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Nutrient and Water Management Strategies for Sustainable Crop Production in the SAT

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Introduction

The current population in India is around 900 million and it continues to grow at an annual rate of 2.14%. By the year 2000 AD, population is expected to cross one billion mark. Feeding this burgeoning population would require 230-240 million tonnes of cereals and pulses and about 26 million tonnes of oilseeds. This demand requires an increase of food production from the present 176 million tonnes.

The dramatic increase in food production during early sixties and seventies came largely from crop intensification - growing more than one crop in a year from same piece of land, and from increased productivity *per se* from the well endowed agricultural lands where fertilizer, irrigation and improved high yielding varieties were used. This increased food production from high input agriculture is likely to be stabilized now. Therefore, the projected increased demand for food must generally be met from the rainfed agriculture and more and more marginal lands would be brought into cultivation. The continuous cultivation of these marginal lands which are already low in organic matter and nutrient content would adversely affect soil structure and water-holding capacity (45).

There is an urgent need to reconcile between short-term productivity gains from marginal land as demanded by increasing population over long-term sustainability of production on these lands. The essential point here is not to allow the marginal land to be degraded. The sustainable production from these lands involve skillful management of the renewable natural resources to fulfil the demand for increased food while maintaining the environmental quality for future. This necessitates the effective management of soil resources and follow prudent integrated nutrient and water management techniques. In this review we discuss the dynamics of integrated water and nutrient management techniques for sustainable crop production in the rainfed agriculture in the semi-arid tropics (SAT).

Characteristics and Constraints of SAT

The dry semi-arid tropics (SAT) is a tropical ecosystem where monthly mean rainfall exceeds mean monthly potential evapotranspiration for 2 to 4.5 months (53). Using this definition in Asia dry SAT includes most of India which contains single largest SAT containing nearly 9% of global SAT (49).

Rainfall Distribution

In the SAT area of India the rainfall varies in amount and distribution. The variation in annual rainfall from 416 to 1431 mm in Hyderabad for the period 1901-1995 is shown in Fig. 1. The areas receiving rainfall from the south-west monsoon have unimodal distribution of rainfall and the ones receiving from both the south-west and north-east have bimodal distribution of rainfall. The rainfed regions are broadly classified as low-rainfall region if the annual rainfall is < 750 mm, medium if the rainfall is between 750 to 1500 mm, and high if the rainfall is > 1500 mm. Besides the seasonal variability, there is a great heterogeneity and spatial variation of rainfall in SAT. For example, at ICRISAT Asia Center (IAC), September was the wettest month (156 mm rainfall) in 1975 but was the driest month in 1977. In 1977 August received fairly good amount of rainfall but it was the driest month in 1975 (54). The coefficient of variation in rainfall ranges from 20 to 43% and length of growing season from 60 to 300 days. The rainfall patterns at selected sites in India are shown in Fig. 2. The rainfall at Hyderabad and Indore is more assured for crop production than at Jodhpur, Anantapur and Dharwad. The rainfall at Jodhpur, Hyderabad, and Indore is unimodal and at Anantapur and Dharwad it is bimodal.

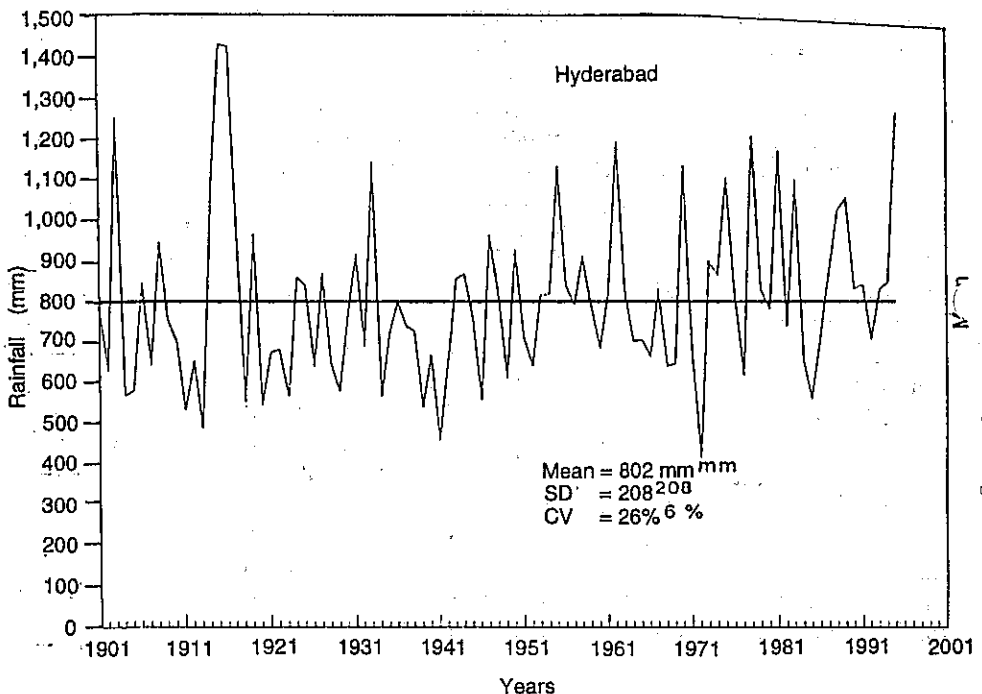


FIG. 1 : Variations in annual rainfall at Hyderabad during 1901 to 1995.

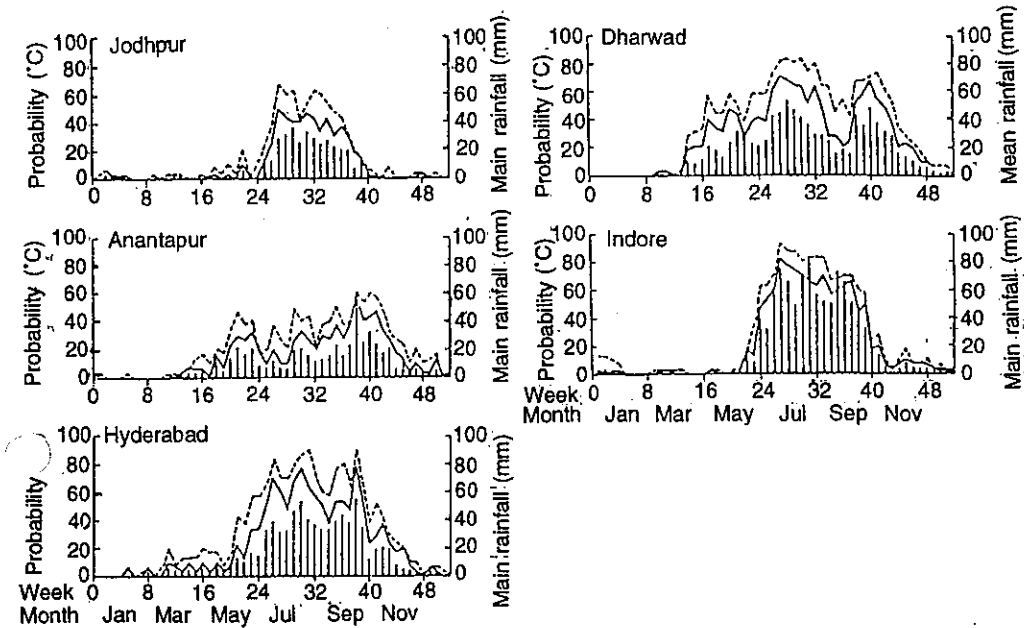


FIG. 2 : Mean weekly rainfall distribution (vertical lines) and the probabilities of receiving at least 10 mm (dashed line) and 20 mm (solid line) rainfall in a week for five locations. Data base: 1941–1970.

Crops and Soils Distribution

The important staple crops of SAT are sorghum [*Sorghum bicolor* (L.) Moench], pearl millet [(*Pennisetum glaucum*) (L.) Leeke], pigeonpea [(*Cajanus cajan*) (L.) Millsp.], chickpea (*Cicer arietinum* L.) and groundnut (*Arachis hypogea* L.). The area and production of these crops in Indian SAT is given in Table 1.

TABLE 1: The area, production and productivity of major crops in Indian SAT, 1991-92.

Crop	Area (million ha)	Product (million tonnes)	Yield (kg ha ⁻¹)
Sorghum	12.60	8.36	664
Pearl millet	10.04	4.64	463
Pigeonpea	3.73	2.19	588
Chickpea	5.65	4.16	735
Groundnut	8.67	7.07	815

Source: [18].

The prevailing temperatures and high mean annual solar radiation, which varies generally between 16 to 21 MJ m⁻² day⁻¹ indicate that the SAT environment possesses a high potential for year round cropping. However, the actual utilization of these resources to potential crop production in the SAT is limited by several constraints. The crop production in rainfed agriculture in better and poorly managed conditions is given in Table 2. It can be clearly seen that at the research farms there is reasonably high yield while the yield at the farmer's fields is about 23% of research farm yield. The major causes for such an yield gap are inappropriate management of natural

resources, poor nutrient and soil water management practices and partially due to the use of unimproved cultivars.

In addition to the variability in the amount and distribution of rainfall, the soils of the rainfed SAT also vary in physical and chemical properties. There is a great diversity of soils in SAT region in Asia as it contains six of ten orders of soil taxonomy. However, Alfisols, Vertisols and Inceptisols are the major soil orders of Asian SAT representing 38, 25, and 9% of the total area of 3.19 million Km² (23). All these soils are used in agriculture under a wide range of management practices. These soils of SAT environment characterized by low organic matter and low available water-holding capacity. Besides Alfisols have a hard setting surface sealing properties which interferes with seedling emergence. Thus the variability in soils and the rainfall provide a spectrum of soil water availability environments for crop production. For example in the Hyderabad region Vertisols have greater soil water availability and for a longer duration than the deep and shallow Alfisols (Fig. 3). Vertisols provide an opportunity for double cropping whereas only single or intercropping is possible on Alfisols in the rainfall environment of Hyderabad.

TABLE 2 : Potential crop productivity in research farm and farmers' field in rainfed agriculture.

Crops	Average yield (kg ha ⁻¹)			
	Research farm		Farmers field	
	No. of trials	Yield	No. of trials	Yield
Sorghum	12	3000	101	610
Pearl millet	14	1900	300	360
Chickpea	8	2820	112	650
Groundnut	5	1500	117	430

Source : [17]

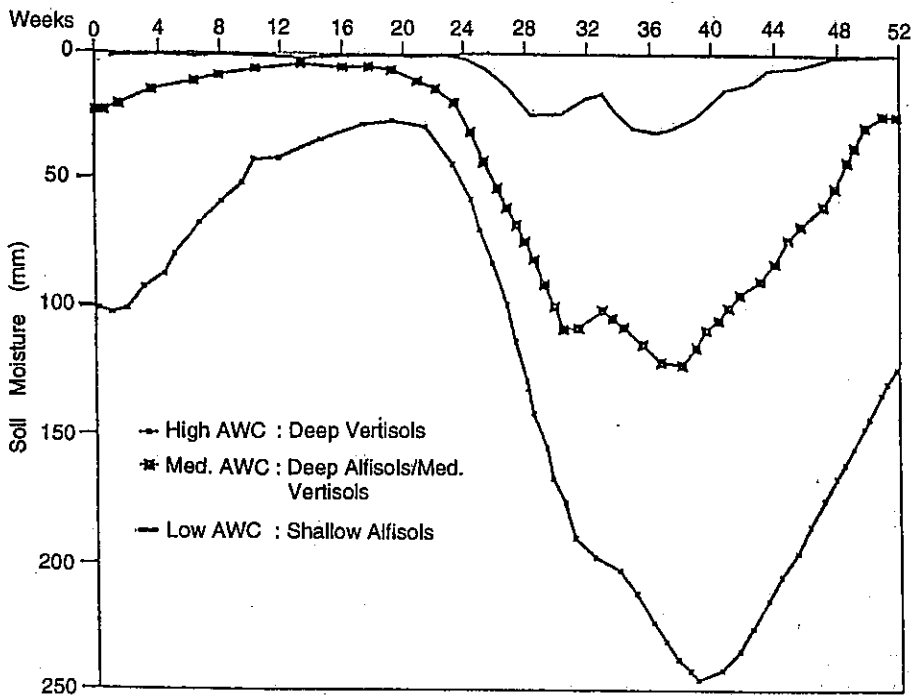


FIG. 3 : Variations in soil profile moisture on a weekly basis in three typical soils of Hyderabad region.

Soil Water Balance

Soil water balance has a significant effect on the efficiency with which the nutrients are used in an environment. Soil water deficiency affects nutrient uptake, while surface runoff and deep drainage moves the nutrients away from the rooting zone. In a study conducted on an Alfisol during 1977 (total rainfall = 420 mm) about 29% of rainfall was lost as deep drainage, while on Vertisol in 1978 (total rainfall = 1200 mm) about 44% of rain was lost as runoff plus deep drainage. In our recent study on water balance of a soybean crop on Vertic Inceptisol (total rainfall = 640 mm), we estimated that about 13% of rainfall was lost as runoff and about 30% as deep drainage. These losses of water have a bearing on the nutrient balance and its use efficiency by crops. At the same time there is need to develop technologies to store and use the runoff and deep drainage water for supplemental irrigation during periods of drought and establishment of post-rainy season crops.

Water Logging and Drought

On heavy clay soils in high rainfall areas water logging is a constraint to crop growth especially in the months of July and August. Moisture availability index (MAI), which is defined as the ratio of dependable precipitation to potential evapotranspiration, can be used to quantify the likelihood of water logging and water deficiency at a given site. Dependable precipitation is further defined as the amount of rainfall expected at 75% probability. When MAI is between 1.00 and 1.33 water availability for crop production is adequate. Above MAI of 1.33 there is a possibility of water logging especially on heavy clay soils. Below MAI of 1.00 the crops suffer from water deficits with decreasing MAI (19). The MAI from June to December for 12 locations is presented in Table 3. The data show that at Indore, Jabalpur, Raipur, Nagpur and Yeotmal the water logging can occur during the months of July and August especially on heavy clay soils. At other locations some degree of drought can occur during any time of the growing season. Anantapur, Solapur, Parbhani and Aurangabad have the lowest MAI indicating that these locations are most prone to drought.

TABLE 3: Moisture availability index of selected locations in SAT India.

	June	July	August	Sep	October	Nov	Dec	Annual rainfall (mm)
Anantapur			0.29	0.47	0.34	0.26		584
Hyderabad	0.34	0.84	0.68	0.70	0.17	0.01	0.0	790
Bangalore	0.32	0.42	0.57	0.71	0.62	0.06	0.0	911
Indore*	0.38	1.50	1.34	0.76	-	-	-	1054
Jabalpur*	0.47	2.57	2.16	0.80	-	-	-	1447
Raipur*	0.52	1.70	1.78	1.02	-	-	-	1388
Akola	0.38	1.13	0.56	0.60	-	-	-	878
Aurangabad	0.42	0.74	0.57	0.57	0.24	-	-	792
Nagpur*	0.70	1.77	1.13	0.60	-	-	-	1242
Parbhani	0.38	0.68	0.50	0.80	-	-	-	853
Solapur	0.36	0.51	0.51	0.66	0.31	-	-	743
Yeotmal*	0.43	1.64	0.97	0.61	-	-	-	1075

* - Places which are likely to suffer from water logging.

Water Management Strategies

Strategies to Alleviate Water-logging and to Improve In Situ Moisture Conservation

In the SAT great variability of rainfall in time and in space, and poor infiltrability of most soils causes a paradoxical situation that the area suffers from both a general water shortage and destructive floods. As a result of high runoff and soil loss, the land resource base is shrinking and its productivity is diminishing. For sustaining productivity there is need to identify soil and water management strategies which would conserve resources and increase their use efficiency.

Research on soil and water conservation and tillage systems at IAC, Central Research Institute for Dryland Agriculture (CRIDA) and other research Institutions in India has resulted in development of improved management packages.

Vertisols

Vertisols in the SAT represent a vast underutilised soil resource and double cropping on these soils can provide important pathway for improving resource utilisation and efficiency. However, due to operational difficulties because of their sticky nature when wet and very hard during dry period traditionally these soils are kept fallow during the rainy season and cropped during the postrainy season.

An improved package of practices for increasing the productivity of Vertisols has been developed at IAC. The essential components of this management strategy are:

- a system of resource conservation, management, and use based on small watersheds;
- land smoothing and installation of drains to ensure effective surface drainage and runoff disposal from the field;
- a well-designed, semi-permanent or permanent broadbed and furrow (BBF) system or well-graded flat system;
- performing primary tillage operations for both postrainy as well as rainy season crops immediately after harvesting the previous season's crop, when the soil has adequate moisture and is friable;
- shallow cultivation of the land (only the beds) whenever an effective rainfall (< 20 mm) is received;
- application of moderate amounts of N and P fertilizer, followed by dry sowing about one week before the expected date of onset of the rainy season;
- use of high-yielding varieties and other recommended agronomic practices.

Various aspects of this approach for the management of Vertisols have been discussed in detail (13).

Alfisols

On Alfisols soil crust and seal formation are serious constraints to seedling emergence and to soil and water conservation. On Alfisols which have less than 1.5% slope, cultivation on flat seed bed is effective in reducing runoff and soil loss as well as in increasing crop yields. Graded raised land configuration (e.g., BBF, ridge and furrow) does not offer any particular advantage for cereal production on Alfisols occurring on these gentle slopes (37). Where supplemental irrigation is part of rainfed crop production, ridge and furrow system is appropriate. On slopes greater than 1.5%, a gated-outlet-contour bund system has shown a good potential to increase and stabilize crop yield. The performance of these practices have been discussed in detail (13, 38).

However, for groundnut, BBF has been found beneficial for increasing pod yield. Bulk density of 0-15 cm soil layer was significantly lower and total porosity of the soil layer was significantly greater in BBF than in the narrow ridges and the flat seedbed treatments in that order. Lowest penetration resistance was recorded in the BBF system.

For improving *in situ* soil and water conservation in the SAT, surface roughness treatments are important. Small scoops (or pits) provide more time for water that would otherwise be lost as runoff to infiltrate into the soil and reduce soil loss by trapping the eroded sediments that would otherwise be lost from the field. Experiments were conducted under natural and simulated rainfall conditions to compare the performance of pitted land with flat land. On Alfisols, pittings significantly reduced runoff (69%) and soil loss (53%) as compared with the runoff and soil loss from flat seedbed treatment. In terms of controlling runoff and soil loss, the largest advantage of pittings over flat cultivation was observed during the early part of the crop-growing season.

On Alfisols the problems of crusting and sealing are encountered more during the early part of the crop growing season before the crop is emerged and canopy is fully developed. One way to reduce crust formation during seedling emergence is to reduce the content of clay and silt particles in the soil surface layer. Occurrence and strength of crusts are positively related to the content of clay and silt in surface soil. For Alfisols, a non-turning tillage system, that in the long term results in a relatively sandy soil surface, is more suitable than a tillage with turning ploughs because inversion brings up soil from the argillic horizon which contains a higher proportion of clay and silt. Till full canopy is developed considerable runoff occurred when the soils were very dry. At IAC shallow tillage in the form of additional intercultivations was found effective in breaking up the crust, improving infiltrations, and reducing runoff and soil loss.

Watershed-based Resource Development : Management and Utilization

In rainfed agriculture, the only source of available water is the rain that falls on a given area. Runoff, soil erosion and drainage represent serious problems for many areas in the SAT, and the solution to these problems lies in evolving development programs which recognize the natural topography and the drainage patterns of the land. In several areas, it is not uncommon to experience significant quantities of runoff at one time of the season and serious drought at another time. The collection of excess water and its utilization to provide greater stability to rainfed agriculture appears to be a viable development alternative in such areas. Thus, the watershed or catchment is the natural framework for resource development, in relation to crop production systems, resource conservation and utilization (22). A watershed-based farming system involves the optimum utilization of the catchment precipitation through improved water, soil and crop management, directly through infiltration of rainfall, after runoff collection and storage or after deep percolation recovery from wells, for the improvement and stabilization of agriculture on the watershed.

ICRISAT in association with the Indian national agricultural research systems (NARS) has been working on watershed-based farming systems on Vertisols and Alfisols since 1975. A large number of improved management systems were tried and evaluated on watershed basis both at research stations and on-farm locations. At IAC, experimental watersheds of 3-15 ha have been laid out with various land and water management systems. These watersheds were designed to ensure that water and soil were both managed in the best possible way : to conserve water in the soil profile when needed but to shed excess, especially during wet periods; to control the flow of excess

water and to store it so that it could be reused. Some of these watersheds are still being managed operationally and are producing crops with excellent yields, demonstrating that it is possible to have a sustainable system of agriculture with good management of the environment. An operational scale comparison between traditional and improved systems on Vertisol research watersheds for 12 years showed that with improved technology integrated in watershed framework produced high stable mean yields (4.3 t grain yield ha⁻¹) under dryland conditions through double cropping as against 0.6 to 0.8 t grain yield ha⁻¹ from traditional method (56). The superiority of the watershed-based farming was confirmed by economic evaluation which estimated 250% return on the increased working expenditure necessitated by changing from the traditional system to improved watershed-based farming system (44). In addition to being of direct benefit to crop yields, improved management on watershed basis has been much more effective than traditional management in reducing resource losses by runoff and soil erosion (Table 4) (37).

TABLE 4: Annual rainfall, runoff, soil loss, and peak runoff rate for a cropped Vertisol watershed with broadbed and furrow system and a watershed with traditional monsoon fallow system (1975-1980).

Year	Rainfall (mm)	Broad bed and furrow at 0.6% slope, cropped			Traditional flat, monsoon fallow		
		Runoff (mm)	Peak runoff rate (m ³ s ⁻¹ ha ⁻¹)	Soil loss (t ha ⁻¹)	Runoff (mm)	Peak runoff rate (m ³ s ⁻¹ ha ⁻¹)	Soil loss (t ha ⁻¹)
1975	1041	162	0.06	1.39	253	0.15	5.21
1976	687	73	0.09	0.98	238	0.16	9.20
1977	585	1	0.01	0.07	53	0.06	1.68
1978	1125	273	0.11	2.93	410	0.15	9.69
1979	690	73	0.08	0.70	202	0.15	9.47
1980	730	116	0.06	0.97	166	0.11	4.58

Source: (37).

Nutrient Management Strategies

Nutrient Demand for Crop Production

Plant requires at least 13 mineral elements for their growth and development. Intensive agricultural systems are characteristically expanded nutrient cycles involving the export of crops from a farm and require continued import of nutrients to the farm. Legumes in association with *Rhizobium/Bradyrhizobium* symbiotically fix atmospheric N₂ through biological nitrogen fixation (BNF) and are an integral part of cropping systems in the SAT. None of the legumes can meet their total N requirement at increased production level through BNF. In the tropics where plant residues are also removed from the field to feed animals, most grain legumes with an exception of pigeonpea (medium- and long-duration) depleted soil N and the grain legumes only slowed the decline of N fertility of the soil (65). When a sole crop of medium-duration pigeonpea was grown in rotation with a sole crop of castor a positive N balance of 18 kg ha⁻¹ was observed at Patancheru during a 2-year crop rotation (Table 5). All available data show that the nutrient reserves of Indian soils are being depleted (51) and nutrient status of soils is declining. In order to sustain the productivity of crops in the SAT appropriate nutrient management strategies based on renewable resource utilisation, BNF and increased input-use efficiency are must.

(REF-14)

TABLE 5: Nitrogen balance sheet^a for different cropping systems for Alfisol, Patancheru, India.

Cropping system ^b by Year			Import (kg ha ⁻¹) ^c (A)			Export (kg ha ⁻¹) ^c (B)		Balance (kg ha ⁻¹) (A)-(B)
	Fertilizers		Leguminous ^d N ₂ -Fixation		Harvest ^e			
	1991	1992	1991	1992	1991	1992 ^f		
S/P	C	60	60	0+80	0	88+68	66	-22
C	S/P	60	60	0	0+46	64	93+46	-37
GP	C	18	60	90+50	0	108+56	72	-18
C	G/P	60	18	0	102+82	65	141+75	-19
P	C	18	60	121	0	115	66	+18

^aN balance calculated based on main import and export sources of N.

^bS/P = Sorghum intercropped with pigeonpea, C = castor, G/P = groundnut intercropped with pigeonpea, and P = sole pigeonpea.

^cEach value within a binomial corresponds to the crop in intercrop.

^dIncluding atmosphere-derived N (fixed N) in leguminous roots.

^eAssumed that groundnut roots were exported by harvest.

^fN contents in mini-plot grown sorghum, pigeonpea and groundnut were used to calculate total N in the harvest for 1992.

Source : (29).

Sources of Nutrients for Crop production

Soil fertility which is an important constituent of soil productivity is largely determined by the organic matter and stored nutrients of the soil. In many soils, a significant fraction of the nutrient store is in the soil organic matter, an extremely important but fragile soil constituent. Crops obtain their nutrient supplies from: (i) soil reserves, (ii) fertilisers and manures, (iii) accretions through precipitation and irrigation water, and (iv) through BNF involving a number of diverse organisms. Although India is the fourth largest fertilizer user in the world, fertilizers account for barely one fourth of the nutrients absorbed by crops (51). The rest comes primarily from soil reserves, organic manures, BNF and residues as well as wastes.

Water Availability x Nitrogen Interaction

The variability in the amount and distribution of rainfall in the SAT affects the productivity and nutrient use efficiency of crops. When rainfall is excessive or unresponsive the nitrogen is lost through leaching or denitrification. When rainfall is deficient the nitrogen uptake is less and it remains in the soil unutilized by the crop. The interaction of rainfall with soil type gives rise to variable yields resulting in variable efficiency in the use of water and nutrients.

Light textured soils are low in organic matter content (< 1%) and are distributed over 500 million ha in sub-Saharan Africa alone (47). When rainfall is not limiting crop yields are lower than their potential yields mainly due to nutrient deficiency. Fig. 4 depicts the modeled response of millet to applied nitrogen in Niger under three rainfall scenarios. When rainfall is not limiting (350 mm mid-season rain) yields of millet do not exceed 1000 kg ha⁻¹ and nitrogen is clearly limiting as reflected by the excellent response rate (kg yield kg⁻¹ fertilizer N). The critical rainfall needed between sowing and mid-season in order to obtain a response to applied nitrogen lies above 200 mm (9). Our understanding of these nitrogen and rainfall interactions is of little help to the farmer as long as weather forecasting remains out of reach. The decision making for the farmer is made more complex due to the interactions of seasonal rainfall with sowing density, another factor that is decided before rainfall estimates are known.

(REF-14)

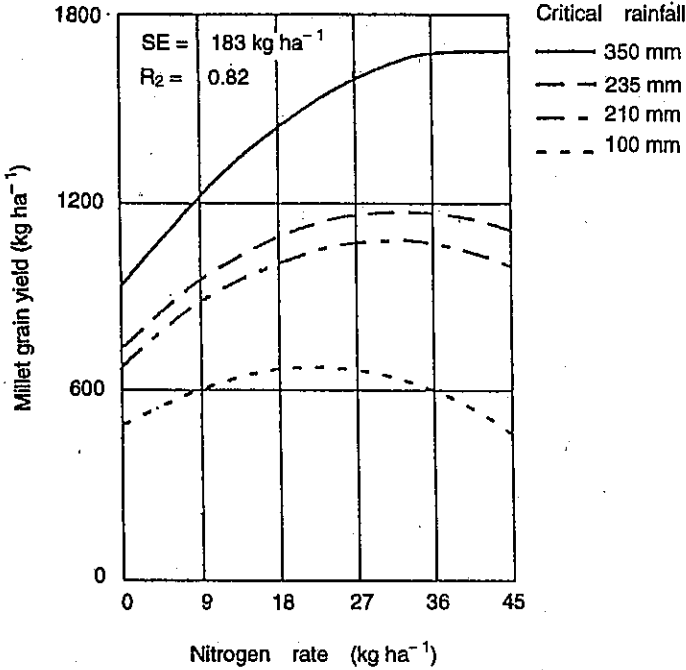


FIG. 4. : Nitrogen response of millet as a function of "critical rainfall." (Source: 9)

In the case of millet grown on light textured Entisols of Sahel (500-750 mm rainfall) losses of applied urea amounted to around 40% when it was split and banded in the wet year 1983 as well as in the dry year 1984, and were presumably due to ammonia volatilization. The plant recovery was around 20% in both years. Nitrogen losses in Alfisols from the slightly wetter SAT (750-1000 mm) ranged from 20-28% for maize cultivation in Africa [34].

Vertisols with mean soil depths of > 100 cm, are commonly associated with soils exhibiting vertic characteristics, such as Ustochrepts and Ustropepts, but too shallow (< 50 cm) to classify as such. In India alone 20 million ha of these soils are found [50]. Research over the past 15 years has indicated that response of sorghum on the Vertisols is good even under rainfed conditions [13]. For the shallow Vertic soil response to fertilizers is more erratic because of poor water storage characteristics [40]. For Vertisols, placement of nitrogen in bands was found to be efficient, and losses were low [32].

Hong et al. [20] studied the response of sorghum to applied nitrogen on a deep typic Pellustert and a shallow vertic Ustochrept, and using labeled fertilizer, traced the fate of nitrogen through the soil-plant system. Response to nitrogen for two soils for the different years is shown in Figure 5. Leaching losses of native soil nitrogen in these heavy clay soils of the Indian SAT reduced yields to half of their potential [20]. Timely sowing might increase the chance of nitrogen interception by the crop, but sowing date options are often determined by the ability to cultivate land and thus by the onset of rain. On the deep Pellustert, fertilizer use by sorghum was rather efficient with plant recoveries of 56% and soil recoveries of 35 to 37%, Moraghan *et al.* [32] conducted similar experiments at the same site in a similarly wet year (1070 mm total rainfall vs. 913 mm in 1983) and reported a total ¹⁵N loss of less than 5% for split applied urea. In the shallow Ustochrept, urea-N recoveries by the plant were substantially lower (36 to

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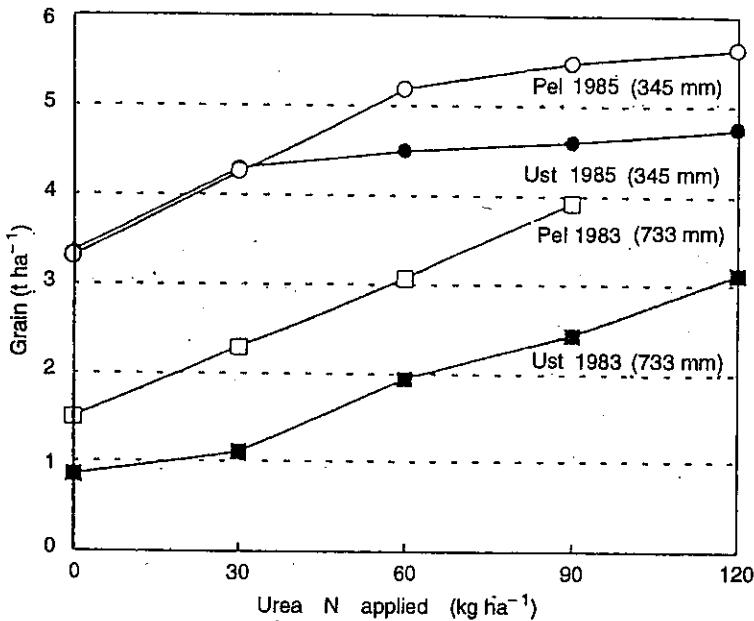


FIG 5: Response of sorghum to urea-N on a shallow Ustochrept and deep Pellustert in years with different rainfall. ICRIASAT, India.

41%) even though soil recoveries were similar to those obtained on the Pellustert (Table 6). Consequently, ^{15}N losses ranged from 21 to 30% or nearly triple those experienced on the deeper Pellustert. Given that the top 50 cm of these two soils are nearly identical in character, the difference must have been due to applied N leaching into the zone below 50 cm where, in the shallow soil, it would be beyond the sampling zone.

TABLE 6: Recovery of sorghum to urea-N applied to two experimental soils cropped to sorghum in different years¹. Pairwise comparison (LSD 95%) within years (significant difference within columns are indicated by different letters).

Soil	Year	N-source	Rain ¹ (mm)	^{15}N recovery			
				Plant	Soil	Total	Loss
Pellustert	1982	Urea KNO ₃	516	56 ^a 66 ^b	35 ^b 26 ^a	91 ^a 92 ^a	9 ^a 8 ^a
	1985	Urea	345	56	37	93	7
Ustochrept	1983	Urea KNO ₃	733	36 ^A 35 ^B	35 ^B 23 ^A	71 ^B 58 ^A	29 ^A 42 ^B
	1984	Urea KNO ₃	485	40 ^b 26 ^a	29 ^b 13 ^a	70 ^b 39 ^a	30 ^a 61 ^b
	1987	Urea KNO ₃	372	39 ^A 55 ^B	40 ^B 27 ^A	79 ^A 82 ^A	21 ^A 18 ^A

1. Rainfall between June 1 and September 15.

Source: [20, 32].

During wetter year (1070 mm rainfall) that NO₃-N applied to a Vertisol was indeed very efficiently (57%) taken up by the crop. In the Ustochrept, the behavior of NO₃-N was strongly dependent on rainfall. In the wetter years the ^{15}N labelled

$\text{NO}_3\text{-N}$ was poorly utilized by the crop in comparison with urea-nitrogen. The lost ^{15}N amounted to 42 to 61% of the applied nitrogen.

It appears that the great difference in susceptibility to loss of $\text{NO}_3\text{-N}$ is due to differences in soil depth, suggesting leaching beyond the rooting zones. Such losses are not only determined by the accumulated rainfall, but also depend on the rainfall distribution. In years with heavy rainfall immediately following fertilizer application, NO_3 moves readily into the poorly rooted parent material. Smaling and Bouma (49) demonstrated that much of the leaching in Vertisols early in the season occurred as bypass flow, utilizing cracks that formed during the dry season prior to their closure. As nitrogen leaching appears to be the predominant cause of nitrogen loss from the shallow soils, and given the unpredictability of the rainfall pattern following fertilizer application, NO_3 sources should be avoided on shallow soils of the SAT. Moreover, in order to minimize the risk of leaching, the fertilizer-nitrogen on shallow soils should be split as frequently as possible.

Biological Inputs for Nutrient Management

Looking at the complexities involved in use of chemical nitrogen fertilizers in the SAT, their prohibitive costs, and their contribution to the environmental pollution, there is an urgent need to explore other sources of nitrogen for sustaining crop production in SAT.

Soil is a habitat for a vast, complex and interactive community of soil organisms whose activities largely determine the chemical and physical properties of the soil. Soil microflora plays an important role in the maintenance of soil fertility because of their ability to carry out biochemical transformations and also due to their importance as a source and sink for mineral nutrients (21). Decomposition of plant and animal residues in soil constitutes a basic biological process which is brought about by successional population of microorganisms. In this process carbon (C) is recirculated to the atmosphere as carbon dioxide (CO_2), nitrogen is made available as ammonium (NH_4^+) and nitrate (NO_3^-), and other associated elements appear in forms required by higher plants (30). In this process, part of the nutrients is assimilated by microorganisms and incorporated into microbial tissues (soil biomass). Microorganisms regulate the nutrient flow in the soil by assimilating nutrients and producing soil biomass (immobilization) and converting C, N, P and S to mineral forms (mineralization). Biological turnover through mineralization-immobilization

TABLE 7: Quantity of nitrogen fixed by some legumes.

Crop	Nitrogen fixed (kg ha^{-1})
Alfalfa	100-300
Black gram	119-140
Clover	100-150
Chickpea	23-97
Cluster bean	37-196
Common bean	3-57
Cowpea	9-125
Groundnut	27-206
Lentil	35-100
Greengram	50-66
Pigeonpea	4-200
Rice bean	32-97
Soyabean	49-450
Peas	46
Fenugreek	44

Source : (39, 60).

leads to interchange of inorganic forms of nitrogen with the organic nitrogen. Conversion of organic nitrogen to available mineral forms ($\text{NH}_4^+ + \text{NO}_3^-$) occurs through biochemical transformations mediated by microorganisms and is influenced by those factors that affect microbial activity (temperature, moisture, pH, organic matter content and rate of residue application, its lignin content etc.) Nitrate is the predominant available form of nitrogen in cultivated soils that are well aerated. Crop and soil management practices influenced fraction of mineral nitrogen in soil. Nitrogen mineralization potential (N_0) of the Vertisol under pigeonpea-based cropping systems was two times more than that of the fallow + sorghum (F+S)-F+S treatment. The "active N fraction" the quotient of N_0 and N_{total} and expressed as percentage varied from 9 to 17% with higher values observed for the soil under pigeonpea-based cropping systems (66).

BNF process is an integral part of nitrogen cycling in the nature. Annually BNF is estimated to be around 175 million tonnes of which close to 79% is accounted for by terrestrial fixation. BNF offers an economically attractive and ecologically sound means of reducing external nitrogen inputs, and improving the quality and quantity of internal resources of nitrogen. Sustainable agriculture relies greatly on renewable resources, and on-farm nitrogen contributions are achieved largely through BNF. The organisms that fix N_2 are conveniently placed into two groups: (i) the symbiotic fixers, or those that fix N_2 in symbiotic association with higher plants, including some nonlegumes; and (ii) the nonsymbiotic and associative fixers, or those that fix N_2 apart from the specific host or are in loose association with the specific host.

Symbiotic nitrogen fixation

The symbiotic partnership between bacteria of the genus *Rhizobium/Bradyrhizobium* and legumes is well known. Out of 17,000 legume species distributed throughout the world, only about 200 are cultivated by man for food, oil, forage, organic mulch or fuel. Estimates for the amounts of N_2 fixed by various legumes are indicated in Table 7. However, as nitrogen fixation is dependent upon physical, environmental, nutritional and biological factors (36, 65) any N_2 -fixing system does not automatically contribute to the nitrogen cycle.

Actinorhizal plants

About 200 plant species (angiosperms) covering 17 genera in the tropics and subtropics are nodulated by N_2 -fixing actinomycetes (*Frankia*). Actinorhizal plants are though far less in number than N_2 -fixing legumes, due to their ability to regenerate poor soils and stabilize eroding land surfaces, produce timber and fuelwoods, they have achieved an important place in agriculture. Field estimates in Senegal and Thailand showed large responses to *Frankia* inoculation with estimates of proportion of nitrogen derived from fixation varying from 0.39 to 0.90 (16, 68).

Nonsymbiotic and associative nitrogen fixation

A number of species of several diazotrophic bacterial genera have been isolated from cereals and grasses (4, 59). The estimates of N_2 -fixed by several crops based on acetylene reduction assay ranged from 3.6 to 90 kg N ha⁻¹ (58). Incorporation of ¹⁵N₂ by nonlegumes have provided direct evidence of N_2 fixation in forage grasses, sugarcane, rice, sorghum, and pearl millet (7, 58).

Plant growth promoting rhizobacteria

A group of rhizosphere bacteria (rhizobacteria) that exert a beneficial effect on plant growth is referred as plant growth promoting rhizobacteria or PGPR. PGPR are

thought to improve plant growth by colonizing the root system and pre-empting the establishment of or suppressing deleterious rhizosphere microorganisms (DRMO) on the roots (48). The mechanisms of pathogen suppression by PGPR include substrate competition and niche exclusion, production of siderophores and antibiotics, and induced resistance. Large populations of bacteria established on planting material and roots become a partial sink for nutrients in the rhizosphere thus reducing the amount of C and N available to stimulate spores of fungal pathogens or for subsequent colonization of the root (12).

Phosphate solubilizing microorganisms

A group of heterotrophic microorganisms are known to have the ability to solubilize inorganic P from insoluble sources. The solubilization of P by these microorganisms is attributed to excretion of organic acids like citric, glutamic, succinic, lactic, oxalic, glyoxylic, maleic, fumaric, tartaric and α -ketobutyric (14). P-solubilizers also produce fungistatic and growth-promoting substances which influence plant growth (31). The efficiency/performance of these microorganisms is affected by availability of a C source, P concentration, particle size of rock phosphate and other factors like temperature and moisture.

Vesicular-Arbuscular Mycorrhizae (VAM)

The symbiotic association between plant roots and fungal mycelia is termed as mycorrhiza (fungus root, plural mycorrhizae). These fungi are found associated with majority of agricultural crops. They are ubiquitous in geographic distribution occurring with plants growing in aquatic to desert environments (33). These fungi belong to the genera *Endogone*, *Glomus*, *Entrophosphora*, *Gigaspora*, *Acaulospora*, *Scutelliospora*, are obligate symbionts and have not been cultured on nutrient media. VAM have been associated with increased plant growth, and with enhanced accumulation of plant nutrients mainly P, Zn, Cu and S mainly through greater soil exploration by mycorrhizal hyphae (1). It has also been suggested that VAM stimulate plant growth by physiological effects other than by enhancement of nutrient uptake (3) or by reducing the severity of diseases caused by soil pathogens (11) or by improving soil structure (52). The results of field trials conducted in India reviewed by Wani and Lee (58) indicated that VAM inoculations increased yields significantly in around 50% trials and the response varied with soil type, soil fertility, and VAM cultures. This scenario is similar to that for *Rhizobium* or *Azospirillum*.

Integrated Soil Fertility Management Strategies

The concept of integrated soil fertility management (ISFM) encompassing a strategy for nutrient management towards soil fertility maintenance based on natural resource conservation, BNF and input efficiency has been proposed (57, 61). This concept involves using the latest knowledge regarding cultural practices, cropping systems and nutrient cycles, and it aims at optimizing and stabilizing agricultural production within a given ecological and socioeconomic environment. The ISFM strategy does not preclude the use of chemical fertilisers but it relies heavily on use of renewable sources such as BNF and organics to their optimum efficiency and minimize use of fertilizers for sustaining crop production. In discussing ISFM in the SAT, as an example we discuss nitrogen and confine our discussion to the ways of increasing efficiency of the inputs.

In the SAT water is the most limiting-factor for dryland agriculture. However, stochastic nature of precipitation in these areas is such that nitrogen may be frequently limiting to crop growth. Some locations may face the drought where as at the same

time waterlogging can occur at other locations (Table 3). Soil nitrate generally accumulates over the dry season in quantities dependent on the amounts of readily decomposable organic matter left in the soil, and may be available for crop establishment. In the tropics, pigeonpea-based systems where pigeonpea is grown as intercrop or in rotation increased organic C content of Vertisol after 9 years. The organic C content of Vertisol under pigeonpea-based systems was higher by 18.4 to 28.9% (4.5 to 4.9 g kg⁻¹ soil) than the organic C content of F+S-F+S plots (3.8 g kg⁻¹ soil) (66). Growing legumes in rotation does improve mineral nitrogen content in soil as compared with the cultivation of non-legume crops. At IAC, Patancheru, results from long-term rotation experiment showed higher amounts of mineral nitrogen content in soil under legume-based systems than the non-legume-based cropping system (66). Further, despite the fact that legumes mine soil nitrogen when grain legumes are grown in rotation or as intercrops, the succeeding nonlegume crops do benefit consistently; their yields are reported to increase by 0.5 to 3 t ha⁻¹ representing a 30% to 350% increase over yields in cereal-cropping sequences (39). Grain yield of maize grown following sole crop of medium duration pigeonpea at ICRISAT was 57% higher than the grain yield of maize following a fallow treatment (27). In a long-term crop rotation experiment that began in 1983 at IAC, mean residual effects of legume-based crop rotations on yields of sorghum over the last ten years were greater than those from sorghum (S) in rainy season followed by safflower (SF) in the postrainy season (S+SF)-S+F plots (41). In a greenhouse experiment, sorghum grown in the soil from the cowpea intercropped with pigeonpea (COP/PP)-S+SF field plots (long-term rotation trial) yielded 63% higher than that grown in the soil from the S+SF-S+SF plots. In other pigeonpea-based cropping systems, sorghum yielded 36% to 56% higher than that from the S+SF-S+SF plot (67). Such increased cereal yields following legume crops were generally attributed to the nitrogen contributed by the legumes. However, this opinion is not held by all (10, 63, 64). Other mechanisms such as increased nutrient availability other than nitrogen, improved soil structure, reduced disease incidence, increased mycorrhizal colonization, and increased availability of nutrients through increased biological activity etc. were also responsible for the increased yields.

Residual effects of preceding legumes in terms of increased yield of following nonlegume crop are generally expressed in terms of nitrogen fertilizer equivalent. In a recent review Wani *et al.* (65) have summarised nitrogen fertilizer equivalent values which ranged from 7 to 135 kg N ha⁻¹ for various legumes (Table 8).

It is evident from the above discussion that legumes in symbiotic association with *Rhizobium/Bradyrhizobium* play an important role in sustaining crop productivity in the SAT. In the ISFM strategies efforts should be directed to enhance the benefits from legumes. In general, inoculations with efficient strains of rhizobia/bradyrhizobia have been tested widely. Similar is the case in case of inoculation with N₂-fixing bacteria in cereals crops also (62). Field performance of inoculation of legumes and cereals is variable and little on-farm data are available on the impact of inoculation on grain yield. Yield responses to inoculation were site-specific, depending on location, species, fertility and other factors (65). The results of 1500 demonstrations on farmers' fields with pigeonpea conducted in Gulbarga district of Karnataka State in India showed 100% increase in yield (1035 vs. 516 kg ha⁻¹) due to balanced use of diammonium phosphate and *Rhizobium* inoculation (8). However, inoculation alone with *Rhizobium* did not increase grain yield to such an extent.

Most of the times only inoculation with N₂-fixing microorganisms has been considered as possibility for increasing BNF benefits. Other avenues like selection of high N₂-fixing crops/varieties, management practices such as tillage, intercropping,

TABLE 8: Residual effect of preceding legume on cereal yield in terms of fertilizer N equivalents.

Preceding legume	Following cereal	Fertilizer N equivalent (kg ha ⁻¹)
Berseem	Maize	123
Sweet clover	Maize	83
Winged bean	Maize	70
Blackgram	Sorghum	68
Greengram	Sorghum	68
Greengram (monocrop)	Wheat	68
Chickpea	Maize	60-70
Cowpea	Maize	60
Groundnut	Pearl millet	60
Cowpea	Pearl millet	60
Chickpea	Pearl millet	40
Lentil	Pearl millet	40
Peas	Pearl millet	40
Pigeonpea	Wheat	40
Cowpea (monocrop)	Wheat	38
Lathyrus	Maize	36-48
Labiab bean	Maize	33
Pigeonpea	Pearl millet	30
Greengram	Pearl millet	30
Groundnut (monocrop)	Wheat	28
Pigeonpea	Maize	20-67
Peas	Maize	20-32
Lentil	Maize	18-30
Greengram (intercrop)	Wheat	16
Cowpea (intercrop)	Wheat	13
Groundnut (intercrop)	Wheat	12
Groundnut	Maize	9-60
Soyabean	Maize	7

Source: (65).

appropriate nutrient amendments are available (61). We need to utilize such avenues for harnessing BNF benefits. Presence of a large genotypic variability for such BNF traits as nodule number, nodule mass and acetylene reduction activity per plant has been known since early 1980s for chickpea, groundnut, pigeonpea, soyabean, cowpea and common bean (36, 65). However, efforts to use this variability in breeding for improved BNF have been limited or non-existent in many of these legumes. High- and low-nodulating (HN and LN) and non-nodulating (NN) plants within chickpea and pigeonpea cultivars have been observed (43, 44). The HN-selection of chickpea cultivar ICC 4948 yielded 31% more than its LN selection at low soil nitrogen level. These studies thus suggest a great scope for enhancing BNF in legumes through host-plant selection.

In general, high nitrogen content in soil, applied or residual, reduces nodulation and N₂ fixation in legumes (63) and also in cereals (59). To improve the contribution of BNF under such circumstances, soil nitrogen must be managed by including an appropriate nitrate-tolerant, high N₂-fixing legume or a genotype of a given legume and/or appropriate cropping and management practices. Based on soil mineral nitrogen status at sowing, need-based application of low doses of nitrogen for increased legume productivity and to maintain soil fertility has been suggested (65). Similarly, use of legumes in intercropping is a common practice but application of

nitrogen to the non-legume crop without appropriate fertilization method can reduce N_2 fixation by the component legume crop. Through appropriate management practices soil nitrogen should be manipulated in intercropping situations for example use of slow-releasing nitrogen formulations, organic nitrogen, and nitrogen placement between cereal rows rather than broadcasting and mixing in the soil must be worked out. Shading by the associated non-legume can also reduce the extent of BNF in the component legumes (35). Strip cropping and/or selection of noncompeting nonlegume crop can overcome both these problems and improve the system's productivity without reducing the contribution of BNF to the system. Appropriate tillage practices, landform treatments, and application of other nutrients such as P and microelements to legumes and alleviation of other biotic constraints for better plant growth play an important role in increasing BNF in legumes (65). For example, greengram, pigeonpea and soybean grown on BBF in Vertisol improved nodulation than when grown on a flat surface (65). During 1995 soybean grown on BBF on Vertic Inceptisol fixed greater quantity of nitrogen (185 kg ha^{-1}) through BNF than the amount of nitrogen fixed by soybean grown on flat – land form treatment (172 kg ha^{-1}) at IAC.

In case of phosphorus we have to rely only on inorganic sources as no other sources such as BNF in case of nitrogen exists. However, with the help of VAM, PO_4 -solubilisers, and PGPR and organic fertilisers efficiency of applied P fertilizers can be substantially increased. As discussed for BNF we need to take holistic approach to harness maximum benefits from microorganisms (61). Along with inoculations of crops with such target organisms, appropriate management practices also need to be followed for optimising benefits from microorganisms (61).

Once benefits from BNF are optimised in the system, the remaining needs of nutrient can be met through organic manures and inorganic fertilisers. Organic manures are time-tested materials for improving the soil fertility and crop productivity. Recently, organic manures have been integrated into the ISFM for high-yielding cropping sequences in contrast to the subsistence level production of the past. Application of 12.5 t ha^{-1} FYM or compost increased yields on an average by 160 to 200 kg ha^{-1} different crops. Recent review on organic manures and crop residues by Gaur (15) describes in detail the crop responses and other aspects of the organic manures. Although on nitrogen basis organic manures were less efficient than fertilisers, combined use of organic manures and fertilisers was found to be superior than the use of fertilizers alone. In addition organic manures are not just sources of nutrients, they have a profound effect on soil physical and biological properties (28, 31). Bationo and Mokwunye (5) argue convincingly that good organic matter management is the key to soil fertility management. They reported that around $15\text{-}20 \text{ t ha}^{-1}$ of manure is needed to obtain the effect otherwise achieved by chemical fertilizers. With the many alternative needs for organic material such quantities are not generally available (5). The best, one could probably hope for is, that organic matter levels be maintained, through a combination of crop residue restitution, fallowing or green manuring. Organic amendments increase the biological activity in soil and reduce the nitrogen losses through immobilization and also the performance of specific group of microorganisms such as azotobacters, azospirilla, PGPR, and VAM is improved in the presence of organic amendments (61). Organic matter additions to the soil are essential to maintain soil fertility as discussed earlier in this Chapter. More details on organic matter have been covered in several reviews (15, 28, 51).

Once biological and organic sources are used the gap of the nutrient demands by the crops can be met through chemical fertilisers. However, efforts should be made to

ensure that efficiency of fertilisers is increased and they are used appropriately without adversely affecting BNF as discussed earlier. In the SAT in light textured soils around 40% of applied nitrogen as urea was lost in Africa (6) and 5 to 21% for sorghum grown on Alfisol in India (32). In all these studies split banding was the most suitable application method and calcium ammonium nitrate appeared slightly more efficient than urea. On heavier textured soils such as Vertisols losses of fertiliser nitrogen are very low (6%) even during a wet year. Inoculation of cereal crops with azospirilla and azotobacters along with nitrogen fertilizer increased the fertilizer nitrogen recovery substantially (62). For increasing the efficiency of fertilizers applied, we need to follow integrated approach such as appropriate formulation of fertilizer, suitable timing and method for fertilizer application. Use of suitable organisms such as VAM in case of P fertilizers or azospirilla and PGPR in case of nitrogen fertilizers, and use of organics in combination with mineral sources (60, 61).

With the increasing pressures on the land to produce more and more food, and fuel it is sure that there will be no rest and recuperation for our soils. Nutrient removal will increase resulting in greater soil depletion and ISFM strategies must be worked out and followed. Based on the knowledge available we need to put the ISFM at work without waiting to learn everything about each component such as BNF or organic manures. Inoculation responses of the crops are not consistent and little is known about the reasons for this (65). However, current need is to use the available knowledge for sustaining crop productivity. Because nutrient application in most SAT areas are well below optimum, various organic and biofertilisers can help to take these towards optimum level and to that extent supplement fertilisers. Possibilities of ISFM strategies are real, attractive and environment friendly. Most nutrient packages for increasing crop yields to feed expanding population from a non-expanding area will continue to be fertiliser driven. However, what we need to achieve through ISFM is the enhanced efficiency of all the inputs (biological, organic and inorganic) for sustaining productivity of SAT soils.

Use of Simulation Models for Optimum Utilization of Water and Nutrients

Due to substantial variability and distribution of natural resources (soil and climate) in the SAT in order to interpolate or extrapolate research findings from one set of environment to another, both in time and space, we need different research tools than transferring agrotechnology through analogy.

Mathematical models are useful tools to understand complex systems such as integrated nutrient and water management in SAT because of existence of interactions among them. Mathematical models include statistical models and process-based dynamic simulation models. Statistical models usually have narrow range of extrapolation within the data range used, while a process-based models can simulate over a wide range of locations and variety of climatic conditions. Use of process-based modeling approach to evaluate water and nitrogen management in SAT is discussed.

Water Management

The rainfall in SAT has been shown to be highly variable. The success of crop production lies in efficiently managing rainwater by maximizing evapotranspiration and soil water storage with concomitant reduction in soil evaporation, runoff and drainage. We present two examples from rainy season and post rainy season.

Rainy season

We evaluated two land surface management treatments for efficiently managing the rainwater to sustain soybean production on a watershed level at IAC. Soybean was grown on flat land along the contours and on BBF system. The BBF system has a

raised bed and two furrows on either side of the bed to drain the excess water to a waterway leading to a surface tank. Our experience during 1995 indicated that BBF landform helped to reduce runoff and conserved more water in the soil. We simulated the water balance components - rainwater runoff and deep drainage to the profile using Ritchie's (42) water balance model. The total rainfall received during growing season was 640 mm. The total runoff was lesser in BBF compared to flat landform. Total runoff during cropping season ranged from 12 to 14%, whereas the drainage accounted for 23 to 33% of rainfall. Thus the total water loss during the season across landform treatments varied from 36 to 45% of rainfall. The crop used only 60% of rainfall. These results indicate the need to develop water harvesting techniques to efficiently use the water which otherwise is lost. The techniques available are the surface level tanks to store the runoff water and deep wells to capture the drained water through underground recharge possibilities. The water thus harvested can be used as life saving irrigation for crops. Alternatively it can also be used to grow high value cash crops such as vegetables or fruit trees in a small area near the tank or well.

Post-rainy season

Western Deccan Plateau of India, comprising mostly of western Maharashtra and parts of Karnataka are the important postrainy cropping regions of India. It is primarily a drought prone area. The rainfall in this region is low to medium (500-700 mm) and highly variable and uncertain for growing a rainy season crop. The major cropping system is sorghum in the postrainy season. Because of variability in rainfall during rainy season it is sometimes possible to grow a short season legume in rainy season in some of the locations. The opportunities must be exploited to make better use of natural resources. In order to achieve this, there is a need to properly understand the season and its potential. This can be achieved by using a water balance model (26) and the historical weather data.

We used 30 years of weather data from Solapur, Aurangabad, Gulberga, Bellary and Bijapur and the water balance model to simulate the water loss (runoff and drainage), water deficits and available soil water in the season. Solapur has greater duration and amount of available water. Aurangabad has best moisture available in rainy season. Both in Solapur and Aurangabad there is a potential to grow a short season legume like greengram in the rainy season, without affecting the production of sorghum in postrainy season. The possibility to grow a legume is a possibility to improve soil fertility through BNF and sustain the postrainy sorghum production in these locations.

Nutrient management

Response of crops to nitrogen fertilizer in the SAT is highly variable and depends on moisture holding characteristics of soil and amount and distribution of rainfall during the season (24, 25). Given the inter- and intra-season rainfall variability in the SAT, it would be extremely difficult to sample all possible variations in nitrogen-response through experimentation. Process-based crop simulation model was effectively used to evaluate the risks involved in nitrogen fertilizer application to dryland sorghum (2).

In several locations in major sorghum growing region in peninsular India, 25 year simulation study indicated that application of 30 kg nitrogen ha⁻¹ at the time of sowing resulted in a clear response to the added nitrogen fertilizer. Beyond this level the prospects of large positive response to the added N were not marked. The study indicated that the risks involved in application of 30 kg nitrogen ha⁻¹ to sorghum in Vertisols was minimal. The simulated results are supported by nitrogen response field studies conducted in Vertisols (25, 55).

Sustaining the crop production in variable environments require a clear understanding of factors that influence optimum utilization of scarce natural resources such as water and nutrients. Effective and modern dynamic tools such as crop simulation models are available today to evaluate the climatic and soil resources over a long period of time. These tools are capable of evaluating various management options on land endowments of SAT.

Summary

The SAT is characterised by variable and unpredictable seasonal rainfall and low organic matter containing soils. Under such situation and with the prevalent socioeconomic conditions in this region to fulfil the demand for food, feed, fuel and fibre, crop production must be increased. For sustaining crop production from such fragile ecosystem we need to adopt holistic approach which can sustain the natural resources such as soil and water and also increase crop production. Water, generally a scarce resource in the SAT, sometimes becomes problematic causing waterlogging. In order to optimize efficiency of water use, appropriate soil management practices through a watershed approach need to be developed and adopted. Along with water, nutrient management also holds a key for increasing crop yields. Through appropriate blending of different sources such as biological, organic and inorganic we need to formulate integrated soil fertility and water management strategies. Water and nutrient interaction play crucial role in enhancing efficiency of the inputs. Through interdisciplinary research and with the help of simulation modeling we need to formulate ISFMs for sustaining crop productivity in the SAT. We must try to harvest and utilise every drop of rain water where it falls. Use appropriate legume-based cropping systems, land management practices, generate organic matter on-farm, and use microorganisms efficiently along with efficient utilization of mineral fertilisers for sustaining crop production in the SAT.

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