Managing the Soils of Sub-Saharan Africa

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Many constraints to intensive food-crop production in tropical Africa are related to tropical soils. Improved technologies are available for different ecological regions. Important technological innovations include manual land clearing, mulch farming, conservation tillage and tied-ridges, agroforestry, cover crops, mixed- and relay-cropping, and early sowing for improved and sustained productivity. Irrigation, animal traction or draft animals, and the use of chemical fertilizers are also important. Much of the agrarian stagnation in Africa is caused by neglect and misuse of the most basic of all resources, the soil. In fact, the root cause of the perpetual famine can be traced to the misuse of soil and water resources and issues related to their misuse. Substantial increases in food production are possible if the proven technologies can be effectively transferred and implemented. Priorities lie in both short-term development projects and in initiating long-term research to understand soil and water resources and how to manage them. The agrarian research must address the issue of improving the welfare of resource-poor farmers.

WORLD AGRICULTURAL OUTPUT ROSE BY 25 PERCENT between 1972 and 1982, but in sub-Saharan Africa per capita food production declined by 14 percent during the same period (*1*). Average Africans are worse off today than they were 10 years ago. Although unfavorable farm policy may be responsible in part for low agricultural output, the capability of soils of tropical Africa to sustain high production with intensive management and continuous cultivation is also being questioned. The imbalance between soil, food, and population raises a number of questions. Are soil resources of tropical Africa capable of sustaining high and economic production? If yes, how should the soil be managed and which farming systems should be used? Can high production be achieved without degrading the soil and the environment?

Only 6.5 percent of the cultivated area is planted in high-yielding crop varieties in Africa (*2*). Improved crop varieties are an important component of the packages designed to boost food production. But high production can only be sustained if the potential and the constraints of the soil resources are understood and appropriate methods of soil resource management are developed. Large-scale mechanized farms on a few fertile soils have been successful, but vast areas of marginal lands are still used extensively. These lands produce low yields and are easily degraded, necessitating long forest fallows. This is no longer affordable because of population pressure. Management of soil and water resources is the key to intensifying agriculture and improving production. Otherwise, the food deficit in Africa is bound to persist, even if rains come in abundance and on schedule.

A tendency to view the African food situation as a crisis without analyzing the critical underlying factors is short-sighted and can be counterproductive to developing the needed database. Although high population pressure and political instability are important causes of weather-related food deficits, the lack of understanding soil and water resources and learning how to live with them are factors underlying the perpetual food crisis.

The emergency assistance to Africa in 1984 was estimated to be about $2 billion (U.S. dollars), and that was not enough to reverse the trend of food deficit (*3*). The total annual official development assistance to Africa has been estimated at $7.7 billion and that amounts to $50 to $100 per person in several Sahelian states (*4*). In comparison the per capita foreign aid to India was only $1.50 per year between 1951 and 1970 (*4*). In spite of this discouragingly familiar trend, Higgins and Kassam (*5*) and many other researchers suggest that soils, if used properly, could at low levels of input produce enough food to feed three times the 1975 population of Africa and one-and-a-half times the projected population of Africa in the year 2000. At intermediate levels of inputs, Africa could feed five times the population projected for the year 2000. Productivity can be increased by reducing environmental stresses and improving resource management.

The Green Revolution of the mid-1960s in Asia succeeded through the use of improved crop varieties and often with irrigation on fertile lands. Most African soils are marginal uplands with little irrigation potential, except in Egypt and Sudan. The paddy culture in Asia has sustained high human population density, but the technology for using the wetlands of Africa is not yet available. There are also health hazards associated with wetlands. Wetlands in Africa are still the sources of such diseases as malaria, river blindness, and bilharzia. Consequently, wetlands have not been intensively used in tropical Africa and will only be used when health hazards are removed and suitable technologies are developed. Intensive use of uplands for high and sustained production is the immediate solution. Improving yield on marginal uplands requires more than just introducing better crop varieties and fertilizers. The productivity of marginal land must be improved.

Research findings from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, and from other national and international institutions indicate definite possibilities of enhancing food production while maintaining ecological stability and preserving natural resources. In this article, I will review recent advances in soil-management technologies that have proven to be successful and compatible within the ecological constraints of tropical Africa. The soil and water resources and their management are specifically addressed in relation to the problems of the sub-Saharan regions.

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Natural Resources

Africa has a total land area of 29.7 million square kilometers (2970 million hectares). The land use in the early 1980s was 181.2 million hectares cultivated, 784.2 million hectares permanent pasture, and 696 million hectares forest; the remaining 1308.6 million hectares are in shrubs, desert, and/or miscellaneous uses (*6*). Human resources, if trained and used properly, can be a major asset. At present, high populations are a definite liability and a major cause of food shortages. The rate of population increase is higher in Africa than in any other major region of the world. It is 3 percent or more in several countries. The population of Africa was 380 million in 1975 and is expected to be 780 million and 1.5 billion by the years 2000 and 2020, respectively (*5*).

The climax vegetation of Africa varies widely, depending on the amount and distribution of rainfall (Fig. 1) (*7, 8*). Tropical rainforests prevail where rainfall exceeds 1500 mm in 5 to 10 months. Tropical xerophytic woodland occurs in regions with rainfall of 200 to 900 mm in 2 to 5 months, and tropical desert vegetation occurs in areas with an annual rainfall of less than 200 mm in 1 month or less.

Equally diverse are the soils of Africa (Fig. 2) (*9*). The most predominant soils of the humid, subhumid, and semiarid regions are alfisols, ultisols, oxisols, and entisols-inceptisols. The highly weathered oxisols, ultisols, and alfisols have low nutrient and water reserves available to plants and are of low inherent fertility. With a low base-saturation percentage, oxisols and ultisols are also low in bases (such as calcium and magnesium) and have high acidity. Together, these soil types occupy about 25 percent of the African landscape. Alfisols are relatively fertile compared with oxisols and ultisols, but they have poorer soil physical properties. Alfisols have a coarse-textured surface horizon overlying a clayey subsurface layer. These soils have a weak structure, and are highly susceptible to crusting, compaction, and accelerated soil erosion. In addition to being subject to high soil erosion, these three soil types are also prone to midseason drought stress. Entisols and inceptisols, with relatively high fertility and favorable moisture regimes, are either found along flood plains and river valleys or are of loess origin. Some soils of semiarid West Africa are characterized by the occurrence of hardened laterite at shallow depth, for example, from 5 to 25 cm below the surface. There may be as much as 250 million hectares of such soils in West African regions. Vertisols have poor soil physical properties and are difficult to manage. Vast acreages of these soils occur in the Nile valley in Sudan, in the Lake Chad basin, in the Accra plains, and in isolated regions in eastern Africa. The relatively fertile andisols of volcanic origin are few and occur in the vicinity of Mount Cameroon and in the highlands of eastern Africa.

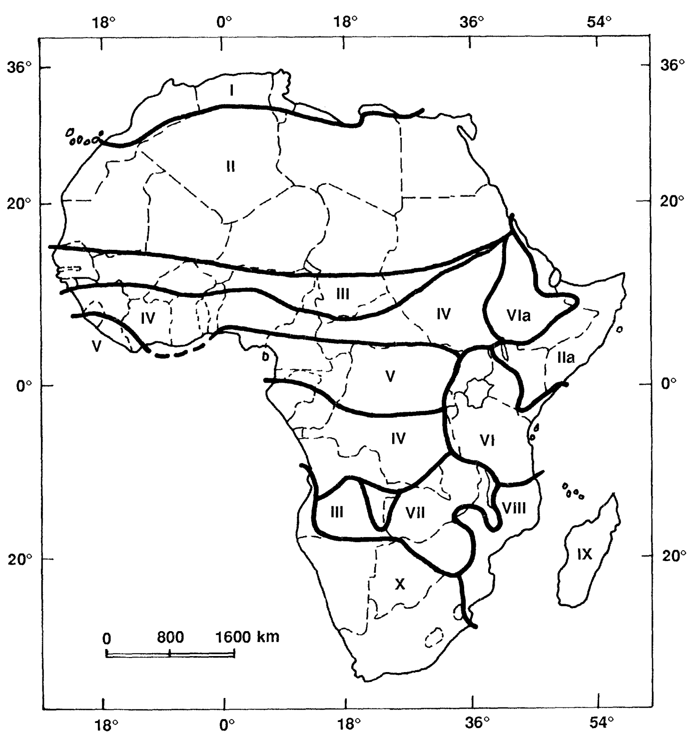

Fig. 1. Ecological zonation map of Africa (*7*). The percentage of land area in different ecological zones is I, Mediterranean, 26; II, northern desert, 33; IIa, Horn of Africa, 5.2; III, semiarid, 7.2; IV, tropical wet and dry, 17.5; V, equatorial wet, 6.8; VI, East Africa, 6.4; VIa, Ethiopian Highlands, 2.3; VII, South savanna plateau, 5.7; VIII, Mozambique, 1.9; IX, Malagasy, 2.2; and X, southern Africa, 9.2.

Table 1. Percentage increase in crop yields by plowing over the unplowed control in semiarid West Africa tropical climates from 1952 to 1969 (*18*).

Crop	Increase in crop yields (%)	
	Vegetation removed before plowing	Vegetation incorporated by plowing
Pearl millet (grain)	21	28
Sorghum (grain)	29	26
Maize (grain)	27	66
Upland rice (paddy)	157	46
Cotton (seed)	27	34
Groundnuts (pods)	19	7

Most uplands have traditionally been used for extensive subsistence systems requiring long forest fallow for fertility restoration and for erosion control (*10*). Until the last two or three decades population densities were low, and food needs and basic necessities were met through cultivation of food staples (root crops, plantain, and native vegetables) grown in association with some perennial cash crops (*11*). Farm size was limited to what could be comfortably managed by family labor. The stability of the system was attributed to a limited number of people living on sufficient land to provide a subsistence way of life.

Traditional agriculture had been compatible with the ecological environment. The stability and ecological compatibility of the system depended on (i) low population pressure; (ii) improvement in soil structure by plant roots; (iii) erosion control through leaf litter, mulch, and continuous canopy cover; (iv) nutrient contribution through ash and recycling by deep-rooted perennials; and (v) pest control through growing a wide range of crop species simultaneously. Attempts at replacing this proven system with disregard to the resulting effects on ecological stability have not been successful (*12, 13*). Such attempts have resulted in accelerated soil erosion, frequent drought stress, and increasing nutrient imbalance.

Effective land management systems and technologies are crucial to sustaining economic production from uplands. Technological options differ among soils and agroecological regions. A logical approach is that of eco-development with due consideration of the interaction between biophysical environment and socioeconomic factors. Maintaining favorable soil physical, nutritional, and biological properties means providing soil conditions of a tropical rain forest: (i) undisturbed soil surface, (ii) continuous supply of organic matter to the soil as mulch, (iii) favorable soil temperature and moisture regimes, (iv) high biotic activity of soil fauna, and (v) minimum losses by runoff, erosion, or deep leaching. Maintaining favorable levels of organic matter and soil physical properties, preventing soil erosion, and replenishing plant nutrients leached out or removed by crops are also required in sustaining high soil productivity. Much of this can be achieved through supplying an

Table 2. Maize grain yield (kg/ha) in tied-ridge systems in Burkina Faso (*22*). DAP, days after planting.

Ridge system	Yield (kg/ha)		
	Low fertilizer	High fertilizer	Mean
No earthing up	1040	1480	1260
Earthing up* at 30 DAP	990	1470	1230
Earthing up at 30 DAP; ridge tied every other furrow	1840	2540	2190
Earthing up at 30 DAP; all ridges tied	2040	3280	2660

*Earthing up means forming ridges and cross ties manually and weeding simultaneously.

adequate amount of organic matter to the soil surface as mulch.

Physical properties of the soil are important in maintaining favorable water and energy balances. Without forest fallow or mulch by leaf litter, the soils are exposed to raindrop impact, causing compaction and crusting, and sheet and rill erosion. Structurally weak soils, such as those found in the tropics, suffer the greatest damage. Reduction in activity of soil fauna, such as earthworms, termites, and so on, is another major reason for deterioration of soil structure, reduction in infiltration, and soil compaction. The problems of soil compaction are aggravated by the introduction of mechanized farm operations and vehicular traffic. Soil compaction reduces the water-infiltration rate, causing depletion of soil fertility, loss of plant-available water reserves, and further degradation of soil quality.

Apart from Australia, Africa is the driest of the continents. Drought stress is severe during parts of the year even in regions where annual rainfall is adequate. Either the rains are concentrated in short wet seasons or the soils have low plant-available water reserves. High-intensity rains concentrated in a few months cause a severe soil erosion hazard (*14*).

Soil erosion is not a monopoly of the intensively used mechanized farms. It can be equally ruinous on mismanaged traditional farms. Accelerated soil erosion has been shown to cause severe and often irreversible reductions in crop yields (*14, 15*). Erosion causes fertility declines due to selective removal of humus and of the clay fraction in lateritic soils. The organic-matter levels, the clay content, and the concentration of plant nutrients in eroded sediments are two to five times higher than those in the parent soil. Crop yields from eroded soils cannot be improved to the level of the uneroded soils even by applying the recommended doses of fertilizers and irrigation (*15, 16*). Tropical Africa has one of the worst erosion problems on arable lands in the world.

Improved Technology

Technological options differ among soils and ecological regions, and are listed below for different ecological zones.

Arid and semiarid regions. The growing season length ranges from less than 75 days in arid regions to 75 to 150 days in semiarid regions. Rainfall in these regions is highly erratic and variable. These regions are represented by zones IIa, III, VI and VII in Fig. 1. The soil and climatic constraints can be alleviated through land clearing and development, tillage methods, mulch farming, fertility maintenance, and irrigation.

Land clearing and development. If new land must be cleared, the main options are hand stumping and mechanical clearing. Although slow and labor-intensive, hand stumping is ecologically the most compatible method. Among the mechanized clearing methods, the chain pulled by two tractors is better than the dozer blade. The mechanically cleared land, however, must be immediately planted to a suitable cover crop (such as *Stylosanthes, Crotolaria,* or *Pueraria*) for an appropriate duration to improve soil structure, and provide the protective mulch cover.

Tillage methods. Alfisols and entisols of semiarid and arid Africa are structurally inert soils. They do not swell or shrink and have low activity of soil fauna such as earthworms. These soils have compacted and crusted surfaces and some form of mechanical tillage is required. Tillage studies conducted by Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres (IRAT) in Senegal, Burkina Faso, Niger, and Chad indicate benefits of deep tillage and soil inversion in soil and water conservation and in improving crop yield (*17*). This tillage may be performed every other year, in the row zone only, or for every season depending on the antecedent soil conditions and crop requirements. In semiarid West Africa, Charreau (*18*) has reported significant improvements in yields of pearl millet, sorghum, maize, upland rice, cotton, and groundnuts by plowing in comparison with the unplowed soil (Table 1). Similar benefits of plowing have been reported for semiarid regions of East Africa (*19*). Seedbed preparation completed at the end of the previous rainy season to facilitate dry sowing or sowing early is another innovation that can permit intensive land use of hitherto underutilized or unutilized vertisols (*20*). Vertisols or the black cotton soils occur extensively in semiarid regions. They have a massive structure and respond favorably to tillage. In arid and semiarid regions, free of tse-tse fly and where raising cattle is a cultural tradition, tillage can be performed with animal traction. Draft animal power is often profitable even at low levels of yields in comparison with the use of motorized equipment. The use of animal traction in this zone free of animal diseases can raise labor productivity five- to tenfold (*21*).

Ridge cropping has evolved as an integral component of subsistence farming and is well adapted for small, low-input subsistence farms. Tied-ridging or ridging with the addition of cross ties in the

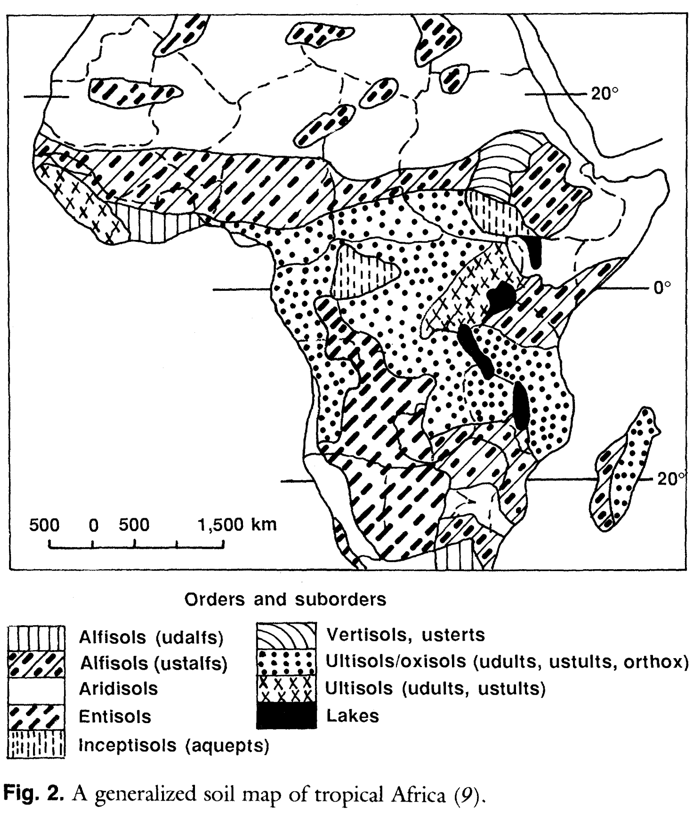

Fig. 2. A generalized soil map of tropical Africa (*9*).

Table 3. Maize grain yield (kg/ha) from a mechanized tied-ridge system for two soils in Tanzania (*24*).

Soil	Yield (kg/ha)		
	Flat	Simple ridge	Tied-ridge
Vertisol (black cotton soil)	3085	3251 (105)*	3274 (106)
Alfisol (lateritic soil)	2628	3029 (115)	3433 (131)

*Figures in parentheses refer to the yield as a percentage of that obtained on a flat seedbed.

furrows is an improvement over the simple traditional ridge-furrow system (Fig. 3). This practice is designed to hold surplus water and to allow more time for infiltration into soil. Results of experiments conducted by IITA's Semi-Arid Food Grain Research and Development (SAFGRAD) team in Burkina Faso have shown substantial yield increases obtained with maize grown under the tied-ridge system (*22*) (Table 2). The beneficial effects of tied-ridge system have also been reported for East Africa (*23–25*) (Table 3). The ridge furrow system and provision of supplementary irrigation may also be promising techniques for vertisols.

Mulch farming. Mulch farming benefits crop growth by improving soil physical properties and by adding plant nutrients. Experiments conducted at Samaru, Nigeria, by Lawes (*26*) showed that mulching improved total porosity and that the infiltration rates in mulched plots exceeded 12.5 cm per hour. In addition, mulch also conserves soil water by decreasing losses due to runoff and soil evaporation. Mulch also enhances the activity of soil fauna and improves soil structure. Experiments conducted in eastern Africa have shown that even for plantation crops on highlands (tea and coffee) mulch farming techniques are the most appropriate for controlling runoff and erosion (*27, 28*) and increasing production.

In addition to soil and water conservation, crop residue mulch also regulates soil temperature. When cleared and clean cultivated, soils with coarse-textured sandy surface horizons experience temperatures of 40° to 50°C at depths of 1 to 5 cm for as long as 3 to 6 hours a day (*29–33*). Germination and seedling establishment of crops are adversely affected by high soil temperatures. These high soil temperatures are both the cause and consequence of the low level of soil moisture. Use of crop residue mulch of 4 to 6 metric tons per hectare regulates soil temperature by decreasing the maximum soil near-surface temperature by as much as 5° to 10°C.

Although the benefits of mulch farming for arid and semiarid Africa are widely recognized, it is the limitation of procuring the

Fig. 3. The tied-ridge system has proven an effective soil and water conservation system in semiarid regions such as Burkina Faso, Tanzania, and Nigeria.

mulch material that makes mulching a practically difficult innovation. This constraint is particularly true for arid and semiarid regions with a prolonged dry season and a large cattle population. Frequent use of cover crops and planted fallows have beneficial effects on soil physical and nutritional properties (*34, 35*). Some tree species (for example, *Acacia albida*) can be grown on the field boundaries or as shelter belts to reduce the risks of soil erosion, and the prunings can be used as fodder and the source of mulch. Because cattle raising is an important component of traditional farming, using farmyard manure and compost is another viable alternative to supplement chemical fertilizers. Integrating livestock raising with tree crops and food crops is an important link in providing the needed diversity for an ecologically sustainable system.

Crop residue mulch for fertility maintenance can also be procured by introducing crop rotations and cropping systems that will produce enough biomass. Growing cereals (millets, maize, and so on) in mixed or relay cropping patterns with groundnuts and cowpeas may produce 50 to 80 percent more returns and involves less risks of failure in a bad year (*36, 37*). Because of the erratic and unpredictable rains, early seeding and establishing an optimum crop stand are the critical aspects of improved cropping systems.

Mulch can also be produced by growing an appropriate cover crop. Economic returns from growing a cover crop can be increased by integrating food crop production with raising livestock. Livestock productivity in the Sahel is limited by the low soil fertility and low and erratic rainfall (*38*). Establishing grain crops (maize, sorghum, or millet) through lightly grazed pastures and browse legumes may be an alternate strategy to optimize the use of limited water and nutrient resources in semiarid environments (*39, 40*).

Irrigation. Insufficient water supply is the most important single factor governing soil productivity. Supplemental irrigation to overcome increasingly erratic water supplies is bound to reduce the vulnerability of crops to adverse rainfall conditions in semiarid Africa. However, irrigation potentials are not well developed in tropical Africa. Irrigation is capital-intensive, costing as much as $5,000 to $20,000 (U.S. dollars) per hectare. Consequently, less than 12 million hectares were under irrigation in 1984 (*41*). It is estimated that only 2 percent of the irrigable land in Africa is irrigated, of which Egypt and Sudan account for more than half. Only 10 percent of all Africa's irrigation is in the vast area between the Sahara and Zambesi. The irrigated land area in Nigeria increased from 18,000 ha in 1975 to 32,000 ha in 1983 (*42*). Runoff in African river systems is generally low. Furthermore, there is a prolonged dry season in most African watersheds. Management of large-scale irrigation schemes is therefore not only capital-intensive but also frequently logistically unfeasible. Small-scale, labor-intensive irrigation schemes are more appropriate for the African situation. The potential for developing low-cost, small-scale irrigation schemes in West Africa awaits realization. The use of dry farming techniques and the expansion of irrigable cropped area deserve high priority in future development strategies. Simple and low-cost techniques of water harvesting and conservation should be given high priority.

Subhumid and humid regions. Subhumid and humid regions are characterized by a rainy season or growing season length of 150 to 270 days and more than 270 days, respectively. In Fig. 1 these regions are represented by zones IV and V, respectively. Major soil-related constraints to intensive food production in these regions are low soil fertility and nutrient imbalance, accelerated soil erosion and harsh environments, unproductive cropping systems, and traditional technologies geared to subsistence rather than commercial agriculture. Improved technologies geared to high, continuous, and sustained production imply maintaining soil physical and biological properties similar to that under undisturbed forest, and yet enhanc-

Table 4. Mulching effects on soil and water loss at IITA, Ibadan. Crop residue mulch was applied at 6 ton/ha and the rainfall of the season was 1022 mm (*14, 15*).

Slope* (%)	Runoff (mm)		Soil erosion (ton/ha)	
	No mulch	Mulch	No mulch	Mulch
1	412	0	9	0
5	483	11	134	0.2
10	303	21	137	0.2
15	375	20	96	0.7

*Erosion was monitored on field runoff plots with natural slopes. Each slope represents a different soil type. Soils of 10 and 15 percent slopes were of a coarse texture and suffered less erosion than those of 5 percent slope.

Table 5. Mulching effects on yield of some tropical crops. Residue mulch of rice husks was applied at about 6 ton/ha (*45*).

Crop	Grain yield (ton/ha)	
	No mulch	Mulch
Maize	3.0	3.7
Cowpea	0.6	1.1
Soybean	0.6	0.8
Cassava	16.4	28.3
Yam*	(13.4) 10.7	(16.1) 17.9

*For yam, the data in parentheses are for an acidic soil in eastern Nigeria while those without parentheses for yam and for other crops are for a soil of about neutral *p*H from western Nigeria.

ing its nutritional properties to facilitate an intensive crop production schedule. Much of this can be achieved through supplying an adequate amount of organic matter to the soil surface as mulch. For example, crop residue mulch applied at 6 to 8 tons per hectare per season can effectively control erosion from croplands (*43, 44*). Mulch rates of 6 ton/ha have been shown to control erosion on slopes of up to 15 percent (Table 4). Mulch cover breaks the raindrop impact, minimizes soil splash, improves infiltration, and improves soil structure (*45*).

Substantial yield increments have been reported by mulching. In Zaire a 10-year study showed that cotton yields were maintained with mulch but that they declined to about one-tenth of mulched levels without residue mulch (*46*). Similar yield improvements due to mulching are reported from South America (*47*). Experiments conducted at IITA and elsewhere have shown substantial increases in yield of maize, cowpea, soybeans, cassava, and yam due to mulching (Table 5). In fact, higher yields are reported by any mulch material over the unmulched bare soil (*48*). In some cases, mulching may enhance the pest incidence, but the overall benefits of mulch outweigh any disadvantages due to pests.

High temperatures and high-humidity conditions are conducive to high-decomposition rates. In fact, the rate of decomposition of soil organic matter in equatorial Africa is about four times as high as that of Rothamsted in the United Kingdom (*49*). Soil erosion also depletes the soil organic matter because the latter is preferentially removed in the erosion process. The ability of the soil to hold plant nutrients also declines with a reduction in organic-matter content. Loss of bases causes acidification and overall impoverishment of soil.

The research findings on mulch are by no means new even to subsistence farmers. Maintaining a mulch cap on yam heaps or complete mulching by palm fronds is a common practice in densely populated regions such as southeastern Nigeria. Because of the substantial quantities of mulch required, however, farmers cannot afford enough plant residue to mulch large fields at an adequate rate. Some relevant agricultural technologies that facilitate an undisturbed seedbed and that ensure large quantities of organic mulch are described below.

Land clearing. Land clearing and development are labor-intensive operations. Consequently, farmers are increasingly relying on mechanized land clearing involving conventional construction equipment. Most of the fertile top layer of soil is either scraped off to the plot boundaries or is washed off with the overland flow. Research in West Africa (*50, 51*) and South America (*52*) has indicated the advantages of manual clearing over machine clearing. Experiments conducted at IITA have shown that if machine clearing is absolutely essential, clearing with the shear-blade is reportedly better than clearing with the dozer blade, tree pusher, or root rake. The data from IITA (Table 6) show that soil erosion is the most severe when forest is removed with tree-pusher and root-rake attachments than with shear-blade or manual clearing. Soil compaction and risks of erosion by shear-blade clearing can be avoided by seeding an appropriate cover crop (*Mucuna utilis, Cajanus cajan*) the year after clearing and growing food crops in unplowed sod that has been chemically or mechanically killed or suppressed.

Conservation tillage. No-till farming, which involves seeding through a crop-residue mulch or sod without plowing, has definite advantages. One is the conservation of soil and water. Other advantages are the lowering of the maximum soil temperature and the maintenance of higher levels of soil organic matter. Favorable soil temperature and moisture regimes in no-till plots provide definite advantages to no-till farming.

Studies conducted at IITA have shown that soil erosion under maize-cowpea rotation is controlled by no-till and mulch farming systems for slopes of up to 15 percent (Table 7). An essential feature of no-till farming is the well-developed surface aggregation due to high earthworm activity. Biochannels made by earthworms and other soil animals enhance water infiltration and facilitate root development. A comparison of maize grain yield for 24 consecutive no-till crops of maize showed definite yield advantages over the plow-based system (*53*). The benefits from the no-till system are not necessarily in absolute terms but in higher yields from lower inputs. Savings in fuel consumption and in time for seedbed preparation are

Table 6. Deforestation effects on water runoff and soil erosion for maize-cassava and maize-cowpea (2-year) rotation during 1979 and 1980 cropping seasons (*50*).

Clearing and tillage method	Runoff (mm)	Soil erosion (ton/ha)
Forest control	1	0.01
Traditional farming (shifting cultivation)	7	0.02
Manual clearing, no tillage	16	0.4
Manual clearing, plowed	80	5
Shear-blade clearing, no tillage	105	4
Tree-pusher root-rake clearing, no tillage	107	16
Tree-pusher root-rake clearing, plowed	331	24

Table 7. No tillage effects on soil and water loss under maize at IITA. The total seasonal rainfall in the first season (1973) was 526 mm (*14, 15*).

Slope (%)	Runoff (mm)		Soil erosion (ton/ha)		Maize grain yield (ton/ha)	
	No tillage	Plowed	No tillage	Plowed	No tillage	Plowed
1	11	55	0	1	4.5	3.6
5	12	159	0.2	8	4.5	3.8
10	20	52	0.1	4	4.0	3.6
15	21	90	0.1	24	3.6	3.0

Fig. 4. Alley cropping involves growing seasonal crops within alleys formed by growing woody perennials as contour hedges. Alley cropping is the most effective when food crops are grown by a no-till system.

definite advantages, although herbicide requirements for weed control are high.

Crop establishment with the no-till system is generally unsatisfactory on soils that have compacted and crusted surfaces and that have inadequate amounts of crop-residue mulch. Some soils with good initial soil physical conditions require little or no tillage for satisfactory crop growth. In soils with compacted or crusted surface layers, tillage can bring about noticeable improvement in crop growth (*53, 54*).

Mulch cover is an essential ingredient of conservation farming. Without an adequate amount of mulch, soil structure deteriorates rapidly and crop yields decline. Mulch can be procured by one or a combination of the following practices.

1) Residue from the previous crop: crop sequences and combinations should be such that at least one crop produces enough residue to be used as mulch. Examples of such sequences are maize-soybean and sorghum-cowpea. Residues from legumes with low carbon-nitrogen ratios decompose quickly. It is the residue from cereals with high ratios that stays longer and also contributes substantially to the soil's organic matter reserves (*43*).

2) Cover crop: a planted cover grown every 3 or 4 years is an important component of the improved cropping system. Quick-growing grass and legume covers provide large quantities of mulch, improve soil structure and organic matter content, suppress weed growth, and improve crop yields (*54–56*). The choice of an appropriate cover crop, however, differs among soils, rainfall regimes, and agroecological environments (*57*).

3) Alley cropping is an agroforestry system in which food crops are grown in alleys formed by hedgerows of trees or shrubs (*58*). The hedgerows are cut back at planting and kept pruned during cropping to prevent shading and reduce competition with food crops (Fig. 4). The practice provides mulch for the associated food crop, suppresses weed growth, creates favorable microclimate, recycles nutrients from deeper soil layers, and provides biologically fixed nitrogen to the companion crop. An important feature of alley cropping is the soil conservation component. When planted along the contours of sloping land, hedges decrease both runoff amount and velocity. *Leucaena* hedgerows planted 2 m apart are especially effective in conserving soil and water (Table 8). In addition to controlling erosion and meeting the diverse needs of the farm household (animal feed and fuel), alley cropping can produce satisfactory yields of maize (Table 8). The yields of cowpeas, however, may be suppressed by shading, competition for soil moisture, and possible allelopathic effects. The system, though labor-intensive, can be mechanized to suit the medium-size farms. Technology for mechanized pruning of hedgerows is yet to be developed to suit diverse requirements. Alley cropping is most effective when food crops are grown with a no-till system.

Cropping systems. Perennial crops are the most logically suited for humid regions. In regions with annual rainfall of 2000 mm and above, plantain, bananas, cassava, and yam are major carbohydrate staples. Plantation crops such as oil palm, rubber, cocoa, and plantain, can be grown on manually cleared land without further seedbed preparation. Soil and water conservation and fertility maintenance is better achieved through growing a cover crop between the widely spaced rows of trees. By frequently adding crop residue mulch, yield of plantain is improved and the life span extendable to about 4 years. Yam and cassava also respond favorably to mulching.

In subhumid regions with the annual rainfall of 1000 to 2000 mm, cassava is grown in association with food grains, maize, and cowpea, for example. Intercropping stabilizes yields even at low levels of inputs (*11*). Mixed cropping of legumes and cereal is also beneficial. Sole crop maize is also profitable in the subhumid region, especially if it is grown in rotation with a leguminous cover crop such as *Mucuna utilis*.

Agro-Chemicals—Are They Indispensable?

Two types of agro-chemicals are important for soils of tropical Africa: fertilizers and pesticides. Highly weathered and leached oxisols and ultisols, being inherently low in fertility, must have a supplemental nutrient supply for facilitating intensive cultivation or increasing food production. Intensive land use and high yields on soils of low inherent fertility can only be achieved by raising the nutrient level through the use of inorganic fertilizers, frequent additions of substantial amounts of organic matter, or both.

Soils of tropical Africa are deficient in nitrogen and other essential nutrients. The use of fertilizer in Africa is much lower than that in Asia, about 19 kg/ha compared with 73 kg/ha (*59*). Furthermore, more than half the fertilizer used in Africa is used by two countries, Egypt and South Africa. Ten African countries (Algeria, Egypt, Kenya, Libya, Morocco, Nigeria, South Africa, Tunisia, Zambia, and Zimbabwe) use 83 percent of the total fertilizer consumed in Africa. Africa's annual fertilizer consumption of 3.4 million metric tons represents about 2.5 percent of the world's consumption. In comparison, the annual fertilizer consumption in Asia is 36.9 million tons (*59*).

Although crop production can be increased by increasing fertilizer use, many small landholders cannot afford the expensive fertilizers. Rather than depending on fertilizer importation, the long-range strategy should be to increase fertilizer production in the region. In the meanwhile, however, soil fertility maintenance should be achieved through soil surface management. Alternative systems of

Table 8. Alley cropping effects on runoff and soil erosion under maize-cowpea rotation measured in 1984 at IITA. Each value is an average of 4 years' data. Alleys were plowed before crop plantings to incorporate the mulch into the soil.

Treatment	Runoff (mm)	Soil erosion (ton/ha/year)	Maize (ton/ha)	Cowpea (ton/ha)
Plowed	232	14.9	4.2	0.5
No-till	6	0.03	4.3	1.1
Leucaena (4 m apart)	10	0.2	3.9	0.6
Leucaena (2 m apart)	13	0.1	4.0	0.4
Gliricidia (4 m apart)	20	1.7	4.0	0.7
Gliricidia (2 m apart)	38	3.3	3.8	0.6

soil fertility management include no tillage or minimum tillage, mulch farming, ley farming, and intercropping with trees and deep-rooted legumes to improve nutrient status. Ley farming is the practice of growing food crops through lightly grazed pastures by a no-till system. This system has proven to be successful in northern Australia (*39*).

Technologies available to meet nutrient requirements are different for different soils, different farming-cropping systems, farm size, availability of essential inputs, and socioeconomic factors. Transformation of low-input subsistence agriculture into a high input commercial enterprise can be done through gradual improvement and by technological innovations appropriate for different stages. The schematic in Fig. 5 explains possible technological innovations needed at different stages to bring about the desired improvement in traditional farming. Although the amount of fertilizers required can be reduced by incorporating appropriate legumes in rotation or adding organic materials, chemical fertilizers cannot be completely dispensed with for commercial farming. Practices such as mucuna fallow, alley cropping, and ley farming contribute some nitrogen (*39, 40, 56–58*). The remainder of required nitrogen and other macro- and micronutrients will have to be provided for.

Herbicides and other pesticides are essential but are not as indispensable as fertilizers. Requirements for pesticides can be substantially reduced by adopting ecologically compatible agricultural practices, such as mixed cropping, crop rotation, cover crops, and biological control measures (*10*). Furthermore, tropical crop breeding programs emphasize resistance by genetic means for sustaining and stabilizing yields.

Eco-Development and Soil Management

The transformation of subsistence farming on small landholdings to a commercially viable enterprise is not only technically feasible but also culturally, economically, and socially acceptable. The approach adopted should be dynamic to suit the rapidly changing social fabric in the tropics. The objective is not to maximize production but to achieve a high, stable, and a desirable level of production while causing minimum degradation of soil quality.

At the present level of development, a low-input system may be desirable. To small landholders of Africa, labor-intensive technology that can be developed and maintained locally with less skilled manpower and limited capital resources may be more attractive than investment in heavy machinery and in chemicals whose effectiveness is uncertain and is governed by the vagaries of climate. The subsistence farmer who risks famine would consider a successful technology to be the one that produces some yield in the worst year rather than the one that produces a high yield in the best.

However, with the world's highest rate of population increase and rising social aspirations, the low-input systems now recommended in Africa as an intermediate measure may be obsolete by the year 2000 when the demands made on soil resources will be greater than ever before. The scientific community should envisage the changing demands and rise to the occasion by providing the appropriate answers when required.

While planning an appropriate research strategy for the future, there is an urgent need for action on the basis of what is already known. At present, some important considerations are the choice of land clearing methods and the postclearing soil management techniques that are ecologically compatible. Substantial food production increases are plausible if these proven technologies can be effectively transferred and implemented.

Conclusion

The data presented here are but examples of improved technology. Results vary from year to year and region to region. Some useful and yield-increasing technologies are available and are awaiting implementation. In addition to high-yielding crop varieties, techniques are known to improve soil, conserve water, and limit erosion.

Research and development priorities should be given to small-scale irrigation. There is also a need for more research on high-yielding crops appropriate for African soils and climate.

Food self-sufficiency in Africa is a definite reality with the technology already available. However, no amount of research can help achieve food self-sufficiency without total commitment and dedication by the nations concerned. The scientific community both within and outside Africa has the knowledge to make a substantial breakthrough in solving the problems and in establishing procedures for updating the practices introduced. This knowledge can only be applied with the cooperation of the people, the governments and the institutions of the region.

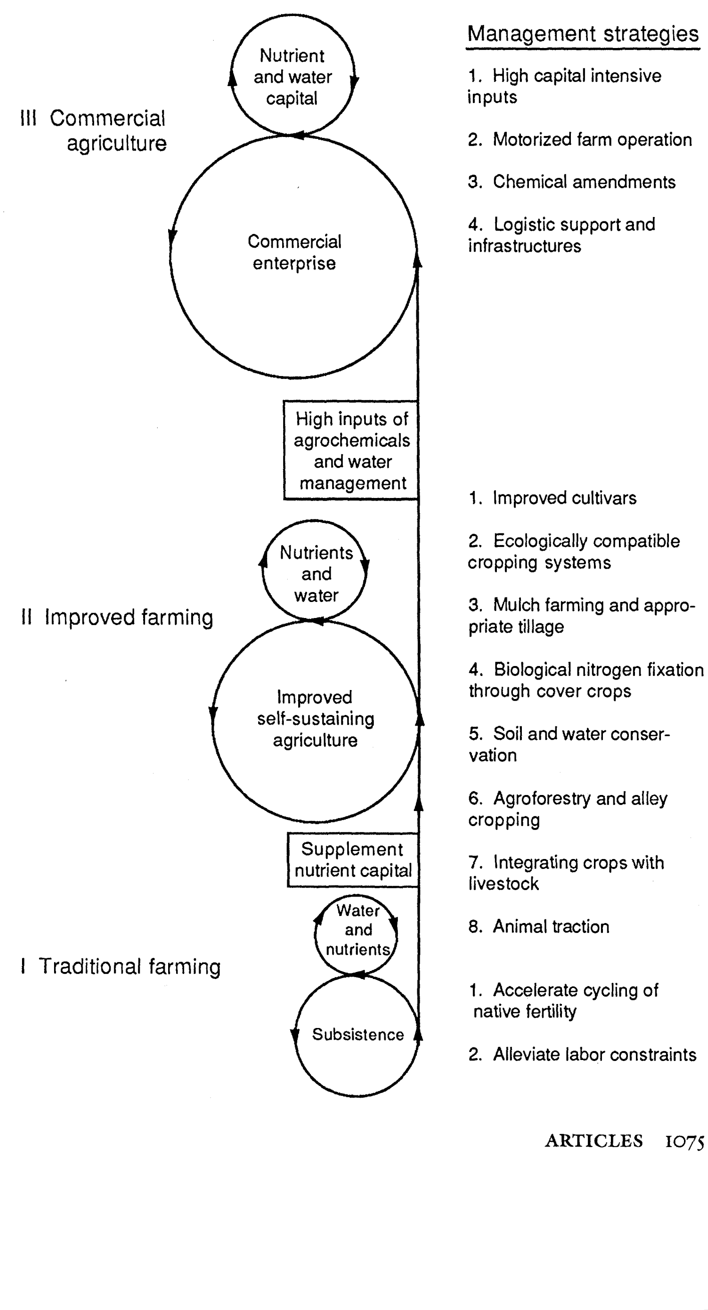

Fig. 5. Possible technological innovations needed to transform traditional subsistence farming to a science-based commercial agriculture. Most resource-poor farmers in stage II can benefit from the improved technological innovations that include mulch farming, no-till, tied-ridge system, biological nitrogen fixation by cover crops, agroforestry and alley cropping, animal traction, and integrating crops with livestock.

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Freezing

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There is no first principles theory of freezing or melting, even for the simplest materials. The prediction of phase diagrams is an important first step in understanding the crystal-melt interface, crystallization near equilibrium, and nucleation. Recently, a new approximate theory for the freezing of classical liquids, known as the density functional theory, has been developed. The predictions of the theory are relatively accurate and its mathematical structure is simple enough to provide an attractive starting point for theories of more complex, dynamical phenomena.

All simple liquids, with the probable exception of liquid helium at low pressures, crystallize at sufficiently low temperatures. By "simple" we mean liquids such as pure argon, sodium, or nitrogen. In addition, the crystallization of huge molecules, such as proteins, is an essential first step in the determination of structure from scattering experiments. Yet for even the simplest classical liquids there is no accurate, universal (or universally accepted) theory of freezing, or indeed of first-order phase transitions in general.

This might seem puzzling, since the thermodynamic conditions for phase equilibrium are well known and simply stated. At a given temperature T and pressure P, the laws of thermodynamics tell us that the phase with the lowest free energy per mole is the stable phase. For two coexisting phases, denoted here by the subscripts S for solid and L for liquid, the temperatures, pressures, and chemical potentials $\mu^{(j)}$ of all components j must be equal:

$$T_L = T_S,\ P_L = P_S,\ \mu_L^{(j)} = \mu_S^{(j)} \qquad (1)$$

From a microscopic point of view, the prediction of phase diagrams is straightforward in principle. One may use the techniques of

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