CLIMATIC VARIABILITY AND CROP YIELDS IN THE SEMI-ARID TROPICS

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ABSTRACT. The climates of the semi-arid tropics are characterized by high incidence of solar radiation, high temperatures and very variable rainfall. Droughts and floods are both common occurrences. Deficient rainfall years may be followed by similar years or years with excess rainfall in no predictable pattern.

Rainfed farming is risky in such conditions and farmers are reluctant to invest in crop production. Traditional agriculture means low but stable yields, low inputs, mixed cropping, large families, low incomes and living standards and outmigration of family members, both seasonal and permanent. Only about 4% of the arable land of the semi-arid tropics is irrigated.

Farmers try to ameliorate the effects of drought through crop management. If the first crop fails they may plant a second or a third. When all crops fail farmers and their families must decrease their food intake, sell movable assets or their land. Without government intervention many people may migrate or even starve.

New technologies now exist that reduce the risks of farming in the rainfed semi-arid tropics. The technologies include improved soil and water management on watershed-based land units, the use of fertilizers and improved seeds, improved cropping systems and supplementary irrigation. The productivity of traditional agriculture is declining and the threat of serious food shortages is rising but the potential for the semi-arid tropics to feed itself in all but the driest years does exist. Institutional and infrastructural improvements will be necessary for this potential to be reached.

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INTRODUCTION

The semi-arid tropics covers much of the African continent (Fig.1). It stretches in a broad band from west to east below the Sahara desert, and includes most of eastern and south-central Africa. In Asia it includes most of India, eastern Java and north-eastern Burma and Thailand. It includes most of the northern quarter of Australia, nearly all of Central America and portions of north-eastern Brazil, Paraguay and Bolivia. More than 600 million people are estimated to live in the region, with 56% of them in India.

Rainfall in the semi-arid tropics is highly variable. In low-rainfall years there may be droughts; in high-rainfall years or even for short periods in low-rainfall years there may be floods. Deficient rainfall years may be followed by similar years or by years with excess rainfall.

Sorghum and pearl millet are the major rainfed cereals of the region. Rice is grown in the river deltas and wheat is grown mainly in the winter season where irrigation is available. The main grain legumes are pigeonpea, chickpea, cowpea and mung bean. Groundnut, safflower, sesame and mustard provide the main cooking oils.

Traditional agriculture in the semi-arid tropics is designed to reduce the risk of losses in dry years, because they can be very severe. The benefits that could accrue in good years are

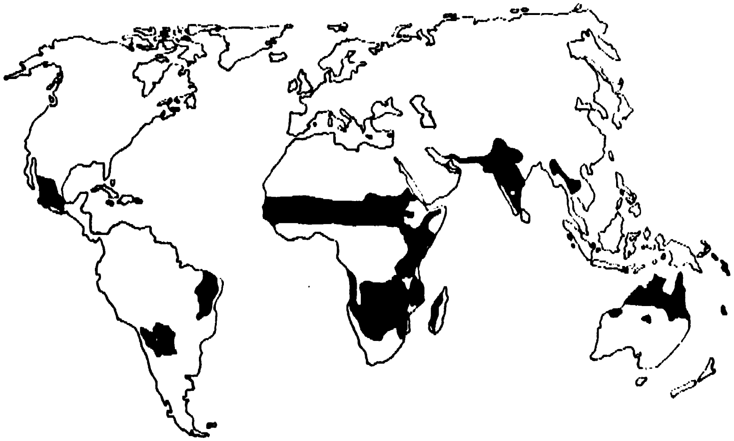

Figure 1. The semi-arid tropics, shown in black.

usually lost. Much of the effort to create new or improved technology for the region is designed to remove the risk of loss in dry years so that farmers will invest more in anticipation of good years.

Food production in semi-arid India is increasing, although not fast enough to improve standards of living very much. In semi-arid Africa food production is declining. A recent report from the International Food Policy Research Institute (1) predicts substantial deficits in cereals in the semi-arid tropics by 1990. India may have deficits of 20 million tons. Per capita deficits in the African semi-arid tropics may be ten times as great as those in India. A large and urgent effort in research and development will be required to avert the human misery that such deficits foretell. The effort will only succeed if the resources of soil and water are used wisely and well, and if the inherent variability in the climate of the semi-arid tropics is offset. Although irrigation will help significantly, particularly to increase production of rice, the potential for large-scale irrigation is quite limited. Most of the arable land must continue to be cropped in rainfed conditions. In consequence this review of present conditions and future prospects deals only with rainfed agriculture.

CHARACTERISTICS OF SEMI-ARID TROPICAL CLIMATES

The semi-arid tropics is a region of high water demand and scarce water resources. Temperatures are high, usually exceeding a mean of 18°C in all months of the year. Total annual rainfall varies considerably from about 400 to 1200 mm. (Table 1).

Rainy seasons are short with most of the rainfall concentrated in two to five months; from April to October in the northern hemisphere and October to April in the southern hemisphere. Seasonal rainfall is often 90% of total annual rainfall.

Of the climatic elements important for crop production - rainfall, temperature and solar radiation - rainfall is most variable. The coefficient of variation for annual rainfall is 20-30%, for annual temperature and solar radiation of the order of 5%. Detailed climatological studies have shown that the distribution of rainfall within the year is also highly variable, and cannot be predicted with any reasonable degree of confidence. Smaller yearly or seasonal totals are associated with larger year-to-year variability.

In tropical latitudes there are large amounts of energy available for evaporation of water. Since solar radiation is the most important component affecting evaporation, and since it

Table 1. Average monthly rainfall (mm) for selected locations in the semi-arid tropics.

Location	Lat ° '	Long ° '	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual*
1. Hyderabad (India)	17 27N	78 28E	2	10	13	23	30	107	165	147	163	71	25	5	761 (93)
2. Dakar (Senegal)	14 44N	17 30W	0	2	0	0	1	15	88	249	163	49	5	6	578 (98)
3. Bamako (Mali)	12 38N	08 02W	1	0	3	15	60	145	251	334	220	58	12	0	1099 (99)
4. Maradi (Niger)	13 28N	07 05E	0	0	0	4	32	60	164	260	110	12	0	0	642 (100)
5. Sokoto (Nigeria)	13 01N	05 15E	0	0	0	13	53	89	165	252	147	15	0	0	734 (100)
6. Ouagadougou (Upper Volta)	12 21N	01 31W	0	3	8	19	84	118	193	265	153	37	2	0	882 (99)

*Percentage of seasonal rainfall (April to October) to annual total is shown in parentheses.

varies little from year to year, potential evapotranspiration is more or less constant from year to year. When rainfall exceeds evapotranspiration, soil moisture reserves are recharged. When rainfall is less than evaporation, soil moisture reserves are utilized. With uneven seasonal distribution of precipitation and with great inter-annual variability, small negative deviations in precipitation are all that are required to initiate drought. In semi-arid India moderate or worse droughts are likely to occur one year in every four (Fig.2).

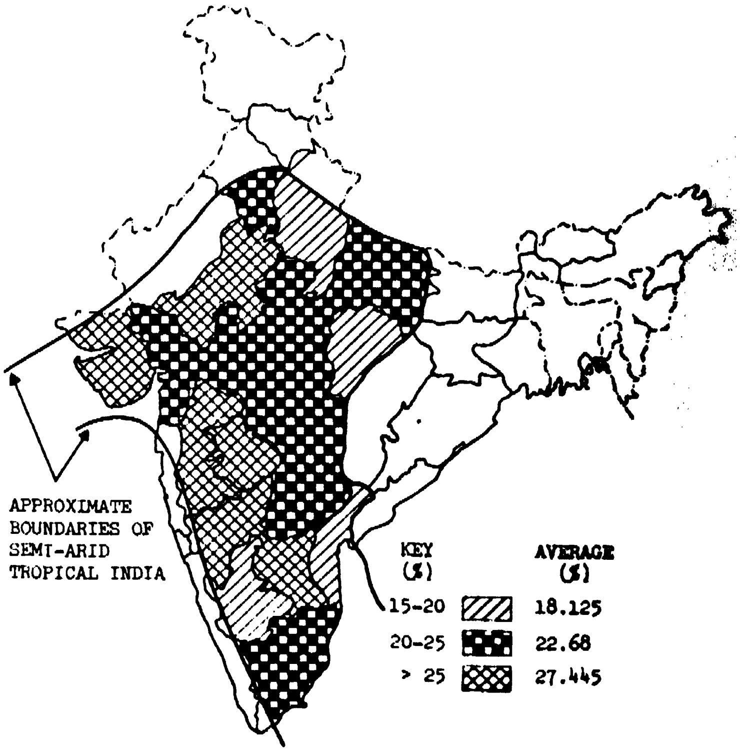

Figure 2. Percentage occurrences of droughts of class moderate and worse in the rainy season in the Indian semi-arid tropics (2).

In most years the rainy season in the semi-arid tropics is long enough for crops to grow. Indeed there is usually excess water in the rainy season, some of which can be stored in the soil, but most of which runs off causing soil erosion. Management of land, crops and livestock are intimately associated with the inflow and outflow of water. In determining the agricultural potentials of any semi-arid area, quantification of the timing, amount and duration of rainfall, the intake, storage and release of soil moisture and the evapotranspiration is essential. For example, Virmani et al (3) using a water balance model incorporating these factors have shown that the length of the growing season at ICRISAT Center on shallow sandy red soils (Alfisols) fluctuates from 12 to 21 weeks and on deep clayey black soils (Vertisols) from 20 to 31 weeks (Table 2). The soil type clearly plays an important part in defining length of growing seasons in a given climatic situation.

FARMING THE SEMI-ARID TROPICS

There are 48 less developed countries with semi-arid tropical climates. There are about 3 ha of geographic land available per person in these countries to provide food, clothing, shelter and the wherewithal to invest in the future. In semi-arid India there is only 0.6 ha of land per person. (4)

Table 2. Length of the growing season (in weeks)[a] for three soil conditions.[b]

Rainfall probability	Available water-storage capacity		
	Low (50 mm)	Medium (150 mm)	High (300 mm)
Mean	18	21	26
75%	15	19	23
25%	20	24	30

[a]From seed-germinating rains (25 June) to end of season [time when profile moisture reduces EA/PE (Ratio of actual evapotranspiration to potential evapotranspiration) to 0.5].

[b]Low: shallow Alfisol; medium: shallow to medium-deep Vertisols; high: deep Vertisol.

India

In India virtually all farmers in the semi-arid tropics are small farmers. The resource base and endowments of farmers in the rainfed areas have been described in considerable detail by Jodha et al (5) and Jodha (6). More than 90% of the holdings are less than 12 ha in size and 70% are less than 8 ha. The land is usually held in 4 to 5 separate fields. Size of holding tends to be inversely related to rainfall or access to irrigation.

Investments are low. Fertilizers, agricultural chemicals and improved seeds are used only on land that can be irrigated. There is usually one draft bullock per farm and a total investment of less than $150 on farm implements and machinery. Althoug only 4% of the arable land is irrigated, 50% of the farmers have access to a source of water for minor or supplemental irrigation.

Sorghum and pearl millet are the major rainfed cereal crops. All arable land is cropped at least once per year, i.e. the cropping intensity is at least 100%. Where there is access to water the cropping intensity is greater, but nowhere seems to exceed 120% (6, 7). Nearly 18 million ha, or 24% of the net sown area of semi-arid India, are fallowed during the rainy season and cropped in the post-rainy winter season.

Intercropping, i.e. growing two or more crops simultaneously is a common feature in the region. It is most common amongst small farmers and where farmers have least access to irrigation. It gives higher returns per hectare and may spread labor requirements more evenly. It is also a hedge against disaster. Rao and Willey (8) examined the stability of 94 experiments involving sole pigeonpea, sole sorghum and sorghum/pigeonpea intercrops. Using a gross return of Rs.1,000 per hectare as a 'disaster' level, they found that sole pigeonpea failed one year in five, sole sorghum one year in eight, but intercropped sorghum/pigeonpea only one year in thirty six.

As many as 84 different crops are used in traditional intercropping systems in semi-arid India, but seldom more than three at one time. The systems used fall into four main categories (6), viz: mixtures of differing maturities, mixtures of drought-resistant and drought-sensitive crops, cash crop - food crop mixtures, and legume-non-legume mixtures.

The farmers of semi-arid India live in caste-dominated villages in nuclear families that usually include dependent parents, brothers and sisters. Standards of living are low but improving. Per capita annual income and literacy rates are generally below the national averages which in 1976 were $150 and 36% respectively (9). Malnutrition and poor health are widespread, but life expectancy has risen substantially in recent years. The infrastructure for development exists and is being improved.

West Africa

Newman et al (10) have comprehensively reviewed the literature on rainfed farming in semi-arid West Africa. Subsistence farming appears to be more common than in India. Much of the land is owned communally, but worked by family units which have usufructuary rights to as many as 16 separate fields on soils of varying quality around the village. The range in size of holdings is similar to that in India, and the main cereal crops are, again, sorghum and pearl millet.

Fertilizers and improved seeds are hardly known and seldom used, but animal manure is used on the fields nearest the village. The use of animal traction is not common. Donkeys are the usual source of animal power when it is used, except in Mali where oxen are fairly common. Because the power available is low, soils are seldom ploughed; and all agricultural operations are time-consuming.

Fallowing and burning are used to return some fertility to the soil. Cropping intensities on commonly used land seldom exceed 75% except for the land closest to the village which is used to grow the most important staple cereals. Land far from the village may be cropped only one year in four. Intercropping is common, usually of cereals with cereals or cereals with cowpea. Cash crops such as groundnut, bambara nut and sorrel are grown on small fields as sole crops.

Traditional villages in semi-arid West Africa have a strong sense of community and often an hierarchical system of control (10). Family units are large and often contain several adult males and 10 to 20 people, but nuclear family units comprising a single adult male and his dependents are increasing. Standards of living are low and food production is declining. Because population growth is high the pressures on land are increasing.

ADJUSTMENTS TO DROUGHT

The traditional farmer in the rainfed semi-arid tropics lives with the possibility of drought. He has learned by experience how to adjust to the inherent variability of climate. Each year he must decide what to plant, where and when. If he is a subsistence farmer he will consider mainly what will survive until harvest to meet the needs of his family. If he is also a commercial farmer - as virtually all farmers are in India - he

will also consider what price he will get for his marketable produce. He must choose amongst several crops and within each crop amongst several types and varieties. He has several fields with differing fertilities and water-holding capacities at differing distances from home, a limited time period in which to plant and insufficient labor to do everything at once. He starts with a bewildering array of choices that are rapidly reduced in number by their primary determinants; the timing, intensities and frequencies of the early rains.

When a farmer first perceives that his crops might fail he will try to improve weed control or thin the stand. Both actions conserve soil moisture. In soils that crack, creating a dust mulch on the surface has the same effect. If any supplementary water is available it will be used on the most important crops. If the first crop does fail he may replant it or plant a second or a third. Near Hyderabad, India, early planted sorghum may be replaced by finger millet in mid-season and even by cowpea or horse gram in the last month of the monsoon. At Jodhpur, in a much drier climate where pearl millet is the only suitable cereal, the farmer has no high-calory alternative if that crop should fail.

Jodha (11, 12) describes the adjustment mechanisms used by farmers in northwest India when crops fail due to drought. First the farmer reduces his social consumption, i.e. he will delay a family ceremony (a marriage) or make lesser inputs into annual festivals. He may also decide to sell off some nonproductive assets. He will come to no permanent harm, nor will his family, and his productive resources will remain intact and available for use when conditions improve.

When the drought is more severe he must adjust in more drastic ways. His first recourse is to reduce the consumption of food. Table 3 shows that the greatest reduction tends to occur in the more expensive, protective foods such as milk, sugar, meat and vegetables. Cereals and pulse crops are the last to be given up. Obviously a serious decline in the consumption of protective foods will seriously affect the farmer and his family. This is particularly likely to be true where the cultural tradition is to deprive the children first (13). Faulkingham and Thorbahn (14) have estimated for an area of eastern Niger that 25% of the children under age 5 died in the last Sahelian drought because of food deprivation.

When the farmer has reduced consumption as low as he dares, he disposes of his assets - first his animals, as he cannot work with them and he cannot feed them. Then he disposes of his farm implements and machinery. Assets disposed of may take several years to recover. In spite of the substantial governmental assistance provided to farmers in Maharashtra during the 1971-72

Table 3. Indexes of Consumption Expenditure by Households in Drought years Relative to Post-Drought Years in Different Areas (Post-drought year situation = 100), from Jodha (12).

Items of Expenditure	Jodhpur (Rajasthan)			Barmer (Rajasthan)			Banas Kantha (Gujarat)		
	Small Farms	Large Farms	All Households	Small Farms	Large Farms	All Households	Small Farms	Large Farms	All Households
Total Food Items	95	99	98	93	110	103	90	97	94
Protective Foods	52	85	64	43	74	58	87	98	72
Clothing, Fuel, etc.	79	85	84	84	83	85	72	76	69
Socio-religious ceremonies	23	56	36	69	50	52	63	18	66

drought, farmers in some of the drier regions, such as Sholapur, had not fully replaced their lost animals in 1978.

The penultimate step is forced outmigration of families. In Gujarat and Rajasthan during the 1972 drought, 40% or more families migrated from 50 to 243 kms from home for periods from 100 to over 200 days (12). Seasonal migration for work or in search of feed is normal in transhumant societies, but in severe drought the migrating families may never return, as was true for the American Great Plains in the twenties and for the Sahel in the seventies.

The final act of adjustment and the most destructive is to sell one's land. No redress is possible and the seller is condemned to a landless life either in the rural labor force or in shanty towns on the fringes of cities. Clearly it is wise for governments to bring in relief measures that will at least prevent starvation and distress sales of land.

From 1971 to 1973, severe drought, similar to that in the Sahel, affected much of India. In the face of widespread crop failures, human and animal migration and the very real threat of starvation, the government of the State of Maharashtra organized massive food-for-work programs in its rural areas. At its peak over 5 million people were employed on relief work, building roads, dams and canals. Subramanian (15) claims that there were no deaths directly attributable to starvation in those years. Many critical and perceptive reporters visited Maharashtra and came away full of praises for the state effort. Wolf Ladejinsky, in the Economic and Political Weekly (Bombay) of 17 February 1973, called the Maharashtra drought "a disaster of unprecedented dimension" and complimented the state government for organizing relief and employment works on such a large scale. John Pilger, in the New Statesman (London) of 8 June 1973, commented, "the Herculean relief efforts of both the Indian and State Governments have undoubtedly prevented [the drought] from becoming a famine in the classic sense with people dying in their tracks."

COMPONENTS OF TECHNOLOGIES TO IMPROVE FOOD PRODUCTION

Past approaches to resource development to increase agricultural production in the semi-arid tropics have achieved only limited success because they have not recognized the basic climatological and soil characteristics of the region nor utilized natural watershed and drainage systems (16). Better technologies are now being developed to ameliorate the effects of drought, increase food production per unit of land and capital, assure stability, and contribute directly to improving the quality of life.

Improved Soil Management Practices

Effective soil management practices in the rainfed semi-arid tropics must produce a suitable seed bed, ensure the proper placement of seed and fertilizer, destroy weeds, conserve soil moisture and minimise runoff and erosion.

Dry season primary tillage is now a common practice on the Vertisols of semi-arid India. The soils are ploughed in March or early April after the post-rainy season crop is harvested. Because there is still some moisture in the soil, the power required for tillage is less than it would be later in the dry season, and the draft animals are well-fed and strong. Some weeds do grow, but these are removed in the final preparation of the seed bed which is done nearer to the onset of the rains. Pre-monsoon showers, which are nearly certain climatic events, soften the soil for the final land preparation.

Crust formation on the surface is a problem with many sandy textured soils in the semi-arid tropics. The power required to break the crust is low for most of these soils [see, however, Nicou and Charreau (17)] but the crust reforms after rains and impedes seedling emergence. Incorporating organic matter into the soil helps to decrease the strength of the crust - probably by increasing soil moisture near the surface - but no satisfactory technology exists so far for dealing permanently with this problem.

Time of planting is important. Planting as early as the rains will permit will generally ensure good yields in most years, but research shows clearly that highest yields are obtained if planting occurs about two weeks later. [Table 8, Randhawa and Venkateswarlu (18)]. Probabilities based on climatological evidence can now be used to predict optimum planting dates.

Accurate placement of seed and fertilizers ensures high seedling densities, vigorous early growth and resistance to drought, but is seldom attained in traditional agriculture. Practicable and economic new technologies to ensure accurate placement in rainfed semi-arid tropical agriculture have yet to be developed. It is probably the area where greatest gains can be made from increased research efforts.

Timely weed control measures are important to conserve moisture and to avoid competition to the standing crop. Poor weed control can reduce yields by 50% or more. The use of herbicides is uneconomic or uncommon except on some cash crops, and weeding is done manually or by using animal drawn implements. Weeding is a major source of employment for landless labor in India, and a major bottleneck to increased production in labor-scarce areas of Africa.

Since the amount of water infiltrating into the soil is a function of the infiltration opportunity time and soil surface conditions, vegetative cover and land slope can be suitably modified to retain most of the rainfall on the ground surface. Reduced tillage maintains crop residues on the surface and contributes to improved infiltration and reduced evaporation and erosion. Land shaping in various forms has similar effects.

Use of Fertilizers

Most of the soils of the semi-arid tropics are of low fertility, being almost universally deficient in nitrogen and phosphorous (19, 20). Sulphur deficiency is common in Africa where the annual rainfall exceeds 600 mm.

Fertilizers are not commonly used in rainfed agriculture. Unirrigated districts in semi-arid India use an average of 18 kg/ha of fertilizers ($N + P_2O_5 + K_2O$) per hectare of cropped area compared to 57 kg/ha in irrigated districts (21). Most of the fertilizer used in the unirrigated areas is used on cash crops such as cotton, tobacco and groundnut.

There is much evidence to show that fertilizer use is economic on the staple semi-arid cereals. Several hundred experiments on cultivator's fields with sorghum, maize and pearl millet in semi-arid India have given average gains of 14 kg of grain per kg of N and 7 kg of grain per kg of P_2O_5. Benefit to cost ratios are 4 or greater (22).

Soil type and particularly water-holding capacity have significant effects on the efficiency of fertilizer use (Fig.3).

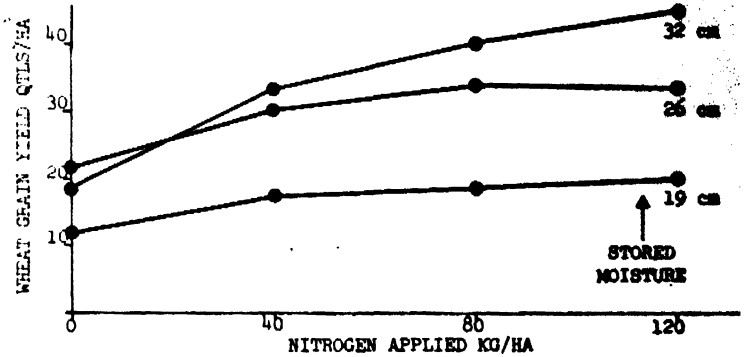

Figure 3. Response of rainfed wheat to nitrogen on soils having different stored moisture (22).

Crops grown on the same soil in the rainy season will usually have higher fertilizer use efficiencies than crops grown in the dry season on receding stored moisture.

Good plant nutrition stimulates early plant growth and root proliferation into the subsoil. The fertilized crop is able to draw effectively on subsoil resources of water and is better protected against drought (23).

Use of Improved and Appropriate Seeds

The combination of genes that reduced plant height and susceptibility to lodging with genes for responsiveness to added nutrients resulted in quantum jumps in the yields of wheat and rice in irrigated agriculture. Similar approaches are proving successful with maize, sorghum and pearl millet grown in rainfed conditions. Improved varieties and hybrids often outyield local varieties. Hybrids that have satisfactory grain quality and levels of disease resistance combined with high yields are attractive to farmers. Although year to year variability in yield is higher for hybrids than for local varieties, the yield gains and other characteristics of good hybrids are sufficient to persuade farmers to take the higher risks involved. In Maharashtra State hybrids now make up 35% of all sorghum planted, and more than 70% in the postrainy season. Average yields in the state are 50% higher than they were ten years ago.

The best crops to use in any particular district depend upon climate, soils and agricultural and socioeconomic traditions. Considerable efforts by the All India Coordinated Research Project for Dryland Agriculture have now determined the most appropriate crops for most of the semi-arid regions of India. For example, Randhawa and Venkateswarlu (18) give tables for most suitable crops and cultivars, for six districts with growing seasons usually less than 20 weeks, seven districts with growing seasons between 20 and 30 weeks and eight districts with growing seasons exceeding 30 weeks. The crop combinations recommended are the results of 3 to 7 years research work.

Intercropping

Farmers in the semi-arid tropics commonly intercrop their land. There is considerable scope for improving the usefulness and productivity of intercropping as can be illustrated by considering two contrasting intercropping systems, sorghum/pigeonpea and millet/groundnut. The first is typical of those systems in which an early cereal (maize, sorghum or pearl millet) is combined with a slow-growing, reasonably tall long-season crop

(pigeonpea, cotton, castor or cassava). The second is representative of systems using a tall cereal combined with a quick-growing low legume (beans, soybean, groundnut or cowpeas).

Sorghum/Pigeonpea. Pigeonpea is a long season crop that matures in 6 months but its early establishment is characterized by prolonged slow growth for as long as 2 months. During this period the crop is inefficient in utilizing resources, e.g. the sole crop during this period intercepts just 50% of available light and produces only 20% of its total dry matter. Intercropping with earlier maturing crops such as sorghum improves the use of natural resources for the total crop period. This combination is very important in the Deccan plateau of India covering Maharashtra, parts of Madhya Pradesh, Andhra Pradesh and Karnataka where sorghum is the staple food. It shows promise in similar environments in West Africa. Its value as a hedge against disaster has already been mentioned.

In the traditional system, farmers grow several rows of sorghum (6-12) with one or two rows of pigeonpea. This cropping pattern is chosen deliberately to ensure a full yield of the staple cereal. The yield of pigeonpea is considered as a bonus. The pattern is inefficient in the use of late-season resources because the pigeonpea is sparsely distributed and cannot cover the ground. Studies by ICRISAT and the All India Coordinated Research Project on Dryland Agriculture have shown that the proportion of pigeonpea can be increased to 2 sorghum : 1 pigeonpea without seriously affecting sorghum yield provided the sorghum population is maintained equivalent to the sole crop optimum (24, 25). The sorghum in this combination has a similar growth pattern to the sole crop and produces 90-95% of the sole crop yield. The pigeonpea, after sorghum harvest, compensates, i.e. it spreads to make use of the entire field space, and can produce 70% of sole crop yield. The combination gives a 60-70% advantage over sole cropping in terms of land productivity. Furthermore, the intercropped pigeonpea is efficient in the sense that a greater proportion of dry matter is harvested as seed yield (30%) compared to the sole crop (20%). Vertisols, with their better water-holding capacity than Alfisols enable intercropped pigeonpea to produce much better growth in the postrainy season resulting in higher relative yields and greater yield advantages (Table 4).

Millet/Groundnut. This combination is adapted to soils with moderate water-holding capacities. Both crops usually mature less than 3 weeks apart, so the intercropping advantage is not as great as for sorghum/pigeonpea. Because the groundnut is an important cash crop, the farmer usually requires quite a high proportion of this crop and a good row arrangement appears to be 1 millet : 3 groundnut with the same within-row

Table 4. Grain yields and land equivalent ratios in sorghum/pigeonpea intercropping on two soil types (Average of 3 years)

	Vertisols					Alfisols				
	Yield		Land equivalent			Yield		Land equivalent		
	Sole	Inter-crop	LES*	LEPP**	Total	Sole	Inter-crop	LES*	LEPP**	Total
Sole crops										
Sorghum	4500		1.00	-	1.00	4573	-	1.0	-	1.00
Pigeonpea	-	1314	-	1.00	1.00	-	1770	-	1.0	1.00
Intercropping										
1:2 Sorghum/ Pigeonpea	4240	945	0.94	0.72	1.66	3641	1140	0.80	0.64	1.44

*LES (Land equivalent ratio for Sorghum) is the relative land area required by a sole crop of sorghum to achieve the yields produced by the same component in the intercrop.

**LEPP (Land equivalent ratio for Pigeonpea) is the relative land area required by a sole crop of pigeonpea to achieve the yields produced by the same component in the intercrop.

population as in the respective sole crops (26). This system has given a proportionate yield of 50% of pearl millet and 77% of groundnut giving a 27% yield advantage over sole cropping (Table 5). The increase comes mainly from the pearl millet which compensates for the low density by increased yield per plant.

Table 5. Grain or pod yields and land equivalent ratios in pearl millet/groundnut intercropping (Average of 3 years)

	Yields (kg/ha)		Land equivalents		
	Millet	Groundnut	LEM*	LEG**	Total
Sole Crops					
Pearl millet	2370	-	1.0	-	1.00
Groundnut	-	2332	-	1.0	1.00
Intercropping					
1:3 millet/G'nut	1177	1796	0.50	0.77	1.27

*LEM (Land equivalent ratio for millet) is the relative land area required by a sole crop of millet to achieve the yields produced by the same component in the intercrop.

**LEG (Land equivalent ratio for groundnut) is the relative land area required by a sole crop of groundnut to achieve the yields produced by the same component in the intercrop.

The advantages obtained in the above combinations are the result of the complementary use of resources over time and space without additional cost. The advantage of intercropping, in fact tends to be higher at low fertility or in low moisture conditions (27); but this does not mean that this practice is valid only in poor situations. Although the relative advantage over sole cropping decreases with higher fertility or better moisture supplies, the absolute advantage in total crop yields is usually increased.

Other Cropping Systems

Many of the Vertisols in India are cropped in the postrainy season after a rainy season fallow. ICRISAT research has shown that some of these soils can be cropped during the rainy season without affecting the postrainy season crop resulting in substantial increases in yields and profits. The rainy season crop must be planted early in dry soils before the onset of the rains, which also avoids the problem of working in wet, sticky soils. Postrainy season crops can be established either sequentially (e.g. chickpea or safflower), or - with some difficulty - by relay planting (e.g. sorghum and pigeonpea). Intercropping of sorghum/chickpea or safflower/chickpea in the postrainy season has been examined but the intercropping advantage is only about 20%. Double cropping is less profitable than intercropping. For example, intercropped maize/pigeonpea is 73% more profitable and 34% less variable than maize followed by chickpea. The problems with the double crop are the additional cost involved in establishing the second crop and the poor crop stands that may sometimes result due to the early cessation of rains.

On soils such as Alfisols the shorter growing period precludes double cropping with two full season crops. But efforts have been made to extend cropping beyond a single season sole crop system, either by intercropping or by using additional short season crops. Sole castor, an industrial crop, or combinations involving it, have given highest net returns (Table 6). Averaged over two years, a sorghum/pigeon

Table 6. Cropping Systems on Alfisols 1978-79, 1979-80

Cropping Systems	Grain yield (kg/ha)		Net monetary returns (Rs/ha)*	
	1978-79	1979-80	1978-79	1979-80
Sole castor	1462	1144	2039	2814
Sole groundnut	1236	1173	1133	2211
Sole sorghum	2516	2241	1402	1466
Sole millet	1940	2099	1158	1915
Sorhum/pigeonpea intercrop	2169/417	1680/831	1873	2855
Millet/groundnut intercrop	849/869	1063/881	1293	2681
Mungbean + Relay castor	634+885	603+737	2075	3393
Mungbean + Sequential castor	593+672	569+613	1766	2928
Millet + Relay Horsegram	1866+594	2099+536	1412	2181

*Gross returns less the cost of seeds, fertilizers and pesticides. Prevailing market prices (Rupees/100 kg) one month after the harvest of the respective crops used for calculating gross returns for 1978-79 and 1979-80 were, respectively, Castor 170 and 185, Groundnut 150 and 250, Sorghum 80 and 90, Millet 80 and 110, Pigeonpea 230 and 260, Mungbean 200 and 330, Horsegram 100 and 102. Cowpea 180 and 222.

pea intercrop has proved almost as good as sole castor and the extended cropping systems have proved more profitable than sole food crops.

Proportionate cropping, i.e. allocating land resources to crops based on formulae relating crop durations to the probabilities of adequate soil moisture can help decrease the risk of loss and increase overall farm productivity. Research conducted at Haryana Agricultural University in northern India showed that allocation of 40% of the land to guar, a very drought resistant crop, with a 120 day growing season, 40% to pearl millet, a drought resistant crop, with a 70 day growing season and 20% of land to mung bean with a 50 day growing season allows the farmer to harvest all the three crops in the best years and at least two crops in all but severe drought years.

Crop rotations are used particularly in semi-arid West Africa to increase production. In low intensity cropping, the cropping sequences include fallow. Charreau (28) recommends one year of fallow or green manure plowed under followed by groundnut by cereal and finally by groundnut or cowpea. The cereal is usually long season pearl millet or sorghum. The effects on soil physical properties of incorporating green manure are well known resulting in beneficial effects on rooting and production of the succeeding crop. Where rainfall is fairly low and irregular as in northern and central Senegal, a four year rotation of fallow or pearl millet as a green manure followed by groundnut followed by cereal followed by groundnut is recommended or a five year rotation such as fallow or green manure - pearl millet - groundnut - pearl millet - groundnut.

In intensive cropping, the fallow period is eliminated and plowed under grass fallow or green manure is replaced by plowed under straw of short-season cereals (29).

Watershed Management

In rainfed agriculture the main source of available water is rain, but many of the soils of the region have poor infiltration characteristics and excess runoff and erosion or waterlogging can be serious problems at various times during the rainy season. The solution lies in developing technologies that make use of the natural topography and drainage patterns. The small watershed is a natural framework for resource development aimed simultaneously at stabilizing and increasing crop production through more effective use of available water and at resource conservation through insitu conservation measures.

At ICRISAT over the last eight years and in operational-scale village-level studies over the last three years, a technology for land and water management on deep Vertisols using graded broad-beds and furrows within small watershed units has proved successful in achieving both the above objectives (30).

The 150 cm wide beds are graded across the contour to a 0.6% slope and are separated by furrows that drain into grassed waterways. The broad-beds are not likely to be breached in heavy rainfall, and allow a flexible planting pattern in rows spaced at 30 cm, 45 cm, 75 cm or 150 cm. They reduce runoff under both fallow and cropped conditions and greatly reduce soil erosion in comparison to ungraded fallow soils (31). The use of graded broad-beds and furrows gives higher gross returns and profits. They can be established successfully within existing field boundaries at some loss in profits.

Dry seeding of the crop about two weeks before the onset of the rains is possible on these soils if the early rainfall is fairly reliable (32) and in most years will enable a postrainy season crop to be taken thereby increasing greatly the gross returns, profits and the rainfall use efficiency.

Supplementary 'life-saving' Irrigation

Dry periods within the monsoon are typical of many semi-arid tropical regions even when normal or above normal seasonal rainfall occurs. The result is usually a reduction in crop yield, especially on soils which have relatively low water holding capacities. The availability of water for supplemental irrigation is an important means to reduce risk and improve production.

During the 1974 rainy season at ICRISAT Center, most of the runoff storage reservoirs were partially (50-70%) filled during the early part of the rainy season, thus providing water, if required, for 'life saving' irrigation during drought. The results of supplemental irrigation to crops on Alfisols during a 30-day drought in late August and early September were spectacular. Yields of sorghum and maize were approximately doubled by the application of one 5 cm irrigation. At product prices prevailing at the time of harvest, gross values of the increase due to the use of 5 cm of water were 3,120, 2,780, 1,085 and 650 Rs/ha for maize, sorghum, pearl millet and sunflower respectively (33).

During the postrainy season, supplemental irrigation can substantially boost crop yields because residual soil moisture is usually insufficient to prevent some drought stress at important physiological stages of growth. Sivakumar et al (34) showed that supplemental irrigations given at the time of panicle emergence and flowering of grain sorghum grown on a deep Vertisol gave an additional yield of 3,560 kg/ha over the control treatment (2430 kg/ha). The net benefit accruing from the supplemental irrigations was Rs.2,500/ha.

CONTRIBUTIONS OF THE RAINFED SEMI-ARID TROPICS TO FOOD PRODUCTION

Most of the cropping in the semi-arid tropics will continue to be done in rainfed conditions by small farmers with meagre resources producing staple cereals of low value for which few price incentives to production exist. Currently yields are low and production is unstable due to aberrant weather and the high incidence of pests and diseases. The semi-arid tropics with 13% of the world's land and 15% of its people produces only 11% of its food.

Food production can be increased in the rainfed semi-arid tropics; in India mainly through improved technology, in Africa mainly by increasing the land area under cultivation. Average yield levels in India for the major rainfed cereals and grain legumes are between 300 and 800 kg/ha. They can be doubled by the use of improved technologies. Taking sorghum as an example, the average yield is 800 kg/ha and the potential under rainfed conditions is at least 2500 kg/ha. More importantly, better farmers are already obtaining 1500 to 2000 kg/ha in rainfed conditions using improved seeds and some fertilizers. The highest yields are obtained on fields where the farmer can use supplementary irrigation. For pearl millet the average is around 600 kg/ha, the potential in rainfed agriculture is about 1500 kg/ha and better farmers' yields are 1000 to 1200 kg/ha. Lifting the averages to the level of better farmers' yields will mean more food production, more agricultural employment or higher returns to labor, more food for the farmers and their dependents, and significantly increased gross returns and profits.

The situation in the Sahel and other regions of semi-arid Africa is less promising. Improved technologies, and, particularly, improved seeds, are not so available and the institutions and infrastructure necessary for successful diffusion of new technologies are less developed (35). The differences between average yields, best farmer practices and potentials appear to be much narrower than in India from the limited evidence available.

There is scope to increase the area under cultivation in Africa without environmental loss. FAO in developing a food plan for Africa considered that for increased production of staple cereals in the Sahel, improvements in cropping patterns would contribute 17%, improved yields 36% and increased acreage 48% (36). Even if the necessary improvements and increases are made, the combined self sufficiency ratio in the Sahel for maize, sorghum and pearl millet will still be below 100 by 1990, with a deficit in excess of 200,000 tons of grain. The total deficit in food grains in the Sahel in 1990, including irrigated crops, is projected to be more than 700,000 tons.

For the semi-arid tropics as a whole, yield and production of sorghum, pearl millet and the two major grain legumes, are increasing slowly (Table 7). Only for sorghum does the increase in production exceed the average annual increase in population for the region, which is approximately 2.5%. Total food grain production in the semi-arid tropics, including irrigated crops in developed countries, is actually in excess and the region is in a position to export food (Table 8). The figures in the table allow mild optimism in the long-term about the prospects for food production in the region, except perhaps for drier areas in the Sahel and except in the driest years. If successful technologies can be transferred within the region, and the necessary institutions and infrastructure provided, some aspects of the variability in climate can be overcome. Sustained increases in production, employment and incomes are possible, but buffer stocks and food aid will always be needed to ameliorate the effects of severe drought.

Table 7. Annual compound growth rates of five major crops in the less developed countries of the SAT during 1964-74 (4)

Crop	Area (%)	Yield (%)	Production (%)
Sorghum	0.71	2.08	2.81
Millets[a]	0.04	1.20	1.24
Chickpea	-1.29	1.46	0.15
Pigeonpea	-0.08	0.83	0.75
Groundnut	-0.40	0.02	-0.38

[a]Includes pearl millet (Pennisetum americanum), as well as the minor millets such as Setarias, Panicums, and Eleusines.

Table 8. Estimated food requirement and food production in the semi-arid tropics*

Parameters	Based on countries in SAT as a whole (a)	Based on percentage area of each country in SAT[1/] (b)
1. Population (persons)	1375.4	625.1
2. Consuming population (persons)[2/] [(1) x .85]	1169.1	531.3
3. Estimated food requirements for adult population (MT)[3/]	233.8	106.3
4. Total food grain production (MT)	316.8	135.2
5. Surplus/deficit of food grains [(4) - (3)] (MT)	+ 83.0	+ 28.9
6. Surplus/deficit (Exports-Imports) of food grains (MT)	+ 11.9	+ 1.7

*Data is based on FAO (Publication Yearbook 1978) results on cereal production in 1976, 1977 and 1978 years. Food refers to cereals only.

[1/]Semi-arid areas and populations were estimated by using Troll map (37) on climatic regions of the world by estimating the regions in V_3 and V_4 (dry Savanna and Thorne Savanna) in each country.

[2/]Consuming population was derived by decreasing 15% of the population under the assumption that this constitutes the population under the age of five years who do not consume much grains (Osmania University, Personal Communication).

[3/]Food requirements were estimated on the basis of 200 kg per adult per year by C. Gopalan et al. (38).

ASSUMPTIONS

(1) In these data no provision is made to separate the cereal yields under irrigated and rainfed conditions; these will be substantially different.

(2) Population in the semi-arid tropics is computed simply by multiplying the population of the country by the percentage area of the country in the region, without giving weight to the density of population.

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