SUSTAINABLE AGRICULTURE :

Issues, Perspectives and Prospects in Semi Arid Tropics

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CHARACTERIZING NATURAL RESOURCES FOR SUSTAINABLE AGRICULTURE IN THE SEMI-ARID TROPICS

S. M. Virmani and H. Eswaran

1. INTRODUCTION

The natural resources of a country are its most sacred endowment. It is a base on which all life depends and in most countries of the world, is the life support system of the country. In the recent past, with burgeoning populations and the national goals of seeking self-sufficiency in food and fiber production, the resource base is slowly being stripped, often irreversibly. The main result is man-induced degradation of land resources through inadvertent, inappropriate or misuse of technological innovations. Even in the United States, until recently about 3 billion hectares of top soil was lost annually with an economic cost of between 3 to 6 billion dollars (Napier, 1986). Few estimates of the concomitant loss of soil fertility are available. In Zimbabwe, a FAO study indicated that on an average, 1.6 million tons of nitrogen and 0.24 million tons of phosphorus are lost per year through erosion and the cost to replace these nutrients would exceed US$ 1.5 billion (Stocking, 1986). This is an amount which most countries cannot afford for maintenance of their agricultural sector. When degradation becomes a continuing process, yields decline and the farmer is forced to eke a living on another piece of land, which in most instances may be a fragile ecosystem -- steeplands or coastal swamps -- since much of the better arable land is already under cultivation. The system then becomes iterative to the determinant of all.

The dilemma today is to reduce this cycle by trying to conserve the land resource base and at the same time, exploiting it to feed and clothe the population. These are the basic tenets of sustainable agriculture that present immense practical problems to their proper implementation, particularly in developing countries.

Eswaran and Virmani (1990) classify the land resources in four categories:

- Unsustainable land: these are the fragile ecosystems which should be retained in their natural state;
- Marginally sustainable: normally under forest or shrub, but if cultivated should be brought under a conservation reserve program for recuperation. In the event of food shortages, they are cultivated;
- Conditionally sustainable: these are agricultural lands which require special attention to soil erosion and degradation. Monitoring of degradation becomes an important activity of the extension service;
- Prime land: this normally serves as the bread basket of the nation and the goal of research support services is to maximize yields.

Each of these four categories of land can revert to the other depending on management. Not only must the management be in tune with the land but also the quality of land must be continuously monitored to evaluate its condition. If onset of degradation is suspected, the kind of degradation must be identified and corrected. Though these are the basic principles of land management, they are also prerequisites for maintaining sustainability.

2. CONSTRAINTS TO ATTAINING SUSTAINABILITY

Farmers are generally aware of the productivity of their land and the changes in productivity that take place with time. They are fully conscious and desirous of increasing and maintaining their production. The most common situation in developing countries is that farmers are not able to sustain the productivity of their land due to one or all of the following reasons:

- socioeconomic status of the farmer
- technology: availability, transfer, and acceptance
- external intervention and support
- intransigencies of the climate
- soil/land constraints

The first three items are beyond the scope of this paper but are crucial in any developmental program seeking sustainable and environmentally-sound agriculture. Swindale (1988) has elaborated the technological and institutional constraints governing sustainable agriculture in detail. The significance of climatic and soil constraints to adoption of improved technologies is well illustrated in the study by ICRISAT (ICRISAT, 1988) on the reasons for interregional variations in adoption of improved cultivars in India. Analysis of factors explaining the variation in adoption ceilings across major cereal-producing regions in India, confirmed that agroclimatic and soil differences were substantially more important than infrastructural and institutional differences for all the five cereals considered. For sorghum, regional adoption was significantly and positively associated with irrigation ($P<0.05$), June rainfall, fertilizer sales, and fractional area sown to sorghum in the rainy season. Adoption was significantly affected by more variable total rainfall, more variable September rainfall, higher man/land ratios, and higher total rainfall, particularly on Vertisols where drainage is a problem.

For pearl millet, adoption was significantly and positively correlated with June rainfall and with regional production potential reflected in yield in the 1950's and 1960's before hybrids were introduced. Soils also highly influenced ceiling levels. These findings suggest that to achieve faster adoption rates, a matching of new genotypes with the climatic conditions and soils of the area is an important first step.

3. LAND AND SUSTAINABILITY

In the semi-arid tropics (SAT), the major control of production and the type of farming system adopted is dependent on the total amount of rainfall, length of humid period, and rainfall reliability at critical periods of the phenological stages of the crop as illustrated in Fig. 1. Soils, their distribution, kinds and microvariability, introduce other constraints to the production process. As the soil component in sustainable agriculture is addressed in the accompanying paper by Eswaran and Virmani (1990), it will not be repeated here. The main objective of this paper is to evaluate the climatic constraints and their role in sustainable agriculture in the SAT.

The SAT are characterized by a high climatic water demand. Several definitions of SAT exist and the criteria used in each vary. (Koppen, 1936; Thornthwaite, 1948; Troll, 1965; Hargreaves, 1971). In view of the importance attached to high climatic water demand in the SAT which is a result of the uniformly high temperatures throughout the year, the system proposed by Troll (1965) is more meaningful in the context of sustainable agriculture. According to Troll, regions in which the mean annual rainfall exceeds potential evapotranspiration for 2 to 4.5 months are termed as dry SAT and when the duration is 4.5 to 7 months, the area is defined as wet-dry semi-arid tropics. This classification is ecological in nature. In the dry SAT, according to Troll, the general vegetation is thorn savanna, while in the wet-dry SAT, it is dry savanna.

Regions of the SAT are characterized by a highly variable rainfall pattern. The coefficient of variability of rainfall is 20-30%. For example at Hyderabad, India, the mean annual rainfall is 780 mm with a CV of 27%; the range is however from about 320 mm to more than 1460 mm in the last 89 years. For the savanna regions in West Africa, Kowal and Kassam (1978) showed that at 16^{o} N latitude and at 0^{o} meridian, the mean annual rainfall of 376 mm is expected to have a range from 242 to 502 mm. This variability is encountered both within years and seasons. The temporal variations have a marked influence on water availability, the length of the growing season and hence, on crop growth and development. In order to characterize the rainfall environment of the SAT in agronomically relevant terms, Virmani et al. (1982) found that the use of a probability approach using short term time intervals (e.g., week or ten day totals of rainfall) was useful for defining the relative dependable periods of rainfall. The data, as shown in Fig. 2, could be used for deciding the length of the water availability period and the probability of the onset of the rains.

A substantial proportion of the rainfall in the SAT usually occurs in a few high intensity storms. Hoogmoed (1981) observed that the intensity usually ranges between 20 to 60 mm/hour, in most instances but intensities as high as 120-160 mm/hr have been recorded and are not uncommon. Hence the soil loss that accompanies the runoff caused by high intensity storms could be substantial. This has been demonstrated at ICRISAT Center (Miranda et al. 1982) and discussed later.

Though soil moisture is needed during the whole growth period of the crop, it is most crucial at critical phenological stages. Crop-weather modelers have evaluated this in sufficient detail for use in models. A stepwise multiple regression analysis between yield and weekly rainfall, can also be employed to obtain a first approximation of the critical stages or weeks during the growth period. Supplementary irrigation, fertilizer use efficiency and other aspects of crop management, may be related to these critical periods.

4. CRITERIA FOR EVALUATING SUSTAINABILITY

For a practical assessment of sustainability, the relevant criteria for evaluating the sustainability of an agricultural system include:

4.1 An Assessment of Risk : The farmer's goal is to be able to produce at a threshold level which is a function of his socio-economic status. His assessment of risk is a function of the production in relation to his inputs. The same relationship will apply in research strategies. If irrigation induces salinity over time, this is obviously not a sustainable technology as the additional inputs needed to arrive at the threshold level may be prohibitive.

4.2 An Assessment of Production — Performance of the Technology : The goals of farmers and scientist is to increase production, which may be yield, quality, durability of the product etc. This may be achieved through resistance to pest damage, better fertilization, or any of the components of the technology.

4.3 An Assessment of Maintenance of Production Over a Time- frame — Stability of the System : The performance of the technology over a time-frame is an equally important consideration. There are two aspects to this. First is the worst case scenario which evaluates the technology in the severest stress situation whether abiotic or biotic (e.g., drought, pest damage). In such a case one will test for the resilience of the system or how the system recovers from the catastrophe. However, when the degradation persists and production is significantly lowered than the accepted threshold, a total revaluation of the technology is required.

4.4 An Assessment of the Impact of the Farming Systems -- Degradation : Another aspect, from a land resource point of view, is of course soil degradation, both the degree and the additional measures or amelioration needed to restore production. These define the stability of the system. There are few investigations in this area, apart from the work of Mbagwu et al. (1984) on the loss of top soil on crop production. There is an urgent need to evaluate the impacts of soil degradation in a more systematic manner.

Different soils behave differently. Changes in productivity as a result of erosion on Vertisols may be imperceptible in the initial stages and only become evident when the effective soil volume is reduced to a critical depth. An Alfisol on the other hand behaves differently; loss of a few centimeters of top soil may show marked differences in productivity. This implies that sustainability must also be seen from a soils point of view. This is further elaborated by Eswaran and Virmani (1990).

4.5 An Assessment of the Economics of the System from the Farmers Perspective — Profitability : All agricultural systems are driven by economics. Profitability must also be considered over a time frame. The basic question in the SAT is, can the farmer survive during the bad years when crops fail and the production levels are low and uneconomic?

4.6 An Assessment of the Environmental Soundness : This is a recent emphasis in agricultural research and development and requires an assessment of the environmental impact of the technology. Few methods are available and fewer long term data have been generated to develop principles and methodology. For some kinds of soil degradation, there are visible indicators. The current need is a quantitative approach to assess environmental soundness.

4.7 Other Factors which include Distance to Market, Land Tenure, and in fact any Factor that Contributes to the General Improvement of the Livelihood of the Farmer — these are Acceptability and Feasibility Factors : These socio-economic and institutional factors are as important as the technological factors in considerations of sustainability and the desire and ability of the farmer to adopt environmentally sound agricultural practices.

5. METHODOLOGY FOR EVALUATING SUSTAINABILITY

The basic criteria for evaluating sustainability may be obtained by answers to the following questions as shown by Virmani and Eswaran (1989) based on the principles of agrotechnology transfer eaunciated by Silva and Uehara (1985):

1. Is it technologically feasible?
2. Is it economically viable?
3. Is it politically desirable?
4. Is it administratively manageable?
5. Is it socially acceptable?
6. Is it environmentally sound?

Eswaran and Virmani (1990) have attempted to quantify these criteria empirically to illustrate the difference between the traditional and improved farming systems. The procedure employed must be refined for wider application.

Another approach is tested here to evaluate sustainability. Any system can be dissected to determine the robustness of its components, and these or the system as a whole could be subject to the tests of sustainability. For purposes of this paper, farming systems technology will be considered. One of the limitations is the absence of long-term data in different agro-ecosystems and therefore, for the purposes of illustration of the concepts and principles being developed here, the long-term experiments conducted by ICRISAT are considered (ICRISAT 1974, 1986).

In 1976 ICRISAT initiated a set of experiments on a deep Vertisol, at ICRISAT Center, Patancheru, India that mimicked the traditional farmer approach and an analogous set, termed 'improved technology' designed to increase the productivity of the land within the socioeconomic framework of the dryland farmer.

In Fig. 3, the yield obtained each year is plotted for the two systems. The annual rainfall is also provided. The difference in production levels already testify to the enhanced yields of the improved technology. The stability of the improved technology is illustrated by the behavior of the system during the 'bad' years when rainfall was low such as in 1985 when the traditional system was more adversely affected. Cumulative yields (Fig. 4) illustrate a similar principle. The traditional sorghum system gives an annual yield increase of about 0.59 t ha^{-1} (CV 25%) while the improved technology, gives about 3.33 t ha^{-1} (CV 23%). If an intercropping system is used (to maximize the utilization of the soil moisture), an annual increase of 4.4 t ha^{-1} is obtained and in addition, this system presents the lowest coefficient of variation (CV 17%) indicating greater stability.

Yield itself is only one criteria of sustainability. Fig. 5a, shows the soil loss in the same watershed. Fig.5b shows soil loss expressed in a cumulative manner. Minimizing soil loss over a period of time is also a goal of sustainability and the improved system has contributed to this. In addition, behavior of the system during adverse times, such as in 1976 when there were intense rain storms, is perhaps a more crucial test. Fig. 5a, shows that though the improved technology was superior, it is still far from perfect.

Behavior of the system over a long period of time is the true test of sustainability. An attempt to evaluate this is made in this paper, using crop yield simulation techniques. In the SAT, as indicated previously, the major determinant of crop performance is soil moisture. A first estimate of yield prediction can be obtained by relating soil moisture (or rainfall) at specific periods during crop growth to its final yield. The weekly rainfall during the growing season was related to measured yield using a step-wise multiple regression. The critical weeks and their coefficients required to predict yield with a reliability of more than 80% was thereby estimated. These equations were then employed to evaluate yield for the period 1901 to 1988, for which weekly weather information for Hyderabad is available. In addition a weather generator model developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) project of University of Hawaii (Richardson and Wright, 1984), was employed to generate rainfall scenarios for a 25 year period from 1988.

The regression equation for yield was then used to estimate the yield for each of the past 89 years and for 25 years in the future; the assumption that all other factors of crop formation were constant and the yield was controlled only by the rainfall variability at the critical periods of crop growth. The data thus obtained are referred to as 'simulated yields' in comparison to the 'measured' 13 years of yield.

In order to asses the risk associated with a given system, a procedure developed by Dumanski (1989) was employed. In this procedure, the probability of obtaining any yield is plotted against the simulated or measured yield. The position of the distribution curve and its shape is indicative of propensity to risk and sustainability of the system.

Figs. 6a, 6b, and 6c, show the simulated yields for the years 1976 to 2014. Fig. 6a, shows few differences between traditional and improved technology for chickpea. As the crop is grown on the stored moisture at the end of the main rainy season, it is highly sensitive to soil moisture conditions and the projections suggest that the improved technology, though having contributed to slightly improving yields (1.07 vs 0.86 t ha^{-1}) has not stabilized it; the traditional and improved technologies show a somewhat similar level of high variability.

Sorghum on the other hand, shows the tremendous improvement in yields through the use of improved technology. The average yield for the improved technology is 3.33 t ha^{-1}, while yields under traditional methods are only 0.59 t ha^{-1}. However, as shown in Fig. 6b, there is still large variability in the predicted yields. The traditional technology shows a much lower level of yield variability. It is possible that if other components of the technology were used to simulate yield, the improved technology would probably show less variability. Yield variability, and thus farmer s income, is better stabilized if a mixed cropping system is adopted. This is illustrated in Fig. 6c, where the mean yield is raised to 4.4 t ha^{-1} and there is a marked decrease in variability over time.

One of the conditions for assessing sustainability is the buffered nature of a given land use. A yield probability assessment for both the 13 years of measured yield and the 89 years of simulated yield was developed (Figs. 7a and 7b). In both figures, a similar pattern emerges. First is that the traditional system is highly buffered as shown by the kurtosis of the probability distribution curves. The traditional system is only affected in extreme drought situations. The improved systems, though being more productive (skewed to higher yields), appears to be less stabilized; the probability curves have a higher kurtosis factor, showing that these are more prone to fluctuations in soil moisture stress.

This analysis clearly shows that in the soil moisture driven model, yield of crops in the SAT is controlled by moisture stress at critical periods. This is amplified by considering an irrigated agriculture system

(Figs. 7a and 7b). In Fig. 7b, the yield for the 13 year period was simulated, using a Resource Capture model (Monteith et al. 1989). If soil moisture is not limiting, as in irrigated agriculture, the sorghum yields would be significantly higher and the yields would be stabilized over time. Fig. 7b, illustrates this irrigated situation in a experiment conducted by Huda (1988) for a ten year period. The shift of the curve to the right and its lowered kurtosis indicates a higher stability and perhaps sustainability in both the measured data (Fig. 7b, and the simulated condition (Fig. 7a). Basically, the irrigated system shows a lower degree of risk even at higher performance levels. The system needs to be tested for longer periods and specifically to examine if there is onset of soil degradation (such as salinization), to establish its sustainability.

This kind of analysis amplifies the point raised by Swindale (1988) regarding the Asian agricultural scene. He notes that, "the Asian agricultural scene reveals considerable differences in productivity. Where high input irrigated agriculture is practiced, there is little gap between potential and actual yields at currently available levels of technology. In contrast, the yield gap may be as high as 80% or more in the rainfed semi-arid areas. The factors responsible are both technological and socio-economic".

It must be stressed again that only one component in the whole system is being considered in the previous analysis and that the interpretations may change if the system as a whole were considered. The fact still remains that soil moisture is the most important component and that increasing yields in the SAT and stabilizing them would require additional research efforts in the areas of moisture conservation and utilization. In the context of this paper, the methodology presented appears to provide a tool to test sustainability of alternate land use systems.

6. RESEARCH STRATEGIES TO ENHANCE SUSTAINABILITY

From a land resource point of view, there are many constraints faced by developing countries to attain sustainability. Foremost is knowledge of the natural resource base. In many countries, detailed knowledge of the soil resources is not available. Even when information is available, due to lack of internationally coordinated standards and quality control methods, there is considerable variation in the quantity and quality of information between countries. Similar considerations apply to the climatic data base. A third common characteristic is the absence of baseline information and long-term monitoring for any of the components to assess sustainable agriculture.

Systems approach, with the application of systems modeling, Geographic Information Systems, complimented with expert systems are becoming useful tools to evaluate sustainability of agriculture. Testing and designing of appropriate systems to fit the socioeconomic profile of the farmer is equally important. Research in utilization of land resources in the context of sustainable and environmentally sound agriculture will require major conceptual changes in the design, measurements, and monitoring of experiments. Component research will have to be complimented with systems research.

As an illustration Virmani et al. (1982) classified Vertisols of central India into two broad production zones on the basis of annual rainfall:

- o Unassured rainfall zone receiving erratic rainfall ranging from 500 to 750 mm, equal to 40-48% of the annual potential evapotranspiration;

- o Assured rainfall zone receiving annual rainfall ranging from 750 to 1250 mm, which is equal to 43-77% of annual potential evapotranspiration.

Each of these zones will require different strategies for increasing and stabilizing dryland production. With the advent of computers a more refined grouping of the agro-environment can and must be made. Approaches, such as the one used earlier point to the improvements in predictions that can be made with reliable long-term data

Matching crop requirements to soil and climatic conditions is a challenge which is continuously being addressed. Fig. 1, shows the current adaptability of some crops to moisture conditions. Research has two roles to play; first to optimize crop performance within their adapted moisture range conditions, and secondly to devise technology to extend the range if necessary. The latter becomes relevant when sequential cropping systems are being considered, specifically when using soil-stored moisture for the second crop.

Sophisticated soil, weather, and crop models are being developed and validated. These currently have mainly a research use due to the fact that there are too many models chasing too few data. To make sustainable agriculture practicable in many countries, an urgent requirement is the generation of reliable data, most important of which are climatic and soil data.

This study has shown that sustainability considerations would require testing of farming systems over extended time periods. Fig. 8, which considers only sorghum, summarizes the observations with respect to the impact of management on production and sustainability of sorghum on Vertisols. The current traditional system is in a sense sustainable but yields are very low. The improved dryland system has significantly improved yields but they are not stabilized yet. Much higher yields are obtained in the irrigated system but extreme care (eg. salinization) must be taken in the SAT situation. The simulated conditions, represented by the yields at minimal stress situation (Fig. 8), is an indication of possible yield ceilings obtained under research conditions. The goal is to reach the genetic potential of the crop.

Fig. 8, illustrates the situation with Vertisols. Other soils will behave differently and will have different potentials and constraints. Currently a lack of data prevents their evaluation. It is therefore necessary to reiterate the conclusion of Swindale et al. (1989): "there should be an increasing emphasis on technologies to increase rainfall use efficiency. Soil quality will play a key role in these technologies. Soil taxonomy can be used with advantage in matching the suitability of different soils to the improved technologies".

In conclusion, the impact of any sustainable agriculture research program or development activity must have some or all of the following components which define IMPACT:

<u>I</u>nexpensive

<u>M</u>arketable

Permanent

Acceptable

Conservation effective

Technology responsive

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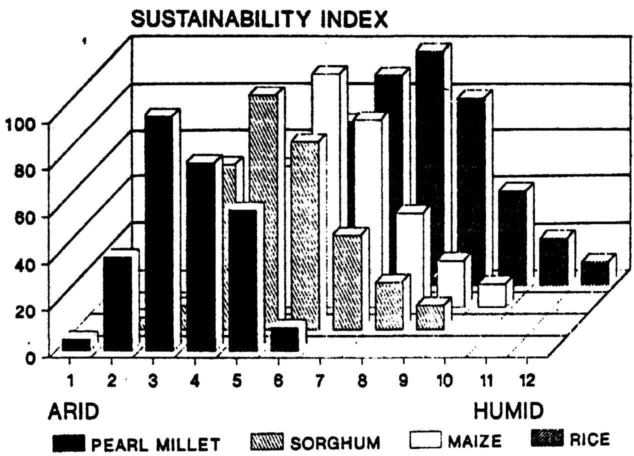


Fig. 1. Adaptability of some crops to moisture conditions.

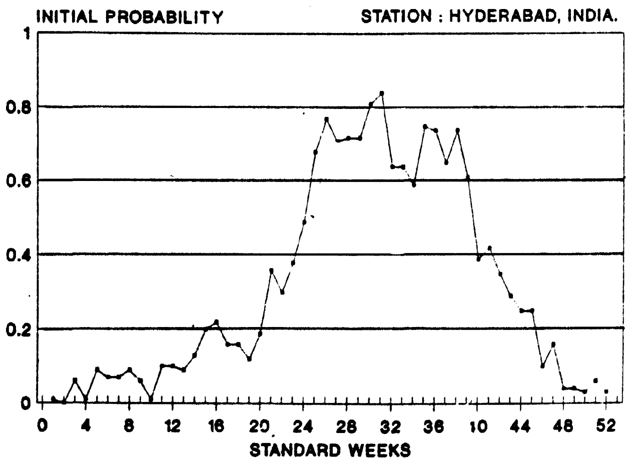


Fig. 2. Probability of receiving weekly rainfall exceeding R/PE >= 0.33

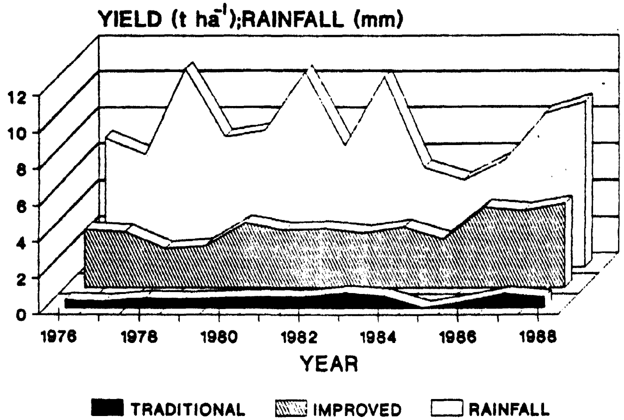


Fig. 3. Sustainable farming systems traditional vs improved Sorghum-based farming systems.

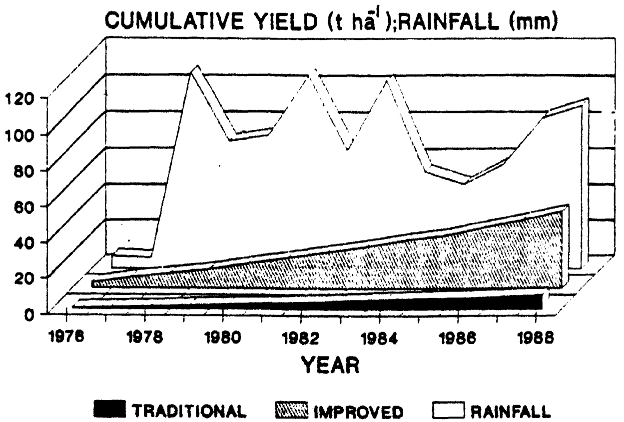


Fig. 4. Sustainable farming systems traditional vs improved Sorghum-based farming system.

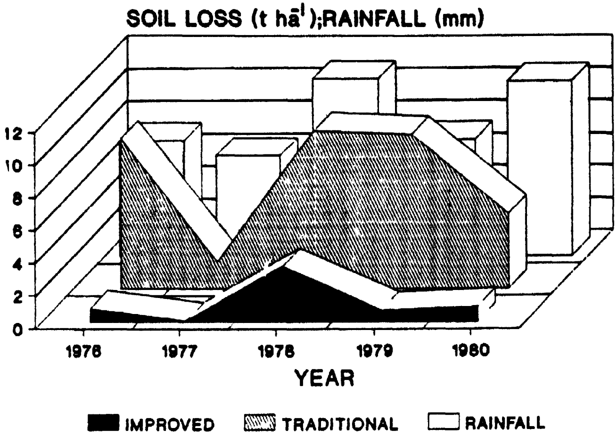


Fig. 5a. Erosion on a deep vertisol under two management systems.
Source : Miranda et. al. (1982)

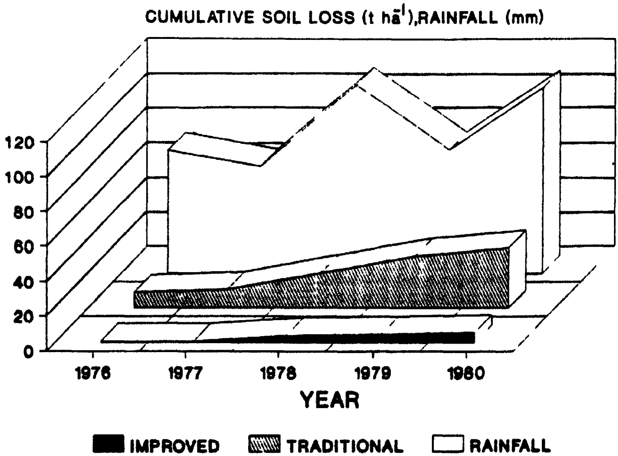


Fig. 5b. Erosion on a deep vertisol under two management systems.
Source : Miranda et. al. (1982)

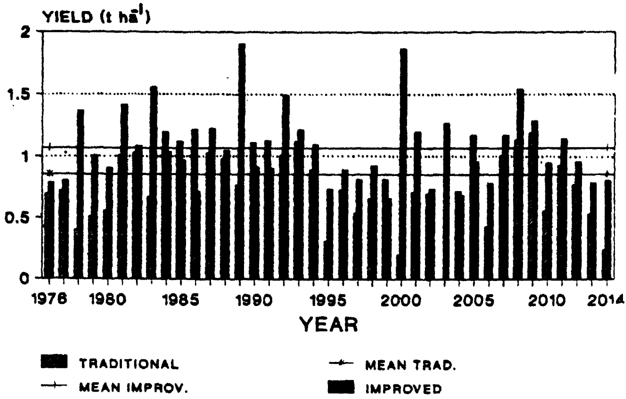


Fig. 6a. Simulated yields of Chickpea under traditional and improved management systems.

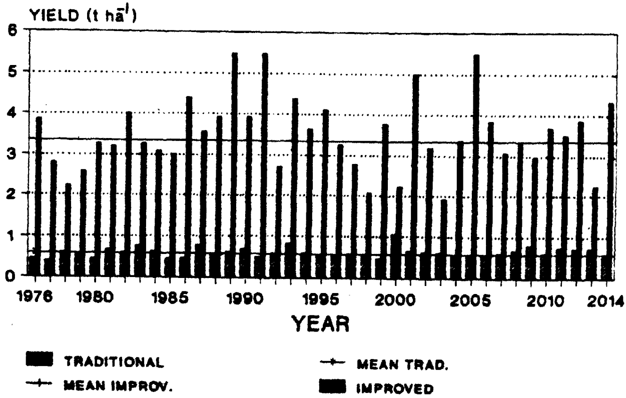


Fig. 6b. Simulated yields of Sorghum under traditional and improved management systems.

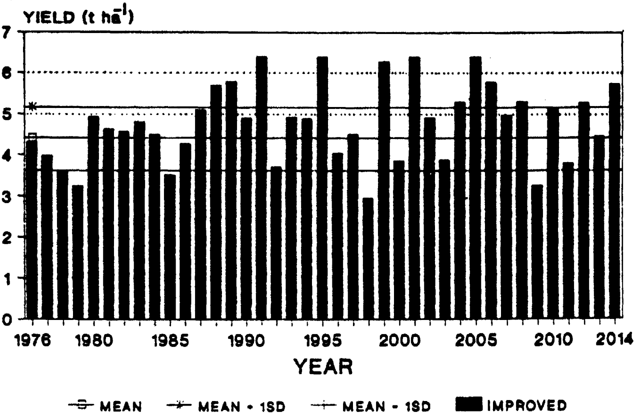
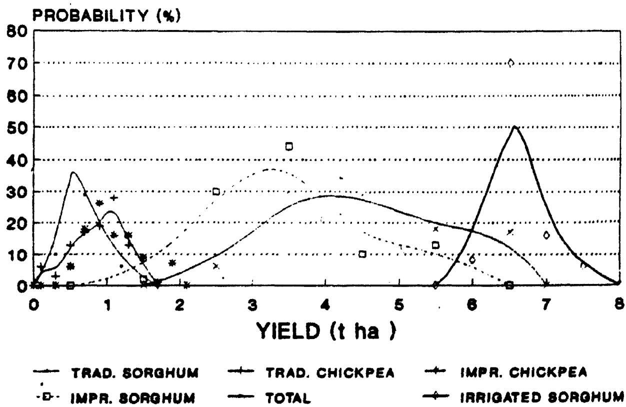


Fig. 6c. Simulated yields of Sorghum when intercropped with Chickpea



7a. Yield probability estimates of traditional vs improved dryland management systems.

Based on 89 years (1901-1989) simulation for Hyderabad,India.

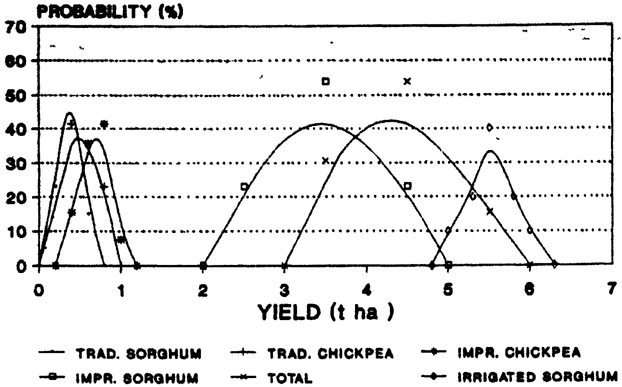


Fig. 7b. Yield probability estimates of traditional vs improved dryland management systems. Based on 13 years (1976-1989) measurement at Hyderabad,India.

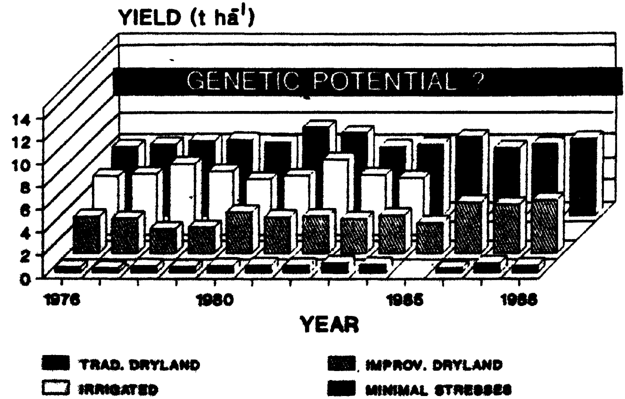


Fig. 8. Management impact on production and sustainability of Sorghum on vertisols.