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Potential Agricultural Productivity in Summer and Winter Rainfall Areas*

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Summary

The productivity of summer and winter rainfall areas in the arid and semi-arid regions of the world was assessed through an evaluation of the climatic characteristics and potential dry matter production in relation to present productivity. Comparison of the average yield data for several crops in different regions with yields achieved under adequate management at experimental stations indicates that considerable potential exists for improving and stabilizing crop yields. The total biomass production is influenced by the intensity and duration of moisture stresses that frequently occur during the growing season. Fertilizer use in the summer and winter rainfall areas is closely related to the amount of rainfall and the availability of water for supplemental irrigation. Current use of fertilizers in these areas is reviewed and the constraints on yield and on the use of fertilizers are discussed. Further discussion in the course of the colloquium should lead to the identification of the means to alleviate these constraints.

1. Introduction

In the semi-arid and arid areas of the world, in view of the world's increasing population, there is an urgent need to increase agricultural production. The agricultural resources of the rainfed areas are limited, water being the chief constraint to improved production. According to estimates made by the *National Commission on Agriculture,* the percentage of net irrigated area to net sown area by the year 2000 in India is likely to be 41 % and agriculture in most of the cultivated areas in India will continue to be mainly rainfed *(Garg [10]).* This will require extension of cultivation to marginal areas, and increased efforts to make efficient use of the available natural and human resources in these areas. Since rainfall is the most important natural resource that should be utilized efficiently, quantification of its availability in different regions and of the effect of water limitation on crop production, is essential to improve existing levels of productivity.

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The purpose of this paper is to examine the current agricultural productivity in the summer and winter rainfall zones in the semi-arid and arid areas of the world and current fertilizer use in these regions and to identify the constraints on crop yields and fertilizer use.

2. Basic characteristics of summer and winter rainfall climates in semi-arid and arid areas

The procedures and criteria employed for classification of the arid and semi-arid areas of the world vary widely *(Koppen [20], Thomthwaite [38], Meigs [24], Troll [40], Hargreaves [14],* and *Papadakis [27]).* In this paper we will consider mainly the tropical and subtropical summer and winter rainfall zones identified by *Koppen [20]* and described in greater detail by *Trewartha [39].*

The summer rainfall areas are alternately under the influence of the equatorial westerlies of the Inter-Tropical Convergence Zone during the high sun period, or summer, and of the dry trade winds and subtropical anticyclone during the low sun period or winter. The winter rainfall areas occur mostly in the subtropics that are alternately influenced by middle-latitude westerlies and their wave disturbances in winter, and the stable eastern end of an anticyclonic cell in summer. The winter rainfall zones are typically located on the subtropical western side of a continent *(Trewartha [39]).*

2.1 Slimmer rainfall climates

The summer rainfall climates are classified by *Koppen [20]* under tropical wet and dry climates, and tropical and subtropical dry climates.

The tropical wet and dry climates are located from about 5 or 10° latitude on either side of the equator up to 15° or even 20° *(Trewartha [39]).* The summer rainfall and winter dry season are characteristically associated with the dominance by contrasting elements of atmospheric circulation in the two seasons. The summer rainfall areas cover almost all continents of the world. The tropical and subtropical dry climates more or less coincide with the more stable parts of subtropical anticyclones and trades in the vicinity of latitudes 20 or 25°N and S *(Trewartha [39]).*

In order to describe the distinct characteristics of the summer rainfall areas, we have selected seven locations from six countries representing a latitudinal range from 12°N to 31°N (Table 1). Except for Asmara (Ethiopia) all the locations are situated in lowland plains.

According to *Trewartha [39]* three temperature periods can be recognized in the summer rainfall areas: the cool dry season at the time of low sun or winter, the hot dry season just preceding the rains, and the hot wet season during the rains. Crops are mainly grown during the wet season and with supplemental irrigation during the dry season. Temperatures may rise very slightly just after the rainy period as a result of clear skies and drier atmosphere. Daily temperatures are consistently high throughout the year, the highest temperatures occurring just before the onset of the rains (Table 2). At Lahore the temperatures from December to February are low. In

Table 1. Geographical attributes of seven locations chosen in the summer rainfall areas of the northern hemisphere.

Location	Country	Latitude	Longitude	Elevation (m)
Asmara	Ethiopia	15°17'N	38°55'E	2300
Bijapur	India	16°49'N	75°43'E	594
Gao	Mali	16°16'N	0°03'W	270
Indore	India	22°43'N	75°48'E	567
Kano	Nigeria	12°03'N	8°32'W	470
Lahore	Pakistan	31°33'N	74°20'E	214
Niamey	Niger	13°30'N	2°07'W	220

Table 2. Mean maximum and minimum air temperature (°C) at selected locations in the summer rainfall areas.

Month		Asmara	Bijapur	Gao	Indore	Kano	Lahore	Niamey
Jan.	Max.	23	30	28	26	13	19	34
	Min.	7	16	14	10	13	5	14
Feb.	Max.	24	33	33	29	33	22	37
	Min.	9	18	17	11	15	8	17
Mar.	Max.	25	36	36	34	37	28	41
	Min.	10	21	22	15	19	13	21
Apr.	Max.	25	38	41	38	38	35	42
	Min.	11	24	25	20	24	18	25
May	Max.	26	39	41	40	37	40	41
	Min.	12	24	27	25	24	24	27
June	Max.	26	33	39	36	34	41	38
	Min.	12	22	28	24	23	27	25
July	Max.	22	30	36	30	31	37	34
	Min.	12	22	27	23	22	27	23
Aug.	Max.	22	30	34	28	29	36	32
	Min.	12	21	25	22	21	27	23
Sep.	Max.	24	31	37	29	31	36	34
	Min.	10	21	26	21	21	24	23
Oct.	Max.	22	31	38	31	34	34	38
	Min.	9	21	26	17	19	17	23
Nov.	Max.	22	30	34	29	33	28	38
	Min.	9	17	21	12	16	10	18
Dec.	Max.	22	29	31	27	31	22	34
	Min.	8	15	17	10	13	6	15

Source: *Griffiths [13].*

the highlands of Ethiopia (Asmara) temperatures are low because of the high altitude. It is relevant also to examine the extreme temperatures that occur in these regions because the crops differ in their sensitivity to withstand temperature stress. Highest temperatures are 48 °C at Gao in Mali and minimum temperatures below 0 °C have been recorded at Indore and Lahore.

Table 3. Mean global solar radiation (MJ/m^2/day) at selected locations in the summer rainfall areas.

Month	Asmara	Bijapur	Gao	Indore	Kano	Niamey
January	21.3	20.7	16.4	18.4	18.9	19.3
February	23.3	23.3	20.0	21.4	20.1	20.8
March	24.8	24.5	21.1	23.1	20.6	20.8
April	25.3	24.9	22.1	25.6	20.3	21.0
May	25.6	24.1	22.0	27.0	21.4	21.2
June	23.0	20.5	21.7	22.3	20.3	20.7
July	17.7	17.8	22.2	16.6	18.6	18.9
August	17.4	19.3	21.2	15.3	16.4	17.6
September	22.7	19.7	20.8	18.7	20.1	19.3
October	23.0	20.1	19.9	21.3	21.7	21.0
November	20.8	19.5	18.0	19.2	20.5	24.3
December	20.0	19.2	16.5	17.2	18.8	18.2

* Radiation data for Lahore were not available.
Source: *Griffiths [13].*

Mean monthly solar radiation also is usually high throughout the year (Table 3) except during the wet season when the increased cloudiness causes a reduction in radiation. Such high energy levels, in the absence of other constraints, are indicative of high potential crop productivity.

Rainfall in the summer rainfall climates is highly variable. The coefficient of variability (CV) of annual rainfall is high. For example, for several locations in the semi-arid regions in West Africa *Cocheme* and *Franquin [4]* found that the CV of annual rainfall ranges from 15 to 38%.

Rainfall variability occurs inter-yearly as well as seasonally. Because most summer rainfall areas are located between the *Inter-Tropical Convergence (ITC)* and the dry trades, the monthly rainfall distribution shows marked annual wet and dry periods with the northwards movement of the ITC during summer and its retreat in late summer. The annual as well as monthly rainfall of any one location varies with its latitudinal position. *Kowal* and *Knabe [21]* showed that, for the northern states of Nigeria annual rainfall decreases by 119 mm for every degree latitude. In West Africa, Kano (Nigeria), located at 12 °N, receives a mean annual rainfall of 873 mm, while only 270 mm is recorded at Gao (Mali) situated further north at 16° 16'. In the summer rainfall areas of northern Australia the mean annual rainfall ranges from 300 mm at 20°S latitude to above 1200 mm at 12°S latitude. In India, however, rainfall variation with latitude is not so simple to explain because of the distinct differences in the atmospheric circulation leading to 'monsoons' over the area.

A substantial proportion of the rainfall usually occurs in a few high intensity storms. The intensity of rainfall usually varies from 20 to 60 mm/hr in most instances, but intensities as high as 120-160 mm/hr are not uncommon *(Miranda et al [25]).* Hence the soil loss that accompanies the runoff caused by such high-intensity storms may be substantial. For example, *Miranda et al. [25]* showed that, over the 5-year-period 1977-1981 at *ICRISAT* Center, in a traditional rainy season fallow system, average soil loss was 6.93 t/ha/year.

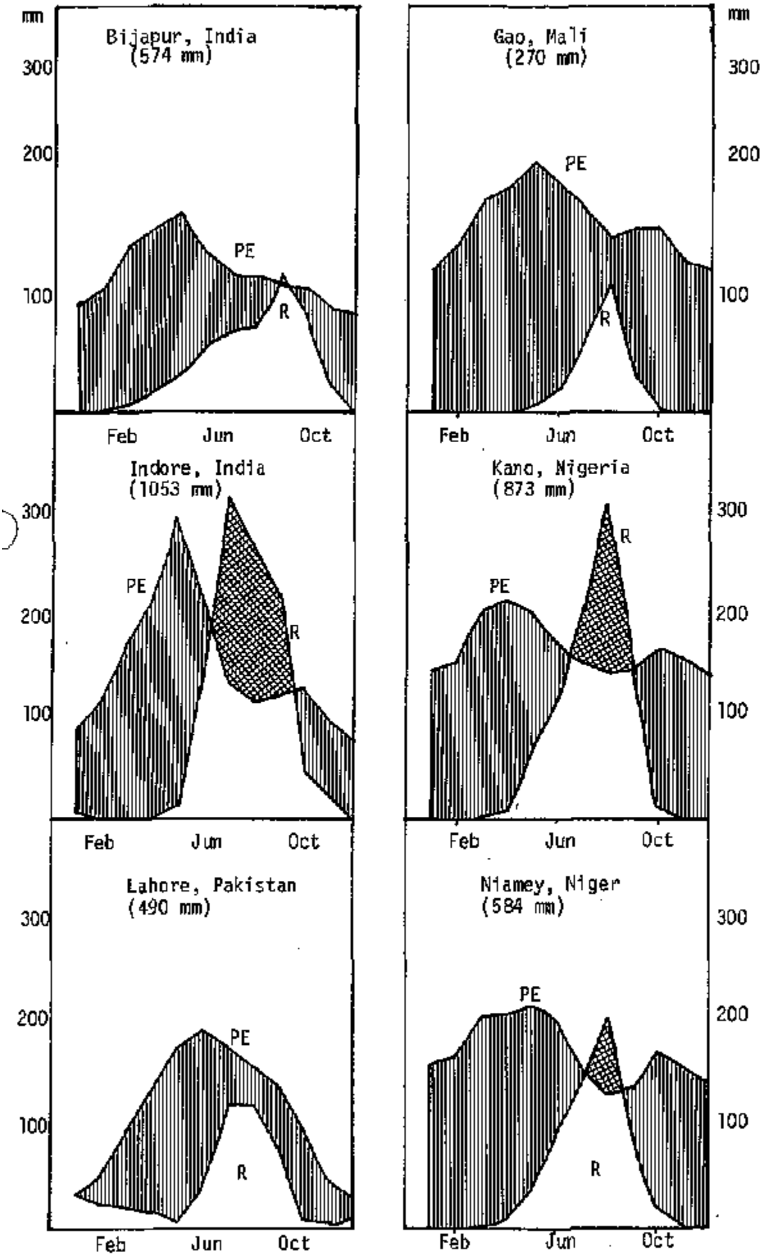

Fig. 1 Monthly variation in rainfall (R) and potential evapotranspiration (PE) at six selected locations in the summer rainfall areas. ▥ Water deficiency; ▦ soil moisture recharge. Mean annual rainfall for the locations is given in parenthesis.

Because of the high radiation energy and uniformly high temperatures, the atmospheric demand for water is high. For example, in central and northern India the average potential evapotranspiration (PE) in June ranges between 6 and 8 mm/day, while in northwestern India and Pakistan it exceeds 8 mm/day *(Sivakumar et al. [33])*.

High rates of evapotranspiration coupled with low and unpredictable seasonal rainfall often lead to periods of water shortage that have serious implications to the production and even the very survival of crops. The moisture balance diagram (Figure 1) for six locations shows that there is only a 2 to 3 month period during the growing season when rainfall exceeds PE, permitting some soil moisture recharge to be followed by utilization in the succeeding months.

2.2 Winter rainfall climates

Most of the winter rainfall or 'Mediterranean' climates in the arid and semi-arid areas occur in the middle latitudes where the climate may be classified as subtropical to warm temperate. The main features of these areas, according to *Trewartha [39]* are: (1) a concentration of the mean annual rainfall in the winter season, while summers are nearly or completely dry; (2) warm to hot summers and unusually mild winters; and (3) abundant sunshine and meager cloudiness, especially in summer. Denoted as 'CS' (which stands for subtropical dry summer) by *Koppen [20],* these occur in west Asia (Turkey, Syria, Lebanon, Israel, Jordan, Saudi Arabia, People's Democratic Republic of Yemen, Yemen Arab Republic, Oman, United Arab Emirates, Qatar, Iraq, Kuwait and Iran); North Africa (Morocco, Algeria, Tunisia, Libya, Sudan and Egypt), central Chile, the southern tip of South Africa, parts of southernmost Australia, and central and coastal southern California.

These Mediterranean areas are typically located on the tropical margins of the middle latitudes along the western sides of continents *(Trewartha [39])* that are affected by the stable eastern end of an oceanic subtropical high. In the cool months of the winter the relative warmth of the Mediterranean sea, and the accompanying low pressure trough, make the Mediterranean basin in west Asia and North Africa a region of convergence, with the associated development of fronts and cyclones.

Depending on the temperatures in summer and winter and the amount of rainfall, Mediterranean regions in west Asia may be further subdivided *(Glenn [12])*. In the coastal strips of Turkey, Cyprus, Syria, Lebanon and Israel the summers are hot and dry. In the eastern parts of Turkey and northern and western parts of Iran, dry and warm summers occur. In the western half of the Arabian peninsula and Oman plateau and in the interior parts of Jordan, Syria, and Israel the climate is semi-arid. In southern parts of Iraq and Iran a steppe climate occurs. In the Mediterranean regions of North Africa a similar zonation, also based on average rainfall, has been suggested *(Griffiths [13])*.

As in the case of summer rainfall climates, we use selected locations in different countries to describe the key climatic characteristics (Table 4). In the winter rainfall climate basic features of the temperature show much more variation between different areas in the region than those of rainfall. In west Asia winter temperatures decrease from south to north, from east to west and from low to high elevations. As

Table 4. Geographical attributes of locations chosen in the winter rainfall areas.

Location	Country	Latitude	Longitude	Elevation (m)
Damascus	Syria	33°29'N	36°14'E	729
Amman	Jordan	31°59'N	35°59'E	766
Baghdad	Iraq	33°20'N	44°24'E	34
Tehran	Iran	35°41'N	51°19'E	1191
Algiers	Algeria	36°46'N	3°03'E	60
Rabat	Morocco	34°03'N	6°40'W	75
Tripoli	Libya	32°54'N	13°11'E	20

Table 5. Mean maximum and minimum air temperatures (° C) at selected locations in the winter rainfall areas.

Month		Damascus	Amman	Baghdad	Tehran	Algiers	Rabat	Tripoli
Jan.	Max.	12.3	12.5	15.8	9.4	15.0	17.0	17.0
	Min.	2.5	3.7	4.3	-0.3	9.0	9.0	8.0
Feb.	Max.	14.1	13.7	18.7	11.0	16.0	18.0	18.0
	Min.	3.3	4.3	5.9	0.6	9.0	9.0	9.0
Mar.	Max.	17.8	17.6	22.7	15.8	17.0	19.0	20.0
	Min.	5.2	6.2	9.6	4.0	11.0	10.0	10.0
Apr.	Max.	22.8	22.6	28.7	20.9	20.0	20.0	23.0
	Min.	8.6	9.3	14.6	8.9	13.0	11.0	13.0
May	Max.	28.5	28.0	35.8	30.2	23.0	23.0	25.0
	Min.	12.6	13.4	20.0	15.7	15.0	14.0	16.0
June	Max.	33.6	31.0	41.0	34.2	27.0	26.0	29.0
	Min.	16.1	16.3	23.4	19.8	18.0	16.0	19.0
July	Max.	35.8	32.1	43.4	36.6	28.0	26.0	30.0
	Min.	17.2	18.1	25.3	22.7	21.0	17.0	21.0
Aug.	Max.	36.1	32.8	43.3	36.3	29.0	27.0	31.0
	Min.	17.5	18.4	24.6	22.8	22.0	18.0	22.0
Sep.	Max.	32.4	30.9	39.8	31.0	27.0	26.0	30.0
	Min.	15.3	16.2	21.0	18.0	21.0	17.0	21.0
Oct.	Max.	27.1	27.5	33.4	23.2	23.0	24.0	28.0
	Min.	12.4	13.7	16.2	11.9	17.0	14.0	18.0
Nov.	Max.	19.8	21.0	24.6	16.8	19.0	20.0	23.0
	Min.	7.7	9.6	10.3	6.3	13.0	11.0	13.0
Dec.	Max.	14.0	14.8	17.7	11.9	16.0	17.0	18.0
	Min.	4.1	5.4	5.5	1.7	11.0	9.0	9.0

Source: *Taha et al [36].*

shown in Table 5, the maximum air temperatures in the winter months in west Asian and north African locations are much lower than those in the warm, dry summer months. The minimum air temperatures also are fairly low, the lowest temperatures being recorded at Tehran. This may be explained partially by continentality and partially by higher altitude. Temperature regimes that are shown in Table 5 have important implications in regard to crop productivity because of the suboptimal temperatures that occur at some locations which can seriously limit growth. The rate of accumulation of heat units or degree days for winter crop also is an important consideration in the assessment of crop productivity.

During the winter months freezing temperatures occur, but with a limited frequency and low severity. In the highlands freezing temperatures are common. For example at Ifrane (1640 m), in Morocco, frosts are reported every month from September to May.

The annual rainfall is concentrated in the period from October/November to April/May. The rainfall distribution in west Asia is very closely related to orography. The mean annual rainfall in west Asia is lower than in north Africa. In the North African Mediterranean zone, precipitation totals in excess of 600 mm/year are confined to very small regions *(Griffiths [13]).* At low elevation snowfall is very rare but, in highland areas, there is usually an abundance of snow. This snow provides a valuable source of water for irrigation in the adjacent lowlands. Since most of the rain falls in the cool season, moisture lost through evaporation is low making it available for crop growth. Mild winter temperatures that permit plant growth also give maximum effectiveness to the modest amount of precipitation.

The reliable rainfall season starts by 25 October at the border of the Turkish mountains, and somewhat later (15 November) in Jordan, and later in Iraq and Iran *(Brichambaut* and *Wallen [2]).* The dates of the beginning and the end of the rainy season, as well as the amount of rainfall and its variability, are factors of importance for crop growth.

Heavy rainfall exceeding 60 mm in a day in many regions of the winter rainfall areas is reportedly uncommon. However, in northern Morocco rainfall in excess of 150 mm/day has been recorded *(Griffiths [13]). Taha et al. [36],* in their description of the climate of the Near East, mentioned that in Turkey a maximum daily rainfall of 231 mm has been recorded.

The low radiation and temperature, coupled with high humidity and low wind speeds in the winter, lead to low evaporative demand in contrast to the high evaporative demand during the growing season of the summer rainfall zones. This pattern permits crop production at relatively low rainfall levels *(Smith* and *Harris [35]).* The moisture balance diagram (Figure 2) shows that, in spite of the low annual rainfall at places such as Damascus, Amman and Tehran, a water surplus often occurs during the growing season. At Damascus, from November to February, average PE rates range from 1.0 to 1.8 mm/day.

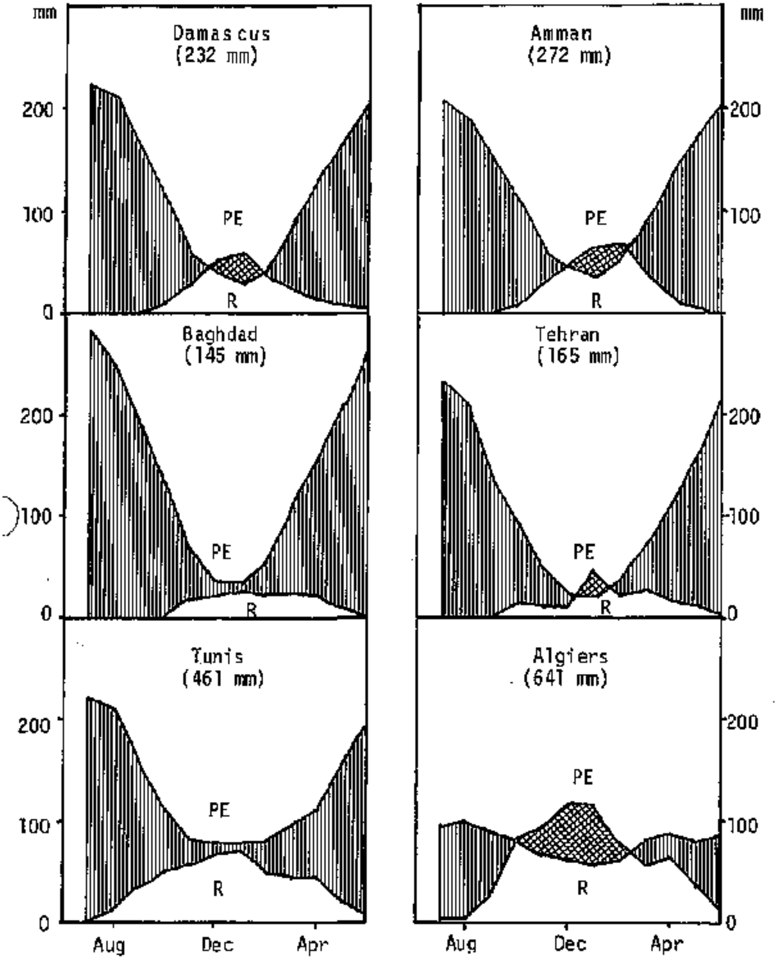

Fig. 2 Monthly variation in rainfall (R) and potential evapotranspiration (PE) at six selected locations in the winter rainfall areas. ▥ Water deficiency; ▩ soil moisture recharge. Mean annual rainfall for the locations is given in parenthesis.

3. Total biomass and economic yield possible from solar radiation - A case study with sorghum

In the arid and semi-arid regions of the world, due to clear skies and low relative humidities throughout most of the year, the solar radiation is uniformly high. One effective methodology for evaluating the potential for biomass production from solar radiation and rainfall is to use a dynamic crop growth model and simulate the effect of available soil moisture on dry matter production and grain yield.

The crop growth model used at *ICRISAT* is the SORGF model *(Arkin et al. [1]),* a dynamic grain sorghum growth model with a feedback capacity. Daily plant growth in SORGF is a function of the difference between average daily air temperature and a base temperature. Daily dry matter production is based on the amount of intercepted photosynthetically active radiation (PAR). The amount of PAR determines the net CO_2 fixed during day-light hours which will change as either water or temperature becomes limiting. *Huda et al. [15]* validated the SORGF model for the semi-arid tropics using multilocation data, and modified several subroutines. The modified model was used in the simulation reported in this paper.

Sorghum simulations were carried out for three locations in summer rainfall arid and semi-arid areas *i.e.,* Timbuktu, Mali (16°43' N lat., 3°00' E long., 263 m elev.), Bamako, Mali (12°38' N, 08°01' E, 331 m elev.) and Hyderabad, India (17°27' N, 78°28' E, 545 m elev.). Temperature and rainfall data for three locations are given in Table 6. For the simulation a sorghum hybrid, of 110 day maturity duration for which data on the total number of leaves and leaf area of each individual leaf are available from *ICRISAT Center,* was chosen. Normal data on global solar radiation, maximum and minimum temperatures, and daily rainfall data of individual years were used as input data in the simulation.

Cumulative probability distribution of simulated dry matter production for sorghum for the three locations is shown in Figure 3. At Timbuktu, in an arid area, the soil moisture is insufficient to establish a crop during 75% of the years. The simulation indicated that biomass production above 2000 kg/ha could be achieved in only *1%* of the years at Timbuktu. On the other hand at Hyderabad in 80% of the years, biomass production could exceed 8 t/ha and in 20% of the years 9 t/ha. At Bamako, the potential biomass production levels could exceed 11 t/ha in 90% of the years.

Table 6. Temperature and rainfall data for the three locations used for sorghum simulation.

Month	Timbuktu			Bamako			Hyderabad		
	Max. Temp.	Min. Temp.	Rain-fall	Max. Temp.	Min. Temp.	Rain-fall	Max. Temp.	Min. Temp.	Rain-fall
	(°C)	(°C)	(mm)	(°C)	(°C)	(mm)	(°C)	(°C)	(mm)
January	30	13	0	33	17	0	29	15	6
February	33	15	0	36	19	2	31	17	11
March	37	18	0	38	23	0	35	20	13
April	40	22	1	39	25	8	37	24	24
May	42	25	4	38	25	63	39	26	27
June	42	27	16	35	23	174	34	24	115
July	38	25	56	32	22	257	30	22	171
August	36	24	81	31	22	337	29	22	156
September	38	24	29	32	22	230	30	22	181
October	39	23	3	34	21	97	30	20	67
November	35	18	0	35	19	10	29	16	23
December	30	14	0	33	17	2	28	13	6

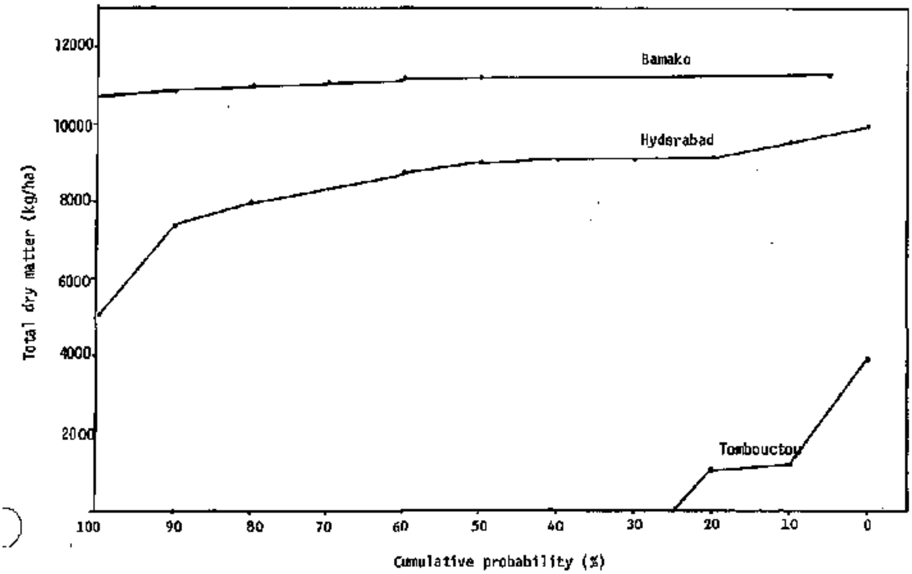

Fig. 3 **Cumulative probability distribution of dry matter of sorghum at three locations in the summer rainfall areas.**

Experiments conducted at *ICRISAT Center* under recommended fertility and crop management conditions during the rainy and postrainy seasons showed that sorghum biomass production levels of 12 t/ha and grain yields of 6 t/ha are attainable (Table 7).

Results obtained at *ICRISAT* on other crops such as pearl millet, groundnut, pigeonpea, and chickpea also suggest that the potential for crop production is considerable and remains yet to be fully exploited by the farmers.

Table 7. Total dry matter and grain yield (kg/ha) of sorghum hybrids achieved under good management at ICRISAT Center.

Year	Season	Total dry matter (kg/ha)	Grain yield (kg/ha)
1979	Rainy	11 660	4290
	Postrainy	7 644	3832
1980	Rainy	11 937	5640
	Postrainy	11 149	6118
1981	Rainy	10 600	5001
	Postrainy	12 529	5663

Source: *Huda et al. [15],*

4. Present productivity in these regions

Most of the cropping in the arid and semi-arid areas continues to be under rainfed conditions, and a majority of the farmers are small farmers with meager resources. Because of the poor resource base - both physical and socioeconomic - the crop yields are low and production is unstable due to variable weather conditions and the high incidence of diseases and pests *(Kanwar [18]).*

Among crops that are grown in the summer rainfall regions of the world (Table 8), rice, sorghum, millet and pulses are the preferred crops. Sorghum and millet are the main subsistence rainfed crops. Although the percentage contribution of rice and wheat from the region to world production is shown to be higher, these crops are predorninantly grown under irrigation or in the higher rainfall zones. About 44% of total pulse production in the world occurs in the summer rainfall regions. Root tubers, vegetables, and maize are the other important crops.

In the winter rainfall zone wheat and barley are the preferred cereal crops because of their tolerance to low temperatures. Vegetables are also grown widely.

Although the currently recorded average yields of these crops when compared to yields achieved in experimental stations are low (Table 9) the potential for achieving higher yields exists. For example, studies at *ICRISAT Center* for *ICRISAT's* mandate crops, *i.e.,* sorghum, pearl millet, chickpea, pigeonpea, and groundnut showed that the average yields in the semi-arid tropics are far below the yields of these crops achievable under rainfed conditions *(Kanwar [18]).*

Table 8. Contribution (%) to world production of different crops* in the summer and winter rainfall zones.

Region	Wheat	Rice	Barley	Maize	Sorghum	Pearl millet	Pulses	Root tubers	Vegetables
Summer rainfall zones									
Asia	9.55	30.39	1.07	2.71	22.99	34.27	23.49	6.51	6.24
Australia**	2.43	0.15	1.78	0.03	1.30	0.08	0.22	0.19	0.08
West Asia	1.39	0.34	0.72	0.04	1.48	0.12	0.63	0.17	3.24
East Africa	0.22	0.06	0.53	1.01	5.89	3.22	2.47	1.66	3.27
Southern Africa	0.04	0.68	0.01	1.21	0.75	1.18	1.23	4.27	2.11
West Africa	0.01	0.39		0.85	24.16	8.48	8.36	3.62	2.93
Latin America	2.96	2.92	0.54	10.23	0.65	14.85	7.10	8.58	4.51
Total:	16.60	34.93	4.65	16.08	57.22	62.20	43.50	25.00	22.38
Winter rainfall zones									
West Asia	4.82	0.09	4.77	0.33	0.03	0.14	2.35	0.81	14.67
North Africa	1.33	0.59	2.14	0.91	0.05	2.24	1.42	0.50	1.58
Chile	0.22	0.02	0.06	0.10			0.31	0.19	0.17
Total:	6.37	0.70	6.97	1.34	0.08	2.38	4.08	1.50	16.42

* Data compiled from *FAO [8].*

** Data for Australia include winter rainfall zone also.

Table 9. Present yield levels (kg/ha) of different crops* grown in the summer and winter rainfall zones.

Region	Wheat	Rice	Barley	Maize	Sorghum	Pearl millet	Pulses	Root tubers
Summer rainfall zones								
Asia	1301	2289	833	1367	956	491	547	10 151
Australia**	939	5330	1108	2953	1406	1183	654	24 105
West Asia	2564	3416	1003	1502	997	1018	1322	10 893
East Africa	1068	2123	922	1009	736	851	613	6 139
Southern Africa	2205	1213	2700	718	550	482	700	6 409
West Africa	1637	1155	-	755	582	506	454	6 939
Latin America	1277	2599	1173	1581	1851	1032	751	9 697
Winter rainfall zones								
West Asia	1521	3446	1264	2272	1964	932	949	19 095
North Africa	1274	2341	1047	1797	1345	1904	943	10 728
Chile	1770	2337	2159	3487	-	-	709	10 140

* Data compiled from *FAO [8].*
** Data for Australia include winter rainfall zone also.

Table 10. Benefit/cost analysis of potentially recoverable yield gaps in important dryland crops

Item	Sorghum	Pearl millet	Chickpea	Groundnut
Potential yield on farmer's field kg/ha: (estimate)	2282	964	1132	1638
Actual yield on farmer's field (kg/ha: All-India average)	634	459	629	819
(Stage II) physical yield gap (kg/ha)	1648 (72)*	505 (52)	503 (44)	819 (50)
Economically recoverable yield gap (kg/ha)	1319	404	403	655
	1121	343	846	1638
	100	40	13.5	125
Additional expenditure on fertilizer (Rs./ha: nitro-	293	293	239	239
Total additional expenditure (Rs./ha)	393	333	252.5	364
Benefit/cost ratio	2.85	1.12	3.35	4.5
Total area under the crop ('000 ha: All-India)	16 208	11 715	7870	7105
Yield gap recoverable area ('000 ha: All-India)	8 104 (52)**	5 272 (45)	4722 (60)	2842 (40)
Present level of production (million tonnes: All-India)	10.3	5.4	4.9	5.8
Potential level of production (million tonnes: All-	20.9	7.5	6.9	7.7
	104	40	38	32

* Percentage of potential yield levels.
** Percentage of total area under the crop.
Source: *Ghodake [11].*

Using all-India data on area, production, and prices of four crops grown in semi-arid areas together economically recoverable 'gap' estimates, *Ghodake [11]* made estimates of the potential level of production in India. The yield gap in this analysis is the difference in yields between demonstration trials conducted at selected centers and the farmer's fields. This gap in yield was attributed to two factors only, *i.e.*, genotype and fertilizer. The results of this analysis, suggest a considerable yield gap in the case of sorghum and groundnut, followed by pearl millet and chickpea (Table 10). With small additional expenditure on seed and fertilizer, it was estimated that large increases in the production of these crops could be easily realized.

Kassam [19] carried out an interesting analysis of the productivity of wheat in the winter rainfall regions of North Africa and West Asia. The procedure he used involved compilations of quantitative climatic inventory, length of the growing period (the period when water and temperature permit crop growth), and soil inventories. By an application of the agroclimatic constraints to the constraint-free crop yields, attainable crop yields were computed for the various major climates and growing period zones. *Kassam's* analysis *[19]* showed that, in the growing period zone of 180-239 days at the high-input level, anticipated yields ranged from 3.6 to 4.9 t/ha. Where the growing period ranged between 120 and 179 days, yields of 2.0 to 3.8 t/ha, at the high-input level were anticipated. At the low input level the anticipated yields were 0.5 to 1 t/ha.

5. Effect of water limitation on biomass production and water use efficiencies

In the absence of other limiting factors such as radiation, temperature, nutrients, etc., it is well known that water use by crops and dry matter production are linearly related. This conclusion can also be corraborated by the fact that net radiation (which determines to a large extent the transpiration rates) and solar radiation (which determines photosynthesis) are linearly related *(Monteith [26]).* Hence it may be surmised, as *De Wit [6]* did, that transpiration or water use and dry matter should be linearly related.

Studies conducted at *ICRISAT* with sorghum confirmed that water use and dry matter production are linearly related *(Sivakumar et al. [34]).* The rates of dry matter accumulation and water-use decreased as profile water depletion became more severe, but the ratio between the two remained uniform (Figure 4). Maximum dry matter production was achieved when water is not a limiting factor indicating clearly the potential that exists in the semi-arid environment for crop production.

Since the simulation comparisons for sorghum discussed earlier indicated that at Timbuktu rainfall is limiting for sorghum production, we have investigated the response to supplemental irrigation of 100 mm at three phenological stages, *i.e.*, sowing, panicle initiation, and anthesis. The results of this simulation (Table 11) indicate that, with three supplemental irrigations at the three stages, biomass production could be increased above 9 t/ha and grain yields could reach 5 t/ha.

The growth of a crop during its life cycle and the biomass production is complex in nature, but water is necessary at all stages for maximum biomass production. Water deficiency at a particular stage could affect the plant in a manner that may have a

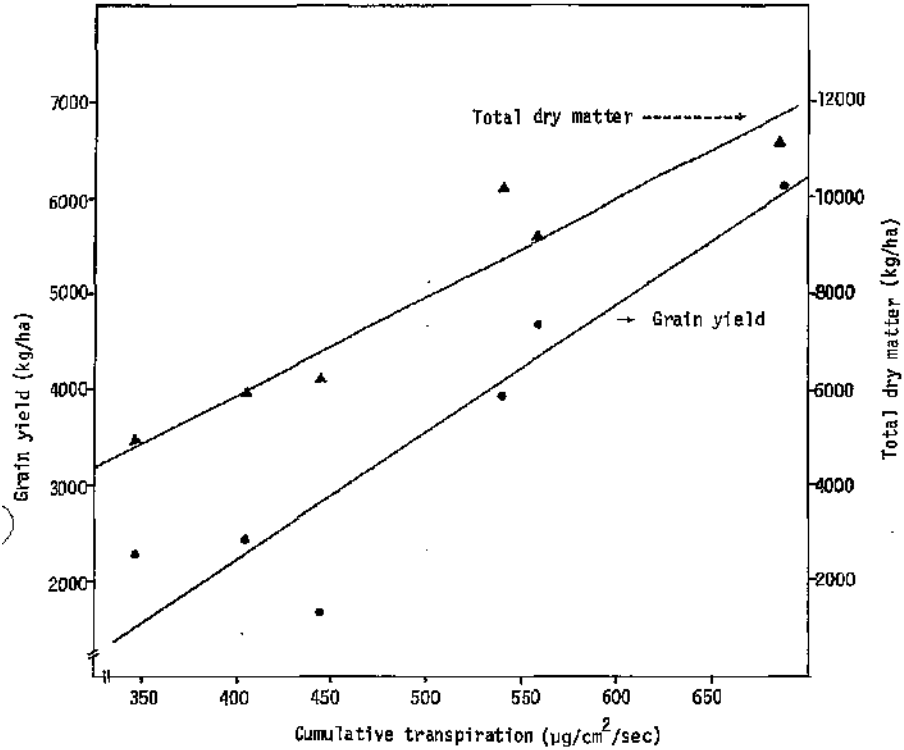

Fig. 4 **Relationship of total dry matter and grain yield of sorghum to cumulative transpiration (data poooled over three genotypes).**

Table 11. Simulated response to supplemental irrigations at three stages of sorghum growth at Timbuktu, Mali (simulation base: 43 years).

Supplemental irrigation (100 mm)			Total dry matter (kg/ha)			Grain yield (kg/ha)		
Sowing	Panicle initiation	Anthesis	Mean	Max.	Min.	Mean	Max.	Min.
-	-	-	4224	3 996	0	191	1798	0
X	-	-	3833	6 398	3525	1725	2879	1586
X	X	-	4506	7 053	4195	2028	3174	1888
X	X	X	9442	10 886	9099	4249	4899	4094

greater or lesser effect on final productivity. In a study conducted at *ICRISAT Center* on the response of groundnut to moisture stress imposed at different phenological stages, we found that stress imposed from emergence to appearance of first pegs resulted in a slight reduction in the vegetative growth during the duration of

Table 12. Dry matter and kernel yield of groundnut under moisture stress imposed at different stages.

Treatments	Total dry matter (kg/ha)	Kernel yield (kg/ha)
Irrigated control	9750	3152
Stress from emergence to appearance of first pegs ..	6550	2373
	4750	686
Stress from first kernel growth to maturity.	3600	384

Source: *Sivakumar et al. [34].*

Table 13. Water use and water use efficiency for crops/cropping systems grown at *ICRISAT Center,* Patancheru.

Crop/cropping system	Season	Soil	Water use (cm)	Yield (kg/ha)	Water use efficiency (kg/ha/cm)
Sorghum	Rainly	Alfisol	24.0	3700	154
Sorghum	Rainly	Vertisol	35.3	4467	127
Sorghum	Postrainy Rainfed	Vertisol	21.6	2430	113
Sorghum	Postrainy Irrigated (19 cm)	Vertisol	36.9	5990	162
Pearl millet	Postrainy Rainfed	Alfisol	9.6	1110	116
Pearl millet	Postrainy Irrigated (14 cm)	Alfisol	15.5	1860	120
Pearl millet	Rainy	Alfisol	15.9	2226	140
Groundnut	Rainy	Alfisol	19.6	1185	60
Pearl millet/groundnut	Rainy	Alfisol	22.8	1227/840	91
Pigeonpea	Rainy	Vertisol	33.5	-	-
Sorghum/pigeonpea	Rainy	Vertisol	33.3	4314 (Sorghum)	130
Maize	Rainy	Vertisol	23.1	3026	131
Maize/pigeonpea	Rainy	Vertisol	21.2	2480 (Maize)	117
Pigeonpea	Postrainy	Vertisol	19.6	1588	81
Maize/pigeonpea	Rainy	Vertisol	24.6	2534 (Maize)	103
Pigeonpea	Postrainy	Vertisol	14.1	1072	76
Chickpea	Postrainy	Vertisol	16.2	1053	65
Chickpea	Rainfed Postrainy Irrigated (6.7 cm)	Vertisol	21.2	1145	54

Source: *Sivakumar et at. [34].*

stress extending up to 30 days *(Sivakumar et al. [34]).* However, once the moisture stress was diminished and the crop received irrigations at 10-day intervals, the recovery from stress was remarkable. When the stress was imposed after kernel growth started, the effect of stress on dry matter production was severe resulting in a low biomass production (Table 12).

In the arid and semi-arid areas where the seasonal variability in rainfall is large, which in turn influences the profile moisture content and distribution, the response to any applied water could be variable. Even within a growing season it was demonstrated with several crops that, depending on the time of planting, the responses could again vary. Under moisture stress, with intercropping systems (where two or more crops are grown together) the relative advantages were shown to be higher than when the crops are grown singly *(Willey et al [45]).*

Water use and water use efficiency data obtained at *ICRISAT Center* for several crops/cropping systems *(Sivakumar et al. [34])* are summarized in Table 13. The data show that sorghum grown on the deep Vertisols during the rainy season or under irrigation during the postrainy season used more water than either a sorghum/pigeonpea intercrop or maize or maize/pigeonpea or pigeonpea. Maximum water use efficiency was recorded in the case of sorghum grown during the postrainy season under irrigation. Maize was the next best crop in terms of water use efficiency. Sorghum/pigeonpea intercrop produced more grain per cm of water used than maize/pigeonpea. Water use by pearl millet was less, but the water use efficiencies of this crop were comparable with those of maize, confirming that pearl millet is a crop to be preferred under low moisture availability conditions. Water use efficiencies of pulse crops grown in pure stands were low. Efficiencies of chickpea and groundnut were comparable, although they were grown in different seasons. Water use efficiency for a millet/groundnut intercrop was better than that of a groundnut crop grown in pure stands. During the postrainy season water use efficiencies of irrigated sorghum were greater, but not those for irrigated millet and chickpea.

6. Water-fertilizer interactions

The influence of water on plant growth and nutrient use is complex, and to a large extent the processes are interdependent. An extreme deficiency of soil water could cause wilting and ultimate death of the plant. But, before such obvious effects set in, the status of nutrients in the soil and the soil's ability to get them may be impaired *(Viets [44]).*

In the arid and semi-arid areas of the world, more fertilizer is used where facilities for supplemental irrigations exist. For example, *Tandon [37]* showed that, in India, irrigated areas form the major loci of fertilizer use.

Significant interactions between moisture and nutrients have been recorded with various crops *(Singh* and *Prihar [32], Meelu et al. [23]).* Depending on the available soil moisture, its management, and fertilizer application rates, crop yields comparable with irrigated agriculture have also been demonstrated. *Meelu et al. [23]* showed that, for rainfed wheat in Punjab, higher doses of N could be profitably used in medium-textured soils with good moisture storage (Figure 5). In investigations on

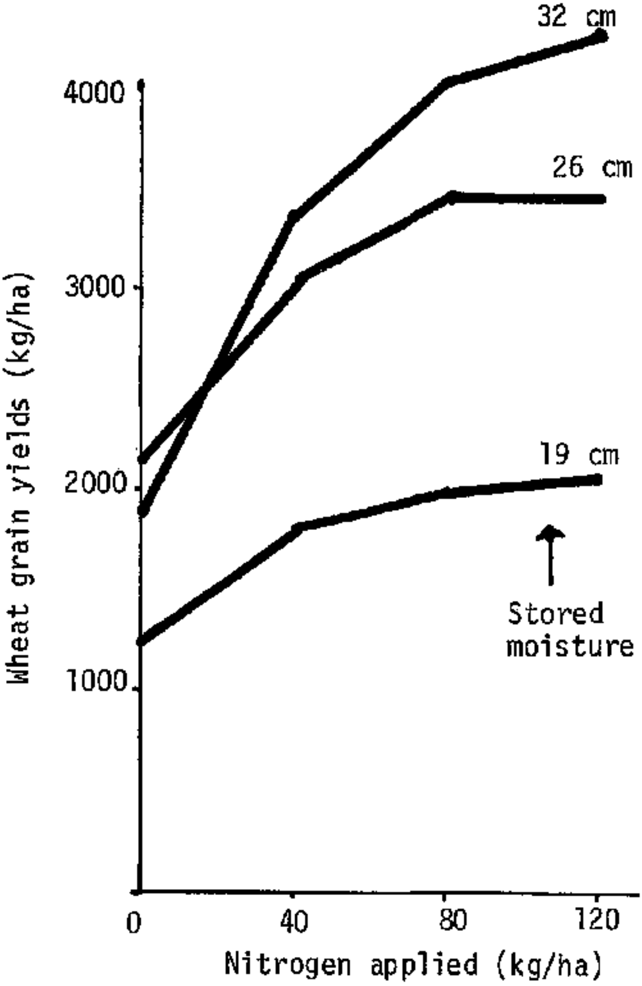

Fig. 5 **Response of rainfed wheat to nitrogen on soils having different stored moisture. (From** ***Meelu et al. [23]*****).**

the effect of nitrogen and irrigation for summer sorghum, *Venkatachari et al. [42]* showed that the increase in yield was 1100 kg/ha from irrigation alone, 2300 kg/ha from 80 kg N at the lower levels of seven irrigations, and 4900 kg/ha when 80 kg N and 16 irrigations were given.

Jha and *Sarin [17]* found, in an all-India analysis, that farmers favored fertilizer use on heavier soils which retain more water than lighter soils, and that the percentage area fertilized correlated with rainfall. They also found, in a study of selected villages, that irrigation and rainfall during the growing season were the primary determinants for fertilizer use in Sholapur (in an area of independable rainfall) but not in

Akola (in an area of dependable rainfall), where in none of their equations rainfall appeared as a significant variable.

Under Mediterranean conditions, fertilizer recommendations are tuned to the average rainfall incidence. For example, for rainfed wheat in Turkey in the lower rainfall areas the fertilizer application is restricted to 40 kg P_2O_5/ha; under good rainfall conditions it is 60 kg N + 40 kg P_2O_5/ha. For high yielding varieties under irrigated conditions the recommendation is 80-100 kg N + 60 kg P_2O_5/ha *(De Geus [5]).* In Jordan fertilizers are mainly used for irrigated wheat in the Jordan valley, but small amounts are used in the dry regions with over 450 mm/year of rainfall. In the fertilizer demonstration trials in Morocco for dryland barley in the southern and northern regions, the NPK treatment of 20-60-0 was found to be best, while for irrigated barley the treatment 20-40-40 was the best *(De Geus [5]).*

The interaction between water and nitrogen was described by *Van Keulen [41]* as follows: 'Growth under nitrogen deficient conditions implies a slower rate of accumulation of dry matter, which, combined with a different distribution of the material, leads to a prolonged period in which vegetation does not cover the soil completely. Under such conditions, direct soil evaporation is longer than under non-deficient conditions where a closed canopy is reached earlier. The amount of moisture available for transpiration is thus smaller under nitrogen deficient conditions.'

Rehatta et al. [29] showed that moisture shortage with equal availability of nitrogen led to reduced uptake of the element showing, thereby, that uptake must be governed by the reduced rate of dry matter production. Hence moisture shortage to plants was assumed to have both a direct as well as an indirect effect on nitrogen uptake: in one case governed by the physical transport processes in the soil, and in the other by the metabolic processes in the plant *(Van Keulen [41]).*

7. Present use of fertilizer

Although current research suggests that for dryland crops fertilizer application is the highest return input *(Chowdhury [3]),* the present use of fertilizer in the summer and winter rainfall zones is low. Data summarized from *FAO Fertilizer Statistics* (Table 14) show that, in the summer rainfall regions as a whole, fertilizer consumption is low. The figures for Asia are high but the fertilizer consumption here is mostly confined to wheat and rice and in irrigated areas. For example, *Shobti [31]* computed that nearly 80% of all fertilizer used in India goes to four crops: rice, wheat, sugarcane, and cotton. Likewise only 16% of the total cropped districts account for 50% of the fertilizer used and it is well known that the bulk of the consumption as well as growth in fertilizer use is in irrigated areas. The farmer's perception of the likely benefits that could accrue from fertilizer application and the support provided through the extension agencies are the major factors contributing to this growth.

Jha and *Sarin [16],* in their study of fertilizer consumption in the semi-arid areas of India, estimated the mean fertilizer consumption in 112 nonirrigated semi-arid districts to be 18.5 kg N + P_2O_5 + K_2O as compared to 57.5 kg/ha in the 78 irrigated districts in the semi-arid areas. In fact the exact estimate for nonirrigated areas is considered to be even lower than 18.5 kg/ha because this includes the fertilizer received by irrigated areas within 'nonirrigated' districts.

Table 14. Consumption *(%)* of world fertilizer use* in the summer and winter rainfall zones.

Region	N	P_2O_5	K_2O
Summer rainfall zones			
Asia	7.69	4.58	2.93
Australia**	0.41	2.71	0.53
West Asia	0.52	0.98	0.02
East Africa	0.26	0.21	0.05
Southern Africa	0.42	2.78	0.22
West Africa	0.15	0.24	0.21
Latin America	3.40	7.61	6.00
Total:	12.85	19.11	9.96
Winter rainfall zones			
West Asia	1.39	1.85	0.36
North Africa	1.35	1.26	0.38
Chile	0.08	0.18	0.05
Total:	2.82	3.29	0.79

* Data compiled from *FAO [9].*

** Data for Australia include winter rainfall zone also.

Table 15. Response of chickpea to fertilizers in experiments on cultivators' fields in India.

Soil type	No. of trials	Yield (kg/ha) without fertilizer	Response (kg/ha) over no fertilizer		
			N_2O	$N_{20}P_{40}$	$N_{20}P_{40}K_{20}$
Calcareous Sierozem ...	68	1153	94	314	464
	48	1338	466	798	954
Redandyellow	58	648	238	364	459
Medium-black	69	464	116	428	387
	243	873	208	454	538
% increase over no fertil-			+ 24%	+52%	+ 62%

Source: *Tandon [37].*

Data on the nutrient removal by the crops grown in the semi-arid areas, however, suggest use of increased quantities of fertilizer that is far in excess of the estimated current use. Using the present levels of productivity for five major crops (sorghum, pearl millet, groundnut, chickpea and pigeonpea) grown in semi-arid regions of India, *Tandon [37]* estimated that these crops remove 3.2 million tonnes of $N + P_2O_5 + K_2O$/year or, on the whole, 72 kg nutrients/ha. The current use of fertilizers on these crops, however, was estimated at only 0.5 million tonnes or 10-11 kg of nutrients/ha, a figure far below the estimated removal by these crops.

Results of experiments conducted at the research stations of the *Indian Council of Agricultural Research,* and in the trials conducted on farmers' fields however indicate significant yield increases as a result of the application of fertilizers. *Tandon [37]* concluded, from data collected over 243 experiments on cultivator's fields, that the yield increases resulting from fertilizer applications of 24-62% over no fertilizer treatment could be obtained for chickpea grown on four soil types (Table 15). *Kulkarni [20]* showed that 20-30 kg N + 40-60 kg P_2O_5 and 0-40 kg K_2O are the remunerative doses of nutrients per hectare for rainfed groundnut based on experiments on cultivators fields in 13 districts for nine crops grown predominantly in the semi-arid and arid areas of India. *Venkateswarlu [43]* computed yield responses to N application that varied from 15 kg grain/kg N to 23.8 kg grain/kg N. Using these data, *ENSP [7]* concluded that these figures are closely comparable with the data obtained under irrigated conditions, considering that the overall yardstick relating food grain production to fertilizer nutrients is about 10:1. These results confirm the conclusion that fertilizer responses in the semi-arid and arid areas can be high and profitable.

Regardless of the actual supply of nutrients to the crops, the advances made in the area of crop improvement and in raising the average yield levels of cultivars have led to greater efficiency of use of nutrients. The availability of a large number of improved, more efficient, fertilizer responsive cultivars for a number of crops grown currently in the arid and semi-arid areas and the steady increase in the acreage under these cultivars points towards a greater need for fertilizers. For example *Rao [28]* in his analysis of genotype-input-management relations for grain sorghum in India concluded that, at an application level up to 50 kg N/ha, sorghum hybrids and some improved varieties have returned 15-28 kg of grain/kg of nitrogen against 6-8 kg for traditional local varieties. Adoption of such improved cultivars coupled with improved management practices has been shown to give increased net returns. *Ryan et al. [30]* showed in their assessment of prospective soil-, water-, and crop-management technologies that on the Vertisols use of local varieties with fertilizer generated additional profits of $ 55/ha and with high yielding varieties, these profits could be doubled.

8. Current constraints on yield and on the use of fertilizer

a) In both the summer and winter rainfall regions water is *the* most limiting factor in crop production. Variability in the rainfall at the beginning and end of the season, and unreliability in mid-season, create risks in arable cropping. The length of the growing season which is limited by the duration of the rainy period sets the limits of the areas where rainfed farming is feasible.

b) In the summer rainfall regions high temperatures, increased wind speed, and advective energy increase the atmospheric demand for water. Potential evapotranspiration rates are usually high, reaching up to 2400 mm/year. In *the* winter rainfall regions, the low average potential evapotranspiration rates on the other hand are advantageous for conserving the low rainfall that occurs.

c) In the winter rainfall areas, mean minimum temperatures and mean temperatures during the growing season could limit crop growth, and sometimes stop or delay crop development.

d) In view of water shortages, lack of suitable varieties that cover the ground quickly, and flower early, and finish grain filling before there is a deficit in moisture, often limits yields.

e) Lack of quick adoption of improved, more efficient, fertilizer responsive cultivars on the farmers' fields is a major constraint.

f) In the summer rainfall regions soil erosion is a problem, and non-adoption of suitable land and water management practices that facilitate drainage and reduce runoff and erosion lead to loss of fertile top soil.

g) Lack of adoption of on the farm of cropping systems and crop management practices that establish a crop at the very beginning of the rainy season, to make most efficient use of moisture throughout the rainy and postrainy seasons for high sustained levels of yield.

h) Soils with shallow depth and low water-holding capacity present problems, even during the rainy season.

i) Due to increased populations and increasing food needs, steeper and more erodable lands are frequently overcropped and overgrazed and forest lands are denuded causing permanent damage to extensive areas.

j) Availability of soil moisture is an important determinant of fertilizer use in the semi-arid areas.

k) Lack of proper extension in the popularization of fertilizer use and the knowledge of the farmer is a major constraint.

1) Fertilizer price and credit are important institutional factors.

m) Regional and temporal differences in seasonal conditions, occurrence of pests and diseases, availability of fertilizer, market and fertilizer distribution network, etc., are important determinants of differences in fertilizer use. *Tandon [37]* computed that mean area per fertilizer sale point is 2.5 times more in the major dryland states than in the rest of India.

n) Lack of suitable management practices that make the best use of applied fertilizer.

9. Conclusions

In the semi-arid and arid areas of the world, where water is the main constraint for agricultural production, analysis of the existing levels of crop productivity suggests that a considerable potential remains to be exploited. In the summer rainfall regions use of improved technologies that include improved seed, fertilizer, cropping systems and water management practices could result in higher productivity and greater net returns to the farmer. In the winter rainfall zones, also, increasing the nutrient supply to the crops is known to give significant yield increases. The climatic features of these areas favor more efficient utilization through a proper choice of crops and cropping systems. A rational assessment of the existing physical and socioeconomic resources could present options that would permit increases in agricultural productivity to be achieved in summer and winter rainfall zones.

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