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IMPROVING PRODUCTIVITY IN SORGHUM AND PEARL MILLET IN SEMI-ARID AFRICA†

The slow and irregular growth of sorghum and millet production in West Africa during the last 25 years has been reported in many recent reviews (USDA, 1981; Paulino, 1987; FAO, 1986). Buffeted by climatic shocks, total output has fluctuated widely between years and on trend has grown nearly 1 percent less than population per year. Modest production increases have resulted primarily from expansion of cropped area; average yields per unit area of sorghum and millet actually declined during the period. Modern technical change, with few limited exceptions, has been negligible.

These patterns describe a relatively inelastic and stationary long-term aggregate supply curve for coarse grains in the region. Reversing these trends would require continuing shifts in the supply curve brought about by declining unit costs of production. Unit production costs can be reduced through declining real costs of the major factors of production and through technical change whereby physical input/output ratios improve.

The objective of this paper is to consider the prospects for improving

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the productivity of sorghum and pearl millet cultivation in the West African semi-arid tropics with an examination of likely changes in each of these two relationships. The paper begins with a brief review of recent production trends and sources of past growth. This is followed by a description of the physical context of agriculture in the West African semi-arid tropics, and an evaluation of demographic change is destabilizing production systems in areas where population pressure has already reached relatively high levels. Past trends in factor costs and probable future changes are considered in the cost of land, labor, and fertilizer. The paper then assesses promising directions for technical change at the farm level in the short and long run. It not only considers the products of on-going and future research, but the research process and orientation as well. The paper ends with a synthesis and summary of implications drawn from the analysis.

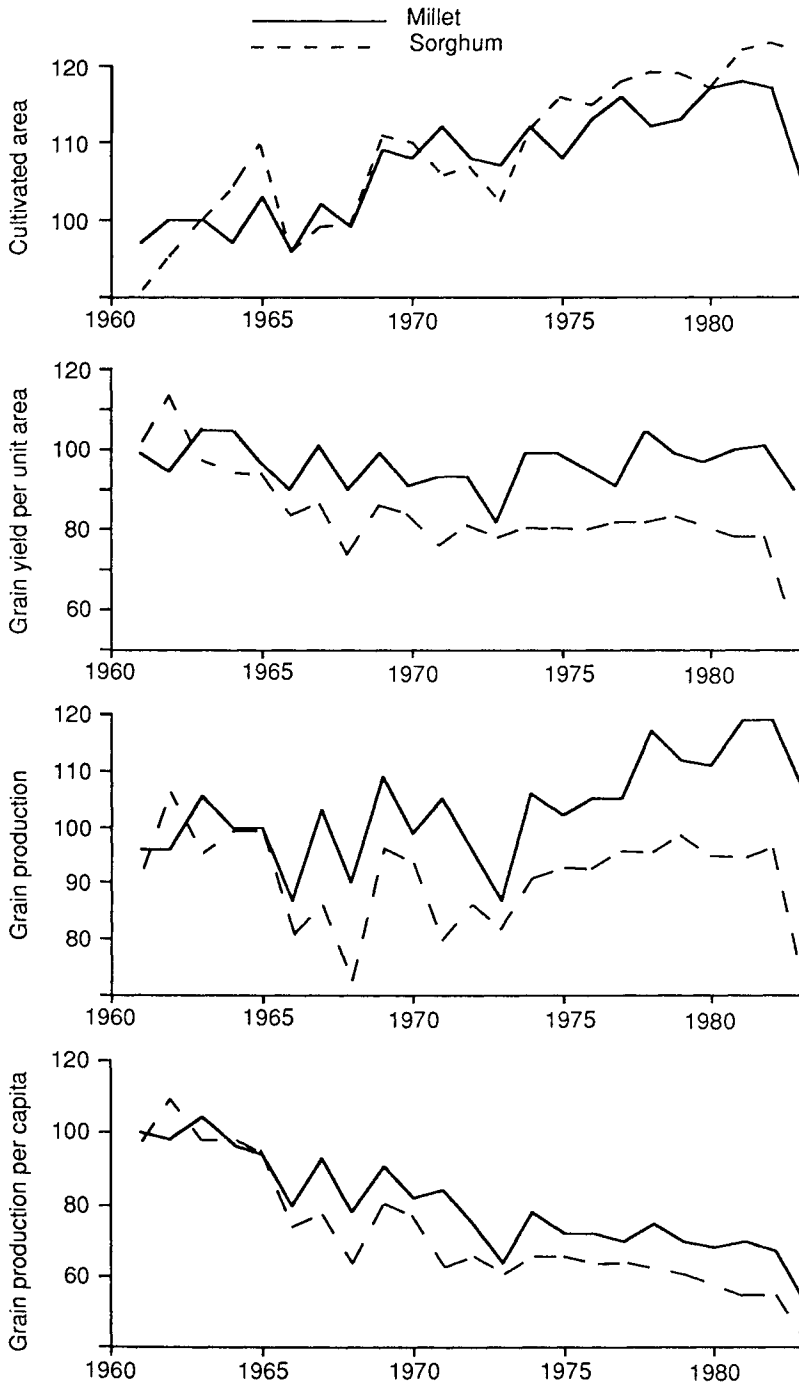
PRODUCTION TRENDS

An examination of past trends provides a useful starting point from which to assess future production outcomes. Statistics on crop production and productivity in West Africa are generally poor. But while it would be unwise to insist on the precision of annual figures for particular countries, somewhat greater confidence can be placed on broad regional trends that cut across national statistics sets. Such data clearly reflect the dismal performance of coarse grains production during the last 25 years (Chart 1). Total production has displayed wide interannual variation that closely mirrors annual rainfall patterns. Particularly large shocks were experienced during 1972 and 1973 and again in 1983 and 1984 when rainfall in the Sahelian states fell more than 35 percent below average long-term levels. Millet production grew at an average annual compound rate of nearly 1 percent since 1961, and sorghum production has remained essentially stagnant, with some estimates actually showing a trend decline in production.

Cultivated area for both crops has grown more steadily, at a moderate 1 percent annual rate, with population growth serving as the principal determinant of area expansion. Paulino (1987) estimates that population in West Africa grew at an average annual rate of 2.7 percent during the period 1961–70 and accelerated to 3.1 percent between 1971–80.

The most unsettling trend is that for yields per unit area. The available data suggest that since 1961 land productivity may have fallen at an average annual rate of 1.5 percent for sorghum and appears to have remained nearly unchanged for millet. Poor yield performance has been due to several factors. A chronic pattern of lower rainfall in the West African semi-arid tropics beginning in the late 1960s was closely reflected in depressed yields. In addition, demographic pressure has induced farmers to increase cultivated area by reducing fallow periods and expanding new cul-

Chart 1.—Index of Area, Yield, Production, and Production Per Capita for Sorghum and Millet in 13 Countries of West Africa, 1960–83
(1961–65 = 100; in percent)



tivation onto soil types that often have lower natural production potential. Finally, use of non-labor inputs on sorghum and millet has not grown fast enough to offset this declining potential, nor to arrest secular degradation of the land base that is occurring in the most densely populated areas, such as in the closely settled zones of northern Nigeria and in the Mossi Plateau region of Burkina Faso.

FACTORS AFFECTING PRODUCTION POTENTIAL

Cultivation of sorghum and millet is concentrated in the semi-arid sub-region of West Africa. The semi-arid tropics are conventionally defined as those areas where precipitation exceeds evapotranspiration from two to seven months annually. This corresponds to mean annual rainfall ranging between roughly 250 to 1300 millimeters (mm). The area includes all of Senegal, the Gambia, Burkina Faso, and Cape Verde; major southern portions of Mauritania, Mali, and Niger; and the northern portions of Ivory Coast, Ghana, Togo, Benin, and Nigeria.

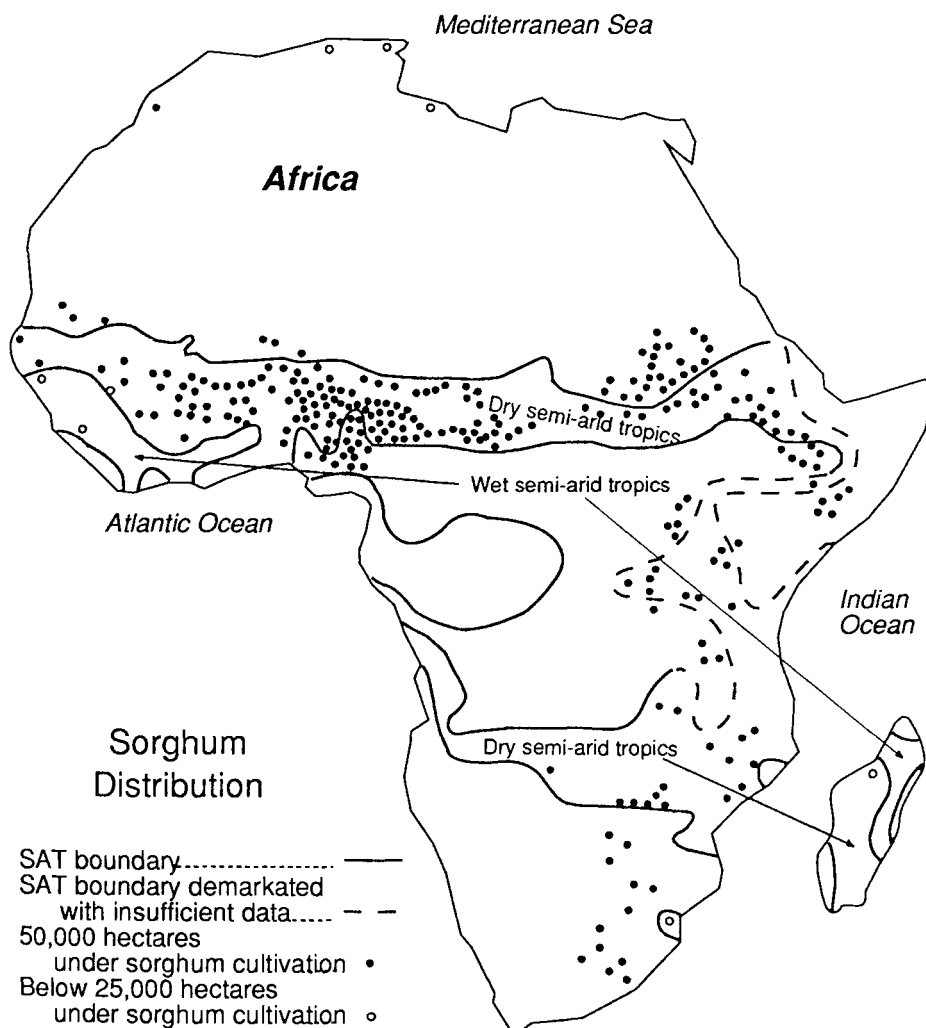
Cereals occupy nearly 70 percent of total cultivated area of this sub-region, absorbing between 50 and 80 percent of total farm-level resources. Sorghum and millet cultivation account for approximately four-fifths of total cereal production (Matlon, 1987). Maps 1 and 2 indicate how production is distributed across the countries of the sub-region.

Within the semi-arid region of West Africa one can distinguish a set of highly diverse physical environments, each with its particular production potential, constraints, and requirements for technical change. Settlement patterns and markets overlaid on these zones further determine the types of technical change that are economically feasible. This section briefly considers characteristics of the climate and soils, and reviews evidence documenting the transition from extensive to intensive cropping systems and its consequences for technical change.

Climate

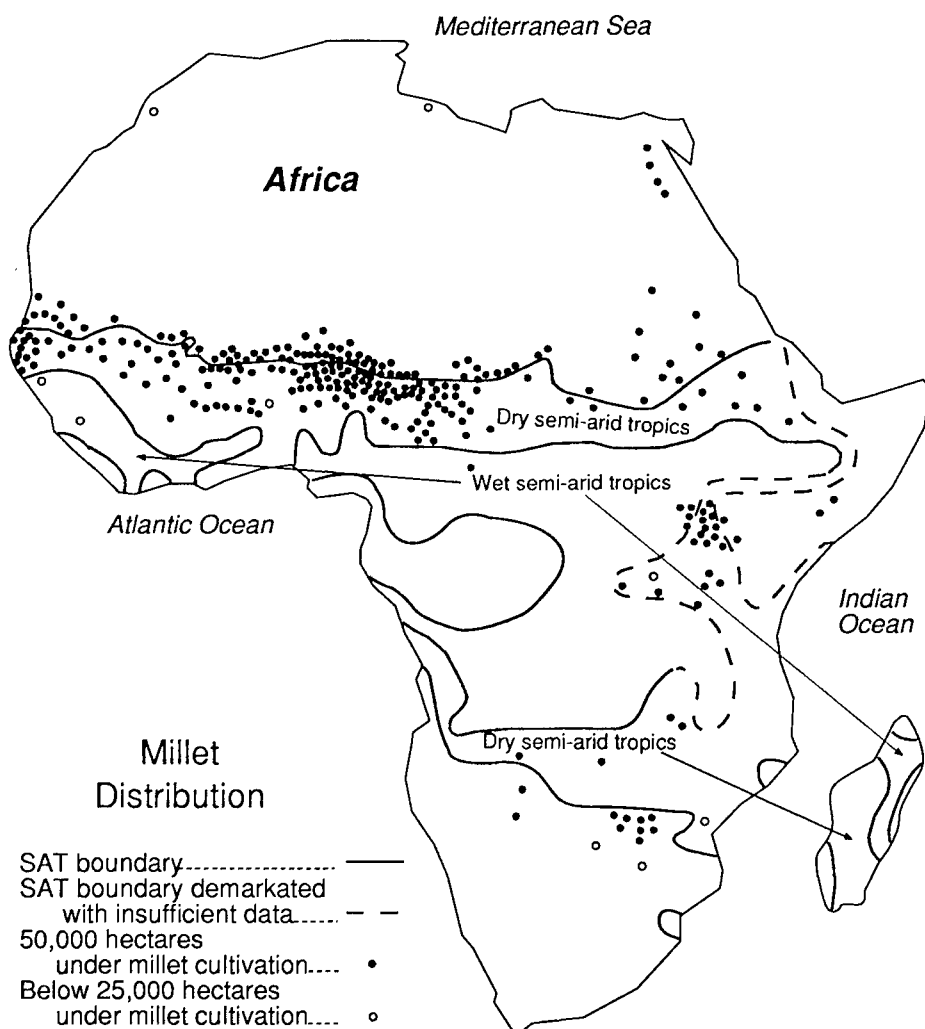
At least four climatic zones can be distinguished within the West African semi-arid tropics, which lie in roughly parallel belts running east to west across the region (see Maps 1 and 2). The major rainfall parameters and a summary of soil suitability for these zones are presented in Table 1. Climatic constraints are more limiting in the Sahel and decline in importance in the Sudanian and Sudano-Guinean zones. These constraints include: a short uni-modal rainy season; high intra-seasonal rainfall variability with risk of periodic drought greatest during critical early stages of crop growth; high evaporative demands that peak at the beginning and end of the rainy period which further increases the risk of drought stress during planting and grain-filling stages; and high rainfall intensity, which

Map 1.—The Distribution of Sorghum Cultivation in Africa



Source: Data are from distribution maps of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India.

Map 2.—The Distribution of Millet Cultivation in Africa



Source: Data are from distribution maps of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India.

can cause run-off losses of as much as 60–80 percent of precipitation and which contributes to considerable risk of top soil loss through erosion.

Table 1.—Land and Population Characteristics of the Major Agroclimatic Zones in the West African Semi-Arid Tropics

	Sahelian	Sahelo-Sudanian	Sudanian	Sudano-Guinean
Annual rainfall ^a (mm)	<350	350–600	600–800	800–1100
Total area (percent)	24	30	21	24
Cultivable soils (percent)	29	30	37	42
Population (percent)				
Rural	18	20	56	6
Total	16	19	59	6
Rural population density (persons/km ²)				
Cultivable	24	67	51	21
Total	7	20	19	9

Source: World Bank, 1985, *Desertification in the Sahelian and Sudanian Zones of West Africa*, Washington, D.C.

^a0.9 probability isohyets.

Soils

The old and highly weathered soils of semi-arid West Africa reinforce the climatic constraints. The loamy sands of the Sahel zone and sandy loams of the Sudanian and Sudano-Guinean zones tend to be naturally low in phosphorous and nitrogen. Due to low percentages of clay and organic matter, the soils are also structurally inert, tend to cap (restricting water infiltration), and are susceptible to compaction which, when combined with their generally shallow depth, results in low water-holding capacity and poor fertilizer use efficiency. The most common soil types are also fragile, subject to high risk of acidification, aluminum toxicity, and erosion under continuous cultivation.

Environmental parameters in the different zones of the West African semi-arid tropics vary systematically around this stylized agroclimatic description. Moreover, because the climatic and edaphic constraints tend to be roughly correlated, there is considerably greater technical potential for bio-mass production in the southern zones. This fact carries important implications for developing efficient strategies for both agricultural research and development, as seen in a later section.

Farming Systems

Over time, West African farmers have developed production systems to sustain production at subsistence levels in these harsh conditions. This sustainability, however, is coming under increasing pressure and is now threatened in many areas.

Traditional farming systems in the West African semi-arid tropics reflect a logical response to the region's low and variable rainfall, poor and fragile soils, and historic land surpluses. Because ample land resources, combined with customary usufruct tenure, provided little incentive for investing in soil improvement, long bush-fallow rotations were the principal means of maintaining soil quality in a low-level but sustainable equilibrium. Limited markets also encouraged a subsistence and risk-avoidance orientation in family-based production units and, as a result, there was little demand for non-labor inputs. Small quantities of organic fertilizers were applied, typically concentrated around dwelling points. Farmers developed an array of intercropping systems that integrated both cereals and legumes to make most efficient use of peak period labor, the most binding production constraint, as well as to diversify output and reduce risk.

While most farmers in the sub-region continue these management practices, population growth and market penetration during the last several decades have begun to destabilize these traditional crop and land management systems. Demographic pressures have forced a reduction in fallow periods below equilibrium levels in rapidly expanding areas, and cultivation is being continuously extended onto more fragile and less productive soils. Growing rural markets for consumer goods and outlets for production have further accelerated these trends.

These exogenous impacts on traditional farming systems are relatively recent and have impacted rapidly. In part because their effects have been masked by nearly 20 years of drought, most farmers have not adequately diagnosed the emerging imbalances and have been unable to develop new and more appropriate systems through a reallocation of their available on-farm resources. Consequently, low-input management continues despite increasing cropping intensities.

These patterns underlie the region's stagnant grain yields and general decline in aggregate food output per capita. A more ominous long-term result—already evident in areas experiencing the most rapid increases in population—is the steady degradation of the land, which points toward further declines in production potential in the future.

Changing Factor Endowments and the Emerging Disequilibrium

World Bank researchers have concluded that by the mid-1980s vast areas in semi-arid West Africa were already overpopulated in relation to the

sustainable production potential of the land base (World Bank, 1985). Attempting to evaluate the magnitude and location of resource imbalances according to agroclimatic zones, they found that the imbalance was most critical and the greatest environmental damage was occurring in the Sudano-Sahelian zone despite an average population density of only 20 persons per square kilometer in 1980 (Table 2). These conclusions are largely consistent with a growing body of location-specific observations that provides empirical evidence of severe environmental degradation in the 300-600 mm rainfall belt (UNEP, 1984; Walsh, 1984; FAO, 1986; World Bank, 1985). Their results also underline the generally low correlation between agroclimatic production potential and regional settlement patterns, as considerable surplus-carrying capacity exists in the more productive Sudano-Guinean zone where average population densities are estimated to be only 9 persons per square kilometer.

Table 2.—Sustainable and Actual Population Densities
in the Major Agroclimatic Zones of West Africa
(Persons per square kilometer)

	Sahelian	Sahelo- Sudanian	Sudanian	Sudano- Guinean
Sustainable population ^a				
Crops	5	10	15	25
Livestock	2	5	7	10
Total	7	15	22	35
1980 rural population	7	20	19	9
Ratio	1.00	1.33	0.77	0.26
Sustainable population				
Fuelwood	1	10	20	20
1980 total population	7	23	21	10
Ratio	7.00	2.30	1.05	0.50

Source: World Bank, 1985, *Desertification in the Sahelian and Sudanian Zones of West Africa*, Washington, D.C.

^aBased on traditional crop and livestock systems.

These results carry four important implications. First, the low zonal correlation between current population densities and agroclimatic production potential implies that a reallocation of rural populations through inter-zonal migration could bring about an aggregate increase in production. This indeed is already occurring informally through the north to south migration of rural populations both within and across country borders. Strategies to formalize and accelerate such population movements, however, deserve only cautious consideration as a means of shifting the regional supply

curve for coarse grains. Socio-political and economic considerations impose strict limits to the volume of migration in a region fractured by state and less formal ethnic group boundaries. Moreover, the production increases once achieved, would be once-and-for-all unless farming systems in higher potential receiving areas were radically improved to assure a process of sustainable intensification. Development projects, such as the *Amenagement des Vallées Voltas* (AVV) in Burkina Faso, that were established in areas freed from onchocerciasis, have found that efforts to induce immigrants out of high density areas to increase their farming intensity in lower density receiving areas were too costly and required coercive methods that were both administratively and politically untenable.

Second, these results dramatically challenge a frequently encountered assumption that semi-arid West Africa is a land-surplus region and that major and sustained increases in future supply can still be achieved by area expansion. The land-surplus assumption is often implicit in much of the mechanization literature. Although this remains true for some countries and sub-regions, most notably for large portions of the Sudano-Guinean zone, on an aggregate level this no longer holds.

The error lies in examining only raw population to land ratios, without considering how the productive potential of the land varies across countries and regions. Binswanger and Pingali (1986) have demonstrated that due to agroclimatic and soil-related differences in land potential, it is inappropriate to compare land endowments across countries according to the simple measure of arable land per capita. They divided total country population figures in 1980 and population estimates for the year 2025 by the Food and Agriculture Organization (FAO) estimates of potential calorie production at intermediate input levels (Higgins, Kassam, and Naiken, 1982) to arrive at a standardized "agroclimatic population density." Their results, which compare African countries with several Asian and Latin American countries generally considered to be densely populated, are striking. Because of the extremely poor quality of its natural resources, Niger is the most densely populated country examined, ranking well ahead of both Bangladesh and India. Nigeria and Senegal are both listed ahead of the Philippines. And Mali, Burkina Faso, and Gambia are all nearly twice as densely populated as Indonesia.

Third, if current farming practices persist, in the Sahelo-Sudanian and Sudanian zones, where 84 percent of the rural population of the Sahelian states live, crop production potential, already low, will decline further (Higgins, Kassam, and Naiken, 1982). This will be caused by the mining of nutrients from soils already chemically poor, and by the loss of organic matter and topsoil through erosion due to continuous cultivation and an increasingly denuded landscape (see later section). Rising rates of population growth and growing urban food demands will only accelerate the decline.

In short, demographic and ecological factors will provide continuing pressure to increase unit costs of production for coarse grains in much of the sub-region for the foreseeable future.

Fourth, unless there are radical changes in the structure of economic activities in the region, technical change in the agricultural sector is essential to arrest and reverse these otherwise negative trends. We briefly consider likely changes in factor costs that will affect the economic feasibility of current promising technologies and evaluate their potential to improve resource productivity in this dynamic context.

TRENDS IN FACTOR COSTS

Changes in factor prices affect per unit production costs of sorghum and millet directly by influencing the absolute value of the denominator in that ratio, and indirectly, by affecting incentives to adopt new production techniques that change the nature of the input mix as well as the physical input/output ratio. The major factors influencing changes in sorghum and millet production during the next two decades will be labor, land, and fertilizer. By examining past trends in costs for each of these factors and by assessing the most likely major changes in the parameters underlying their supply and demand, probable directions of relative factor cost movements can be determined.

Agricultural Wages

The principal determinants of the supply of agricultural labor are the rate of population growth, the overall labor force participation rate, and the share of the labor force in agriculture (which is a function of the competing demand for labor in other sectors). Principal demand side factors are the demand for labor in the urban industrial sector as well as in coastal countries, and factor biases embodied in new agricultural technologies.

Available data suggest that the farm labor force in the West African semi-arid tropics has grown at nearly 2 percent annually since 1960, and most observers project a continued rapid expansion during the next 25 years. Rising rates of natural growth, a major share of the work force in the agricultural sector, and very high rural labor force participation rates (associated with the small family-farm production structure) underline these projections. Table 3 shows that annual growth rates for the general population and the labor force have increased during the last two decades and are projected to rise even further by the end of the century. Although the shares of the farm labor force have declined slightly, they remain high, generally at or above 70 percent. This means that only very rapid growth in the non-agricultural labor force can reduce the absolute size of the population employed in agriculture.

Table 3.—Past and Projected Trends for Populations and Labor Forces
in Selected West African Countries
(Percent)

	Average annual population growth rates			Average annual labor force growth rates			Percent labor force in agriculture		Average annual urban growth rates	
	1965-73	1973-84	1980-2000	1965-73	1973-84	1980-2000	1965	1980	1965-73	1973-84
Burkina Faso	2.0	1.8	2.0	1.6	1.4	1.7	89	87	6.5	4.8
Chad	1.9	2.1	2.5	1.6	2.3	2.3	92	83	6.9	6.5
Mali	2.6	2.6	2.6	2.2	1.9	2.4	90	86	5.4	4.5
Mauritania	2.3	2.1	2.7	1.9	2.3	2.1	90	69	16.0	5.1
Niger	2.3	3.0	3.2	2.1	2.8	3.0	95	91	7.0	7.1
Nigeria	2.5	2.8	3.4	1.7	2.0	3.1	72	68	4.7	5.2
Senegal	2.4	2.8	2.9	1.7	2.2	2.4	83	81	4.2	3.8

Source: World Bank, 1985, *Desertification in the Sahelian and Sudanian Zones of West Africa*, Washington, D.C.

A numerical example illustrates these relationships (Binswanger and Pingali, 1986):

If 70 percent of the labor force is still in agriculture, and the total labor force is growing at 2 percent per annum, the non-agricultural labor force would have to grow at 6.6 percent per annum merely to keep the absolute number of workers in agriculture constant. To reduce the agricultural labor force by even 1 percent per annum, the non-agricultural labor force would need to grow at an extremely rapid 11.3 percent per annum.

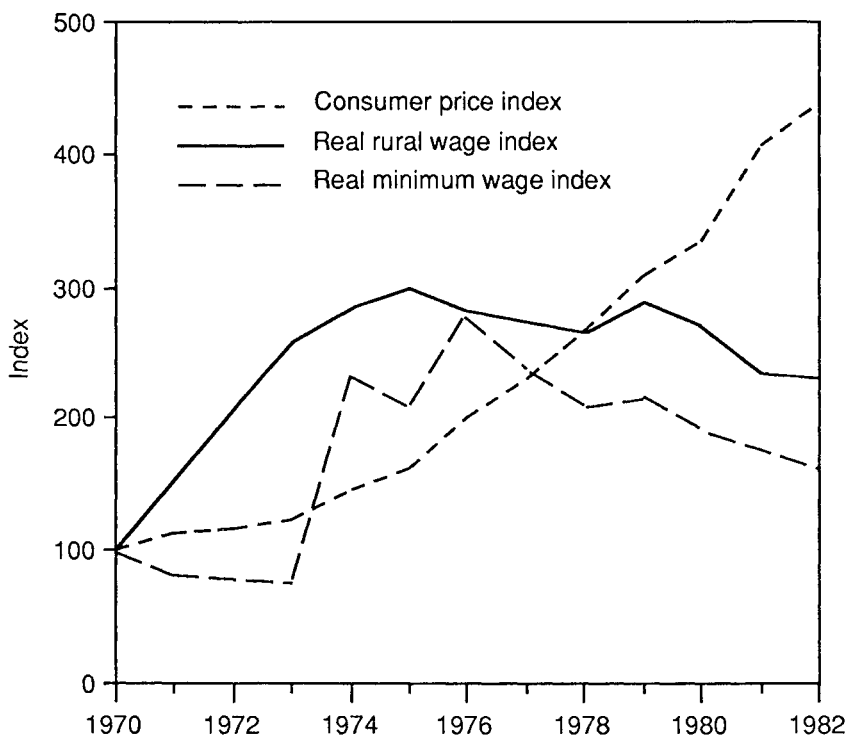
Such a structural transformation is unlikely to occur in semi-arid West Africa before the year 2025. Labor force growth rates generally exceed 2 percent and are rising, and rates of urbanization (a crude proxy for growth of the non-agricultural labor force) are generally less than 5.5 percent and falling for five of the seven semi-arid tropics countries examined.

Rapid growth in the rural labor force combined with a fixed land base and near stagnant technology have created powerful downward pressures on rural wages in most countries of the region. Information on rural wages in West Africa are notoriously poor due to thin labor markets, wide seasonal and inter-regional differences, and the lack of systematic data collection. As a result, to infer trends from the spotty data points collected over time would be unwarranted for most countries. Oyejide (1986) provides perhaps the best trend estimates for Nigeria that may not be unrepresentative of conditions elsewhere in the region (at least since 1975 following the initial wage impacts of the oil boom) (Chart 2). His data show rapidly rising nominal, but steadily declining real rural wages.

Barring profound changes in technology or macroeconomic policies to increase real returns in agriculture while simultaneously stimulating more rapid demand for labor in the urban sectors, rural labor markets will remain under considerable pressure to absorb new entrants. In short, most probable conditions suggest that real wages are likely to decline further.

Binswanger and Pingali place these forces into an interesting international perspective. Taking into consideration likely demographic changes as well as growth in the non-agricultural labor force, they projected residual growth in the agricultural labor force through the year 2025 for several African and Asian countries. Labor force figures were then expressed relative to the production potential of the arable land base in each country assuming uniform technological change to intermediate input production systems (see earlier section). Their results, shown for the seven major sorghum- and millet-producing countries of West Africa in Chart 3, indicate that agricultural labor density for five of these countries will exceed the level of India over the projection period.

Chart 2.—Index of Real Minimum and Real Rural Wage Rates and Consumer Price Index for Nigeria, 1970–82



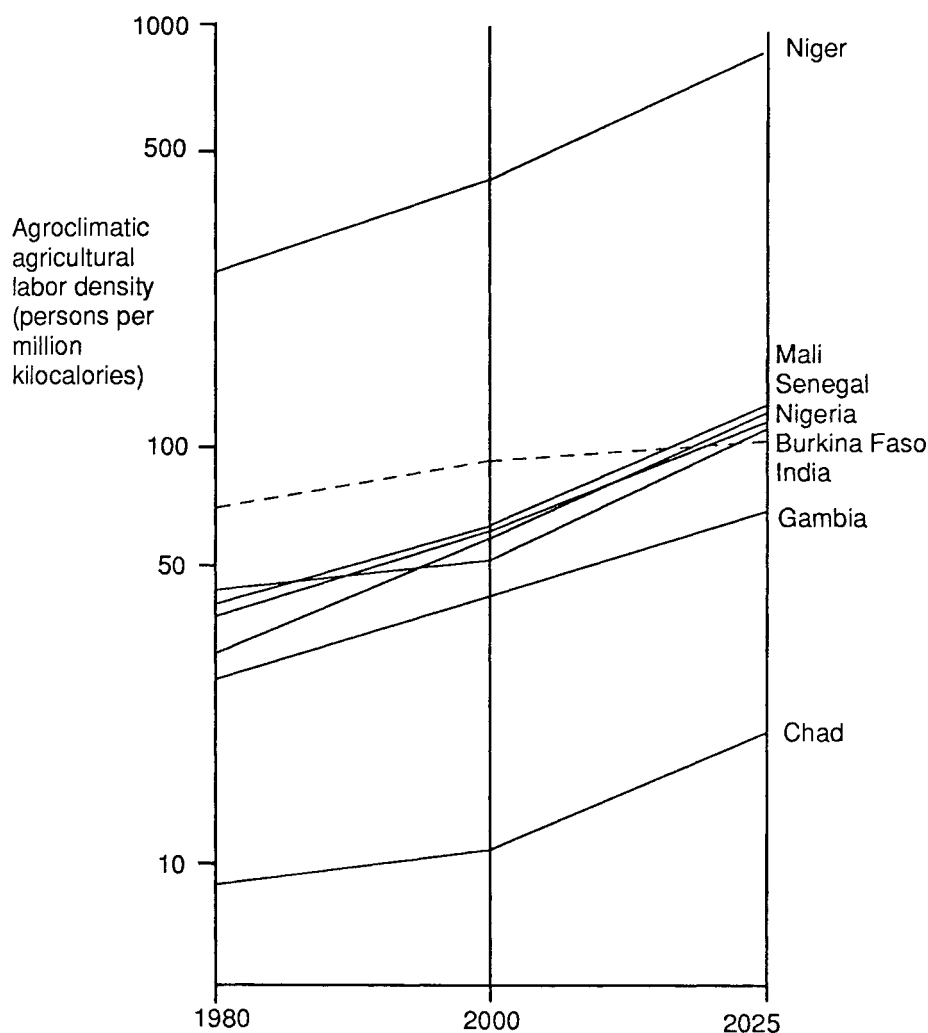
Source: T. Ademola Oyejide, 1986, *The Effects of Trade and Exchange Rate Policies on Agriculture in Nigeria*, International Food Policy Research Institute, Washington, D.C.

Land Costs

The effects of increasing labor force density on land costs are clear. As land becomes more scarce its relative value in production increases. Parallel institutional changes also occur as the transition from former communal systems of usufruct to various forms of private control and ownership will be completed over widening areas. And as the value of land increases, rising costs are increasingly reflected as monetized rents and sale prices. The development of output markets and expansion of cash cropping add further impetus to the transformation of land tenure systems.

These changes have already occurred unevenly in various portions of the West African semi-arid tropics. Over most areas of the semi-arid tropics a variety of use-right systems still prevail that give kin groups and occasionally individual farm families a not insignificant degree of security in

Chart 3.—Trends in Agricultural Labor Density for Seven West African Countries and India, 1980–2025



Source: Hans P. Binswanger and Prabhu L. Pingali, 1986, *Resource Endowments, Farming Systems and Technology Priorities for Sub-Saharan Africa*, Agriculture and Rural Development Department, World Bank, Washington, D.C.

land use decisions (Feder and Noronha, 1987; Matlon, 1989). In closely settled portions of Northern Nigeria monetized land markets, rent charges approaching marginal value products, and even the use of land as collateral in credit markets were reported decades ago. And, in densely populated portions of the Mossi Plateau in Burkina Faso, these patterns are emerging on the fringes of large towns and cities.

Driven by a rapidly growing farm labor force, these trends provide two necessary incentives for the development of more input-intensive production systems. First, as land costs increase relative to costs of other factors, the land-saving benefits to yield-increasing technologies make variable input use and land improvement investments more profitable. Second, the evolution to privatized land tenure can reinforce these incentives by insuring greater tenure security, a necessary precondition for major investment in land improvements.

Fertilizer Costs

Fertilizer, particularly in combination with input-responsive improved cultivars, is generally the most common element of land-saving or yield-increasing technologies. In the past, however, low technical response, poor infrastructure and high fertilizer prices have kept fertilizer use in the West African semi-arid tropics among the lowest levels the world. At least the latter trend is likely to continue.

Among the seven Sahel countries (excluding Cap Vert), 74 percent of all chemical fertilizer consumed in 1983/84 was imported (FAO, 1985). If one includes Nigeria, this share rises to 94 percent. Moreover, with the possible exception of phosphorous-based fertilizers, for which important deposits are located in nine West African countries, there is little prospect for substantially decreasing that share in the medium term (McClellan and Notholt, 1986). This means that foreign exchange costs and transport costs to the largely landlocked countries of the semi-arid tropics will remain high. Although investments in rural road construction may reduce transport costs somewhat, the low density of rural populations means that delivery and extension costs per kilogram of fertilizer will remain high compared, for example, to Asian conditions.

The high import share also means that the region will remain vulnerable to world price movements. An examination of past trends in world fertilizer prices shows that with the exception of several discrete and generally temporary price shocks (for example, 1974), constant prices for the most common forms of nitrogen, phosphorus, and potassium fertilizers show an uneven but perceptible trend decline between 1962 and 1987 (Bumb, 1989). However, the available data do not allow one to confidently project a continuation of these trends well into the future. Medium-term projections recently made by International Fertilizer Development Center (IFDC) sug-

gest that global fertilizer markets will tighten slightly through 1995, placing moderate upward pressure on real fertilizer costs (Bumb, 1989). Global deficits between projected supplies and demand are most likely to emerge for urea and phosphate, with a declining surplus projected for potash over the period.

Despite a significant increase in fertilizer production capacity, Sub-Saharan Africa will remain a major deficit region for each fertilizer well into the future. Between 1987 and 1995, IFDC projects that the regional deficit for Sub-Saharan Africa will decline for urea, but increase sharply for both phosphate and potash. Combined with information on projected global price trends, it is reasonable to expect moderately rising real fertilizer prices in West Africa over the medium-term. As important, however, is the issue of availability. Due to generalized foreign exchange shortages, it is likely that fertilizer supplies in Africa generally, and in West Africa in particular, will depend in part on donor assistance thus adding to this sector's uncertainty.

TECHNOLOGY OPTIONS FOR INCREASING COARSE GRAINS PRODUCTION

A characteristic of the recent literature on African agriculture is the often polemic debate as to the merits of current on-shelf technologies. Two schools of thought, the technological optimists and pessimists, emerge. But both tend to rely on limited evidence (for example, experiment station results or on-farm adoption "failures"), to employ partial and static conceptual frameworks that fail to fully consider the natural diversity of the West African semi-arid tropics and the transition they are experiencing, and to either over- or underestimate the capacity of both support services and farmers to respond to new technical opportunities. A more holistic, dynamic, and ultimately more balanced approach is obviously necessary.

This section attempts such an approach through a brief assessment of the major groups of production technologies. It highlights the extent of past technical change at the farm level, factors constraining adoption, the current and future scope for adoption, potential leverage on production by agroclimatic region, and probable effects on the long-term production potential of the resource base.

Technologies can be classified in many ways depending upon one's analytical objectives. For present purposes, they are grouped according to their primary impacts into four sets: (1) high-input yield-increasing technologies; (2) yield-stabilizing technologies; (3) labor-saving technologies; and (4) land-conserving and enhancing technologies.¹ Although these sets

¹ This approach has benefited, but is distinct, from a similar typology developed by Binswanger and Pingali (1986).

are not necessarily exclusive—a particular intervention may have multiple characteristics and impacts—the typology remains useful to identify the major strategies for technological change and to assess their fit with diverse environments and needs as identified in the preceding sections.

High-input, Yield-increasing Technologies

This set includes technologies that involve increased use of variable inputs to reduce the amount of land needed to produce a given output. Variable inputs can include purchased or recycled inputs such as chemical fertilizer, improved seeds, and manure, or additional labor used in precision planting and more intensive cultivation. Net benefits to yield-increasing technologies are directly related to the cost of land saved, and inversely related to the opportunity cost of the additional capital or labor employed.

Technologies in this set are economically suited to factor environments where: (1) land is scarce and preferably valued in monetary terms; (2) cash or credit is not a binding constraint, due either to major cash-cropping activities or income generated off-farm; and (3) labor during the periods of additional use is not constraining. Furthermore, biochemical components of yield increasing technologies achieve maximum technical efficiency when planting densities can be safely increased above levels typical of low-input systems. This can be done without significantly increasing yield variability and farmer risk only when adequate soil moisture is maintained during critical crop growth periods and when fertilizer is not lost to the system through run-off or deep percolation. When these economic and agroclimatic conditions overlap, the environment is well suited to most high-input, yield-increasing interventions.

Before examining this technology set in detail, it is helpful to establish the approximate magnitudes of yield gains that experimental results from the region indicate are technically feasible. Table 4 summarizes typical sorghum yields for various management treatments as observed in research station trials and on-farm tests conducted in the Sudanian zone. Comparable yield ranges would be somewhat lower in the Sahel and Sahelo-Sudanian zones, and higher in the Sudano-Guinean zone. Typical yields for millet would be 10 to 20 percent lower.

Though the precision of these yield figures should be treated with caution, it is clear that existing techniques can increase grain yields per unit area substantially. The issue then is not technical yield potential, but whether these high input-using techniques in fact reduce unit production costs when farmers' factor endowments and opportunity costs are properly considered. A brief review of the major components of yield-increasing technologies suggests why instead unit costs often increase when these techniques are applied at high levels, and why the scope for adoption remains relatively narrow.

Table 4.—Technology Packages and Sorghum Grain Yields
Including Components of Improved Management
in the Sudanian Zone of West Africa
(*Kilograms/hectare*)

Improved management component	Grain yield
None	500–700
Variety	400–800
Plowing	600–950
Fertilizer	700–1200
Plowing, fertilizer	900–1500
Plowing, fertilizer, tied ridges	1000–2000
Variety, plowing, fertilizer, tied ridges	1500–3000
Plowing, fertilizer, irrigation	2000–3500
Variety, plowing, fertilizer, irrigation	3000–4500

*These approximate yield ranges are estimated from a variety of research station trials and on-farm tests conducted in Burkina Faso during 1980–86 and should be treated only as illustrating rough orders of magnitude.

Irrigation.—Large scale irrigation was a necessary precondition for the seed-fertilizer intensification strategy that has dramatically reduced unit costs of producing rice and wheat in many areas of the world. By assuring adequate soil moisture, irrigation allows planting densities and fertilizer doses to be increased efficiently without increasing farmers' risk.

Although several studies suggest that technical factors would permit a ten-fold expansion of irrigated area in the eight Sahelian states where the need for water control is greatest, nearly all economic analyses are far less sanguine (USDA, 1981; CILSS, 1980; FAO, 1983). Investment costs range from \$5000 to \$20,000 per hectare, or on average more than four times those in typical Asian conditions (World Bank, 1981; CILSS, 1980). Deep and poorly recharged aquifers, highly seasonal water flows, flat topography, and high import content of both materials and technical assistance contribute to these high costs.

On the benefit side, potential yields are rarely achieved due to poor water control, the absence of double cropping, inappropriate technical packages, and the lack of complementary inputs. Potential savings in land costs due to increased yields also tend to be negligible due to the low opportunity

cost of land in areas of low population density where most schemes have the greatest technical potential. Finally, problems in management and maintenance systems have driven large portions of existing perimeters out of production. According to some observers, more than 11 percent of current irrigated area in the eight Sahelian states require major rehabilitation or reconstruction (CILSS, 1980). In short, nearly all modern large-scale irrigation schemes in West Africa have not reduced unit costs of production, but instead have generally increased production costs substantially.

Many observers report considerably greater potential for smaller scale irrigation (WARDA, 1989; Eicher and Baker, 1982; Lallement, 1986; OTA, 1986). However, such perimeters would be more efficiently sown to rice or maize, and, where market opportunities exist, to higher value crops such as vegetables. As a result, it is unlikely that sorghum and millet production will be importantly improved even by small scale techniques in the foreseeable future. Rather, their production may actually be depressed with such developments as labor is drawn away from rainfed sorghum and millet production into more profitable cash-oriented irrigation activities.

Fertilizer.—Deficiencies in phosphorous and nitrogen pose major constraints to increased sorghum and millet production on most soil types in the West African semi-arid tropics. These deficiencies together with the region's historically low consumption of chemical fertilizers suggest considerable potential for a rapid expansion. Fertilizer consumption per hectare in the region has in fact grown at an annual rate of nearly 20 percent since the early 1960s but from an extremely low base.² Moreover, with the exception of Niger, most fertilizer is applied to cotton, groundnuts, maize, and rice rather than to sorghum and millet (Mudahar, 1986).

Constraints to further increases of chemical fertilizer use on sorghum and millet are both economic and technical in nature. Likely increases in world fertilizer prices, considered in an earlier section, will dampen potential demand somewhat. On the other hand, government reforms related to structural adjustment policies, in particular the reduction of fertilizer subsidies, are likely to increase aggregate fertilizer consumption by relaxing state fiscal constraints thereby permitting larger total imports (McIntire, 1986). The presence of black market prices in countries where fertilizer is subsidized confirms this expectation.

But while total fertilizer supplies are likely to increase with lower subsidies, fertilizer consumption patterns by agroclimatic zone and by crop are likely to be substantially modified with particularly adverse effects on millet production, and to a somewhat lesser extent, on sorghum. As prices paid

² In 1975, for example, the average quantity of nutrients applied to food crops among the Sahel states was 1 kg/ha, compared to 1.4 kg/ha for all of West Africa; 3.1 for East Africa; 29 for North Africa and the Middle East; 23 for Asia; and 33 for Latin America (Matlon, 1987).

by farmers rise, economic incentives to use fertilizer will be eliminated first in lower rainfall areas and for crops with lower technical response rates.

Typical response rates for the most common food grains, as measured by the yield increment per kilogram of NPK nutrient at moderate fertilizer levels, are shown in Table 5. Rice is most responsive, followed by maize, sorghum, and then millet. Because these rates are taken from research station trials where complementary management practices (deep plowing, incorporation of fertilizer, high plant density, complete weed control) ensure maximum technical response, they overstate gains expected with farmer adoption. Under farmers' management, such complementary practices are often not possible or uneconomic, and as a result response rates are one-third to one-half of the levels shown (Matlon, 1987).

Table 5.—Typical Grain Yield Responses
to Nitrogen and Phosphorous
(*Kilogram grain/kilogram nutrient*)

Crop	NPK ^a	Nitrogen ^b	P ₂ O ₅ ^c
Rice	n.a.	21.4	8–15
Maize	13.5	20.4	5–12
Sorghum	10.3	9.9	4–8
Millet	3.1	5.9	4–8

^aFrom trials conducted by the Institut de Recherches Agronomiques Tropicales et Cultures Vivrières (IRAT) during 1978–82 on research stations in Burkina Faso reported in J. Bonnal, 1983, *Rapport de Mission en Haute Volta: Aspects Economiques du Problème de l'Utilisation des Volta-Phosphates*, IRAT-Institut Voltaïque de Recherche Agronomique et Zootechnique (IVRAZ), Paris.

^bFrom literature review in John McIntire, 1986, "Constraints to Fertilizer Use in Sub-Saharan Africa," in U.A. Mokwunye and P.L.G. Vlek, eds., *Management of Nitrogen and Phosphorous Fertilizers in Sub-Saharan Africa*, Martinus Nijhoff, Boston.

^cRanges from FAO fertilizer trials in Africa (McIntire, 1986).

Economic incentives to use fertilizer follow the same order assuming roughly similar grain prices across crops. These results mean that where farmers cultivate several crops, millet and sorghum often receive the lowest priority in the allocation of fertilizer, and would be the first crops for which fertilizer use would become nonprofitable as fertilizer prices rise with reduced subsidies.

At the national level, a similar argument holds concerning the allocation of fertilizer across agroclimatic zones. Because technical response is greater where soil moisture is more assured, fertilizer use efficiency is

greater in the more humid zones. Interregional differences in cropping patterns reinforce this effect as the shares of total area sown to rice and maize are substantially greater in the Sudano-Guinean zone, for example, than in the Sahelian zone, where millet, the least responsive crop, predominates. Two years of farmers' tests conducted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in three agroclimatic zones in Burkina Faso demonstrated that at unsubsidized costs and when applied to local sorghum cultivars at profit-maximizing doses, compound fertilizers gave an average benefit-to-cost ratio of two or greater only in the Sudanian and Sudano-Guinean zones. Average negative returns were observed for both years when applied to millet in the Sahelian zone.

For these reasons, as fertilizer supplies increase at less subsidized prices, the most rapid expansion in consumption is likely to occur in the Sudano-Guinean zone, with applications growing most rapidly for maize and rice. Only moderate growth in fertilizer use is likely in the Sahelo-Sudanian zone and no significant growth is likely in the Sahel. Compound fertilizer use on millet is likely to remain low in all zones and could actually decline with the elimination of subsidies in several countries as efficiency considerations focus extension efforts toward other more responsive crops and higher potential regions.

Because of generally low population densities in the Sudano-Guinean zone (see Table 1) the primary benefit to increased fertilizer use will be decreased labor costs per unit of output rather than land savings.³ Without the land-saving benefits usually associated with yield-increasing technologies optimum fertilizer doses, even in the relatively high potential Sudano-Guinean zone, will remain moderate until population densities increase substantially. In short, extremely large aggregate supply responses should not be expected even in that high potential zone as fertilizer supplies increase.

Rock phosphates offer a unique set of possibilities and problems. Large regional deposits would suggest considerable savings in foreign exchange and transportation costs. However, due to considerable quality variation, in particular with regard to solubility and availability for plant uptake (Pieri, 1985), only rock phosphates from the Tilemsi deposits in Mali (and possibly the Tahoual deposit in Niger) have potential to be applied directly (Bationo, Mokwunye, and Baanante, 1985; Bationo, Mughogho, and Mokwunye, 1986). Two methods to improve solubility have been developed—granulation and partial acidulation with sulfuric or phosphoric acid—but

³ The increased labor required to apply chemical fertilizer and to provide additional weed control is generally negligible and proportionately less than the grain-yield increment. This is not true for applications of organic matter produced or collected and transported by the household (highly labor-intensive activities), which restricts that source of nutrients to regions where higher population densities reduce labor costs relative to land.

these also give inconsistent results across sources and are associated with application problems. Finely granulated rock phosphates from deposits in Burkina Faso, for example, gave uneconomic responses over four years of on-farm trials conducted in that country by Purdue University, and farmers encountered considerable problems in applying the dusty material (Purdue, 1986). On-farm trials in Niger conducted collaboratively by ICRISAT and IFDC showed that applied to millet, partially acidulated rock phosphate can be economic when nitrogen is not limiting, rainfall is adequate, and planting is early. Variation in these conditions can give inconsistent results implying considerable risk for farmers. Single superphosphate has generally been found to be technically superior to partially acidulated phosphates, but additional processing is required adding considerably to its cost.

A cogent assessment of rock phosphate's current potential is given by Purdue University (1986):

To be agronomically and economically feasible, the solubility problems of rock phosphate will have to be overcome. The present effectiveness of acidulation requires further on-farm testing. Once rock phosphate become agronomically and economically feasible, fertilizer plants and distribution networks would require several years to develop. A source of sulfuric or phosphoric acid at economically feasible prices is also required (Pieri, 1985). Thus rock phosphate appears to be a technology most appropriate in the intermediate run, after the technical problems of solubility and application are resolved economically at the farm level.

A final cautionary note concerns possible problems in managing the long-term consequences of continuous application of some chemical fertilizer formulas. The results of long-term soil fertility experiments in Burkina Faso (Pichot et al., 1981) and Senegal (Ange, 1984) indicate that in the absence of substantial additions of organic matter, continuous applications of commonly available compound and nitrogenous fertilizers can actually reduce the soil's production potential as acidification, aluminum toxicity, and possible deficiencies in micro-nutrients emerge. Whether similar problems may arise with the use of partially acidulated rock phosphate is not known. Additional basic and applied research is clearly needed in these areas.

Greater reliance on organic sources of soil nutrients to complement, but not entirely substitute for chemical fertilizers, is also necessary. But except for areas with high population pressure—where greater use of organic fertilizers is required simply to maintain soil productivity—labor requirements for generating and transporting organic fertilizers will restrict unit cost reductions unless forage and transportation bottlenecks are economically resolved first.

High-Yielding Cultivars.—Research aimed at improving the productiv-

ity of sorghum and millet cultivars in the West African semi-arid tropics have had little impact on production to date. After several decades of research, probably less than 5 percent of total sorghum and millet area in the region is sown to cultivars developed in modern crop improvement programs. Moreover, under normal rainfall conditions, and with low to moderate input levels under farmers' management, the yield advantage of most improved cultivars rarely exceeds 15 percent and is often negative (Andrews, 1986; Matlon, 1985).

Several constraints underlie this record. With the exception of Senegal and Nigeria, both of which benefited from a long history of bilateral technical assistance, national sorghum and millet improvement programs in West Africa are relatively young and weak. For example, in 1986 there were only 11 national scientists involved in sorghum breeding throughout West Africa, and many of these are only trained to the Master of Science level (ICRISAT, 1986). International and regional research institutions have only been established within the last fifteen years, a relatively recent time frame for crop improvement research, and in 1986 included only seven sorghum breeders on their staffs.

Moreover, while the international institutions are well suited for screening large numbers of cultivars to identify sources of desirable traits, the region's enormous agroclimatic diversity requires that the final stages of crossing and selection be done within national programs to ensure adequate local adaptation. Most national programs will be able to develop the capacity to play this role efficiently only over the next ten to fifteen years. Early efforts to short-circuit this process through the direct introduction of high-yielding sorghum and millet cultivars developed elsewhere in the world have generally not succeeded. The introduced materials were generally poorly adapted to the biotic and abiotic stresses of the West African environment and fit poorly into local farming systems (Matlon, 1985).

Seed multiplication and extension services are also chronically weak such that promising materials that are identified face major constraints in getting off the research station on a scale sufficient to determine their true potential. The striking contrast with similar services for cash crops, such as cotton and groundnuts, however, suggest that this is less a problem of national capabilities than of priorities and probably could be solved in the very short-term if there were the political will and if sufficiently promising sorghum and millet cultivars were developed.

Technical deficiencies in many selected sorghum and millet cultivars have also been an important constraint. Focused primarily on yield potential, few crop improvement programs have paid adequate attention to post-harvest characteristics and consumer preferences in their selection procedures. Problems in storage (for example, susceptibility to fungal damage), processing (for example, difficult threshing, incomplete husk removal

or grain breakage) and cooking (for example, unacceptable color, texture, consistency, or taste) have prevented widespread adoption of otherwise promising materials (ICRISAT, 1986; Stoop et al., 1981).

Experiments confirm that most selected cultivars are significantly more responsive to improved fertility and soil tillage than local varieties (Matlon, 1985). However, when adopted by farmers into extensive and diversified systems within which the potential benefits to land-saving technologies are marginal and where other crops such as maize, rice, or cash crops are even more responsive to purchased inputs, economic incentives lead farmers to continue to provide low input management to their sorghum and millet. And at low input levels, many elite cultivars perform poorly, often yielding less than local cultivars.

A growing number of crop improvement programs in the region now recognize these problems and have begun to allocate somewhat greater resources to objectives other than maximizing potential grain yield. Food scientists in Mali, Niger, and Nigeria are working with breeders to help select for desired post-harvest traits. Production stability is also becoming a more important goal as breeders are placing greater emphasis on selecting for resistance or tolerance to a wider range of biotic and abiotic yield loss factors. In the past some programs have systematically screened materials against the region's major pests and diseases, but primarily to avoid introducing materials with greater susceptibility than locals. Breeders are now placing more effort to increase tolerance and resistance traits to improve adaptability to abiotic stresses imposed by the soils, climate, and low input management (ICRISAT, 1986). Characteristics receiving greater emphasis include good seedling establishment under low tillage, tolerance to periods of drought, and improved plant expression (for example, full panicle exertion) under low soil fertility. The development of earlier maturing materials continue as a means of escaping early and late season drought. Recent collections of West African sorghums and millets are proving a valuable source for many of these traits since local cultivars typically have greater hardiness and adaptability to local conditions than exotic materials (Chanterreau, 1985).

In this context, it is not surprising that among the few cases where improved millet and sorghum cultivars have achieved limited success in rainfed semi-arid tropics systems, all involve varieties with improved adaptation to farm level stresses. The millet varieties *Sauna III* (widely grown in Senegal), *CIVT* and *P3 Kolo* (Niger) and *Ex-Bornu* (Nigeria), and the sorghum varieties *Ouedezoure* and *Gnofing*, grown extensively in the Sudano-Guinean zone of Burkina Faso, are improved local varieties based on selections from local materials. Similarly, improved sorghum cultivars recently released in Burkina Faso are believed to be achieving some uptake by farmers due to their substantially reduced maturity periods that provide farmers with im-

proved options for forced late planting situations,⁴ and due to enhanced resistance to the parasite *Striga* combined with more moderate earliness.⁵ Recent releases of improved millet varieties in Senegal are also characterized by earlier maturity for drought escape.⁶

Despite these successes in achieving a degree of farmer adoption, it is important to recognize that the aggregate production impact of more stable cultivars under low input management is probably small. This strategy can succeed in the medium-term to reduce downside risks somewhat, especially during drought, and to permit farmers to expand cultivation onto marginal land types. But in the longer-term this itself could accelerate degradation of the land base unless the improved cultivars simultaneously increase farmer incentives to move toward higher input management. In short, while yield stability is necessary to insure adoption and to reduce farmer risk, improved cultivar responsiveness to enhanced soil fertility and tillage is crucial in the longer run as a component of more intensive production systems.

With increasing population density, incentives supporting this strategy will increase, although they will remain greater in regions, such as the Sudano-Guinean zone, where agricultural production potential is greater. If sufficient resources are allocated to sorghum breeding for this region, it is reasonable to expect well adapted and more input-responsive cultivars to become available during the next five to ten years and to make an important contribution to reducing unit costs of production. In contrast emphasis on stability will continue to receive disproportionate emphasis even in the longer term for sorghum (and especially millet) improvement programs focused on the Sahelian and Sahelo-Sudanian zones. In these latter zones no major cultivar-led production breakthrough can be reasonably expected in the foreseeable future.

Labor-intensive cultural practices.—When observers with previous experience in the highly intensive cropping systems of Asia or elsewhere first visit farmers' fields in the West African semi-arid tropics, they often comment on the enormous potential for increased production if farmers simply increased plant populations, "rationalized" their crop mixtures (or sole cropped), or weeded earlier and more often. What they fail to understand is that in land-using systems, such changes would cost more of the scarce factor, peak period labor, while realizing negligible benefits in land savings.

Low plant densities are farmers' adaptation to low soil fertility and soil moisture, and a means of reducing down-side risk during drought. More intensive weed control is strictly constrained by an inelastic labor supply and would require a reduction in total cropped area and an increase in unit production costs (due to decreasing returns to labor), thereby reducing

⁴ For example, that IRAT variety, *IR204*.

⁵ For example, the ICRISAT varieties *Framida* and *ICSV1002*.

⁶ ICRISAT varieties *IBV8001* and *IBV8004*.

overall household output. And evidence is now overwhelming that the crop mixtures employed by farmers are both economically and technically efficient, particularly when returns to labor and the benefits of production stability are considered (Fussell and Serafini, 1985).

In short, given available technologies, prices, and factor endowments, greater labor use per hectare and marginal adjustments in cropping patterns have little potential to improve aggregate production. Increasing labor use per unit area will naturally occur as farm labor density increases and farm wages decrease relative to land costs. But at constant technology, such increases in labor use alone would most likely increase unit production costs.

Tied ridging (the diking of furrows at one- to two-meter intervals to create micro-basins that trap rainfall) has been proposed as one method to increase labor use with greater than proportional production increments. Two years of on-farm testing in Burkina Faso have shown that on moderately heavy soils (estimated at 40 percent of cultivated soils in Burkina and 15 percent in Mali) returns to labor in millet, sorghum, and maize can be substantially increased even under low fertility conditions (Purdue, 1986). Because response to tied ridging is inversely related to rainfall, tied ridging does reduce downside risks in drought years but provides only marginal gains when rainfall is adequate. Under high rainfall conditions, tied ridging can actually depress yields, especially on heavy soils (Rodriguez, 1983). These factors limit the suitability of tied-ridges primarily to the Sudanian and Sahelo-Sudanian zones, as soils are too sandy in the Sahel, and rainfall too high in the Sudano-Guinean zones.

The major constraint to large scale adoption of tied ridging techniques, even under suitable agroclimatic conditions, is prohibitive incremental labor costs, which are estimated at between 100 and 200 hours per hectare for manual ridge and tie construction. Although prototypes of animal drawn equipment have been developed by the International Institute for Tropical Agriculture (IITA) and ICRISAT to reduce this labor requirement, further adaptive research is needed before their adoption potential can be realistically assessed. In the absence of such equipment, the current adoption potential for manual tied ridging is probably limited to maize, which responds best to improved soil moisture, and which is cultivated on small highly manured plots adjacent to farm dwellings.

In the longer run, changing factor endowments in the most populated pockets of the Sahelo-Sudanian and Sudanian zones may make manual tied ridging sufficiently attractive for large scale adoption, but in sorghum rather than millet cultivation due to its greater responsiveness. Average sorghum grain yield increments on the order of 50–100 percent are feasible if tied-ridging techniques are combined with improved soil fertility management to exploit the technical complementarity between soil moisture and improved

fertility.

Yield-Stabilizing Technologies

Primary benefits to yield-stabilizing technologies are reduced production variability, especially downside risk caused by stochastic yield loss factors, and increased mean yields through enhanced resistance or tolerance to chronic yield reducers. This broad technology set includes cultivars resistant to the most common biotic and abiotic stresses and management practices that minimize periodic soil moisture deficits.

The previous section briefly considered the place of stress avoidance and resistance traits in sorghum and millet improvement programs. Binswanger and Pritchard (1987) have correctly argued that while such traits are relevant for all regions, they derive greater importance in land surplus areas (since no additional chemical or labor inputs are required) and in more arid conditions where production variability is highest, fertilizer efficiency is restricted by inadequate soil moisture, and where farm-level cash constraints are most binding.

Because crop improvement scientists are currently placing greater emphasis on incorporating greater stability in improved cultivars, it is reasonable to expect considerable progress in the near term. Major advances, for example, can be expected for *Striga* resistance in both millet and sorghum, and for mildew resistance in millet. Drought resistance is more problematic although enhanced opportunities for drought escape are likely as a range of better adapted early maturing cultivars become available. Projecting the production impact of such gains, however, is difficult as very few rigorous yield-loss assessment studies are available. It is unlikely, nevertheless, that on average such gains would exceed 10 to 15 percent of aggregate regional production in the foreseeable future.

Supplemental life-saving irrigation technologies, while containing considerable emotive appeal, have very little large-scale potential for sorghum and millet due to the high costs of irrigation discussed earlier. Substantial improvements in water control along lowland water courses and adjacent to swamp lands through small scale labor intensive approaches are technically and economically feasible, but their potential leverage on sorghum and millet production is also probably small. In most areas, profitability is considerably greater if such areas are used to produce vegetables or other specialty crops for urban markets.

The advantages and constraints of tied ridging as a means to avoid yield loss under drought conditions was discussed above. The only other major technology set to be considered as a means of minimizing moisture stress is water harvesting which is treated in a later section.

Labor-Saving Technologies

A characteristic of upland farming systems throughout semi-arid West Africa is their sharply seasonal patterns of labor use (Delgado and Ranade, 1987). Constrained by a rainy period which extends over only four months in the Sahel to seven months in the Sudano-Guinean zone, the demand for large and timely labor inputs is concentrated in the months of May to July when planting and first weeding are performed. Due to a lack of landless laborers and poorly articulated labor markets, the supply of peak period labor is highly inelastic, and output is directly affected by the amounts, quality, and timeliness of labor employed in these operations.

To be attractive to farmers, technical innovations must not only avoid increasing peak period labor use, but should also increase returns to such labor. The limited potential of increased fertilizer use to increase yields faster than peak period labor outside of the relatively more humid zones was emphasized earlier. Alternative technologies that reduce peak period labor requirements can increase production primarily to the extent that area expansion is permitted; or, in areas where this is not possible, to the degree that improved timeliness or quality of labor use can increase yields per unit area directly.

Herbicides.—Herbicides and mechanization are the two principal labor-saving innovations available for consideration. Although herbicide use has been promoted to a limited extent for cash crop systems in the Sudano-Guinean zone, there has been no substantial adoption despite the lack of an important cash constraint. The limited available evidence on herbicide use in sorghum systems also gives little grounds for optimism. In a study in northern Nigeria, Ogunbile (1980) found that at current factor costs, manual and animal traction weeding were both more economic than herbicides. Additional technical constraints include limitations to the most common cereal/legume intercropping systems imposed by broad spectrum herbicides.

Despite these problems, there may be some current potential for profitable herbicide use in areas with particularly high peak season wages, and additional adaptive research is warranted. Over the long run, however, rising population pressure will further constrain area expansion possibilities. This and associated reductions in real wages relative to land costs make the future profitability of chemical weed control for sorghum and millet doubtful.

Mechanization.—Mechanization has a long but checkered history in the West African semi-arid tropics. Large investments in tractorization were made as early as the 1950s in several West African countries where policymakers viewed the replacement of hand hoes with tractor cultivation as a highly visible means of directly modernizing the agricultural sector. In Benin, Ghana, Mali, and Nigeria, tractors were introduced in the context

of large-scale farms and custom-hire schemes. Field studies, however, have shown that nearly all such schemes have been uneconomic, requiring large subsidies to create demand for tractor services at the farm level. Problems include high foreign exchange shares for both initial investments and recurrent costs, chronic maintenance problems that result in gross underutilization and rapid depreciation of equipment, and inadequate yield response to plowing on the relatively light soils that are best suited to sorghum and millet. Given probable increases in fuel prices and in foreign exchange constraints for most West African countries, it is unlikely that tractors will play an important role in sorghum and millet production in the foreseeable future.

Although efforts to introduce animal traction technologies into semi-arid West Africa were initiated in the early 1900s, less than 15 percent of farmers in the semi-arid tropics currently employ traction systems. Moreover, a large number of field surveys that compared adopters and non-adopters have documented the generally negligible impact of animal traction cultivation on sorghum and millet production, as well as their complex and often counterproductive effects on labor use and productivity.

The potential gains from animal draft power in sorghum and millet cropping systems vary by region according to both agroclimatic and economic factors (Jaeger and Matlon, 1990). High utilization of animals and equipment is crucial for the profitable use of animal traction technologies (Jaeger, 1986). In a broad survey of mechanization in sub-Saharan Africa, Pingali, Bigot, and Binswanger (1987) found that low utilization has frequently been caused by the extension of equipment and techniques into agroclimatic environments for which they are ill-suited, and by not taking into consideration key aspects of the manual farming systems being replaced. For example, the introduction of traction plowing is most appropriate in zones where: (1) due to a long rainy season, and particularly to an extended preparatory rainfall phase, farmers had been able already to prepare the soil manually without delaying planting; (2) the farming system has evolved into a grass-fallow rotation such that stumps have been removed and do not slow traction tillage; and (3) where the soils are relatively heavy and thus provide high technical response to improved preparation.

The introduction of traction plowing in these circumstances would not only have potential yield effects, due to an improvement in the quality of soil preparation, but would also save labor in the soil preparation activity. In areas where surplus land is available and where labor in other operations, especially weeding, is not limiting, this labor savings can be translated into further production gains through the expansion of cultivated area. The general failure to provide weeding equipment in addition to the plow, however, has often severely limited area expansion and led to gross underutilization of equipment and animals (Jaeger, 1986; Sargeant et

al., 1981).

These conditions suggest that within the West African semi-arid tropics plowing is best suited for the Sudano-Guinean zone. In more arid zones where the shorter rainy period leads farmers to plant directly without soil preparation, the introduction of traction plowing is in fact labor-using rather than labor-saving, and creates an additional conflict between plowing and timely planting. Thus in the Sahel and Sahelo-Sudanian zones, mechanized plowing will have limited adoption potential until earlier maturing (later planted) cultivars are more widely available.

The labor-saving effects of animal traction techniques for weeding operations are substantially clearer. In a study of farmers in three agroclimatic zones of Burkina Faso, Jaeger (1986) found that the marginal rate of technical substitution between manual and traction weeding labor was consistently greater than 5. This indicates considerable technical potential for increased production through area expansion where surplus land of good quality is available.

In summary, the immediate potential of well targeted animal traction techniques and appropriate equipment is substantially greater than past performance and limited adoption would suggest. Looking to the future, however, it should be recognized that natural population growth and inter-regional migration will, within the next two or three decades, largely preclude sizable reductions in unit production costs resulting from the labor-saving, area expansion effects of animal traction alone. In the long run, as the value of land increases relative to farm labor, greater emphasis must be placed on the role of animal traction in raising yields per unit area in sustainable intensified systems. Where conditions permit high utilization, mechanized plowing will derive greater importance. Less orthodox tillage techniques, such as tied ridging, will probably also contribute importantly to yield increases in the Sudanian Sahelo-Sudanian zones. Nutrient and biomass recycling in more integrated mixed-farming systems will also be a critical element in maintaining soil quality under continuous cultivation. This means that animal drawn carts will become increasingly important as a means to overcome labor constraints in the harvest of crop residues for animal feed and to achieve a more efficient spatial distribution of organic matter over farmers' fields (Prudencio, 1983).

Land Conservation Technologies

In locations where high population density has brought large areas under continuous cultivation, field evidence suggests that farmers have developed methods to maintain the soil's chemical status at a low-level equilibrium by recycling crop residues, manure applications, low doses of chemical fertilizer, and the use of legumes in rotation and as intercrops (Prudencio, 1983). More problematic, however, is the degradation of soil physical

properties by the loss of surface horizons, and the associated changes in soil depth and texture that often accompany continuous cultivation. Experimental data and on-farm evidence show that inappropriate mechanized cultivation can contribute importantly to this process. The deterioration of the land base is further accelerated where loss of vegetative cover on up-slope watersheds increases surface water flow over cultivated fields. What remains are structureless soils with high susceptibility to capping and thus low infiltration, and extremely low water-holding capacity. Eventually such soils can no longer be cultivated, which contributes further to the land shortage problem in a circular and accelerating fashion.

Techniques to arrest and reverse physical deterioration include a variety of run-off management systems that focus on erosion control and/or water harvesting. To date, experience with these methods in the West African semi-arid tropics has been limited in scale, highly localized, and most often initiated by a variety of nongovernmental development organizations outside of public research and extension systems (Harrison, 1987).

The primary benefit of these techniques is to maintain the long-term productivity of the land base. Nevertheless, an increasing number of field evaluations shows that significant short-term yield gains are also possible. A three-year evaluation of impermeable earthen bund anti-erosion systems which had been constructed during the previous five years in three agroclimatic zones of Burkina Faso showed an average grain yield increase of 30 percent (170 kg/ha) on farmers' sorghum fields and 43 percent (90 kg/ha) on millet fields (ICRISAT, 1985). Permeable rock-bund water-harvesting systems show even greater short-term productivity effects. A four-year evaluation of such systems constructed by farmers in the highly degraded Yatenga region of Burkina Faso demonstrated yield gains of nearly 55 percent across both crops (Wright, 1985).

Because these systems reduce run-off loss of organic matter and fertilizer while increasing water infiltration, they are also highly complementary to packages of fertilizer and input-responsive cultivars. Farmers' tests of a package that included permeable bunds, low dose compound fertilizer, and an improved sorghum cultivar conducted in the Sahelo-Sudanian zone of Burkina Faso showed a first year yield gain of 180 percent (>300 kg/ha) over drought-affected controls (ICRISAT, 1985).

Because bunding systems require little or no cash outlay, and construction is done during the dry season when the opportunity cost of labor is low, these techniques are well suited to resource-poor farmers. Economic analyses of the package tested by ICRISAT showed that a break-even annual sorghum yield increment of only 155 kg would assure a return of 15 percent on the labor and cash investment (ICRISAT, 1985). This increment was exceeded by 67 percent of farmer participants in the Sahelo-Sudanian zone, but by less than 20 percent in the Sudano-Guinean zone.

A relatively greater short-term benefit to erosion control in the Sahelo-Sudanian zone compared to the higher potential Sudano-Guinean zone was also confirmed in the evaluation of earthen bunds in Burkina Faso (ICRISAT, 1985). Greater drought stress, more surface water flow due to the higher proportion of cleared areas, and more degraded soil status contribute to the technical advantage in the Sahelo-Sudanian zone. Higher population pressure in that zone (see earlier section) also combines to provide the necessary economic incentives for considerable adoption potential in those areas that are under the greatest risk of environmental degradation.

Whether the full potential of these systems will be exploited in appropriate regions is uncertain, and will probably require a reorientation in approach of national extension systems. Past efforts at imposing anti-erosion systems through top-down, capital-intensive approaches have generally failed (Marchal, 1979). More recent projects have shown the necessity of a high level of farmer participation in site selection, design, and construction in order to achieve broad adoption and lasting impact (Wright, 1985). The traditionally hierarchical approach of most national extension systems poses an important but not insurmountable institutional constraint to the type of dynamic interaction with farmers that is needed. This also suggests that although the long-term social benefits of these systems justify an economically efficient role for subsidies, the use of public expenditures should be highly selective so as not to undermine local initiative in design, construction, and maintenance.

SYNTHESIS AND CONCLUSIONS

A coherent assessment of the prospects for reducing unit costs of producing coarse grains must be based on three pillars. First, there should be a clear recognition of the range of agroclimatic and demographic conditions that characterizes the West African semi-arid tropics. These factors combine to segment the region into a diverse set of sub-regions with varied technical potentials and factor endowments that determine the feasibility and impacts of particular types of technical change. Generalizations across the West African semi-arid tropics are rarely justified.

Second, a realistic assessment should explicitly recognize the time frames within which particular technical changes can be developed and/or adopted on a broad scale. Portions of the sub-region are experiencing an unprecedentedly rapid transformation from extensive to intensive production systems, a transformation that in some areas is fundamentally eroding the production potential of the resource base while modifying factor endowments and factor costs. Technical innovations appropriate for a given region in the 1980s will not necessarily be appropriate by the year 2000, and vice versa.

Third, some assumptions as to future research resource allocations are unavoidable. Predicting the pace and nature of progress in technical research is highly problematic. Inefficiencies in defining research priorities and uncertainties in finding solutions to often complex technical problems are compounded by (even greater than?) uncertainties as to whether sufficient resource commitments to agricultural research can be sustained by donors and national policymakers alike.

Any attempt to offer a detailed forecast of the types of technical changes that can be expected—where, in what time frames, and with what impacts on production—would be conjectural and inevitably proven wrong by subsequent events. This concluding section briefly reviews each major agroclimatic zone to suggest what are the most promising technical changes currently available or likely to become available by the end of this century. Only moderately increased resources are assumed to be available for sorghum and millet research in the region. The section concludes with a discussion of research policy implications.

Prospects for Productivity Gains by Zone

Table 6 presents a qualitative summary of the most probable patterns of potential technical change by zone; that is, where research and development resources can achieve significant impact in the medium-term. Two points are clear. First, the potential for major increases in supply exist only in the Sudano-Guinean zone and to a lesser extent in the Sudanian zone where yield-increasing and labor-saving technologies fit best. Yield-stabilizing and land-conserving technologies, which have little direct impact on shifting the regional supply curve, should be given highest priority in the Sahel and particularly in the Sahelo-Sudanian zones. Second, even in the higher potential agro-ecological zones, yield-increasing technologies are appropriate primarily in areas of relative land scarcity, and in the long-run as more generalized land scarcity begins to emerge.

The Sahel.—Environmental constraints are such that there is very limited potential to significantly reduce unit costs of coarse grains production in the Sahelian zone, and probably little justification to allocate substantial resources to that effort. In the near term, technologies that dampen the impacts of recurrent drought can be of some benefit in reducing downside yield risks. Shorter-cycle millet varieties, some of which are already available, could help farmers escape early or late season drought. Cultivars that incorporate mechanisms to resist or tolerate drought more efficiently than locals are not currently available, and it is doubtful whether such materials will be developed during the next decade. In the longer term, once population densities increase sufficiently to justify investments in land improvement, water-harvesting systems may have some potential if formidable technical problems posed by the light deep soils of this zone can be solved.

Table 6.—Prospects for Different Types of Technical Change
in Sorghum and Millet Production in the West African
Semi-Arid Tropics

Agroclimatic zone	Yield increasing	Labor saving	Yield stabilizing	Land-base conserving
Sahel				
Land abundant	—	—	++	+
Land scarce	—	—	++	++
Sahelo-Sudanian				
Land abundant	—	+	++	++
Land scarce	+	—	++	+++
Sudanian				
Land abundant	—	++	+	+
Land scarce	++	—	+	+++
Sudano-Guinean				
Land abundant	++	+++	+	—
Land scarce	+++	++	+	+

The more fundamental policy issue is whether increasing agricultural activities in this zone, through the development of such technologies, should be encouraged. Expected benefits will be relatively small compared to the costs of the necessary research investment. Moreover, population densities in the Sahel zone are already at the sustainable margin for crop and livestock activities combined, and exceed the fuel wood-carrying capacity by sevenfold. Continued expansion of the farming population will only contribute to zonal desertification, which is already severe in some areas. Extensive livestock-raising is probably the more rational and ecologically sustainable activity to promote.

The Sahelo-Sudanian Zone.—Characterized by the greatest imbalance between actual and sustainable populations, the immediate challenge in this zone is to arrest the trend toward increasing unit production costs caused by degradation of the land base and by the expansion of cultivation onto marginal soils. Low cost farmer-adapted run-off management techniques have been developed within the region and have shown considerable potential to achieve that goal. Early adoption experiences, however, suggest that such land-conserving techniques are most readily taken up in pockets of intense population pressure where land degradation is already highly visible and its consequences widely appreciated by farmers. Complementary stress-reducing and avoiding technologies are either now available, or probably will be developed within the next decade. These include well adapted short-cycle millet and sorghum varieties that are resistant to *Striga* and to

other major biotic yield loss factors.

However, because these developments will primarily prevent further declines in productivity while stabilizing production marginally, significant increases in sorghum and millet production are unlikely. Major and sustainable improvements in productivity through high-input, yield-increasing techniques can be reasonably expected only in the most highly populated sub-regions, and after investments in run-off management systems reduce loss of top-soil and nutrients, and improve soil moisture. For these reasons, it is unlikely that significant yield increases will occur over major portions of the zone before the year 2000.

In less populated areas within the Sahelo-Sudanian zone, investments in land conserving and enhancing technologies probably will not be attractive to farmers until demographic pressures mount further. For these areas, stress resistant or avoiding cultivars that reduce yield variability (but again with only marginal productivity benefits) are now promising. In those areas of low population density with heavier soils there may be potential for significant gains in productivity with the adoption of mechanized ridge tying once farmer adapted labor-saving equipment are developed. Since few resources are currently being allocated to this problem, however, major advances cannot reasonably be expected before the mid-1990s at the earliest.

The Sudanian Zone.—Land-conserving and yield-stabilizing technologies are also appropriate in most portions of the Sudanian zone. Higher rainfall in this zone also means that there is somewhat greater adoption potential for yield-increasing packages as well where economic conditions permit. In areas where land shortages have already emerged, moderate doses of chemical fertilizer and recurrent applications of organic matter combined with well adapted input-responsive cultivars already available can achieve significant productivity gains, particularly on those land types with more assured soil moisture. In order to improve fertilizer use efficiency, reduce farmers' risk, and expand the use of such low-input packages to a wider range of land types, they should be applied in conjunction with run-off management systems. Sorghum rather than millet is likely to benefit most from such intensification due to its greater responsiveness to enhanced soil moisture and soil fertility.

In areas of low to moderate population pressure, there are currently fewer incentives for farmers to invest in land-conserving techniques, such as run-off management, which are complementary to a moderate input-intensification package. Mechanized tied ridging, if developed, may be a more appropriate means to remove the soil moisture constraint thereby permitting low risk and profitable use of such packages in these areas.

Animal traction mechanization of weeding operations provides some short-term potential for productivity improvements through area expan-

sion in those areas with the lowest population pressure. Continued population growth, however, will largely eliminate these gains, possibly within the next two decades, as area expansion will increasingly occur at the expense of manual farmers and onto marginal land types. Bio-mass recycling complementarities of more closely integrated crop-livestock systems may yield greater long-term benefits in this zone than animal traction as a power source alone. The dilemma is that in high density areas where bio-mass recycling is most necessary technically and where labor costs in these labor-intensive activities are lowest, forage opportunities are severely reduced and animal nutrition becomes a major constraint. Research is addressing this problem, but economically feasible solutions have not yet been developed.

The Sudano-Guinean Zone.—The broadest technical options for substantially improving current and future productivity exist in this zone. Due to lower population pressure, higher and more assured rainfall, a longer cropping season and generally better soils, either yield-increasing or labor-saving techniques can be profitably adopted, with the choice of technique a function of localized factor endowments.

Ironically, the highly diversified cropping systems that also reflect the considerable technical potential of this zone also pose an important constraint to major breakthroughs in sorghum or millet production. In those areas where mechanization has permitted considerable area expansion within the Sudano-Guinean zone, as in southern Mali and southwestern Burkina Faso, for example, farmers have found it more profitable to expand cash crop cultivation, such as cotton for which there is a highly elastic demand, rather than sorghum or millet. Similarly, where environmental conditions allow important cultivation of maize or upland rice, as farmers begin to intensify through improved soil preparation and fertilizer use, they rationally give first priority to those crops rather than to the less responsive sorghum or millet. This suggests that as population growth increases incentives for intensification, sorghum breeding programs targeting this zone must develop substantially improved input responsiveness if sorghum is to remain competitive. Parallel progress in maize or rice improvement, however, may further erode sorghum's competitiveness in the long run.

Implications for Research Policy

The diversity of production environments in the West African semi-arid tropics, rapid demographic change and associated degradation of the resource base carry several important implications for designing effective research strategies and supporting policies.

First, national research programs must be considerably strengthened if even modest productivity gains in aggregate sorghum and millet production are to be achieved during the next several decades. International and

regional research institutions do not and will not in the foreseeable future have the resources to develop technologies appropriate for all or even most of the major production environments. The limited transferability of technologies means that while the international and regional institutions have a comparative advantage in the conduct of basic and some applied research, national institutions must do much of the applied and most of the adaptive research that is necessary to develop new technologies that fit diverse situations. Moreover, the international and regional institutions have a vital role to play in strengthening national research systems through formal and informal training, technical backstopping, and a variety of scientific networking activities.

Second, in order to maximize relevance and efficiency, research objectives must be based on a more disaggregated set of recommendation domains that recognize key differences in factor endowments at regional, sub-regional, and farm-type levels. Rainfall, soils, and population density provide a minimum data set for regional zonification. On-farm diagnostic studies are also important to determine key constraints and available resources for major farm types, and to measure the potential leverage of alternative technical innovations *before* scarce research resources are committed to develop them. Early on-farm testing is equally important to provide immediate performance feedback and to test and refine recommendation domains.

Third, it follows that objectives should be defined as appropriate for specific recommendation domains, and for clearly defined time frames. Increasing yield through moderate or high input packages is not yet a generally appropriate objective for most of the West Africa semi-arid tropics, although it will derive greater importance as populations grow into the next century. The time-lags in developing well adapted technical innovations must be considered in initiating research toward such products. Nevertheless, stress reduction or avoidance, labor-saving, and particularly land conservation and enhancement, are objectives of considerably greater relevance in the majority of sorghum and millet systems in the semi-arid tropics for the short and medium term.

Policymakers face difficult decisions in allocating scarce research and development resources among zones and between crops. Efficiency criteria alone would lead to an allocation that maximizes the return to investment; that is, toward objectives for which net benefits are larger and can be achieved earlier. The greater agroclimatic potential and more favorable factor endowments of the Sudano-Guinean zone mean that the largest payoffs from the application of existing technologies and from current and future research probably will occur in that zone. Similar efficiency arguments can be framed to give sorghum higher priority than millet, and maize and perhaps rice higher priority than either sorghum or millet.

It is true that *regional* equity criteria focused uniquely on producer incomes would suggest greater emphasis on sorghum and millet, which are well adapted to the more arid and marginal production environments. However, the poorest producers are also generally deficit cereal producers, and the shares of cereals in the diets of both the urban and rural poor are extremely high. Thus from a societal and *interpersonal* perspective, equity concerns would also be best served by pursuing efficiency goals oriented toward maximum impact on aggregate grain production to reduce the real cost of cereals. In short, both efficiency and equity goals would suggest that larger shares of research and development resources should be allocated to higher potential zones and crops, with relatively declining shares allocated to sorghum and millet in the medium and long run.

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