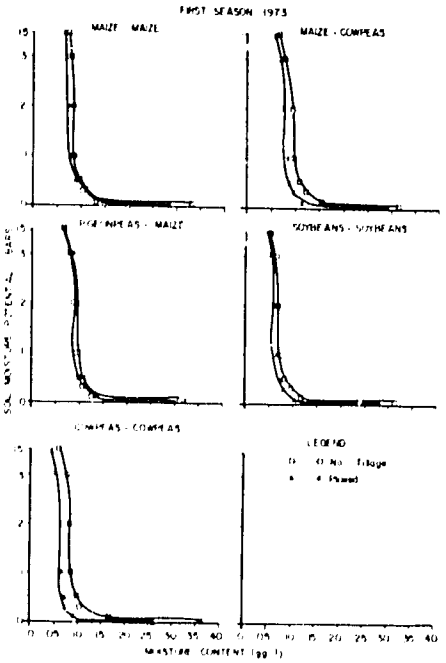

Fig.38. Soil moisture release characteristics for plowed and mulch tillage plots under different crop rotation.

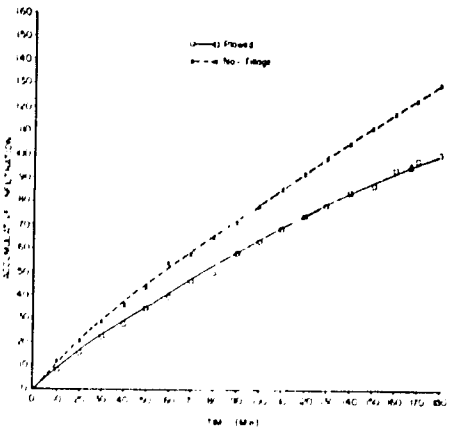

Fig.39. Accumulative infiltration as affected by plowed and mulch tillage techniques.

plication under mulch (no-tillage) and conventional (plowed) plots for three consecutive seasons on maize grain yield is shown in Figure 40.

In general, equivalent yields for maize were obtained under mulch tillage treatments as compared to those of plowed plots. Irrigation is necessary only during prolonged dry spells, par-

Table 13. Tillage effects on soil chemical properties.

Treatments	*Organic carbon %*	*Available P (ppm)*	*NO_3-N (ppm)*	*C.E.C. me/100g*	*Exchange cations (me/100g)* Ca^{++}	Mg^{++}	K^{+}	Na^{+}
			August 1972					
Plowed	1.69	10	33	4.4	2.29	0.55	1.06	0.16
No-tillage	2.26	27	40	5.4	2.46	0.83	1.19	0.15
			February 1973					
Plowed	1.40	27	25	–	3.29	0.67	0.37	–
No-tillage	1.82	37	35	–	3.84	0.76	0.36	-

Table 14. Effects of tillage and crop rotation on soil chemical properties (0-10 cm depth, sampled July, 1973)

Rotation	Organic Carbon (%)		Total Nitrogen (%)		Bray Phosphorus ppm		Exch. K me/100g		Exch. Ca me/100g		Exch. Mg me/100g		Exch. Na me/100g	
	NT*	P	NT	P	NT	P	NT	P	NT	P	NT	P	NT	P
Maize-Maize	1.21	1.44	0.183	0.196	99.53	79.53	0.489	0.372	5.190	3.359	0.896	0.471	0.129	0.081
Maize-Cowpeas	1.91	1.41	0.186	0.143	48.67	62.70	0.497	0.379	3.859	3.792	0.905	0.696	0.101	0.092
Pigeon Peas-Maize	1.51	1.24	0.136	0.127	44.76	41.40	0.325	0.401	3.493	2.860	0.878	0.494	0.090	0.075
Soybeans-Soybeans	1.76	1.30	0.160	0.123	42.50	42.13	0.860	0.369	4.192	3.260	1.550	0.559	0.122	0.078
Cowpeas-Cowpeas	1.51	1.28	0.173	0.106	24.53	7.53	1.003	0.514	4.691	2.961	1.584	0.700	0.104	0.081
Average	1.68	1.31	0.167	0.127	51.98	46.65	0.635	0.407	4.285	3.186	1.162	0.584	0.109	0.081

*NT = No tillage P = Plowed

Table 15. Effects of tillage and crop rotations on soil chemical properties (10-20 cm depth, July 1973)

Rotation	Organic Carbon (%)		Total Nitrogen (%)		Bray Phosphorus ppm		Exch. K me/100g		Exch. Ca me/100g		Exch. Mg me/100g		Exch. Na me/100g	
	NT	P	NT	P	NT	P	NT	P	NT	P	NT	P	NT	P
Maize-Maize	1.22	1.42	0.116	0.139	19.76	13.27	0.539	0.316	5.948	3.193	0.869	0.641	0.130	0.104
Maize-Cowpeas	1.18	1.31	0.136	0.140	14.06	29.26	0.362	0.360	3.779	2.994	0.739	0.573	0.101	0.113
Pigeon peas-Maize	1.11	1.17	0.110	0.110	17.97	22.50	0.398	0.339	[illegible]	3.193	0.938	0.549	0.096	0.090
Soybeans-Soybeans	1.32	1.18	0.120	0.116	15.63	15.63	0.963	0.344	[illegible]	3.456	1.032	0.687	0.119	0.087
Cowpeas-Cowpeas	1.06	1.03	0.110	0.083	8.45	8.93	0.645	0.311	3.277	2.296	1.127	0.696	0.093	0.070
Average	1.18	1.22	0.177	0.116	19.16	21.90	0.621	0.336	4.973	2.927	0.941	0.629	0.108	0.093

ticularly at silking stage (1972 second season, Fig.40). And during the normal rainy season, irrigation enhances leaching of fertilizer. For the first two seasons, fertilizer showed response only under no-tillage plots. The competition between micro-organism and maize for fertilizer under no-tillage may be responsible for significant yield increase on fertilized over unfertilized plots. It seems that nitrogen requirements under mulch tillage techniques are generally higher than under conventional methods of clean seed bed preparation.

Satisfactory grain yields for cowpeas, pigeon peas, soybeans and sweet potatoes have also been obtained under mulch tillage treatments (Table 16). Significantly higher maize yield from the mulch tillage plots was obtained in the first season of 1973 as compared with those of the plowed treatments. This differential maize yield response was attributed to a long dry spell of three weeks in the early flowering stage. The crop under minimum tillage showed less symptoms of drought stress as compared with the plowed plots.

The fertilizer requirement under mulch tillage is generally higher than that of plowed land. Plants on unfertilized mulch tillage plots show frequent symptoms of N and P deficiency. These symptoms are particularly noticeable in soybeans which, despite denser stand, show severe P deficiency symptoms and stunted growth.

The weed competition in the mulch tillage and plowed plots may have a significant effect on grain yield. Weed growth can be suppressed by the dead crop residue in the minimum tillage plots. The weeds of Graminae family were prominent in the plowed plots as compared to bush regrowth and broad-leaved weeds in the mulch tillage plots. For example, the total quantity

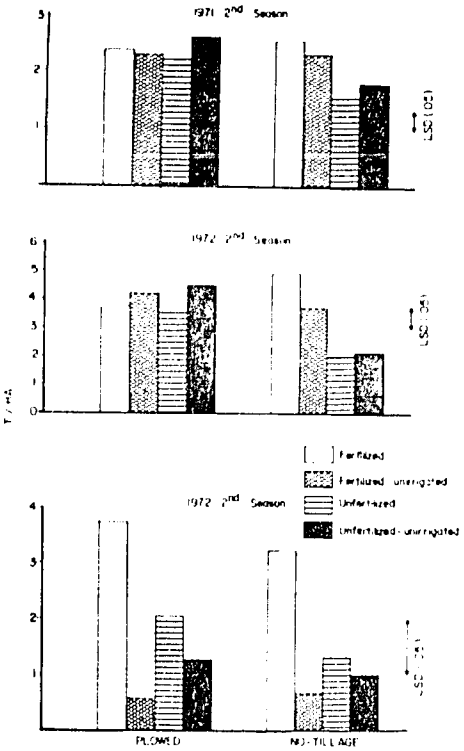

Fig. 40 Effect of mulch tillage and plowing on maize grain yield at two levels of fertilizer and irrigation.

of weeds harvested four weeks after planting maize in 1972 first season was 20 kg and 0.5 kg per plot of 200 m^2 in the plowed and no-tillage plots respectively.

Mulch Tillage Techniques

Mulch tillage techniques are based on the principle of causing least soil disturbance and leaving the maximum of crop residue on the soil surface and at the same time obtaining a quick germination, an adequate stand and a satisfactory yield. The minimum tillage necessary to obtain a good stand and satisfactory yield in any particular situation depends upon soil type, the nature of vegetation cover, previous soil management practices and the nature of crop to be grown.

Mulch Tillage Under Labor Intensive Farming: Under labor intensive farms, like most of the farms in West Africa, crops such as maize, soybeans, cowpeas, pigeon peas and cassava can be planted directly after bush clearing, while leaving most of the leaves and

Table 16. Comparative crop yield in mulch and conventional tillage (1st season, 1973)

Crop	*Grain yield (kg/ha)* *Mulch tillage*	*Conventional tillage*
Maize	4500.0	3000.0
Cowpeas	748.0	639.2
Soybeans	846.0	1066.0
Sweet potatoes	22,000.0	17,750.0
Pigeon peas*	26,250.0	25,000.0

* *Total dry matter.*

small branches and dried weeds in the inter-row area. To some extent this is what the farmers under shifting cultivation do. Under the mulch tillage system, fertilizer can be broadcast directly on the soil surface before planting and the top dressing can be made closer to the plant row at the appropriate time.

If the plot is heavily weedy, use of paraquat at a rate of 2.5 l/ha sprayed three to four days before planting can control the weeds. The crop can then be directly planted in the dead weed growth. If the weed growth is high, slashing and leaving them on the soil surface will facilitate planting. Planting is generally done by hand. One manual weeding at two to three weeks after planting may be enough to control weeds.

Partially or Completely Mechanized Farms: The choice of the mulch tillage technique on large-scale mechanized farms, now developing in West Africa, depends on the soil conditions at the time of planting, previous soil management and crops to be grown. The general soil preparation by plowing and harrowing is replaced by spraying with paraquat, a contact herbicide, at the rate of 2.5 l/ha sprayed 3 to 5 days before planting. One of the following methods of seed bed preparation and planting can then be adopted by using sub-surface tillage equipment to till the soil under the crop residue and keep the mulch on the surface.

Sod Planting: Planting is done directly in unplowed soil with chemically killed sod, weeds, cover crops or in previous crop residue. In this method, paraquat or any other contact herbicide is used to replace plowing and manual, mechanical weeding or residual herbicides (atrazine, lasso etc.) used for pre-emergence weed control. Crops can be planted either by a hand planter or by opening a narrow trench (5 to 7 cm wide and 5 cm deep) for the seed.

Mulch Tillage: A chisel plow can be used in the previously shredded crop residue to break open the hard crust or hard pan underneath the soil. Care should be taken not to invert the soil so as to leave the maximum of crop residue on the soil surface.

Strip Tillage: Tillage is eliminated in most of the inter-row areas and a narrow strip is opened to facilitate planting and the placement of the fertilizer. The crop residue is left undisturbed in the inter-row zone.

Disc Plant: One discing prior to planting and leaving most of the crop residues on the surface can also help open a crusted field and improve its infiltration, water holding capacity and root penetration.

Till Plant: Tractor driven equipment can be used on large farms to slash and remove the previous crop residue from the row to the inter-row zone and also open a small trench as a seed bed, in one operation.

Bed Plant: This method can be used for surface irrigated crops. Small furrows can be opened at a distance of 1 to 1.5 m raising the bed in between and then planting manually or with a mechanical planter directly on the bed.

Relative Merits of Mulch Tillage in the Humid Tropics

No-tillage or mulch tillage technique has no magic to produce crop on soils which will not produce under conventional tillage. These techniques

require a careful husbandry of all the factors of production. Some of the advantages of this system of land management are:

Steady Yield Returns Over a Long Period: Mulch tillage technique may not give the maximum yield in the best season but it will produce a satisfactory crop in the season with poor rainfall distribution and long dry spells. Under some soil conditions, mulch tillage technique may even outyield the conventional tillage.

Soil Erosion and Run-Off Control: Tropical soils, because of their structural instability and high rainfall erosivity, are extremely susceptible to soil erosion. Highly erodible soils on steeper slopes, otherwise considered uncultivable under conventional methods, can safely be cultivated by minimum tillage techniques. If soil erosion is the serious limiting factor in replacing shifting cultivation by a permanent system of land utilization in the humid tropics, minimum tillage is definitely desirable.

Soil Moisture Storage: Drought susceptible tropical soils will certainly produce higher yield under minimum tillage techniques, because the soil moisture storage is superior to that of conventionally plowed soils.

Soil Temperature: If supra-optimal soil temperature prevails in the early stages of crop growth, the mulch effect in the minimum tillage plots will help improve soil thermal regime and quicken the germination.

Soil Structure Maintenance: Soil structure is maintained at its original level. The principal factor of rebuilding the surface soil horizon under bush fallow, as under the cover of native vegetation like earthworm activity, is maintained even when soil is under arable crops.

Savings in Labor and Power: There is generally a 50% reduction in power requirement with judicious mulch tillage techniques. The labor is also less.

Savings in Time: Time of planting the second season crop is critical in western Nigeria. There is little time between harvesting the previous crop and planting the next. Planting done after the third week of August is risky due to short rainy season. The time required for preparing the seed bed can be minimized by no-tillage or mulch tillage techniques.

Minimizing Losses Due to Lodging: The experience at IITA shows that crop lodging is less for the maize planted with minimum tillage than any other techniques.

Fertilizer Efficiency: The loss of the fertilizer elements in run-off water is less by minimum tillage than by other techniques.

Improvements Needed in the Mulch Tillage Technique

Presently, mulch tillage technique is not perfected; it is yet soil and crop specific. Basically it should work for all crops and soils. Its specificity calls for its improvement toward versatility. The mulch tillage technique involves a new system of soil and farm management which has different requirements for husbandry. Research needs to be conducted for this new system toward:

Mechanization: Suitable machinery is required for planting, fertilizer application and weed control. The equipment design and cost should consider the small scale farmers. The emphasis should be placed on hand operated or small motor driven equipment.

Fertilizer: The fertilizer requirement for mulch tillage crops is different from that of the conventionally cultivated plots. There is a need to know the rate, time, method and kind of fertilizer application for most of the crops. The effect of mulch on microbial population and nitrogen availability needs to be investigated.

Weed Control: Herbicides are costly. The efficient use of crop residue as a weed control device should be explored.

Crop Rotation: Proper crop rotation is an important aspect of mulch tillage technique. The use of grasses and leguminous cover crops in the rotation is essential, particularly for the badly managed and compacted soils. A crop which produces enough residue should be used in rotation with low-dry-matter-producing crop.

Disease and Insect Control: Economical methods of disease, insect and nematode control need to be developed for this new system of soil management.

The Future of Mulch Tillage Systems of Soil Management in the Tropics: Mulch tillage technique holds great potential for soil and water conservation. Soil losses under conventional tillage will be drastically cut when managed by mulch tillage techniques. Soil conservation is particularly important for those tropical soils with shallow surface horizon and low water holding capacity. Mulch tillage technique has a promising future for semi-arid areas also with severe drought problems. Available water holding capacity of the soils is greatly enhanced by the mulch farming technique.

In addition to the benefits from an agricultural viewpoint, mulch farming practices have good future for pollution and environmental control. Rivers that run orange with soil during the rainy season will be devoid of sediments and farm chemicals such as herbicides, pesticides and fertilizers which will be filtered through the soil.

Large-scale mechanized farms in West Africa are noted for their limited successes. Such projects should be approached with caution. Unrealistic adoption of technology from the temperate countries in the tropics can lead to disastrous consequences. Mulch farming techniques offer a good possibility to substitute traditional agriculture by permanent viable systems of land use.

With the increasing pressure of population on land, mulch tillage techniques can bring even marginal land with steeper slopes under cultivation for arable crop production in the humid tropics. The farmers can be encouraged to adopt this practice if they are assured of the economic value of this system of soil management. Coordinated effort of agricultural and social scientists is needed to overcome these obstacles.

Useful References

Adams, J. E. (1970). Effect of mulches and bed configuration: II Soil temperature and growth and yield responses of grain sorghum and corn. Agron. J. 62:785–790.

Allan, W. (1965). The African Husbandman. New York 1965.

Allmaras, R. R., and W. W. Nielson, (1971). Corn (*Zea mays* L) root configuration as influenced by some row-interrow variant of tillage and straw mulch management. Proc. Soil Sci. Soc. Amer. 35:979–980.

Arndt, C. M. (1945). Temperature-growth relationships of the roots and hypocotyles of cotton seedlings. Plant Phys. 20:200–220.

Bond, J. J. and W. O. Willis (1961). Soil water evaporation: Surface residual rate and placement effect. Proc. Soil Sci. Soc. Amer. 33:445–448.

Bond, J. J. and W. O. Willis (1971). Soil water evaporation: Long term drying as influenced by surface residue. Proc. Soil Sci. Soc. Amer. 35:984–987.

Beauchamp, E. G. and D. J. Lathwell, (1967). Root zone temperature effects on the early development of maize. Plant and Soil 26:224–234.

Beauchamp, E. G. and J. F. Tarrance, (1969). Temperature gradients within young maize plant stalks as influenced by aerial temperature. Plant and Soil 30:241–251.

Brouwer, R., P. J. Jenneskens, and G. J. Borggreve, (1961). Growth response of shoots and roots to interruption of the nitrogen supply. Jaarb, I.B.S., Wageningen 1961: 29–36.

Brouwer, R., (1962). The influence of temperature of the root medium on the growth of seedlings of various crop plants. Jaarb, I.B.S., Wageningen 1962: 11–18.

Brouwer, R. (1964). Response of bean plants to root temperature: I Root temperature and growth in the vegetation stage. Jaarb, I.B.S., Wageningen 1964: 11–22.

Brouwer, R. and A. Hoogland (1964). Response of bean plants to root temperature: II Anatomical aspects. Jaarb, I.B.S., Wageningen 1964.

Bruce-Okine, E. and R. Lal (1975) Erodibility as determined by raindrop technique. Soil Sci. 1975 119 : 149 – 157.

Cary, J. W. (1966). Soil moisture transport due to thermal gradients. Practical aspects. Proc. Soil Sci. Soc. Amer. 30:428–443.

Chaminade, R. (1970). Agricultural research work carried out by IRAT. L'Agron. Trop. 25: 1–16.

Charreau, C. (1968). Rain and erosion. Afr. Soils, 13: 241–244.

Charreau, C. (1969). Influence des techniques culturales sur e développement du ruissellement et de l'érosion en Casamance. L'Agron. Trop. 24, 9:836–842.

Charreau, C. and R. Fauck (1971). Mise au point de l'utilization agricole des sols la region de Sefa (Casamance). L'Agron. Trop. 25: 151–191.

Charreau, C. and R. Nicou (1971). L'amélioration du profile cultural dans les sols sableux et sable argileux l'agron. 26: 1183–1247.

Charreau, C. and R. Nicou (1971). L'amélioration du profil cultural dans les sols sableux et sable argileux de la zone tropicale sèche ouest-africaine et ses incidences agronomiques. Agron. Trop. 26, 9:903-78.

Charreau, C. (1972) Problèmes posés par l'utilisation agricole des sols tropicaux par des cultures annuelles – Paper read at FF/IRAT/IITA seminar on Tropical Soil Research, Ibadan. May 1972.

Chinwuba, P. M. (1965). Problems of expanding maize production in Nigeria. Fed. Dept. of Agric. Res. Memo. No. 75.

Collis-George, N. and R. Lal (1971). Infiltration and structural changes in soil as influenced by initial moisture content. Aust. J. Soil Res. 9: 107–116.

Cook, R. L. Turk, and H. F. McColly (1953). Tillage methods influence crop yields. Proc. Soil Sci. Soc. Amer. 17:410–414.

Cook, R. L., H. F. McColly, L. S. Robertson, and C. M. Hanson (1958). Save money-water-soil with minimum tillage. Mich State Univ. Est. Bull. 352.

Cook R. L. (1972). Minimum tillage and the environment, Proc. 20th Ann. Meeting of the Agric. Res. Inst. Nat. Acad. Sci. 12:23-96.

Cunningham, R. K. (1963). The effect of clearing a tropical forest. J. Soil Sci. 14:334-345.

Dabin, B. (1959). Schedule of three years of erosion (1956–58) at the Adiopodoume station (Ivory Coast). Paper presented at 3rd Inter-African soil conference Dalaba: 629 – 636.

Dixon, R. M., and A. E. Peterson (1971). Water infiltration control, a channel system concept. Proc. Soil Sci. Soc. Amer. 35:968-972.

Dubois H., and M. Lecompte (1969). Note sur le conservation des sols et la regeneration forestiere a la station et dans le paysannat de Bambesa. Bull. Agric. Congo Belg. 40:256:267.

Duckham, A. N., and G. B. Masefield (1971). Farming systems of the world. Chatto and Winden, London. Pp. 382–383.

Fournier, G. (1967). Research on soil erosion in Africa. Afric. Soils 12:53-96

Gardner, W. R., and D. I. Hillel (1962). The relation of external evaporative conditions to the drying of soil. J. Geophys. Res. 67:4319–4325.

Gardner, W. R. (1965). Movement of nitrogen in soil. ASA Monograph 10:555–577.

Grobbelaar, W. P. (1963). Response of young maize plants to root temperature. Mededelingen van de Landbouwhogeschool Wageningen, Nederland. 63(5), 1963.

Hudson, N.W. (1957). Erosion control research. The Rhodesian Agric. J. 54: 297–323.

Jack, C.V., W.D. Brind; and R. Smith (1955). Mulching. Commonwealth Bureau of Soil Sci. Tech. Comm. No. 49.

Jeater, R. S. L., and H. C. McIlvenny (1965). Direct drilling of cereals after use of paraquat. Weed Res. 5: 311 - 318.

Jurion, F., and J. Henry (1969). Can primitive farming be modernised? I.N.E.A.C. Hors. Series 1964.

Kannegieter, A. (1967). Zero cultivation and other methods of reclaiming Pueraria fallowed land for food crop cultivation in the forest zone of Ghana. Trop. Agriculturist Vol. CXXVIII.

Kannegieter, A. (1969). The combination of short-term Pueraria fallow zero cultivation and fertilizer application. Its effect on a following maize crop. Trop. Agriculturist Vol. CXXV nos. 3 and 4.

Klute, A., F. J. Scott and F. D. Whisler, (1965). Steady state water flow in a saturated inclined soil slab.

Kowal, J. (1972). The hydrology of a small catchment basis at Samaru, Nigeria: III Assessment of surface run-off under varied land management and vegetation cover. Niperian Agric. J. 7:120–123.

Kowal, J. (1972). The hydrology of a small catchment basis at Samaru, Nigeria: IV Assessment of soil erosion under varied land management and vegetation cover. Nigerian Agric. J. 7:134–147

Kuipers, H. (1970). Historical notes on the zero-tillage concept. Neth. J. Agric. Sci. 18:219–294.

Lal, R. (1973). Soil temperature, soil moisture and maize yield from mulched and unmulched tropical soils. Plant and Soil Vol. 40:129–143.

Lal, R. (1973). Effects of seed bed preparation and time of planting of maize in western Nigeria. Expt. Agric. 9:304–313

Lal, R. (1973). No-tillage effects on soil conditions and maize production in western Nigeria, Plant and Soil Vol. 40:321–331.

Lal, R. (1973). Effects of constant and fluctuating soil temperature on the growth, development and nutrient uptake of maize seedlings. Plant and Soil Vol. 40:589–606.

Lal, R., and S. K. Hahn (1973). Effects of methods of seed bed preparation, mulching and time of planting on yam *(Dioscorea rotundata)* in western Nigeria. Symp. Int. Soc. Trop. Root Crops. IITA Dec. 2–12, 1973.

Lal, R. (1974). Soil erosion and shifting cultivation. FAO Soils Bull. 24:48–72.

Lawes, A. D. (1962). Rainfall conservation and yield of cotton in Northern Nigeria, Samaru Res. Bull. 16.

Lemon, E. R. (1956). The potentialities for decreasing soil moisture evaporation loss. Proc. Soil Sci. Soc. Amer. 20:120–125.

Macartney, J. C., P. J. Northwood, M. Dagg, and R. Dawson (1971). The effect of different cultivation techniques on soil moisture conservation and the establishment and yield of maize at Kongwa, Central Tanzania. Trop. Agric. (Trinidad) 48: 9–23.

Meyer, L. O., and J. V. Mannering (1967). Tillage and land modification for water erosion control. In conference proceedings of the tillage for greater crop production. ASAE Publication Proc. 168:58–62.

Müller, J. and O. De Bilderling (1953). Les methods culturales indigenes sur les sols equatoriaux de plateau. I.N.E.A.C. Belge Bull. Inform 2: 21–30.

Nigeria, Fed. Dept. Agric. Res. Annual Report 1964–65 and 1965–66.

Northwood, P. J., and J. C. Macartney (1967). The effect of different amounts of cultivation on the growth of maize on some soil types in Tanzania. Trop. Agric. (Trinidad) 48:25–33.

Nye, P.H., and Greenland, D. J. (1960). The soild under shifting cultivation. Commonw. Bur. Soils Tech. Common. No. 51, Harpenden, England.

o, B.N. (1965). Effects of mulching and frequency of weeding on the performance and yield of maize. The Nigerian Agric. J. 2:7–9.

o, B.N. (1969). Maize experiments on the Nsakka Plains: III, Effects of different kinds of mulch on the yield of maize in the humid tropics. L'Agron. Trop. Vol. XXVIII: 1036–1047

a, Vasquez, and P. Nel. (1957). La agriculture moderna y la conservation de les recurses naturales. Agri. Trop. 13, 3:163–180.

ra, H.C., and P.A. Jones (1954). A tillage study in Kenya: II The effects of tillage practices on structure of soil. Emp. J. Expt. Agric. 23: 323–331.

ra, H.C., R.A. Wood, H.W. Brzostowobi, and P.H. Hosegood (1958). Water conservation by fallowing in semi arid tropical East Africa. Emp – J. Exp. Agric. 26: 213–228.

, E.J. (1967). Ten years of erosion and run-off records in Senegal. L'Agron. Trop. 22:123–152.

, E.J. (1970). Importance relative de l'erosion du drainage oblique et vertical dans la pédogénèse actuelle d'un sol ferrallitique de moyenne Cote d'Ivoire. Cah. O.R.S.T.O.M., Ser Pedologie 94: 468–482.

, E.J. (1971). Influence des moficiations du milieu natural sur l'erosion le bilan hydrique et chimique suite a le mise en culture sous climat tropical. O.R.S.T.O.M., Abidjan 1971.

, E.J., and R. Bertrand (1971). Contribution a l'etude de la methode des bandes d'arret pour lutter centre l'erosion hydrique en Afrique de l'ouest. Resultata experimentaux et observation sur le terrain. L'Agron. Trop. 11:1270–1283.

ll, V.W., and B.A. Keen (1971). Studies in soil cultivation:X The results of six-year cultivation experiment. J. Agric. Sci. 31:326–347.

, A. (1970). Annual report Savannah Forestry Res. Station, Samaru, Zaria. 1970–71: 35–38.

, A.J., and R.F. Montgomery (1962). Soils and land use in central Western Nigeria. The Govt. of Western State of Nigeria publication.

of Ghana Ann. Rep. Agric. Res. Station Nungue 1969–70.

avel, C.H.M. (1972). Soil temperature and crop growth, In: Optimizing The Soil Environment Toward Greater Crop Yields. Ed. Daniel Hillel, Academic Press, New York and London (1972).

/an Doren, D.M., Jr. (1967). Changes in seed environment due to tillage. In conference proceeding of the tillage for greater crop production ASAE Publication Proc. 168:5–9.

Van Duin, R.H.A. (1956). On the influence of tillage on conduction of heat, diffusions of oil and infiltration of water in soil. Thesis Wageningen Versl. Landbouwk Ondrez. 62(7), 82 pp.

Valker, J.M. (1970). Effect of alternating versus constant soil temperature on maize seedling growth. Proc. Soil Sci. Soc. Amer. 34:889–892.

Valker, J.M. (1969). One-degree increments in soil temperature affect maize seedling behaviours. Proc. Soil Sci. Soc. Amer. 33:729–736.

Vatts, W.R. (1972). Leaf extension in *Zea mays* L. Leaf extension and water potential in relation to root zone and air temperature. J. Exp. Bot. 23:704–712.

Vatts, W.R. (1972). Leaf extension in *Zea mays* II. Leaf extension in response to independent variation of the temperature of the apical meristem of the air around the leaves, and of the root zone. J.Exp. Bot. 23:713–721.

Vilkinson, G.E. (1970). The infiltration of water into Samaru soils. Samaru Agric. Newsletter 12: 81 – 83.

Villis, W.O. (1962). Effect of partial surface covers on evaporation from soil. Proc. Soil Sci. Soc. Amer. 26: 598–607.

V.M.O. (1958). Practical soil moisture problems.