Part II: Promising Technologies

Technology alone is not the answer to Africa's need for food security, but it can play an important role in equipping the continent to meet the challenges ahead. Chapter 5 looked generally at the opportunities available to use technology to enhance low-resource agriculture in Africa. It concluded that the technologies offering the most promise for contributing to the food security of resource-poor farmers and herders share some common characteristics: they are technically and environmentally sound, socially desirable, economically affordable, and sustainable.

By meeting this broad spectrum of conditions, a technology or technology package not only stands to be scientifically y successful (that is, it effectively increases production, reduces degradation, inhibits losses, or otherwise helps meet food production needs), but it is more apt to be socially acceptable. A technology cannot have a significant impact in the long term if it is not acceptable to and adopted by the people who must use it.

Using the concepts outlined in this report, OTA identified a range of technologies that offer promise to improve food security in Africa. These technologies meet a variety of needs, from improving soil and water management to reducing post-harvest losses. The list is illustrative, not comprehensive. Chapters 7 through 11 examine these promising technologies, which fall into five general categories:

- technologies to improve the use of soil and water resources,
- technologies to improve cropping practices,
- technologies to improve crop and livestock genetics,
- technologies to improve the use of animals, and
- technologies to reduce losses.

Chapter 7
Improved Use of Soil and Water Resources

CONTENTS

Box

Figures

Tables

Chapter 7

Improved Use of Soil and Water Resources

SOIL AND WATER MANAGEMENT[1]

Summary

Africa's lands are under pressure to provide increased production to feed the continent's growing population. To meet this increasing need, farmers have shortened fallow periods on lands already in use and they have expanded cultivation onto lands of marginal productivity. The result is that many agricultural lands are now showing signs of widespread environmental degradation (36,72). Unchecked erosion is just one type of degradation and it can lower the productivity of crops and rangeland by reducing the availability of water, nutrients, and organic matter (64,80). Severe soil erosion has already reduced crop yields in some areas and continued erosion will be a major obstacle to achieving food security (76).

Reversing Africa's environmental decline will be costly. To gain perspective on the cost of addressing soil erosion, it is useful to examine the U.S. situation. The U.S. Federal Government has spent at least $15 billion to finance an array of soil conservation programs since the 1930s. Yet soil erosion continues to be a problem in the United States (32,38), and what success there has been is attributable primarily to national policies that encourage farmers to take high-risk lands out of production. Programs that reduce today's production to increase tomorrow's would not be popular in most African countries given existing food shortages.

Thus, solutions to Africa's environmental problems will have to focus on conservation measures that increase, or at least do not reduce current production significantly. Resource-poor farmers and herders would find it difficult to absorb the additional costs that may arise from implementing conservation measures. Since good conservation practices often benefit all segments of the population, government and private organizations also must be prepared to assume responsibility and costs for regenerating and maintaining a healthy resource base.

The following discussion has been organized according to whether the technologies are used primarily to increase water availability or to deal with excess water. Recession farming, microcatchments, building bunds and planting on the contour, and tied ridges all deal with increasing water availability. Drainage, terracing, minimum tillage, mulching, and other soil-conserving vegetation practices deal with excess water. Note, however, that while it is convenient to group technologies according to their primary function, a technology frequently serves multiple purposes. Mulching, for example, helps deal with excess water as well as reducing water runoff. In the process, it also controls soil erosion. Moreover, it is an effective way to increase soil moisture, improve soil fertility, and reduce weed problems. In addition, while the discussion of technologies for increasing water availability emphasizes the arid/semi-arid zone, seasonal water shortages can occur in any zone including the humid lowlands. Similarly, excess water and resulting soil erosion can be a problem even in arid areas during the heavy storms of the rainy season.

[1]This material is based primarily on the OTA contractor reports prepared by Rattan Lal, International Institute for Tropical Agriculture, Ibadan, Nigeria; Lawrence A. Lewis, Clark University, Worcester, MA; and W. Gerald Matlock, Desert Agricultural and Technology Systems, Inc., Tucson, AZ (app. A).

Improving the natural resource base is an essential step not only to ensure the well-being of the vast rural population, which can seldom afford to purchase inputs such as fertilizers and irrigation, but also to open the door to changes that make greater use of external inputs possible when they become affordable. Africa is less able than other regions to pay the expense of conservation programs, yet it can least afford to ignore natural resources conservation. The technologies discussed here are among the most efficient and affordable means available for managing soil and water resources for the resource-poor farmer.

Technologies To Increase Water Availability

Recession Farming

In this traditional practice, crops are grown on saturated floodplains as the land becomes workable after annual floods. As the floodwater recedes, farmers use planting sticks to make shallow holes up to 1 meter apart as sites to plant seeds from several kinds of crops. The mixture of plants that emerge rely on flood water stored in the soil.

The flood recession system works well for crops that have a short growing season such as many varieties of sorghum and millet. Only heavy clay-rich soils in low areas are suitable for this type of farming because they are flooded long enough to absorb sufficient water and have the physical conditions to retain it (48).

Recession farming is used throughout Africa wherever possible because it is an efficient and productive system. It is common along major rivers as well as on the margins of temporary ponds and lakes that line tributaries (48). It is particularly important in West Africa, where the availability of water along the Senegal, the Volta, and Niger Rivers contrasts sharply with the otherwise arid conditions typical of the region's rainfed farming.

Benefits of recession farming to resource-poor farmers may be undermined by other development interventions to manage water. In particular, construction of large-scale dams that eliminate annual flooding downstream can seriously interfere with recession farming. These impacts seldom seem to be accounted for in calculating costs and benefits of large-scale programs. It may, however, be possible to reconcile these conflicts better and sustain future benefits of recession farming. For example, a controlled artificial flooding of the Senegal River is being attempted to enable farmers to continue recession farming in conjunction with developing new large-scale irrigation systems (21).

Water Harvesting Microcatchment

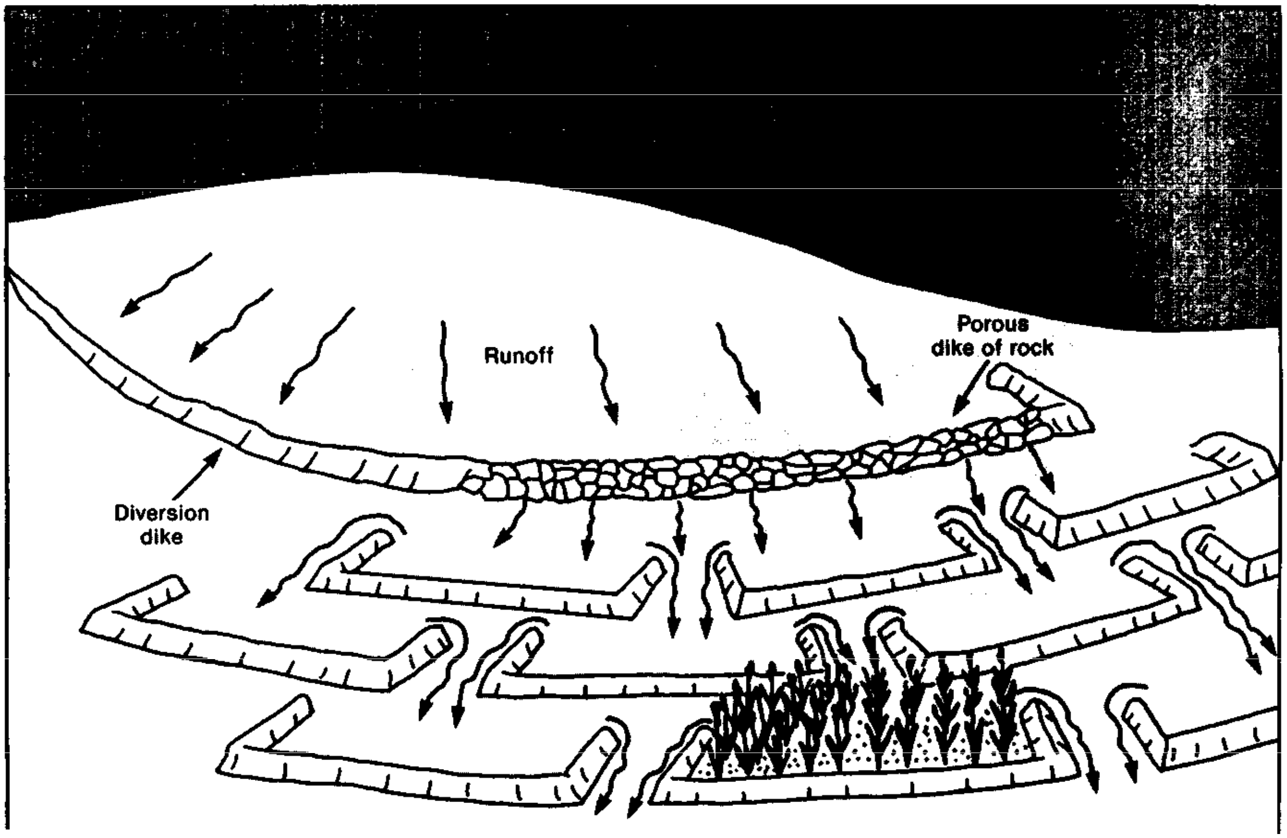
With these techniques a portion of land serves as a catchment area to produce runoff used for growing crops on the remaining land and for meeting human and animal water needs (11, 16,61,70). One approach uses modified furrows in which normal row spacing of crops is doubled, with the space between the rows sloped toward the plants. Excess runoff may be caught in a reservoir and used for supplemental irrigation.

Microcatchments a few meters in size are also excellent conservation measures (75). They can be placed on the contour to form an overlapping network that conserves both water and soil (figure 7-1). Where it is difficult to determine the contour, small microcatchments in the form of Vs or half-circles can be positioned to catch runoff (figure 7-2).

As with all technologies that concentrate rainfall, care must be taken to ensure that too much water does not collect during heavy rains. Provisions can be included to allow excess water to escape safely and thus provide protection against potentially severe erosion.

Water harvesting microcatchments have been introduced into several places in Africa: Cape Verde, Burkina Faso, Kenya, and Niger (61,73). The Peace Corps and several private voluntary organizations (PVOs) have promoted their use

Figure7-1 .—Contoured Microcatchments to Control Soil Erosion and Water Runoff



SOURCE J Tabor and B Djiby, "Soil and Soil Management for Agriculture, Forestry, and Range in Mauritania, " Mauritania Agricultural Research Project II, supported by the U S Agency for International Development (Tucson, AZ" College of Agriculture, University of Arizona, April 1987).

because the techniques are relatively inexpensive and individual farmers decide to use them.

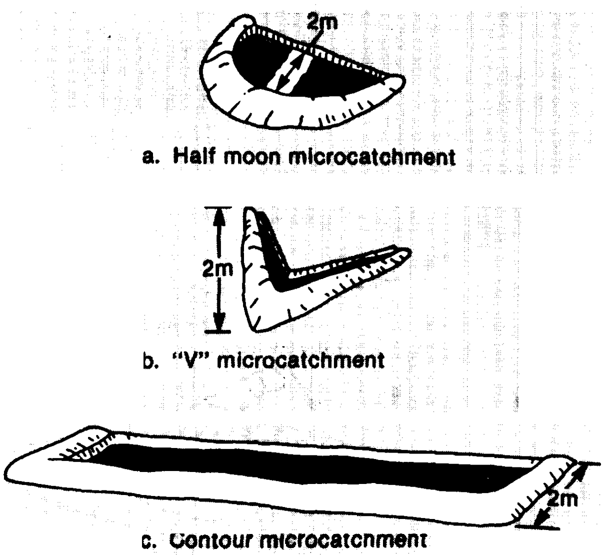
Building Bunds and Planting on the Contour

Planting crops in rows that follow the land's contour slows runoff and enhances infiltration (22). When ridges or bunds–embankments of rock or soil—are built to follow the contour of the land, the areas above and immediately below the barrier store more than normal amounts of soil moisture,

Crops can be planted on the contour on gentle or steep slopes, although in steep terrain provisions must be made to allow excess water to escape during major storms to prevent the entire system or hillside from being washed out. For example, cross-dikes can be used to confine washout, or spillways can be included at regular intervals to carry away excess water (48).

Bunds, on the other hand, are only feasible on gently sloping land. Large-scale, dirt bunding projects in Burkina Faso have increased crop yields and brought long-term soil conservation benefits (24). Stone-pile bunds used in the Yatenga plateau of Burkina Faso are even more promising. By introducing an inexpensive and simple device for determining the contour—a transparent hose attached at both ends to poles marked at half-centimeter intervals—Oxfam was able to improve on the tradi-

Figure 7-2.—Three Types of Microcatchments



SOURCE: J. Tabor and B. Djiby, "Soil and Soil Management for Agriculture, Forestry, and Range in Mauritania," Mauritania Agricultural Research Project II, supported by the U.S. Agency for International Development (Tucson, AZ: College of Agriculture, University of Arizona, April 1987), m = meter

tional practice of using lines of rocks to slow runoff. The new bunds trap topsoil, organic matter, and seeds, and they have been successful in helping revegetate the barren, encrusted wasteland that now covers an estimated 15 percent of this area (26,89).

Tied Ridges

Tied ridges are a variation of the microcatchment approach for trapping and holding water. Again, ridges are built to follow the land's contour, but in addition, the furrows between ridges are linked by cross-ties (small dams) to create closed microbasins 1 to 5m long (see photo). The cross-ties are kept lower than the ridges so they act as spillways in the event of heavy rainfall. The small basins retard runoff so water has more time to infiltrate, and soil water storage is increased. This practice is particularly effective in areas not subject to high-intensity rains, on freely drained soils, and on gentle slopes.

Tied ridges often have been introduced in conjunction with fertilizers, resulting in significant yield increases. For example, research stations in Burkina Faso showed increases of 1,000 kg/ha for maize, 930 kg/ha for sorghum, and 570 kg/ha for millet using a tied ridge/fertilizer combination (23,68). However, on-farm trials in the same area only produced increases of 10 to 40 percent of research station results, and at these low levels the additional labor requirements discouraged use of the technology (49, 68). Recent work by the International Institute of Tropical Agriculture (IITA) and the Semi-Arid Food Grains Research and Development (SAFGRAD) project suggests that a mechanical ridge-tier, using animal traction, adds little to farmers' labor and can increase yields substantially (65). Purchasing and maintaining animals can be a problem, however. Animals must be strong enough to work at the beginning of the rainy season, yet most will be undernourished from having just endured the dry, "hungry" season.

Even when built properly, tied ridges are susceptible to excess water buildup from heavy rainfalls. Rushing water can break over a succession of ridges causing deep rills or gullies. Under these circumstances, runoff control needs to be augmented with other practices such as drainage improvements or terracing.

Tied-ridge technology was introduced into West Africa in the 1950s and is being actively researched (65). The technology is also present in the drier parts of eastern and southern Africa, including parts of Malawi, Botswana, and Tanzania (13,69). The technique's heavy labor demand has restricted its use in all of these areas, but this constraint should be lessened with the advent of the IITA/SAFGRAD mechanical ridge-tier or similar devices. The increased soil moisture that results from tied ridges reduces the economic risks associated with purchase of commercial fertilizers, and fertilizer use, in turn, contributes to yield increases that can help pay for the cost of this combination of technologies.

Photo credit: D. Woods Thomas/Purdue University

Tied ridges trap rainwater in this West African millet field.

Technologies To Deal With Excess Water

Drainage Practices

Soils require drainage either because a high water table exists or because a relatively impermeable subsurface layer retards water infiltration, so the soil above the impermeable layer becomes saturated. Saturated soil is poorly oxygenated and prohibits root development for most crops.

Subsurface drains, such as tile pipes, are an effective technique for lowering the water table. They are rarely used in Africa, however, because they are expensive and difficult to install. Open drains are common because they are less expensive and easier to build. However, they have many disadvantages including:

- reducing the area available for production,
- harboring weeds and rodents,
- requiring high maintenance, and
- creating favorable conditions for numerous waterborne diseases if stagnant water remains in them,

Open drains used on slopes can create an additional problem: if they are not lined or vegetated, or if poorly designed, they can be a catalyst for erosion and gully formation. In addition, problems worsen if the diversion channel is not large enough to handle major storms. In practice, most drains are underdesigned for a multitude of reasons, including: poor rainfall records, lack of space, high costs, and shortage of technical personnel to design and survey the drains properly. Therefore, erosion control using drainage is often ineffective. In fact, drains can aggravate problems because failed structures can allow sheet erosion to worsen into gully formation.

Water-saturated soils also can be due to excessive rainfall which infiltrates the surface layer but is trapped by an impermeable layer below. Under these circumstances it is important to reduce the amount of incoming surface water. Diversion bunds or ditches, built on a slight diagonal to the contour, can be used to intercept runoff and divert it at a non-erosive velocity to a suitable disposaI point (74).

Proper drainage can increase the availability of arable land substantially. In Rwanda, for example, where rural population densities are high, artificially drained lands along valley bottoms are widespread and contribute significantly to the country's food production. In addition, because water tables remain close to the surface during the drier seasons, these zones often remain in production when adjacent lands are dry and idle (41).

Terracing

Terracing agricultural land is one approach to slowing water runoff. It is important in humid areas to prevent excessive infiltration leading to mass movements of saturated soil. Thus, adequate drainage must be provided in terrace design.

Figure 7-3 shows an inexpensive and simple way to build a terrace:

1. leave vegetated strips of noncultivated land spaced across the slope between cultivated areas;
2. build a cutoff drain immediately along the lower edge of the noncultivated strip; and
3. allow erosion on the upslope part of the field and deposition along the edge of the vegetated strips to create terraces over a 5- to 6-year interval (86].

Figure 7-3.—Simple and Inexpensive "Fanya juu" Terraces

SOURCE: Larry Lewis and Leonard Berry, *African Environments and Resources* (Boston, MA: Allen Urwin, 1987).

One place where terraces have reduced soil erosion is in the Kenyan Highlands, where they are termed "fanya juu." More importantly from the farmers' perspective, however, is that they also have increased crop yields. For instance, in Machakos, Kenya, maize production increased 50 percent when terraces were installed. This increase probably resulted from the combination of soil saved and water and nutrients retained by terracing (40). Such substantial increases are essential to balance the construction costs of terraces and the planting space they take up.

"Fanya juu" terraces are not new to Kenya. During the colonial period a large number of such terraces were built, often using forced labor. Largely as a backlash, the terraces were either destroyed or left to deteriorate by the people after Independence. However, encouraged by funding from a Swedish development agency, farmers have revitalized "fanya juu" terracing in certain areas and many farmers have continued these efforts after external funding ended. This suggests that the benefits now accruing to farmers are attractive enough to justify the labor needed to build and maintain the terraces. The Kenyan government has only needed to provide technical assistance to align the terraces, Unfortunately, "fanya juu" terraces can be built only where topsoil is abundant, and these areas are few. Labor requirements are considered too costly to construct and maintain these terraces in most areas (41).

Minimum Tillage, Mulching, and Other Soil-Conserving Vegetation Practices

These practices—all of which achieve their benefits through the presence of an organic cover on the soil—are among the most effective methods of conserving water and reducing soil erosion (36,37,39,41). In contrast to engineering methods, soil-conserving vegetation practices require minimal soil manipulation.

Maintaining adequate cover is important particularly at the start of the rainy season in the humid tropics and always important in areas of steep slope (>15 o) (12). Where slopes exceed 15 degrees, vegetation and engineering methods, such as terracing, need to be integrated for effective soil erosion control (41). Some areas, however, are more valuable if left in natural vegetation. Steeply sloped watersheds, for example, may provide more important services than would be gained by converting them to agricultural land.

Soil-conserving vegetation practices should be emphasized as the first approach for managing excess water given the general constraints on capital, labor, skills, institutions, and infrastructure existing for most resource-poor farmers, However, these practices inevitably involve trade-offs for the resource-poor farmer.

Minimum tillage, sometimes called conservation tillage, involves seeding through crop residue or sod without plowing. Plowing and other forms of cultivation breakup the soil and temporarily increase water infiltration while lowering run-off. However, soon after being tilled, soil structure generally breaks down, decomposition of organic matter accelerates, and erosion potential increases(6). Minimum tillage is an effective tool against this erosion, By leaving a cover of vegetative material, the soil is less susceptible to wind and water. This technique also allows farming on steep slopes that are severely erosion-prone. For example, minimum tillage maize can be grown on a slope of 15 percent while allowing erosion of substantially less than 1 ret/ha (table 7-1) (27,36).

Minimum tillage should be encouraged as a substitute for plowing throughout African humid areas. In addition to controlling soil erosion, the practice lowers the maximum soil temperature, helps maintain high levels of organic matter, and reduces the need for labor inputs during the planting season (36). Herbicide requirements for weed control are high, however, and these chemicals sometimes are not affordable or accessible to resource-poor farmers. Heavy herbicide use raises further concerns regarding environmental and human health, Plowing in arid areas sometimes is more appropriate than minimum tillage because plowing increases infiltration in compacted soils with low organic matter content (36,46,58).

In minimum tillage systems, crop residues left behind from the previous season's harvest act as a mulch and can reduce water run-off and soil erosion dramatically (table 7-2) (36). However, crop residues in Africa, such as cereal stalks, often are needed for fodder, cooking fuel, or building material. The amount of mulch can be increased by managing the crop sequences and combinations or growing a cover crop specifically for this purpose. Mulch material also can be brought in from elsewhere and added

Table 7-1 .—The Effects of Plowing and No Tillage on Soil and Water Loss[a]

Slope	Water runoff (mm)[b]		Soil erosion (ton/ha)[b]		Maize grain yield (ton/ha)	
	No tillage	Plowed	No tillage	Plowed	No tillage	Plowed
1%	11	55	0.0		4.5	3.6
50/0	12	159	0.2	1	4.5	3.8
10%	20	52	0.1	4	4.0	3.6
15%	21	90	0.1	24	3.6	3.0

aMaize production at the international Institute of Tropical Agriculture, Ibadan, Nigeria. The season's rainfall (1973) was 526 mm.
[b]mm = millimeters; ha = hectares
SOURCE: Rattan Lal, "Managing the Soils of Sub-Saharan Africa," *Science, vol. 236,* Mar. 29, 1987, table 6, p. 1073.

Table 7-2.—The Effects of Mulching With Crop Residues on Water Runoff and Soil Erosion[a]

Slope	Water runoff (mm)[b]		Soil erosion (ton/ha)[b]	
	No mulch	Mulch	No mulch	Mulch
1%	412	0	9	0.0
5%	483	11	134	0.2
10%	303	21	137	0.2
15%	375	20	96	0.7

aResidues were applied 6 ton/hectare and the season's rainfall was 1022 millimeters.
[b]mm = millimeters; ha = hectares
SOURCE: Rattan Lal, "Managing the Soils of Sub-Saharan Africa," *Science, vol. 236,* Mar. 29, 1967, table 4, p. 1073.

to the field. Alley farming (see ch. 8), for example, may serve as a source of tree prunings that can be used for mulch and other purposes (36). Animal manure is another source of mulch. Although obtaining and transporting large amounts of manure can be a serious obstacle, the benefits can be a key factor supporting a farmer's decision to incorporate animals in the farming system.

Potential

The technologies discussed above could contribute to the sustainable use of soil and water resources. Although they commonly offer only a modest economic advantage in terms of increased production, especially during years with normal rainfall, they offer the great advantage of helping to stabilize production during years of too little or too much rainfall. Equally important is their long-term value in safeguarding the soil resources upon which future production will be based.

Water availability can be increased and made more reliable in virtually all areas that suffer from inadequate or erratic water supply. A survey based on rainfall and soil data suggests that as much as one-half of the area in many arid and semi-arid countries could use water harvesting technology (l). During years of normal rainfall these practices will improve the soil but may not bring any significant increases in yield. However, in years with below average rainfall they can help stabilize production because they have improved the moisture retention capacity of the soil. Crop yields from a water harvesting scheme in Burkina Faso were little more than yields obtained from traditional farming methods in 1982 when rainfall was about 450 mm. But in 1983, a drought year, the yield from fields using the technology was 48 percent greater than on neighboring farms (61). In the Lake Region in Tanzania, results from 14 trials between 1939 and 1946 showed that cotton, maize, and sorghum yields in ridged plots were almost always higher than in flat cultivated plots. The only exceptions, 1942 and 1945, were years of above-average rainfall. Yields from ridged plots in the drier years were impressive, especially considering that the unridged plots suffered crop failure (6).

These soil and water management technologies are relatively non-capital-intensive. Labor, for the most part, can be supplied by farmers during the off-season. Men, women, and children all can be involved in their construction, operation, and maintenance.

These technologies also can be used to enhance the intensive production provided by small home gardens. For example, preliminary data collected in Cape Verde show that an intensive garden of only 500 square meters with adequate water for two crop seasons per year will provide all the food required for a family of six. Developing and storing water supplies to accomplish this is a realistic goal (48). Home gardens traditionally have been tended by women to produce vegetables, spices, and other specialty crops. Improved water management technologies will reduce the time spent carrying water from distant sources, and the surplus food and specialty crops produced can be sold in local markets, thus increasing the income available to women and their families.

Problems and Approaches

A major challenge facing agricultural development in Sub-Saharan Africa is the ability of poor rural populations to meet their immediate food needs without undermining the long-term sustainability of the resource base that supports them. The soil and water conservation technologies described above would involve investing resources today in order to provide continued benefits in the future. This trade-off could be very difficult for African farmers, as well as African governments, faced with immediate needs for short-term survival.

While these problems are difficult to solve, some successes exist. For example, the Government of Rwanda and international conservation groups are cooperating to protect mountain gorillas and farmers' water supplies despite pressure to clear forested park land for additional settlement. The Pare National des Volcans was Africa's first national park, established in one of the poorest and most densely populated countries.

One-half of the park's original area already had been cleared for agriculture by 1969 when deforestation was proposed for approximately one-half of the remaining area. Analysis suggested that clearing would provide land for only 3 months' population growth under the most optimistic conditions. Further, studies showed that economic arguments existed for retaining the forested watershed, which provides clean water supplies for human and livestock consumption, keeps water tables high enough to enable local farmers to harvest multiple crops, even in the dry season, and which will be needed to ensure the full productivity y of a proposed hydroelectric dam downstream. Also, the park and the mountain gorillas have stimulated a major tourist industry, contributing approximately $1 million in annual revenue, Rwanda's third largest source of foreign revenue and the fastest growing economic sector (50,87).

The proposal to clear additional land was abandoned in 1979 and several steps were taken to ensure the park's protection. Guards were hired to stop wildlife poaching and gorillas were habituated to humans so that tourists could be assured of seeing them. Also, long-term education projects began to gain the support of local people. Thousands of Rwandans were educated regarding the significance of the park via posters, calendars, radio broadcasts, and slide and film presentations (87).

Ultimately, the success of such projects depends both on ensuring that local people share in the benefits, as well as the costs, of conservation measures (e.g., by taking part in the tourist industry) and on providing alternatives for the people who would have gained land or income from other proposals. AID's work in Latin America suggests that poorer farmers can successfully implement conservation projects when these factors are accounted for (85).

Increased attention by development assistance agencies could speed development and implementation of small-scale water and soil management systems, but the approach would need to be long term. Site-specific adaptive research is needed to diffuse these practices successfully. One project entitled Technologies for Soil Moisture Management, funded by AID's Science and Technology Bureau and implemented through the U.S. Department of Agricul-

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ture's Agricultural Research Service, is expanding its efforts in Africa and is planning on-farm trials to study the economic viability of several of these technologies (53). Pilot projects are needed in several locations to adapt the technologies to the different agroecological conditions of Africa. Newsletters, other publications, seminars, and workshops, for example, could link regional pilot projects and practitioners of the technologies (10). Improved and expanded extension efforts also will be required. Short courses could be provided in-country to increase the number of professionals and paraprofessionals skilled in using small-scale soil and water management methods (47).

These conservation technologies stand to benefit from the more general research needs discussed in chapter 5. For example, farming systems research is needed to improve understanding of factors determining technology adoption rates. Another specific need is for a land classification system that can be used in tropical Africa. The Land Capability Classification developed for conditions in the United States (33) often has been applied to tropical areas (20), but generally is not suitable for African conditions. For example, the system classifies all lands with slopes greater than 7 degrees as unsuitable for cultivation. This is too restrictive for Africa, where manual cultivation is common and erosion potential is lower as a result. Other aspects of Africa's farming systems, precipitation patterns, and soil attributes differ greatly from conditions for which the U.S. land classification system was devised (41). An applied land use classification system for Africa could build on the U.S. Department of Agriculture's efforts to adapt the Soil Classification System and map Africa's soils (8) but also should take advantage of indigenous methods of classifying the land according to its uses (75).

IMPROVING SOIL FERTILITY[2]

Summary

Low soil fertility is a major constraint to improving African agricultural productivity (78). Fertility levels vary throughout the continent, but they are generally low because of extensive weathering of the soils (7). Traditional farming systems relied heavily on fallow periods to restore the land (36,59). But this practice is less viable now in much of Africa because of human population increases. Consequently, more intensive management is necessary to replenish soil fertility. Soil fertility can be maintained or improved through a variety of practices that optimize the benefits of internal farm resources. For example, the soil and water management technologies discussed previously can conserve nutrients by reducing soil erosion and by reducing leaching of nutrients below crops' root zones.

Organic fertilizers also can improve or help maintain soil fertility. For example, legumes and other biological nitrogen fixers typically can add some 100 kg of nitrogen per hectare per year (ha/yr) in the tropics (18). And nutrient losses after harvest can be reduced by as much as 50 percent when crop residues are left in place or returned (82). Manures are another option for adding nutrients to soils. Nutrients are released gradually through the decomposition of plant and animal wastes—an advantage in the wet tropics, where soluble nutrients are quickly leached. Plant and animal wastes also increase soil organic matter, which can be as important as nutrients themselves. Soils rich in organic matter maintain water effectively and have favorable soil structure, thereby promoting root development. Vesicular-

[2]This material is based primarily on the OTA contractor report prepared by P.L.G. Vlek, A.U. Mokwunye, and Ms. Mudahar, international Fertilizer Development Center, Muscle Shoals, AL (app. A].

arbuscular mycorrhizae, a group of naturally occurring fungi that live in association with plant roots, are not fertilizers per se but they are another biological means by which nutrient availability can be increased. These fungi improve plant roots' ability to withstand drought and to absorb phosphorus from the nutrient-poor soils (82).

The use of inorganic fertilizers, as well as organic fertilizers, will be necessary if Africa is to feed itself. Currently, inorganic fertilizers-phosphate rock and more highly processed commercial fertilizers-are used at very low levels in Africa (82). Numerous economic and institutional obstacles are responsible for the current low consumption rates and deter rapid increases in commercial fertilizer use.

Development assistance could continue in its efforts to encourage increased use of commercial fertilizers, but it also could increase emphasis on organic fertilizer alternatives. These techniques are less capital-intensive than those that rely heavily on commercial fertilizers and substitute labor and management information for cash (15). An important long term benefit of these practices is that they increase soil organic matter-and soil organics act as sites to hold nutrients—thereby increasing investment returns from applying phosphate rock and more highly processed commercial fertilizers when available.

Organic Fertilizers

Biological Nitrogen Fixation

Biological nitrogen fixation (BNF) is the process by which microbial organisms reduce or "fix" atmospheric nitrogen into a form usable to plants. Three categories of processes can be distinguished based on the biology of the micro-organism:

1. Symbiotic: the micro-organism and the host plant form an intimate relationship beneficial to both partners; for example, Rhizobium-legume symbiosis and *Azolla-Anabaena* symbiosis.
2. Associative: the micro-organism is non-symbiotically associated with root systems.
3. Free-living: the micro-organism is completely independent; for-example, free-living bacteria or blue-green algae.

These processes are universal and their benefits accrue to farmers without active intervention. However, management decisions by the farmer concerning crop selection and farming practices affect the extent of these benefits. The quantities of nitrogen fixed vary widely, depending on crop and environmental conditions, but the benefits of biological nitrogen fixation in tropical regions can be substantial (table 7-3). It is generally accepted that nitrogen fixation of around 100 kg/ha/yr can be expected from the majority of grain and forage legumes. Higher levels are possible for *Leucaena,* other woody perennials, and forage legumes with a continuous growing season (18).

In addition to the nitrogen provided through fixation, mulch from leguminous trees and shrubs returns accumulated nitrogen to the soil. Deep-rooted trees like *Acacia* extract nutrients that are otherwise beyond the reach of annual crops, while stabilizing the soil and reducing soil erosion (see ch. 9). These nutrients then en-

Table 7-3.—Conservative[a] Estimates of Biological Nitrogen Fixation Rates for Different Fixers

Nitrogen fixer	Rate (kg N/ha/yr)[b]
Grain legumes	50-150
Forage legumes and cover crops	100-250
Tree and shrub legumes	75-150
Anabaena-Azolla symbiosis	50-100
Non-symbiotic and associative nitrogen fixation	10-30
Free-living fixers	5-15

aConsiderably higher rates than these have been reported in the literature, but OTA considers these rates more realistic for on-farm conditions.
[b]kg N/ha/yr = kilograms nitrogen per hectare per year

SOURCES: J. Halliday, Director, Batelle-Kettering Laboratory, Yellow Springs, OH, personal communication to OTA, 1987; P. Vlek, et *al.,* "Soil Fertility Maintenance in Sub-Saharan Africa, " contractor report to the Office of Technology Assessment (Springfield, VA: National Technical Information Service, December, 1987); J. Halliday and P. Somasegaran, "Modulation, Nitrogen Fixation and Rhyzobium Strain Affinities in the Genus Leucaena," *Leucaena Research in the Asia. Pacific Region,* edited by the Canadian International Development Research Center (Ottawa: IDRC, 1983), rich the topsoil as fallen leaves decay and as manure from leaf-fed animals is recycled. The soil is also enriched indirectly when trees, rather than crop residues and manure, are used as the source of fuel for cooking and heating needs.

The biologically fixed nitrogen available for crops may be less important than other benefits from BNF. When leguminous crops are harvested, between 60 and 90 percent of the accumulated nitrogen is taken from the system. In grain legumes, for example, the majority of fixed nitrogen is harvested with the seed, which on average contains twice the level of nitrogen than the plant as a whole (19) and makes a critical nutritional contribution to people's diets. Probably no more than 60 percent of the nitrogen left in organic residues after harvesting is available for the next crop, or 6 to 24 percent of the total nitrogen accumulated by the plant (18). Thus, the principal benefit from legumes that are harvested arises from the fact that they can be grown without the addition of nitrogen fertilizer. Crops that are able to fix nitrogen are "free" in terms of outside nitrogen demand. The surplus they leave for the following crop is a small but significant bonus to the resource-poor farmer. In contrast, "green manures' '–nitrogen-fixing plants specifically grown to be plowed or hoed into the soil rather than harvested—can provide the majority of nitrogen needed for the subsequent crop. Leguminous trees and shrubs also can be used as a valuable tool in reforesting degraded lands (18).

It would be difficult to find a farmer or herder in Africa who does not reap the benefits of BNF in one form or another. Scattered native leguminous plants grow on abandoned land, and many traditional farming systems include a leguminous crop in the rotation (e.g., millet/cowpea and maize/cowpea in West Africa and maize/bean in East Africa). However, resource-poor farmers and herders do not receive maximum benefits from BNF. The greatest potential seems to be in developing:

- legume-based pastures for fodder production (see ch. 11);
- increased use of leguminous trees in agroforestry systems, such as alley cropping (see ch. 8);
- legume-based cropping systems; and
- increased use of *Azolla* in rice fields.

Advanced research on related topics, such as gene transfers, primarily is occurring at institutions outside Africa and, if successful, may in time find its place in the African context. Current BNF technology is principally related to inoculating plants with effective strains of *Rhizobium*, selecting and multiplying the micro-organisms, and manufacturing and applying the inoculants. Little inoculant is used in sub-Saharan Africa. However, some inoculated legumes, such as soybeans, have been introduced from other areas and are routinely used by commercial farmers in Zambia, Kenya, Zimbabwe, and Rwanda (82).

Azolla is a genus of small aquatic ferns that are capable of forming symbiotic relationships with a blue-green cyanobacteria, *Anabaena azollae*. The fern provides nutrients and a protective leaf cavity for the *Anabaena*, which provides fixed nitrogen for the fern. The *Azolla/Anabaena* association thrives in the aquatic conditions present during rice production—conditions that prohibit the growth of most legumes. The fern grows extremely quickly, doubling in weight every 3 to 5 days. When it is incorporated into the soil, this "green manure" is a rich source of organic matter, nitrogen, and other nutrients, many of which might otherwise have been washed away. In addition to acting as a soil amendment, *Azolla* suppresses weeds, can be used as fodder, and is even used to a limited extent for human consumption in Asia (45).

The use of *Azolla* in rice production, a well-established practice in Vietnam and China, is only in an experimental stage in Africa. The West African Rice Development Association has led in the research and extension of this technology, but it still is only used by a few African farmers (81).

Vesicular-Arbuscular Mycorrhizae

Mycorrhizae are beneficial species of fungi that penetrate plant roots resulting in a symbiotic relationship between these fungi and the host plant that can lead to increased crop yields. One type—the vesicular-arbuscular mycorrhizae (VAM)—are the most important group of these fungi for agronomic crops. Maize, cowpea, and onion, for example, cannot take up phosphorus from low-phosphorous soils unless their roots are infected with VAM. The VAM act as extensions of the plant's root system, providing an increased surface area for absorbing nutrients. This is particularly useful for the more immobile nutrients such as phosphorus, zinc, and copper. Mycorrhizal activity is enhanced by the high temperatures, low moisture, and low phosphorus-conditions encountered in much of semi-arid and tropical Africa (34).

VAM, like BNF, benefits farmers and herders in Africa through natural processes without deliberate management. Improvements in mycorrhizal technology will help farmers make efficient use of phosphorus from all sources in Africa's phosphorus-poor soils, however. Unlike BNF, though, it has proven difficult to culture VAM on artificial media, and therefore it is best done using roots of susceptible plants (52). It is difficult, though, to obtain pathogen-free inoculum in quantity with these methods. Additional work needs to be done before VAM technology will find its entry into African agriculture. It seems that VAM is not likely to reduce the need for organic and inorganic fertilizer but is more likely to play a role in concert with those other inputs to improve efficiency of phosphorus use (82).

Manure

Manuring refers to the recycling of organic material so that the nutrients in animal and plant wastes are used to improve soil quality. Although this section focuses on the use of livestock wastes as manure, several other types exist. "Night soil," human excrement, is an important source of soil nutrients in densely populated Asia, but its use is culturally unacceptable in much of Africa. Household litter containing organic wastes such as food byproducts also is a source of nutrients and its use in African gardens could be increased. Crop residues can improve soil fertility in addition to offering other benefits (ch. 7). "Green manures" are crops grown specifically to be plowed back into the soil. They sometimes consist of grasses, but since they more typically are legumes, they were discussed in the preceding section on biological nitrogen fixation.

With the exception of "green manures, " which make inorganic minerals more accessible for plant growth, manuring does not, in itself, generate nutrients (57). The conversion of forage to manure (e.g., by cattle) results in a net loss of organic matter and minerals. For example, results from a study on a Rwandan farm show that 3.8 tons of dry forage containing 370 kg of minerals produces approximately 2 tons of dry animal manure containing only 300 kg of minerals (67). On the other hand, manuring is an important means of transferring nutrients from pastureland to cropland, or returning some of the nutrients that animals harvest to the field. The benefits are largely attributable to the increase in soil organic matter and include (5):

- improved soil macro-structure;
- increased water-holding capacity of the soil, particularly the topsoil;
- improved infiltration and erosion control;
- prevention of soil hardening;
- improved soil cation exchange capacity, of particular importance for the sandy soils of west and southern Africa;
- increased supply of slowly releasing inorganic nutrients;
- prevention of phosphate fixation by iron and aluminum oxides; and
- development of a favorable environment for microbial activity in the soil.

Despite the relatively high number of animals per capita in Africa, the use of animal manure is not great. In arid areas where cattle husbandry is strictly nomadic, collecting dung is impractical and it would be uneconomical to transport this material to crop growing areas. Moreover, the wisdom of exporting *nutrients* from the low-fertility rangelands is highly questionable. Under semi-nomadic husbandry practices, however, an association can exist between herder and farmer, whereby cattle are allowed to graze crop stubble in exchange for their manure. This system has been shown to be more economical than if the farmers owned and managed the livestock (9). The practice can help maintain soil fertility, but is insufficient to allow sustained cultivation without additional nutrient input.

Even on farms where crops and animals are produced, manuring sometimes is not common presumably because it is not economically viable (30,35). Manure requirements for crops are high (e.g., from 5 to 20 tons of fresh manure per hectare) (25), and managing manure *is* labor-intensive and requires transport and tools. Therefore, manuring has more potential for use in vegetable plots and home gardens than in the larger, more distant fields used to grow cereals and other staples. The primary reasons for keeping animals are for security, traction, meat, or milk (see ch. 11), but manure can be a byproduct that makes the adoption of animals more attractive.

The most effective means of collecting animal manure undoubtedly is by keeping animals stabled day and night. This yields about 8 times the animal's weight in manure per year. Alternatively, the animal can be stabled only at night, in which case it produces 3.5 times its weight in manure per year (17).

Inorganic Fertilizers

Phosphate rock is not used abundantly in African agriculture, but can be a locally important fertilizer, especially on acid soils. It can either be applied directly or processed before use. Several factors affect plants' ability to use phosphate rock. Some of these factors are related to the chemistry and mineralogy of the rock, others to the properties of the soil, or to the physiological makeup of the crop. The mineral can be used in several ways, in increasing order of the degree of processing required:

1. direct application of finely ground rock;
2. development of granular forms of the rock to improve handling characteristics;
3. combination of the finely ground rock with other materials such as elemental sulfur, manures, and compost; and
4. production of partially acidulated phosphate rock to improve volubility. The most processed forms involve substantial cost and energy to manufacture.

Photo **credit:** *Banoun & Caracciolo/U.N. Food and Agriculture Organization*

Farmers applying inorganic fertilizer to a yam field in Nigeria.

The most highly processed forms of fertilizer, commercial fertilizers, are sometimes called conventional, chemical, petrochemical, or fossil fuel-based fertilizers. In addition to minerals found in rocks, commercial fertilizers use compounds present in fossil fuels as their raw materials. Fossil fuels are also used to supply the energy necessary to process the materials. Therefore, commercial fertilizers, especially those high in nitrogen, are comparatively expensive to produce. However, they can be an extremely convenient method of supplying minerals in forms very accessible for plant growth.

Current commercial fertilizer use in Sub-Saharan Africa is the lowest in the world. The region contains approximately 7 percent of world population, but uses only 0.9 percent of world commercial fertilizer supplies. The average consumption rate is about 6.4 kg nutrients ha/year; by comparison, in 1983 the average consumption rate was 85 kg/ha/yr for the world, 33 kg/ha/yr for Latin America, and 81 kg/ha/yr for Asia (25). National consumption rates vary considerably in Africa, however. Three countries—Nigeria, Zambia, and Zimbabwe—account for 50 percent of the total consumption in Sub-Saharan Africa. Much of this fertilizer is used on cash crops rather than on local food crops. With the exception of a few countries such as Nigeria and Niger, about one-half to two-thirds of the fertilizer is used on crops grown primarily for sale.

All of the mineral resources needed to manufacture commercial fertilizers occur in varying amounts in Sub-Saharan Africa. Data suggest that adequate quantities of phosphate and nitrogen raw materials may exist, but potash and sulfur resources are inadequate to meet the region's needs (82). It is not known if exploitation of these resources is technically and economically feasible under present conditions. The advantages of using indigenous resources, even in times of adequate world supply, include supply security, foreign exchange savings, reduced transportation cost, and employment generation.

Since phosphorus deficiency has been identified as a major soil constraint in Africa, national and international research organizations have shown interest in developing the deposits of phosphate rock that exist in 26 Sub-Saharan African countries (51). However, only two countries, Zimbabwe and Senegal, produce phosphate fertilizers in any significant quantity, and farmer use remains low despite efforts such as those in Senegal, Mali, Burkina Faso, and Niger to provide farmers with phosphate rock at prices lower than imported fertilizer (82). Also, excluding deposits in eastern Senegal, Mali, and Niger, most of Africa's known deposits are "unreactive' '-their natural form is not conducive to plant uptake and therefore requires considerable processing. And in the dry, dusty, and windy environments of the Sahel, application of finely ground phosphate rock—the most effective form—is too labor-intensive.

The full benefits of phosphate rock are realized for several years after application. This may mean that return to investment on the labor and capital costs is more favorable than initial calculations might suggest (53). However, farmers may find it difficult to capture these residual benefits unless they can develop appropriate crop rotations. Problems associated with farmer unwillingness to make such investments without secure land tenure can further undermine adoption of this practice (82).

Potential for Improving Soil Fertility

Organic Fetilizers

Organic fertilizers can play an important role in ensuring that soil fertility is adequate for producing stable yields of African crops. One approach is BNF, which can be promoted through wider use of legumes in intercrops and rotations, agroforestry systems, and in fodder pastures, and greater use of *Azolla* in rice production. Even if a crop is not able to fix nitrogen, nutrient loss can be reduced by as much as 50 percent if crop residues are left in place or returned to the soil (82).

Manures can increase yields substantially, but economic analyses have rarely been conducted. These analyses would be complicated because of the indirect effects of manuring on improving soil quality (29). Manuring can be expected to become more widespread in the future as animals become more fully integrated into farming systems.

The decomposition of plant and animal wastes in soil has other important benefits: gradual release of nutrients and increased water retention. Furthermore, soil with adequate organic matter can take full advantage of phosphate rock and more highly processed chemical fertilizers, increasing yields beyond those obtained by adding organic matter or commercial fertilizer alone (table 7-4; figure 7-4).

Inorganic Fertilizers

The known reserves of phosphate rock that are economically accessible with current tech-

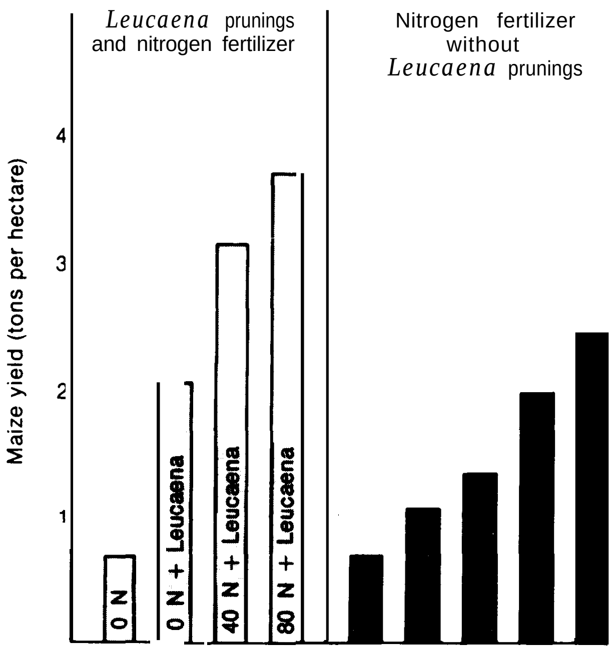
Table 7-4.—Effect of Manure and Commercial Fertilizer on Sorghum Yield at Saria, Burkina Faso

Treatment	Sorghum yield (kg/ha)[a] Without nitrogen	With 80 kg/ha nitrogen
Without manure	1,831	2,798
With 10 tons of manure per hectare	2,409	3,591

aKg/ha = kilogram per hectare.

SOURCE: Christian Pieri, "Food Crop Fertilization and Soil Fertility: The IRAT Experience," *Approriate Technologies for Farmers in Semi-Arid West Africa,* Herbert Ohm and Joseph Nagy (eds.) (West Lafayette, IN: Purdue University, 1985), table *11, p. 89.*

Figure 7-4.—increased Maize Yields in an Alley Cropping System Using Prunings From *Leucaena leucocephala*, a Nitrogen-Fixing Tree, and Varying Rates of Nitrogen Fertilization



SOURCE: International Institute of Tropical Agriculture, *IITA Research Highlights* 1984 (Ibadan, Nigeria: IITA, 1985).

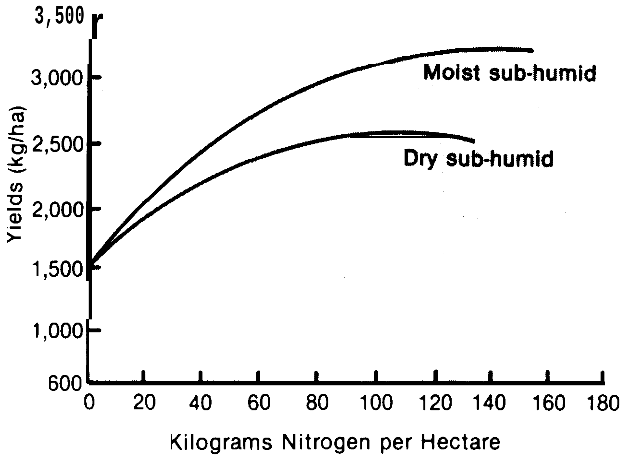
nology are small in most sub-Saharan countries. However, these reserves are large enough to meet phosphate fertilizer requirements of some countries for decades. Significant yield increases are possible even using unprocessed phosphate rock. For example, the application of 30 kg P_2O_5/ha of indigenous rock in a trial in Niger almost doubled the yield of millet (from 300 kg/ha to almost 600 kg/ha). Similar results have been obtained in many coastal West African countries and in Kenya (2).

Small-sized granulation of the fine rock powders (minigranules) using binders may be an effective way of avoiding the dust problems associated with using the fine powder. The adoption of this technology will depend on the cost of pelletizing.

Reducing the amount of acid needed to digest the rocks fully (partial versus full acidulation) results in a product that is only slightly less reactive than the fully digested material. In several field trials in various parts of tropical Africa (2), partially acidulated products made from normally unreactive phosphate rocks produced similar yields as the fully acidulated superphosphate. Because savings exist in acid consumption during the production, products are expected to be cheaper than imported commercial fertilizers.

Little question exists that Africa will have to increase its use of commercial fertilizers if it is to decrease the gap between food demand and supply. The ability of commercial fertilizers to increase yields is undeniable (figure 7-5), but two major concerns arise regarding their use in Africa. First, few economic analyses of fertilizer use under African conditions have been done, and those studies that do exist mostly reflect the ideal conditions found at agricultural research stations (e.g., deep plowing, complete weed control) (49). The high cost of commercial fertilizers and the variability of response under on-farm conditions, especially rainfed agriculture, argue for extreme caution when extending this technology to farmers with little margin for failure. Second, some studies of the long-term effects of continuous use of commercial fertilizer on the soil suggest that it can

Figure 7-5.—Response of Maize to Nitrogen in Different Climatic Zones



SOURCE: Paul Vlek, A. Mokwunye, and M. Mudahar, "Soil Fertility Maintenance in Sub-Saharan Africa, " contractor report prepared for the Office of Technology Assessment (Springfield, VA: National Technical Information Service, December 1987).

actually depress yields unless large amounts of organic material, such as animal manure, also are added to the soil. Trials in Burkina Faso showed steadily declining sorghum yields over 18 years due to soil acidification, potassium deficiencies, and aluminum toxicity (63). These findings tend to reinforce the need to view inorganic fertilizers as supplements to, and not replacements for, organic fertilizer.

Problems and Solutions

Low soil fertility is one of the principal obstacles to sustained crop production in Africa. Alleviating this constraint will require a concerted research and development effort. Current approaches to soil research are largely fragmentary and a coordinated effort is needed that addresses the problems and options of ensuring soil fertility maintenance in different agroecological zones.

Increasing the use of organic fertilizers should bean integral part of this strategy. Optimizing the *use* of organic fertilizers is particularly important for those resource-poor farmers in isolated regions, where input delivery systems are problematic. Considerable opportunity exists to increase organic fertilizers use by expanding use of legumes in agroforestry and intercropping systems, and by better integrating crops and livestock in African farming systems (see chs. 8 and 10, respectively). Improving benefits of biological nitrogen fixation in African farming systems will require increased support for training African professionals and technicians, and increased research relevant to Africa, for example, on legumes in multiple-cropping systems. Such research and training could be supported through the funding of an international BNF Resource Center (18).

Increased use of inorganic fertilizer also will be essential to meet Africa's future soil fertility needs. The fertilizer sector in Africa is in its infancy. One constraint is the lack of consistent, long-term government and donor policies regarding fertilizer use. African governments are either ill-prepared or unwilling to create such policies. Donors sometimes exacerbate the situation. For example, until 1983, the policy in Rwanda was to reemphasize fertilizer use. FAO and the European Economic Community helped convince the government that fertilizers were an essential ingredient for the future and Rwanda proclaimed 1985 the year of the fertilizers. However, U.S. AID and its German counterpart, GTZ, adhered to the earlier policy that gave a low priority to fertilizer use. In the meantime, Rwanda still lacks a comprehensive, long-term plan for the development of the fertilizer sector (82).

Most countries in Sub-Saharan Africa are facing fertilizer supply and demand problems (56, 90). Frequently, fertilizer is not available at the right time and place, and many countries are unable to meet even low fertilizer demands or reduce supply fluctuations. Factors contributing to low fertilizer demand include:

- low crop response;
- lack of knowledge on fertilizer practices;
- high fertilizer cost and lack of cash or credit;
- high risk of losing money as a result of the variability in crop response and prices;
- low crop prices; and
- lack of complementary farm inputs such as fertilizer-responsive crop varieties, water, and insecticides.

Successful fertilizer programs require soil fertility maps, geologic research on important mineral deposits, establishment of soil testing laboratories, formulation of soil- and crop-specific fertilizer recommendations, and initiation of well-designed fertilizer demonstrations under farmers' field conditions. At present, fertilizer recommendations for specific agroclimatic conditions, crops, farming practices, and soil conditions generally do not exist. Current government recommendations not only may be inappropriate but actually maybe counterproductive.

Accomplishing these tasks would require a major commitment of resources. According to the International Fertilizer Development Center, an estimated 1,600 people per year are needed over the next 20 years to work in sub-Saharan Africa's fertilizer sector, including fertilizer production, marketing, and use (82).

Fertilizer research programs are likely to be more effective if they adopt a farming systems approach that emphasizes the economic feasibility of fertilizer use and includes on-farm trials. Effort should be directed at reducing variability in crop's response to fertilizers, but economic analyses should not fail to include the risk associated with fertilizer use. Also, analyses should be realistic about portraying field—not ideal—conditions. When farmers use fertilizers on their own fields, their financial returns typically are only one-half to two-thirds those gained under experimental conditions. In addition, farmers generally pay more for fertilizers than the official, government-sanctioned, price (49).

In situations where economic analysis supports fertilizer use, credit may be needed. If so, providing credit at a market rate of interest should help reduce inefficient fertilizer use. As an alternate strategy, fertilizer sales on credit could be linked with crop marketing, that is, farmers could repay the fertilizer loan after harvest from receipts of crop sales. This idea has been used successfully by cooperatives in several Asian countries. Private traders, who are also fertilizer dealers, often practice such a sales strategy (82).

SMALL-SCALE IRRIGATION[3]

Summary

The Sahelian droughts of the early 1970s and mid-1980s that affected most of the continent have dramatically illustrated Africa's susceptibility to erratic and inadequate water supply. At least half of Sub-Saharan Africa, excluding the Sahara Desert, is arid or semi-arid, and untimely supply of water for crops and animals adversely affects much of the remaining area. Against this backdrop, the allure of irrigation needs no explanation.

FAO estimates that irrigated cultivation is practiced on 4 percent of the land classified as arable and under permanent cultivation in tropical Africa (77). An estimated 43 to 50 percent of this area could be considered low-resource agriculture (77,79). In much of the small area where large irrigation schemes are feasible, they already exist. Therefore, the remaining opportunities for irrigation in Africa are primarily for small-scale approaches (84).

Each of the four small-scale irrigation practices described here operates within a particular socio-ecological niche (table 7-5). They may be quite beneficial under specific, often geographically limited conditions, but unfeasible or economically unattractive elsewhere. This is especially true of channeled, poldered, and non-mechanized water-lifting practices,

[3]This material is based primarily on the OTA contractor report prepared by Alfred S. Waldstein, Associates in Rural Development, Burlington, VT (app. A).

Table 7-5.—Estimates of the Distribution of Small-Scale Irrigation Technologies in Africa

Type of system/location	Number of users	Area (in hectares)	Number of schemes
Channeled systems			
East African Highlands:			
Tanzania	NK[a]	117,000	NK
Kenya	NK	900	NK
Malawi	NK	5,000	NK
Madagascar Highlands	NK	700,000	NK
Middle & Lower Shabelle River (Somalia)	NK	16,000	NK
Poldered systems			
Upper Guinea coastal lowlands	700,000-900,000	NK	NK
South-east Lake Chad	NK	4,000	NK
Water-lifting systems			
Sahel:			
Burkina Faso	NK	6,200	600 +
Chad	NK	2,500	NK
Niger	NK	14,500	NK
Coastal west Africa			
Gambia	NK	10,000	NK
Southern Africa			
Zimbabwe	NK	400	NK
Mechanized water-pumping systems			
Zimbabwe	7,000	4,700	67
Nigeria	NK	800,000	NK
Niger	NK	36,500	500+
Sudan	NK	140,000	NK
Chad	NK	8,000	NK

[a]NK = **not known**

SOURCES Compiled from a number of references in" A.S. Waldsteln, "Low-Resource, Small-Scale Irrigation In Africa:' contractor report to the Office of Technology Assessment (Springfield, VA National Technical Information Service, December 1987) and AS. Waldstein, Personal communication, revisions to OTA contractor report, 1987

and less so of mechanized water pumping systems. To determine which technology to implement under given circumstances, planners and decisionmakers must take the following into account:

- local ecology, hydrology, geology, and topography;
- implementation and maintenance costs;
- access to investment credits;
- national pricing, import/export, and foreign exchange policies;
- access to material, services, and inputs required to support the technology;
- proximity and access to markets;
- availability of and competition for labor; and
- local systems of land and water rights.

Small-scale irrigation could become an important component of a strategy for intensifying agricultural production throughout much of Africa. Its benefits—increasing and stabilizing cropland productivity-are often sustainable for two reasons. First, costs to develop the systerns generally are low, being more labor- than capital-intensive. Second, the initiative to develop and maintain small-scale irrigation rests with the users, so management grows out of the users' social system rather than being imposed on it. Also, small-scale irrigation projects can avoid many of the health, environmental, and social problems associated with large-scale projects {62,66,77).

Development assistance can support small-scale irrigation through technical and socioeconomic research; training extensionists in management options and supporting their involvement in farming systems research; and fostering national and local credit programs for generating investment capital.

Small-scale irrigation, for the purposes of this report, is characterized by:

- **systems managed as an integral unit by an institution created by, composed of, and led by users;**
- **users make the decisions regarding the role irrigation will play in their agricultural production strategies and farming systems;**
- **usually the cost of development and operation of the system is low and covered, in large part, by user labor and inputs; capital costs, in particular, are low and normally can be assumed by users; and**
- **users generally develop the technical skills to design, build, and operate the system through a continuous iterative process.**

Gravity Diversion Systems

Channeled Systems

Water is diverted into this type of irrigation system, from streams, springs, and lakes, by a network of channels. Individual fields are divided from each other and separated from the channels by low bunds. Fields are usually flooded by breaking the bund at one point to allow water to enter. The break is closed off with mud, wattle, or a sack filled with sediment at the end of watering. The water is being used, in effect, to extend the rainy season and reduce the risks of rain-fed agriculture. Irrigation, plus rainfall, typically allows more than one harvest per year. The system can be designed, built, operated, and maintained primarily with local labor, and the users can meet most institutional needs. Initial costs sometimes are not low, but operating costs typically are.

The main locations using gravity diversion channeled irrigation systems are the highlands of East Africa and Madagascar, and the Middle and Lower Shabeelle Valley in Somalia. In Somalia, about half the land on the Middle and Lower Shabeelle is irrigated by gravity fed channels. The technique is used in Tanzania on an estimated 117,000 ha, or 82 percent of all irrigated land (55), and in Madagascar on 70 percent of the 1 million ha under irrigation (28). Gravity-fed channeled irrigation, by contrast, covers no more than 4 percent, 800 to 900 ha, of irrigated land in Kenya (31).

Many of these systems, such as those along the Shabeelle River in Somalia, have been in existence at least since colonial times. They have fallen into disuse due to problems with water-borne disease, labor recruitment, migratory wage labor, land tenure problems, and unfavorable systems of justice and administration (14,31,60). The most important constraint to wider use, however, is that although investment requirements are small, returns on investment also are small. These systems do not include storage, so water is only available seasonally.

Poldered Systems

Poldered systems are made up of an intersecting network of channels built on low-lying swampy plains to help conduct the inflow and outflow of water. The purpose of poldered systems of the Upper Guinea coast is to drain water to the sea in the rainy season and conduct salt-water inland, especially at high tides, during the dry season. Sea water is permitted to enter the polders in the dry season, after harvest, to maintain soil plasticity. Salts are leached from the soil by flooding the channels with fresh water at the beginning of the next rainy season. After the soil has been de-salted, the polders are closed and crops planted. Farmers use the residual moisture from the river water in conjunction with rainfall to produce their crops (42,43,44).

The poldered systems around Lake Chad are managed differently, They are created by building dikes to trap water between two islands in the lake. Water infiltrates the lake bottom and people plant in the exposed moist, heavy clays. Later, they open the dike to flood the land again and wash out accumulated salt (3). As with the channeled systems, the poldered systems are technically and institutionally within the control of the users. The cost of technology is low in cash terms, although labor costs can be high. Most existing poldered systems support subsistence production.

Just as with channeled systems, poldered systems date back to or even precede the colonial era. However, the Lake Chad polders have fallen out of production in recent years. A succession of drought years has caused a major recession of the lake's shores and empoldered areas now may be many kilometers from the water's edge. In addition, many polders in Guinea-Bissau were destroyed during the war for independence, which ended in 1974.

Polder technology is feasible only in well-watered, lowlands with rich soils. Because of their particular ecological requirements, little extension of these systems is possible. Rain often is critical: in coastal areas, lack of rain means that saltwater will not be flushed downstream and salts accumulate; and in the Lake Chad region, without rain the lake level cannot rise enough to flood the polders. Polder technology is used mainly for subsistence. However, some production is on a large enough scale to produce substantial surpluses for market. Since the polders are virtually surrounded by water, these areas tend to have relatively easy water access to markets in areas where market roads may be lacking.

Water-Lifting and Pumping Systems

Water-Lifting Systems

Water-lifting technologies available to resource-poor farmers and herders include calabashes, buckets and pails, tin cans of various sizes, paddles, waterwheels and shaddoufs (a traditional water-lifting device), and handpumps. All of these technologies depend on a relatively high water table since they use human or animal energy to lift water from hand-dug wells into the main channel of the irrigation system. As a general rule, because of the physical limits of human drawing power, one well can irrigate only 0.25 to 0.5 hectares this way. The scale of operations made possible by a single well is so small that this irrigation technology needs practically no institutional support.

Photo credit: George Honadle

Water pumped by hand, by small engines, or by windmills provides irrigation for vegetable gardens such as this one in Botswana.

These water-lifting systems are usually operated seasonally to supplement rain-fed food production or livestock herding. Also, they may operate during the dry season to produce high-value crops for market, such as vegetables. However, sometimes small water-lifting systems are operated year-round for additional uses. In Chad, for example, in addition to the usual dry season crop of vegetables, maize germinates with help from a water-lifting system, then matures under rainfed conditions. Thus, water-lifting systems make possible a second cropping season and effectively extend the rainy season for staple food crops (83).

Irrigation technologies that rely on human or animal power to feed water into the system are scattered across Africa, concentrated in low-lying areas where the water table is relatively close to the surface. They are especially common across the Sahel from Senegal to Sudan. In addition, a number of systems exist in northern Togo, northern Ghana, and throughout Burkina Faso. These systems **are** fed from village barrages (small dams) that store rainwater runoff. Water-lifting systems are relatively scarce in eastern and southern Africa where the water table generally is deeper and soils rockier and more difficult to penetrate with wells.

Although the technology is not new, most of the water-lifting systems in Africa are relatively recent. They have developed rapidly in the Sahel since the onset of the series of drought years starting in the late 1960s. Systems in southern Mauritania date from the mid-1970s, and use of the shaddouf water-lifting devices in the Lake Chad basin dates from the same period. These recent systems are being used by small, scattered groups. Herders in Chad from the north and east came to the shores of Lake Chad to practice shaddouf cultivation when they lost their herds. People in northern Burkina Faso and southern Mali are using water-lifting technologies to grow potatoes to compensate for the drop in millet and sorghum production caused by recent dry conditions. Rural farm families using these systems tend to be less well-off than average (with the exception of the Niayes area in Senegal and some parts of Niger). Better-off families either had resources to invest in pumping or managed to preserve their livestock.

Water-lifting technologies can be profitable where markets are nearby because of their low costs for construction, operation, and maintenance. Recent advances in developing inexpensive and reliable handpumps, however, are particularly encouraging (box 7-1). Even under these conditions, though, handpumps are often used only in the off-season to produce a small crop or during droughts. People may try to expand their operation by investing in pumping as market and production opportunities develop. Therefore, water-lifting technology can be considered a transitional step toward more intensified, highly mechanized, agriculture using handpumps.

Mechanized Water Pumping

Mechanized water pumping makes it possible to draw relatively large quantities of water from wells or rivers. Pumping schemes are operated by a wide variety of users, such as private entrepreneurs, cooperatives, and village organizations. The cost of buying, operating, and servicing the pumps makes this practice more expensive than other low-cost irrigation technology. Typically, only a minority of the local population benefits from pumping schemes because of the rigorous implementation requirements (e.g., initial investment costs). However, in some cases, whole villages are involved. Despite the expense, pumps are capable of generating significant returns for their users.

Mechanized pumps, because of fuel costs, usually are operated only during the dry season to grow high-value crops for market. Also, mechanized water pumping systems tend to be concentrated within convenient transport distance of large markets. More than other low-technology irrigation, they need support services, such as trained mechanics, to stay in operation.

Water pumping using small diesel engines to power pumps is the most widespread and rapidly expanding low-resource technology used in African irrigation, and examples are scattered Africa-wide (84). Their presence is a function of three factors: availability of water, access to credit for the initial cash investment, and access to lucrative markets.

Water pumping systems are common along Africa's large rivers; for example, at least 400 such systems exist in Senegal, Mauritania, and Mali along the Senegal River. People also pump water from lakes and holding ponds. The International Irrigation Management Institute estimates that private pumping schemes in Sudan provide water to 134,000 ha (28). These schemes in general are so dispersed or isolated that it has been impossible to survey them, but thousands of pumping systems, no doubt, exist throughout tropical Africa.

Constraints to their wider use include the expense of purchasing and operating pumps, lack

Box 7-1.—Handpumps

Manual pumps have long been recognized as one of the most promising hardware options for village-level water supplies in most rural areas, but a variety of obstacles have hindered reliable handpump operation in many developing countries. Many imported models were simply too costly; spare parts were expensive and hard to get; breakdowns were frequent; and maintenance and repair systems—where available—were overly centralized and burdensome. As recently as a decade ago, the United Nations Children's Fund (UNICEF) reported that at any given time 70 to 80 percent of handpumps installed in India were nonfunctional. The performance records for handpump projects in Africa were equally disappointing.

However, handpumps do show promise. Through a network of field-testing activities in some 17 developing countries supported by a collaborative United Nations Development Program/World Bank project, a half-dozen countries across three continents are now producing handpumps locally. The "handpumps project" also has provided detailed information for a comprehensive manual which will aid in handpump selection, design, and use in countries throughout the developing world,

From India to Malawi

Beginning in the late 1970s, UNICEF supported local production of an innovative design called the "Mark II" which set new standards of reliability and cost-effectiveness at the village level. At least 150 million people in India are presently served with safe water supplies using almost half a million Mark II pumps.

Soon, experiences and lessons learned in India were carried to a local production programme in Malawi under government and project sponsorship. The new "Maldev" design spread rapidly across the country. However, like the Mark II, the Maldev pumphead relied on fitted metal bearings which suffered rapid deterioration and were difficult to properly replace at the village level.

From Malawi to Kenya

A technical team in Nairobi, working with local manufacturers and the DuPont company, produced a modified Maldev design featuring injection molded plastic bearings. Working through other design problems with the Malawi pump, the Kenyan team began field-testing the "Afridev" pumphead, proving that the plastic bearing concept could be cheaper to maintain and easier to repair at the village level.

The Kenya Water for Health Organization was enlisted to train rural women in proper use and maintenance of the prototype pumps. By the end of 1986, the first 200 Afridev pumps were rolling off the production lines,

According to World Bank regional project officer, David Grey, the Afridev system represents a major conceptual breakthrough because:

> . . . it's designed to exploit the benefits of modern materials and technologies, especially plastics. It is suitable for local manufacture in developing countries. It's easily maintained using minimal skill and few tools. It features a universal small diameter, long stroke cylinder for all well depths, simplifying spare parts requirements and minimizing stress forces.

The total cost of the complete pump assembly is no more than US$400, and most of the below ground components for the system are made of standard PVC plastic which is readily available in Kenya and other east African countries. The cost of locally-produced replacement bearings is only US$4 for a complete set.

Back to Malawi—and Beyond

Through the collaborative network set up by the project, the improvements featured in the Afridev system were soon being carried back to Malawi. There they were integrated into the local manufacturing processes and taken to the village 1evel where women, once again, are becoming the central personnel for pump maintenance and repair. The Afridev design is also being adopted in Ethiopia and Tanzania where project officials feel confident that local production and use can begin in 1988.

SOURCE: Anonymous, "Handpumps Across the South," *Cooperation South, No. 2,* **1987**, pp. *3, 17.*

of credit, shortage of spare parts, and local incapacity to repair equipment. Appropriate engineering is also a major shortcoming with many pumping schemes. The canal layout of many schemes is not well planned, and consequently, they distribute water inefficiently (84].

Potential

FAO estimates that 5.3 million ha, or 4 percent of the land classified as arable and under permanent cultivation, are under irrigated cultivation in tropical Africa (77). From 43 to 50 percent of this could be considered low-resource agriculture (77,79) (table 7-6).

The topography of Africa is not conducive to large-scale irrigation, in contrast to Asia, for example, which had at least 56 percent of the world's irrigated cropland in 1981 (88). Other than the interior delta of the Niger River, no large alluvial plains exist in Africa with multi-season water supplies and soils with adequate clay content (84). Systems already exist in much of the limited area where large irrigation schemes are feasible. Therefore, the remaining opportunities for irrigation development in Africa are primarily of smaller scale (84).

Small-scale irrigation can contribute to food security in a variety of ways:

- increasing crop or livestock production;
- reducing risk of crop/animal failure by increasing dependability of water supply;
- enabling the production of a second crop by lengthening the growing season; and
- increasing income for the above reasons, including production of new crops, particularly vegetables.

Small-scale irrigation projects commonly are less expensive than larger schemes (71,77), and may be less susceptible to health problems caused by disease-carrying organisms that flourish in standing water. Management needs for small-scale projects usually are easier to satisfy. Research organizations, development agencies, host governments, and users generally agree that these technologies have great potential under the right ecological and demographic conditions (84).

FAO estimates expansion of irrigation through the year 2010 could average some 50,000 ha/yr. Rehabilitation of existing schemes would add 25,000 ha/yr and expansion of traditional and small-scale irrigation could reach 150,000 ha/yr (49,54,77).

Among the low-cost irrigation technologies, diesel pumping has the greatest technical potential for increasing productivity and it can be used under the widest environmental conditions. However, it is also the most expensive and the most dependent on outside resources.

Table 7-6.—Distribution of Modern and Traditional Irrigation in Sub-Sahara Africa

Regions*	Modern and large- & medium-scale	Small-scale and traditional	Total
	Million hectares		
Sudano-Sahelian Africa	1,917	340	2,257
Humid and Sub-humid West Africa	144	1,190	1,334
Humid Central Africa	18	60	78
Sub-humid & Mountainous East Africa.	282	910	1,192
Sub-humid & Semi-arid Southern Africa	308	150	458
Total	2,669	2,650	5,319

“Countries included in FAO regions.
1. Sudano-Sahelian Africa:
Burkina Faso, Cape Verde, Chad, Djibouti, The Gambia, Mali, Mauritania, Niger, Senegal, Somalia, Sudan.
2. Humid & Sub-humid West Africa:
Benin, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Nigeria, Sierra Leone, Togo.
3. Humid Central Africa:
Cameroon, Central African Republic, Congo, Equatorial Guinea, Gabon, Sao Tome & Principe, Zaire.
4. Sub-humid & Mountainous East Africa:
Burundi, Comoros, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Seychelles, Uganda.
5. Sub-humid & Semi-arid Southern Africa:
Angola, Botswana, Lesotho, Malawi, Mozambique, Nambia, Swaziland, Tanzania, Zambia, Zimbabwe.

SOURCE: UN. Food and Agriculture Organization (FAO), *Afrlcan Agriculture: The Next 25 Years, Annex IV, Irrigation and Water Control,* **FAO, Rome, 1966, p, 16.**

The less expensive technologies—channeled, poldered, and water-lifting systems—have less potential for expansion, primarily because of environmental considerations, but all could be improved by technical assistance. Furthermore, these approaches can serve as first steps toward long-term intensification of food production. Access to markets for all these technologies would be an important incentive for users to incur the cash and labor costs of intensifying production (84).

Small-scale irrigation could make a particularly important contribution in Africa because it decreases farmer vulnerability to drought-induced crop failure by ensuring a more reliable water supply. However, increased costs and reliability of outside inputs have a strong bearing in defining the economic advantages of improved water supply schemes. Irrigation generally requires greater inputs of time, effort, and capital than rain-fed agriculture or livestock herding systems normally practiced in tropical Africa. Shortage of labor is cited as a major constraint to irrigation development in Africa, except in more densely populated areas where labor supply is readily available (84). Evaluating these sorts of considerations, as well as examining a range of water supply options that best accommodate local conditions, should precede efforts to extend irrigation technology.

Caution is also needed when introducing small-scale irrigation to minimize problems of social inequities that irrigation technologies can create (4). Even under the best of conditions, low-resource irrigation will be possible only at particular sites that represent a relatively small part of the cultivable land. Pressures, tensions, and competition may develop around these sites for access to land. Avoiding such conflicts may require that local and national governments address complex and difficult land tenure issues. The impact and contributions to women's economic activities should also be specifically considered.

Several factors have appeared in recent years to create a promising environment for the expansion of low-resource irrigation:

- African governments and development agencies are investing in it;
- the policy climate is becoming more favorable;
- production crises in many countries are motivating donors, host governments, nongovernmental organizations (NGOs), and local citizens to expand irrigation;
- the increasing priority of food self-sufficiency encourages expansion;
- the international research community has recently launched a series of research programs on it; and
- it is well-suited to diffusion through NGOs *(84)*.

Problems and Approaches

Much agreement exists among African governments and development agencies over the necessity of developing the irrigation sector. The nature of this development is less clear, however. Many African nations envision new, large-scale irrigation projects (62). Yet, these types of projects are proportionately more costly and are associated with numerous health, environmental, and social problems (62,77). A growing consensus places increased emphasis on small-scale projects. However, development assistance has not given high priority to these low-cost irrigation technologies (84). The chief reasons are their locale-specific applicability and requirements and the high cost of administering the project relative to the other project costs and economic benefits.

NGOs have an important role to play in the diffusion of low-resource irrigation technologies and can serve as intermediaries for AID and other large development agencies. NGOs are interested in, and well-suited to, assisting in the design and implementation of low-resource irrigation projects. Technical expertise varies greatly among NGOs, however, and many could benefit from technical assistance and support from the major development agencies (84).

The potential for expanding low-resource irrigation systems in Africa stems in large measure from the user's ability to retain independence and flexibility in operating them. Keeping the costs of developing, operating, and maintaining the systems low is essential in this regard. Further, expanding the potential of low-resource irrigation technologies should enable adaptations to meet a diversity of conditions. This may mean devoting as much attention to human resource development as to construction activities themselves.

Although small-scale irrigation is inexpensive locally, it will require significant levels of funding to reach its potential on a broad scale. The rough estimate provided by FAO for development of irrigation, large- and small-scale, calls for "US$475 million per year, or a total of $12 billion through year 2010, while incremental operating costs of irrigation would amount to an additional US$130 million" (77). Initiation of rural credit programs to underwrite individuals and groups to implement irrigation schemes is an important additional cost. Resources also will have to be allocated for research, training, extension, and policy support if small-scale irrigation is to have a large, beneficial impact.

Research

Some research is underway. For example, the Club du Sahel is launching a study to update its research of almost a decade ago on irrigation in the Sahel, and this will treat low-resource irrigation for the first time. Funding levels will determine how quickly these other important topics will be addressed:

- Farming Systems Research: To encourage wider adoption of low-resource irrigation technology, studies are needed of the role of irrigation in farming systems. Too often, studies are done on the management of irrigation systems, but not on the relation of this activity to other agricultural and non-farm activities. Such research could be a precondition for the design and implementation of an irrigation scheme. Farming system studies could catalog local resources, give a socioeconomic profile of beneficiaries, and evaluate their strategies for irrigation production in terms of risk aversion and long-term sustainability of production.
- Technical: More needs to be known about groundwater hydrology and surface water resources, including salinity levels and recharge rates. France's Office of Overseas Scientific and Technical Research (ORSTOM, by its French acronym) carried out a series of hydrological studies in the Chad portion of the Lake Chad basin in the late 1960s and early 1970s. The U.S. Coastal and Geodetic Survey performed similar research in the mid-1960s in the Nigerian part of the basin. But reliable hydrological data are unavailable for much of Africa. Extension of low-resource irrigation will have to be pursued cautiously in the absence of information on water supplies.

Training and Extension Services

Beyond the lack of knowledge and technical training in groundwater hydrology, the potential of irrigation technology suffers from a shortage of Africans trained in agricultural engineering, Villages, small groups, and private individuals without this expertise will find it difficult to obtain assistance in laying out efficient irrigation systems.

Training is also needed to help develop new or modified low-cost technologies to increase the performance of low-resource irrigation systems. For example, this could include ways to increase the efficiency of using the shaddouf, or low cost ways to reduce water infiltration in canals.

Researchers and funding also are needed to develop baseline data on the evolution of these technologies and to estimate their potential with increased confidence.

Most African extension services are poorly prepared to mobilize local groups to design, build, operate, and maintain low-resource irrigation schemes. Extension personnel, in general, have not been trained to see low-resource irrigation as a system with complex relations to other aspects of socioeconomic life. For example, extension staff commonly have narrow, technical backgrounds and may not be trained in community organization. Yet, in principle, extension services would be the key link between irrigation planners and organized groups of beneficiaries.

Policy Reform

Several areas of government policy, in particular, tax policy, land tenure issues, and decisions on private versus parastatal control, have major effects on irrigation. Issues for African governments include:

- Ensuring that inputs needed to foster irrigation and agricultural intensification are not so heavily taxed that they become unaffordable. Many African governments now are concluding that it is counterproductive to heavily tax imports that support food production. However, many need support in analyzing their tax policy for its effects on the extension of low-resource irrigation.
- Problems of land title and tenure can be serious constraints inhibiting the growth of small-scale irrigation (84). Without secure land tenure, farmers are unwilling to make necessary investments to develop and maintain irrigation systems. Changes in land tenure regimes, however, should account for those shifting cultivators and pastoralists dependent on traditional or communal systems of property rights. Similarly, provisions could be made to discourage land speculation that displaces poor farmers or herders in the wake of increasing land values resulting from irrigation projects,
- Improving the efficiency of many parastatal organizations or backing privatization efforts to transfer control from parastatal organizations to local organizations and other users. Many low-resource systems in Niger, Mali, Sudan, and elsewhere are excellent candidates for privatization (84).

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