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--A--Nutrient Management in Vertisols in the Indian SAT

--C--J.R. Burford, K.L. Sahrawat and R.P. Singh[1]

--D--Summary

Nutrient inputs are one of the important components of improved farming systems for deep Vertisols within the assured rainfall area (>800 mm a^{-1}) of the Indian SAT. In this area, deficiencies of nitrogen, phosphorus, and zinc are the most common in the staple cereal crops. Fertilizer use remains low, apparently due to uncertainty over the reliability of responses to nutrient inputs. Another reason for the low fertilizer use has been the need to use several component inputs in combination (especially improved cultivars, fertilizers, and agronomic management) to ensure optimum benefits from each input. Our recent research has attempted to delineate the most responsive environmental situations, to attempt to minimize risk by the farmer.

At ICRISAT Center, yields of rainy-season sorghum were reliable as they consistently attained 5000 kg ha^{-1} grain in six successive seasons, when nutrients were supplied; but, in the absence of fertilizer, grain yields were as low as 1500 kg ha^{-1}. Nutrient inputs were a much more important determinant of sorghum yield than

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variations in seasonal rainfall. Use of {15}N-labeled fertilizer has shown that rainy-season sorghum was quite efficient in the use of added fertilizer-N, except in the much wetter (1200 mm a{+-1}rainfall) than normal (800 mm a{+-1}) year with a traditional (local) means of fertilizer-N application. Compared with improved application methods, uptake of N by the crop in this year was reduced from 45% to 30%, and losses (presumably as gasses) increased from 7% to 25%. Because ICRISAT Center is located on the edge of the assured rainfall area, these results on the reliability of responses and losses of fertilizer have much relevance to the whole area in which annual rainfall rises to as high as 1300 mm a{+-1}.

Preliminary research on phosphorus has confirmed earlier agronomic experiments indicating a lower requirement for fertilizer-P on Vertisols. Of particular interest are the indications of the need for re-evaluation of soil-test procedures, and the modest rate of fixation of phosphorus by Vertisols.

Past research has given major emphasis to determining the nutrient requirements of single crops. Needed in the future are two types of general approaches: research into the variability in responses from year to year, especially as affected by water x soil x crop interactions, and long-term studies to assess the strategies for maintenance of fertility. Specific subject areas of high priority are studies on N, both for the efficiency of fertilizer and the potential benefits of legumes; and the needs for phosphorus, especially in relation to long-term cropping systems (rather than for single crops). Both are suitable for network activities, both within and outside India, because of the combination of similar and dissimilar environments across the SAT.

--B--Introduction

The low nutrient status of most SAT soils has been recognized for several decades, but fertilizer use in rainfed agriculture across the SAT is very low, especially on the staple food crops. This low usage contrasts with the widespread realization by farmers of the benefits of nutrient inputs in irrigated agriculture in India (Tandon and Kanwar 1985); and, for Vertisols, the contrast is most marked, because nutrient inputs were identified very early as an important component of the improved farming systems for deep Vertisols in the assured rainfall areas of India (Virmani et al. 1988; Willey et al. 1988). Even on Vertisols, farmers have been very cautious, however, in their adoption of fertilizer inputs for dryland agriculture. In this paper, therefore, we discuss some of the historical developments leading to the current increasing awareness of the importance of nutrient inputs in dryland agriculture, and we show the effectiveness of nutrient inputs for the improved double cropping technology for Vertisols. Finally, we indicate the needs for future research on Vertisols, especially for network activities.

--B--Nutrient Status of Indian Soils

Nitrogen, phosphorus, and zinc are the main elements that need to be added to soils to ensure satisfactory crop production in the SAT of India. These needs have been clearly demonstrated by many thousands of agronomic experiments, both at research centers and in farmers' fields (Kanwar 1972; Randhawa and Tandon 1982). Supporting evidence has been provided by extensive surveys involving tissue analyses of crops and the available nutrient status of the soils (IARI 1982). These complementary studies indicated that nitrogen deficiency in the staple cereal crops was almost universal, that phosphorus fertilizer was needed on about 50% of soils, and that zinc was the third important nutrient. The impetus for such extensive surveys of soil and crop nutrient status arose from the need to establish nutrient requirements of crops in extensive irrigated schemes.

--C--Irrigated agriculture

The combination of nutrient inputs, improved cultivars, and an assured soil moisture regime through irrigation have been the basis of the "green revolution" that has so markedly improved grain production in India. The acceptance of the importance of nutrients led to India being the third largest consumer of fertilizer-N in the world in 1981 (FAO 1985). Consumption in India was then 4.1 million (Sahai et al. 1982). Most of this fertilizer is applied in irrigated agriculture, and will be so in the short-term future because nutrient inputs are still less than the estimated needs in many irrigation areas (Jha and Sarin 1984).

Most of the research associated with these irrigation schemes of the original green revolution aimed at increasing the production of rice or wheat, the premier food grains in India. Relevant to dryland agriculture, however, is one excellent example (Fig. 1) which shows the benefits of improved seed and fertilizer for grain sorghum--one of the two staple cereals grown by subsistence farmers in the drier agroclimates of the tropics. The yield of the traditional (local) long-duration and long-strawed cultivar of sorghum was only about 1200 kg ha[+-1] without fertilizer-N, which contrasted with the satisfactorily high yield (over 3500 kg ha[+-1]) with N fertilization from the short-statured, short-duration, improved cultivar (Swarna) and hybrids (CSH 1 and CSH 2); even without inputs of N, the yield of the improved cultivars was 50% more than that of the local; and the improved cultivars were much more responsive to inputs of N than the local cultivars.

These results, and many others since, have amply demonstrated the excellent response of improved cultivars to nitrogen inputs when the soil moisture regime is assured throughout the life of the crop; but the responses under the variable moisture regimes of dryland farming areas are much less certain.

--C--Rainfed agriculture

The potential benefits of nutrient inputs in dryland agriculture have become recognized only within about the past 10-15 years, despite their recognition much earlier in irrigated agriculture. Perhaps the major reason for this slow recognition was the essentiality of irrigation for the heart of the green revolution in India--in the near-arid environment of the Punjab. Regardless of the cause, the earlier prevailing view was that the major factor limiting improved productivity in rainfed agriculture was the lack of a reliable moisture regime, due to an unreliable rainfall. Drought was perceived to limit productivity much more than nutrient deficiencies. An indication of the relatively recent change in views is the conclusion that nutrients are the most important component of improved systems for rainfed agriculture, and that their importance had not be adequately recognized (Kanwar 1981).

Acceptance of the need for nutrients is derived from many experiments showing good responses (e.g, Table 1). Similarly, at ICRISAT Center, initial attempts at developing an improved system for deep Vertisols showed the additive effect of improved nutrients, agronomy, and cultivars on yields of rainy-season cereals (Table 2). Nevertheless there remains some caution over the use of fertilizers, because of variability in responses between years and locations (Table 3). In interpreting these results a response of about 3 kg grain/kg N applied is required to cover the costs of fertilizer, and farmers require a 2.5-3.0 fold return i.e. 8-9 kg grain/kg N to interest them in an input (Tandon 1980).

--C--Fertilizer use in rainfed agriculture

Despite the encouraging results shown in Tables 1 and 2, the adoption of fertilizer in dryland agriculture in India has been particularly slow. Over 1977-79, the average input of nutrients in the dryland districts of the country was only 18.5 kg ha{+-1}a{+-1} (Jha and Sarin 1984); the inputs are expressed in the oxide form, i.e., N + P{-2}O{-5} + K{-2}O, and a dryland district is one in which less than 25% of cultivated land was irrigated. But these average rates of fertilizer application did not reflect the fertilizer applied to the staple food crops (sorghum, millet) of the drylands. Of the total nutrients applied over a district, most, sometimes all, was applied to either cash crops (for example, groundnut, cotton, castor, chillies, tobacco,) under rainfed agriculture, or to small areas of irrigated land (e.g., paddy rice, sugarcane) within the rainfed area; in both these situations farmers may apply large rates of fertilizer. The amount of fertilizer applied by the subsistence farmer in the Indian SAT to his dryland staple food crops--sorghum and millet--is indeed very small.

The reasons for the slow adoption of fertilizers in the cultivation of dryland cereals are not well understood, although some factors are fairly obvious. First, dryland agriculture has been given research emphasis only in recent years, because of the earlier views that low and variable rainfall was a major constraint. Second, fertilizer inputs are most effective only when several improved components are introduced concurrently, e.g., improved cultivars and a range of factors that fall within the umberella of improved agronomy. Third, and most important in the view of Jha and Sarin (1984), is the uncertainty of the responses of crops to fertilizer additions; variability in responses had earlier been clearly demonstrated (Kanwar et al 1973) though inadequate attention has been given to its effects on adoption of fertilizers. Our research over the past few years has aimed to improve understanding of the factors causing variability in responses, to allow a better delineation of the conditions under which nutrient use would be most effective, and therefore reduce the uncertainty currently attached to the use of fertilizer in dryland agriculture especially on Vertisols. Pertinent results are given in the sections that follow.

--B--Nutrient Inputs for Deep Vertisols in the Rainy Season.

Nitrogen has been given most emphasis in our studies of nutrient management on deep Vertisols, because of the prevailing view that phosphorus inputs were less important for crops on Vertisols than on lighter-textured soils such as Alfisols and Entisols (Arakeri 1980; Tandon and Kanwar, 1984). An additional reason for giving priority to nitrogen is that an assured moisture regime is essential for maximum responses to fertilizer-N; and, the most important attribute of Vertisols--their high water-holding capacity--should minimize the effects of dry periods during the rainy season. It is therefore on Vertisols under moderately assured rainfall that we would expect to get the most consistent responses to the total nitrogen supplied to a crop (from soil and fertilizer sources). For such detailed studies, ICRISAT Center provided a useful benckmark site, for studying nutrient responses.

--C--Nitrogen on sole sorghum

A summary of responses to applied N on deep Vertisols over six successive years at ICRISAT Center provides a good example of the year-to-year variation in responses in rainy-season cropping (Fig. 2). The first increment of applied-N (usually 40 kg N ha{+-1}) always gave worthwhile responses. Even in the particularly harsh year of 1979--when the southwest monsoon arrived late, and was not stable for several prolonged droughty periods up to sorghum anthesis in late August--the initial increment of N caused a response of 13.3 kg grain/kg N applied which, at prevailing grain and fertilizer prices, represented a benefit:cost ratio of about 4:1.

Figure 2 clearly shows that seasonal conditions at ICRISAT Center did not appreciably restrict the maximum yield of rainy-season CSH 6 sorghum on deep Vertisols, provided that adequate nitrogen was supplied. With adequate N inputs, yields attained the quite satisfactory level of 5000 kg ha(+-1) in each year, even in the particularly harsh 1979 season. This contrasts with lower yields on Alfisols in this year (ICRISAT 1984), and reinforces the comments made by other workshop contributors that Vertisols are potentially one of the most productive soils in the SAT, mainly because of their high water-storage capacity; this is sufficient to maintain crop growth during droughty periods within the rainy season in addition to supporting growth for extended periods after the rains cease.

The area delineated as assured for rainy-season cropping on deep Vertisols was based on a criterion of a high probability of a rainy-season crop to survive and produce grain (Virmani et al. 1988). This concept did not, however, extend to the next step of assessing the potential productivity of crops, and especially the responsiveness to nitrogen for which we might expect, *a priori*, that the assuredness of rainfall would need to be higher. Nevertheless, because ICRISAT Center is located on the edge of this area, described as assured for crops' survival, we can predict with reasonable confidence (on the basis of the data in Fig. 2) that this assured area is also that in which rainfall is sufficiently assured for moderately high and reliable grain production by rainy-season sorghum.

While the data in Figure 2 show a high reliability of responses to a first increment of nitrogen, they also indicate that the magnitude of responses and the amount of fertilizer needed varies considerably. These are inversely related to the yield without N inputs. Preliminary examinations indicate that these, in turn, may depend on a combination of seasonal rainfall and the nitrogen-supplying capacity of the soil; research on these aspects is needed.

The percentage of fertilizer-N absorbed by crops provides a useful guide to the efficiency of fertilizer-N use. For sole crops of rainy-season sorghum at ICRISAT Center --grown under the recommended agronomic practices used for the double-cropping of deep Vertisols, especially dry seeding ahead of the arrival of the rainy season (see Virmani et al., this workshop) and improved methods of fertilizer application --uptakes are usually greater than 50% (Moraghan et al. 1984; Hong, pers. comm.). These are similar to results expected from experiments elsewhere in the world where the use of fertilizer by the crop is efficient. The uptake of fertilizer by sorghum crops was assessed by the "apparent N recovery" method, or was measured using isotopically-labeled [15]N fertilizer; the improved method of fertilizer-N application involved applying the fertilizer in bands below the soil surface, in split applications involving one-half of the total at seeding, and one-half at the first weeding (about 10-14 days after emergence of the crop).

Improved methods of fertilizer application appear to be essential in high rainfall years. In 1981, when the total rainfall was 1200 mm, application of all the fertilizer at seeding gave a low uptake by the crop of only 30%--a value which usually indicates inefficiency--and the unaccounted-for N (presumably lost as gases) was 26% (Table 4). The improved application method, involving split-application and band-placement of fertilizer, increased N uptake to over 45%, and decreased the apparent losses to less than 7%. The improved application methods gave little or no advantage in drier years. As ICRISAT Center is located on the dry edge of the assured rainfall zone (for Vertisols), this result obtained in a very high rainfall year at ICRISAT Center has considerable relevance for the Vertisols under higher average rainfall. The nitrogen losses appear to be due to denitrification, as leaching through these heavy clay soils is expected to be very slow.

The above [15]N-recovery data were the first to be obtained for Vertisols under dryland agriculture in India. They are particularly valuable because they counter some earlier popular opinions that fertilizer-N is not efficiently used by cereals in the rainfed SAT of India. Even further, however, it shows the need for care in fertilizer application. The need for simpler and especially cheaper implements is clear (see von Oppen et al., this workshop), but implement development should not ignore the need for timing and possibly placement of fertilizer-N.

--D--Nitrogen on cereal/legume intercrops

The intercropping of pigeonpea with sorghum, with a regular row-arrangement of 1:2 rows of pigeonpea:sorghum, provides a highly successful means of increasing productivity by about 40-60%, compared with growing these two components as sole crops (Willey et al., this workshop). The yield of such intercropped sorghum, maturing towards the end of the rainy season, is usually expected to be in excess of 90% of that of a sole crop; for medium-duration pigeonpea, maturing several months later, yields are about 60% of the sole crop. The sorghum/pigeonpea intercrop system gives about the same productivity as sorghum (or maize) and chickpea sequential crops grown in the rainy and postrainy seasons respectively; but it is more reliable because it avoids the need to establish the second crop at a time of declining reliability of rainfall (see Willey et al. 1988). But there was no systematic study of the effectiveness of fertilizer-N applied to the cereal; because of completion between the two components of the intercrop system, fertilizer application was expected to be less efficient than with the sole crop. Comparisons over 3 years show that the responsiveness of sorghum was decreased only slightly by the introduction of the pigeonpea intercrop (Fig. 3); and, although the stimulation of the growth of sorghum by fertilizer-N caused some depression of pigeonpea yields, the overall increase in productivity was still 40% with N-inputs as high as 120 kg ha{+-1} (Fig. 4).

--D--N in cropping systems: residual effects of fertilizer

The proportion of fertilizer-N, applied to rainy-season cereal crops, that became incorporated into the soil was quite high (up to 40%, see Table 4). Availability of this incorporated-N for subsequent crops is, however, low. Only 1-3% was taken up by a subsequent crop, either safflower grown in the postrainy season or sorghum in the rainy season of the following year (Moraghan et al. 1984). This result is in accord with data showing the very slow release of fertilizer-N once incorporated into the soil matrix (Jansson 1963; Westerman et al. 1972; Dowdell et al. 1984.

--D--N in cropping systems: legumes

Until recently, agricultural research in India had given emphasis to the use of fertilizer-N for the alleviation of nitrogen deficiency in cereals. While this reflects the ready acceptance of fertilizer use by farmers in irrigated agriculture, the lack of ready adoption of the use of fertilizer-N in rainfed agriculture leads to speculation of the possible role of legumes for providing "free" inputs via the biological fixation of N by legumes.

Legume-based systems have been particularly successful for providing N-inputs where fertilizer was of marginal economic benefit (see Donald 1964; Russell 1984). These systems used grazed pastures for the legume phase. But, in India, there is not a tradition of pasture development for animal production; legumes are grown for their grain as part of the crop-production system. The produce thus removes a substantial proportion of the N fixed by a grain legume crop, especially for improved cultivars with a 'high harvest index', i.e., the proportion of grain to total biomass. Improvements to cultivars by plant breeders are usually directed at least partly to improving the harvest index. This can lead to the removal of more nitrogen in grain than has been fixed during the crop growth (Henzell and Vallis 1977).

Perhaps it was such logic that led to a lower priority being given to research on the possible beneficial effects of biological N fixation by grain legume crops. Ignored was the fact that pigeonpea has only a low harvest index, sometimes less than 0.20 for the medium- to long-duration types, and that it also sheds its senescing leaves from flowering onwards. Although the farmer removes the stalks from the field, he removes relatively little nitrogen in this process, because the stalks have a very low N content.

Addition of nitrogen by fallen leaves may add 40-60 kg N ha{+-1} to the soil (Sheldrake and Narayanan 1979). These, plus root material and nodules remaining in the soil, have been shown to have good residual effects on a subsequent cereal crop (Kumar Rao et al. 1983) that are equivalent to an application of fertilizer-N of about 30-40 kg N ha{+-1} (Fig. 5). While not large, even a moderate input is valuable for a crop as responsive as sorghum to N inputs; this input could double yields, because the soil appears to supply as little as 30 kg N ha{+-1} to cereal crops.

Results such as the above have led to the establishment at ICRISAT of long-term experiments that examine the yields and residual effects of various combinations of crops, to assess the optimum combinations of legumes and cereals for maintaining productivity. Such experiments are urgently needed for the various agroclimates and soils in the Indian SAT, because their results will provide the basis for planning the optimum balance of fertilizer- and legume-N inputs.

--C--Phosphorus

The need to establish the phosphorus requirements of crops grown on Vertisols has been given much less attention than that given to nitrogen, for two quite clear reasons. First, phosphorus is given a lower priority in India than nitrogen, as it generally appears to be less necessary on Vertisols than on other soils (Arakeri 1980). Second, strategies for phosphorus application can be much simpler to develop, because of the strong residual effects of previous applications, and the possibility of making general recommendations on a soil basis that apply over quite wide areas (Smith 1968).

Preliminary experiments at ICRISAT have indicated that Vertisols differ from other soils with respect to the behavior of P in the soil. Pigeonpea may respond to phosphorus applications on Alfisols of low available P status (<3 ppm Olsen P in the 0-15 cm soil depth; but it has not yet responded on Vertisols at ICRISAT Center even with the soil available-P (Olsen) levels less than the extremely low value of 1.5 ppm. Further, sorghum--which is much more responsive than pigeonpea to P applications (ICRISAT 1981)--usually responds to P application on Vertisols only when the Olsen-P value is less than about 2 ppm (Fig. 6). This is a very low critical level when considered against the general recommendation in India of 5 ppm being possibly adequate and 10 ppm being sufficient.

The causes for the apparent difference in the behavior of P in Vertisols, in comparison with its behavior in other soils, is not immediately clear. Studies under more closely controlled conditions, in pot experiments involving soils from carefully selected sites on

Alfisols and Vertisols, failed to demonstrate a difference between the soil-test/crop-response relationships for the two soils when the Olsen test was used to assess soil P status. But a wide divergence was shown when the more-exhaustive Colwell adaptation of the Olsen test was used. This was surprising, because the Vertisol, with its higher buffering capacity, was expected to release more "sorbed" P than the Alfisol. Although Vertisols in India are reputed to have a high P-fixation capacity, relatively little difference was found in the fixation rate of benchmark Vertisols and Alfisols at ICRISAT Center (ICRISAT 1985).

Other evidence indicates that the P status of Vertisols may vary substantially across the SAT. Some Vertisols in Australia have not required P inputs even after many years of continuous cropping, and those in India and Sudan appear to require only small inputs, but some Ethiopian Vertisols appear to require substantial inputs (Tamirie, pers. comm). Further research is needed to resolve the various issues raised about the behavior of P in Vertisols, mainly because any recommendations for nutrient additions to soils must be derived from known data about the highest and most reliable benefit:cost ratio options.

--C--Other nutrients

Apart from nitrogen and phosphorus, zinc is the only nutrient required over substantial areas in India. The high clay content and alkaline pH of Vertisols is undoubtedly responsible for the widespread occurrence of zinc deficiency. Sorghum is much less susceptible than maize, but current remedial measures are not very satisfactory. Soil applications are most effective, but are costly and wasteful because the amount of zinc sulphate needed for improved cropping systems may be about 20-25 kg ha{+-1} about every 3 years. Deficiencies can be alleviated, or completely ameliorated, by spraying 0.5% zinc sulphate solution onto the crop; but, with severe deficiencies, the application may need to be repeated 2 or 3 times. Temporary waterlogging of Vertisols may initiate or intensify some nutrient deficiencies, for example zinc deficiency on maize and iron chlorosis on groundnut.

--B--Vertisols: Postrainy season cropping

The nutrient requirements of postrainy season crops have received much less attention than rainy season cropping. Responses are smaller in the postrainy season crops than the rainy season crops (Tandon 1980; Tandon and Kanwar 1984) and the frequency of profitable responses may also be smaller (Kanwar et al 1973). The main reason for the smaller reward from inputs to postrainy season crops is undoubtedly the fact that they usually rely on water stored in the soil profile for most (sometimes all) of their water requirements. These crops usually approach maturity with their moisture supplies approaching exhaustion; drought stress during their growth is common. Additionally, nutrients placed at the usual depth (5 cm) in the soil may be easily accessible to plant roots for only a short time, because the nutrients may increase nutrient uptake and yield (Rao and Das 1982; Morghan et al 1984) but the magnitude of nutrient response will still be limited by the supplies of water available to the crop.

Research is urgently needed on nutrient requirements of postrainy season crops on Vertisols. But, as indicated above, complex interactions may be involved. Systematic approaches, involving studies of the mechanisms involved, would appear to be more productive than empirical approaches.

--B--Further Research Needs

The above findings on the nutrient requirements of crops on Vertisols at ICRISAT Center can be applied to the watershed-based double cropping technology for deep Vertisols in the assured rainfall areas in India. We can extrapolate with some confidence, especially for nitrogen, for several reasons. These are that ICRISAT Center is located on the 'dry' edge of the assured rainfall area, responses to nitrogen are especially dependent upon an assured moisture regime, and the Vertisols in India appear to be a reasonably homogenous group (Swindale 1988). We may therefore conclude, from the data in Figure 2, that lack of nutrients, especially N, is a much more important constraint to production than drought in this target area. This finding clearly indicates the need for further research to determine the best means of improving and maintaining the nutrient status of these soils; this may involve fertilizers, legumes, or a combination of both.

For cereals grown in the rainy season, fertilizer-N is used efficienciently are good under the moderate rainfall conditions at ICRISAT Center. But, more research is needed on the application methods under higher rainfall because of the higher probability of waterlogging, and losses by denitrification. For postrainy season cropping, much more research is needed, as this has been a neglected area. The reliability of responses to nutrient inputs in this season has not yet been given serious consideration.

Although the advantages of legumes are known, more emphasis needs to be given to legume-N inputs. The preliminary results shown here from ICRISAT Center are being substantiated in more detailed work. Clearly, there is a need to develop general relationships that permit the planning of crop sequences and crop combinations that will maintain fertility for a range of soils and rainfall environments.

For phosphorus, initial results shown here indicate the need for a reassessment of the behavior of P in Vertisols. The need for a lower critical limit for a soil test for sorghum on Vertisols has, it seems, not yet been generally recognized. Additionally, the variations in P status across the SAT appears to have received little attention.

In summary, there exists a full agenda of research topics that justify attention within a Vertisol network. Commonalities and contrasts in Vertisol climates and soil characteristics provide a challenging research framework in which a network approach offers a faster solution to crop production problems than that achievable by researchers working in relative isolation in their own countries.

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Table 1. Responses of rainfed sorghum to optimum or near-optimum levels of nitrogen application in field experiments in India in the rainy season (Tandon and Kanwar 1985).

No	Soil (trials averaged)	Location (cultivars)	Yield of zero N plots (t ha[+-1])	N level (kg ha[+-1])	Response(3) (kg grain/ kg N)
1	Alfisol (8)	Hyderabad (Hybrids)(1)	1.35	80	21.6
2	Alfisol (3)	Vizianagaram (CSH 1)	2.67	100	21.9
3	Vertisol (2)	Hyderabad (CSH 6)	1.18	120	28.5
4	Vertisol (2)	Dharwar (CSH 1)	2.39	100	14.2
5	Vertisol (8)	Akola (CSH 1)	1.35	60-80	24.2
6	Vertisol (5)	Akola (CSH 1)	1.47	100-120	16.7
7	Vertisol (3)	Dhule (CSH 1)	2.97	100	12.7
8	Vertisol (2)	Kohlapur (CSH 1)	2.39	100	17.2
9	Vertisol (2)	Nagpur (CSH 1)	1.88	75	24.2
10	Vertisol (3)	Parbhani (CSH 5)	3.11	120	20.6
11	Vertisol (3)	Kota (CSH 1)	0.77	75	10.1
12	Vertisol (3)	Rajkot (CSH 1)	1.37	90	14.8
13	Vert-Alf (5)	Jhansi (Mau T1; T2)	1.22	60-80	13.6
14	Mollisol (6)	Pantnagar (CSH 1)	2.60	80-100	11.9
15	Entisol (6)	New Delhi (CSH 1)(2)	2.66	60	24.3
16	Entisol (4)	New Delhi (CSH 1)(2)	0.82	100	16.0

1. Hybrids CSH1, CSH5, CSH6.
2. Protection irrigation when needed, Inceptisols/Entisols both occur.

Table 2. Effects of stepwise improvement in cultivar, fertilizer, and land management, on yields of maize grown in the rainy season on a deep Vertisol, ICRISAT Center, 1976 (ICRISAT 1977).

Variety	Land management	Fertilizer	
		Traditional (FYM)	Improved (NPK)
Traditional	Traditional	450	1900
	Improved	660	2610
Improved	Traditional	630	2220
	Improved	960	3470
LSD P = 0.05		474	

Table 3. Summary of response of rainy season crops to fertilizer-N (Rao and Das, 1982).

Crop	Range of response (kg grain/kg N)
Sorghum	3.4-43.4
Pearl millet	2.1-24.8
Finger millet	5.0-42.4
Maize	4.1-67.4
Rice	4.5-33.9
Setaria	5.9-17.9
Sunflower	1.5-22.6
Castor	2.9- 7.2
Groundnut	1.3- 6.0
Linseed	1.2-11.5
Sesamum	1.3-5.0

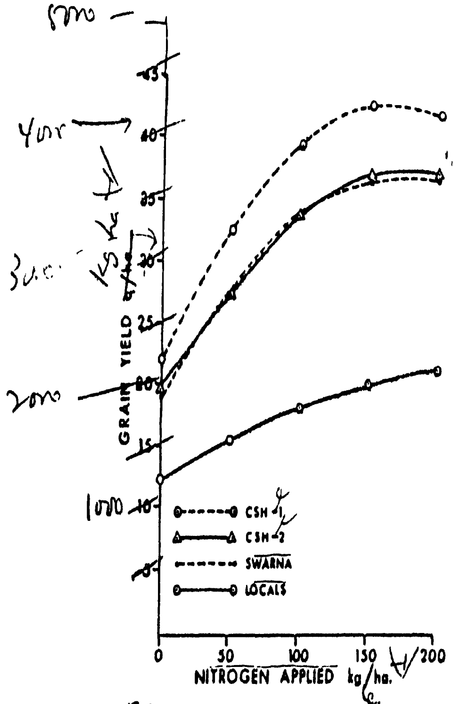
Table 4. Effect of method of application of urea (72 kg ha{+-1}) to CSH 6 sorghum on grain yield, N uptake, and N recovery; Vertisol, ICRISAT Center, rainy season, 1981 (from Moraghan et al. 1984).

	Broadcast over soil surface			
	Left on surface	Incorporated{1}	Split band{2}	SE
Grain yield (kg ha{+-1})	4260	4110	5220	+ 225
N-uptake (kg ha{+-1})				
From fertilizer	22	21	40	+ 1.1
From soil{3}	40	39	45	-
Recovery of fertilizer-N (%){4}				
Plant	31	30	55	+ 1.6
Soil	42	45	39	+ 2.7
Plant + soil	73	75	94	+ 2.4
Assumed losses	27	25	6	-

1.Immediately prior to seeding.
2.Half the total fertilizer-N applied at seeding, and half 14 days after emergence.
3.Calculated from 15{-N} content of plant.
4.Determined by 15{-N}.

FIG 1

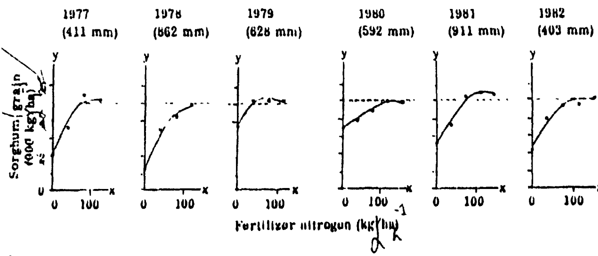
JRCT figs 1-6



~~Figure 1.~~ Comparative yield response of four sorghum cultivars to nitrogen application during the *kharif* season Yield values given represent an average of 25 experiments conducted at various locations in the AICSIP program during the period of 1965-70.

From: Singh et al, 1972

FIG 2



Regression equations:

1977: $y = 1020 + 62.4x - 0.28x^2$ $R = 0.81$ rxo = 1003
1978: $y = 1310 + 53.3x - 0.19x^2$ $R = 0.97$ rxo = 386
1979: $y = 3020 + 37.8x - 0.23x^2$ $R = 0.92$ rxo = 280
1980: $y = 3340 + 10.0x - 0.60x^2$ $R = 0.90$ rxo = 123
1981: $y = 2580 + 44.3x - 0.17x^2$ $R = 0.97$ rxo = 358
1982: $y = 2340 + 40.8x - 0.15x^2$ $R = 0.91$ rxo = 610

~~Figure 11~~ 2. Response of sole-cropped hybrid sorghum (CSH 6) to applied N on deep Vertisols, ICRISAT Center, rainy seasons 1977-82. Seasonal rainfall given in parentheses after year.

From: ICRISAT, 1984

FIG. 5.

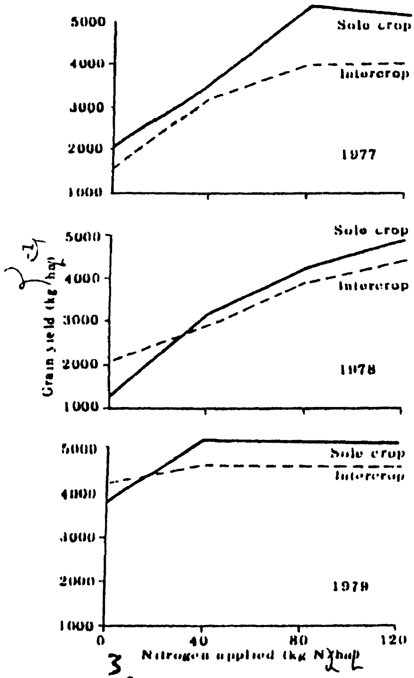


Figure 3 Response of sole and intercropped rainy-season sorghum to nitrogen on Vertisols at ICRISAT Center, 1977-79.

From: ICRISAT, 1981

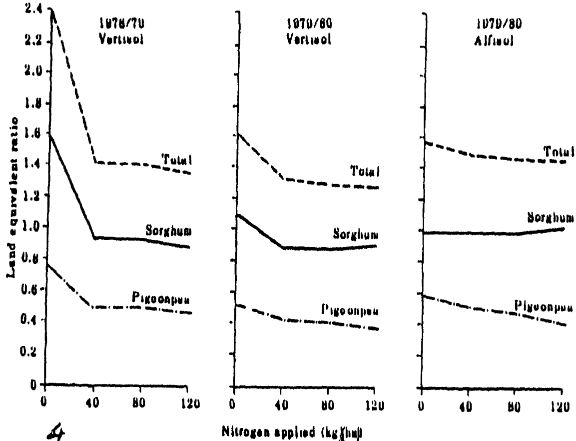


Figure 4. Effect of nitrogen fertilization on the land equivalent ratios in sorghum/pigeonpea intercrops at ICRISAT Center, 1978-80.

From: ICRISAT, 1981

Fig 5

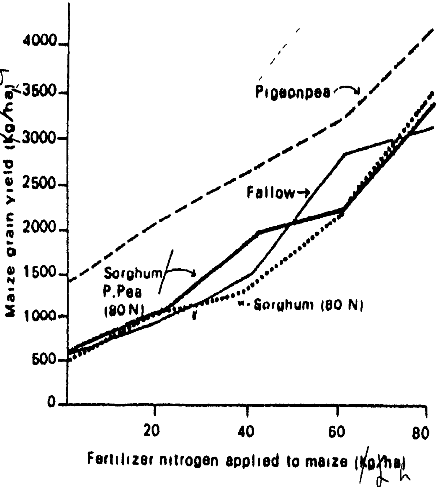
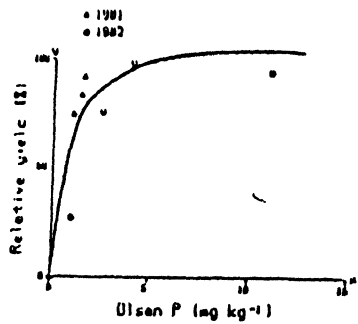


Fig.5. Effect of pigeonpea grown in the previous season on the response of maize grain yield to fertilizer nitrogen application (From Kumar Rao et al. ~~1981a~~). 1983).

Figure from Johansen Institute ...

FIG 6.



$y = 96.7(1 - e^{[illegible]x})$

Figure 6. Relationship between relative grain yield ($Y_{P_0}/Y_{P_{max}}$) of rainy-season sorghum CSH 6 and available P (Olsen) in 0-15 cm depth of Vertisols; field experiments, ICRISAT Center, 1981 and 1982.

From: ICRISAT, 1985