ANALYSIS AND EVALUATION OF TILLAGE ON AN ALFISOL IN A SEMI-ARID TROPICAL REGION OF INDIA

Promotor: ir.H.Kuipers, hoogleraar in de grondbewerking en de gronddynamica

STELLINGEN

1.

Het grondbewerkingsonderzoek zoals verricht in Nederland laat zich slecht vertalen met soil tillage research.

2.

Het is onwaarschijnlijk dat vooruitgang in de landbouwproduktie in vele ontwikkelingslanden uitsluitend op kleine bedrijven gerealiseerd kan worden.

> Ryan and associates, 1975. Socio-economic aspects of agricultural development in the semi-arid tropics. In: Int. workshop on Farming Systems. pp 389-431, Hyderabad, India. ICRISAT Nov 18-21, 1974.

3.

Bodemclassificatie is nauwelijks bruikbaar voor het voorspellen van grondbewerkingsbehoeften.

4.

De bevolking van India is waarschijnlijk groter dan de natuurlijke hulpbronnen toelaten, zelfs onder de meest ideale omstandigheden en met de modernste technieken.

> Bowden, L. Development of present dryland farming systems. In: Agriculture in semi-arid environments. pp 45-72. Ecological Studies V. 34.

5.

Zero tillage als erosie bestrijdende maatregel is niet toepasbaar in semi-aride tropen indien mulches een essentieel onderdeel zijn.

6.

Bij het beheersen van het onkruidbezwaar met mechanische middelen alleen, is handwieden in de plantrijen noodzakelijk en lonend.

Dit proefschrift

7.

De toepassing van het principe van grondbewerkingszones is een uitermate geschikt alternatief wanneer weinig trekkracht beschikbaar is.

8.

Het rijpadensysteem garandeert snelheid in en nauwkeurigheid van de uitvoering van opeenvolgende veldwerkzaamheden.

Dit proefschrift

9.

Het nauwkeurig op diepte zaaien verhoogt opkomst en opbrengst van het gewas aanzienlijk.

Dit proefschrift

10.

In ontwikkelingslanden is selectieve mechanisatie een belangrijk element van systemen welke meer voedsel produceren en meer mensen werk bieden.

Giles, G.W. 1975. The reorientation of agricultural mechanisation for developing countries. Agricultural Mechanisation in Asia. 6(2):15-25, Autumn, 1975.

11.

Bij het vredesvraagstuk is niet het kernwapen de kern, maar het wapen.

M.C.Klaij

Analysis and evaluation of tillage on an Alfisol in a semi-arid tropical region.

Wageningen, 26 oktober 1983.

PROEFSCHRIFT
TER VERKRIJGING VAN DE GRAAD
VAN DOCTOR IN DE LANDBOUWWETENSCHAPPEN,
OP GEZAG VAN DE RECTOR MAGNIFICUS,
DR.C.C.OOSTERLEE,
IN HET OPENBAAR TE VERDEDIGEN
OP WOENSDAG 26 OKTOBER 1983
DES NAMIDDAGS TE VIER UUR IN DE AULA
VAN DE LANDBOUWHOGESCHOOL TE WAGENINGEN

VOORWOORD

Als bilateraal assistent-deskundige had ik het voorrecht te mogen werken in het Farming Systems Research Program (FSRP) van het International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) te India.
In het FSRP-team werkten vele wetenschappers samen, onder de inspirerende leiding van Dr. B. A. Krantz. Als agronoom heeft hij steeds veel belangstelling getoond voor grondbewerkings- en zaaitechnieken. Van hem heb ik veel steun ondervonden in mijn werk.
Dr. Jacob Kampen, destijds de leider van het Soil and Water Management Subprogram van het FSRP ben ik bijzonder erkentelijk. Als aanvoerder in de slag, de 60 hectaren Vertisol en tientallen hectaren Alfisol binnen een kort tijdsbestek in te zaaien met behulp van ossentraktie, had hij uitgesproken meningen en ideeen over het verbeteren van de gebruikte werktuigen en technieken. Hij toonde zich steeds bereid te luisteren, en te discussieren over mijn onderzoeksactiviteiten en plannen.
Bij de uitvoering van de experimenten kon ik altijd rekenen op de toegewijde Iqbal Ahmed, die een bijzondere aanleg bleek te hebben voor het gebruik van werktuigen, en op zeer nauwgezette wijze voor mij waarnemingen heeft gedaan.
Gedurende de vier jaar bij ICRISAT wist ik mij gesteund door professor ir. H. Kuipers en zijn staf. Hem ben ik veel dank verschuldigd voor de ondervonden warme belangstelling voor mijn onderzoeksbezigheden. In het bijzonder wil ik hem danken voor zijn aanmoediging na mijn terugkeer in Nederland dit proefschrift te schrijven, en voor zijn bemoeiingen dit financieel mogelijk te maken.
Ing. B. Kroesbergen wil ik dank zeggen voor de wijze waarop hij zich ingezet heeft voor de fotografische afwerking van de figuren.
Ook Dr. C. Dirksen ben ik erkentelijk voor het vinden van de tijd ter correctie van de Engelse tekst.
De Stichting 'Fonds Landbouw Export Bureau 1916/1918' ben ik dank verschuldigd voor het beschikbaar stellen van een subsidie ter bijdrage in de kosten verbonden aan dit proefschrift.

M.C.KLAIJ

ANALYSIS AND EVALUATION OF TILLAGE
ON AN ALFISOL IN A SEMI-ARID
TROPICAL REGION OF INDIA
(with a summary in Dutch)

CONTENTS

CHAPTER 1

INTRODUCTION

This paper covers the research aspects of tillage experiments conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in India, during the years 1977 to 1981.
ICRISAT has a global mandate for; crop improvement research of sorghum; pearl millet; chickpea; pigeon pea and groundnut; for research in farming systems; socio-economic constraints; and to communicate information by conferences, training etc.

The tillage research was conducted within the frame work of the Farming Systems Research Program (FSRP). The general objective was to investigate possibilities for improving soil cultivation measures to increase and stabilize crop yields.
More specifically, minimum tillage methods suitable for small farmers were evaluated in terms of their effects on soil, crop and weeds. Attention was also paid to the effects of tillage, seedbed preparation and sowing methods on crop establishment.

The literature research and writing of the thesis were completed at the Soil Tillage Laboratory of the Agricultural University at Wageningen, The Netherlands.

CHAPTER 2

THE SEMI-ARID TROPICS, A BRIEF GENERALISATION

2.1 THE SEMI-ARID ENVIRONMENT

2.1.1 Climate

The semi-arid tropical regions lie between the low latitude zones of wet equatorial climate and the belts of dry tropical climate centered on the tropics of Cancer and Capricorn. These intermediate regions are subject to a distinctly seasonal climate resulting from general circulation patterns of the atmosphere controlled by mechanisms described by Arnon (1972), Cocheme and Franquin (1967), Krishnan (1975), and Webster and Wilson (1971).
The seasonal swing of the weather is governed by the latitudinal movement of the low pressure Inter Tropical Convergence Zone (ITCZ) which follows the zenithal position of the sun. In the summer of the northern hemisphere, the low pressure zone is sufficiently far north to pull air masses originating above the ocean, over the continent. The resulting trade winds carry moisture from the ocean and are commonly called monsoons.
As a result, in the absence of mountain ranges and great lakes, as is the case in West Africa north of the equator, the amount of annual rainfall and duration of the rainy season, generally decrease both gradually and drastically when moving towards the dry belts. Closer to the equatorial zone the two passages of the zenithal sun are more widely spaced in time. Therefore, the dry seasons are much shorter and the rainy season shows a bimodal pattern. However, there are too many exceptions for this to be a general rule (Webster and Wilson, 1970).

The outstanding feature of the semi-arid tropical climate is its high annual potential evapotranspiration, which may be two to four times the annual rainfall. The average values are not at all meaningfull in the light of the considerable seasonal variation; on a monthly basis rainfall may well exceed the potential evapotranspiration for a prolonged period of time.
A typical cycle of seasons is the following: in the beginning of the calendar year long sunshine hours, low relative humidities and strong winds boost evapotranspiration to high rates, reaching their maximum values towards the end of the hot summer. Typical values are 5 to 7 mm/day on a monthly basis. Daily evaporative demands can be extremely high; a maximum daily open pan evaporation of 19.2 mm was recorded in May 1975 at ICRISAT's research center (ICRISAT ,1976).
At the onset of the monsoon, the maximum daily temperatures drop considerably and the cooling rains increase the humidity level and cloudiness. These

contribute towards pushing the evapotranspiration to its absolute seasonal minimum. On a rainy day the open pan evaporation has been as low as 1.7 mm, but it can be as high as 8 to 10 mm during dry spells on a clear day (ICRISAT, 1976).
As the rains recede the daily number of sunshine hours increases and with it the temperature. The atmospheric humidity declines sharply, thereby increasing the rate of evapotranspiration either to a secondary maximum or to the level of the beginning of the year.
The annual mean temperature exceeds 18 degree Celsius and the monthly variation is normally less than 10 degrees.

Rainfall is erratic and the beginning of the rainy season is often uncertain. Frequently, more than 90% of the total rainfall occurs during the rainy season. There is an enormous variability in the rainfall quantities within a rainy season, which may be interspersed with drought periods.
The precipitation itself is often in big, high-intensity storms and a major portion of the total rainfall may fall in a few showers.

A precise geographical delineation of where a main semi-arid tropical climate occurs, let alone its breakdown into agronomically meaningfull subdivisions, is difficult and depends on the criteria used.
At ICRISAT, Troll's system of classification was used to define the bounderies of ICRISAT's geographical mandate area (Kampen and associates, 1975). Troll (1965) distinguished five regions within the tropics and classified the semi-arid tropics as follows:

V3: wet and dry tropical climates with 4.5 to 7 humid months
V4: Dry tropical climates with 2 to 4.5 humid months.

During a 'humid' month rainfall equals or exceeds the potential evapotranspiration. The V4 zone is subclassified into regions having summer rains, and regions where rainfall occurs in the cool winter season. The latter climates cover an insignificant part of the semi-arid tropics.

2.1.2 Soils

Ancient shields of crystalline rocks or highly indurated sediments of pre-Cambrium age form the substrate of much of the semi-arid tropics of West-Africa (Ahn, 1977). Similar geological structures are found in significant semi-arid tropical areas in the North-East of Brazil, Southern Africa, Australia, and the Indian Deccan plateau (Bowden, 1977).
As a result of the absence of base-rich rocks, the derived soils generally are low in plant nutrients; in particular nitrogen deficiency is widespread (Henderson, 1979). In Africa (Jones and Wild, 1975; Ahn, 1977; Richardson, 1968) and India (Krantz and associates, 1975), both nitrogen and phosphorus are reported deficient.

Many soil classification systems were developed, mostly on the basis of a specific purpose, such as the suitability and potential of cropping, drainage or land use (Buringh, 1979). At least six major classification systems are used in the tropics, each with its own terminology. The lack of a common language impeded development of a meaningfull correlation between them, and

worked against the transfer of important management findings from one area to another (Sanchez, 1976). The most objective and comprehensive system, so far, is the U.S. taxonomy system (Buringh, 1979; Sanchez, 1976).
Approximate correlations between the major systems used in the tropics are given by D'Hoore (1968) and Sanchez (1976). The latter presents a geographical distribution of the major soil types over the tropics.

Alfisols are the third most common soil order in the tropics, but they are very prominent in semi-arid regions, where they were previously mapped as Latosols, especially in West-Africa, India and Sri Lanka (Sanchez, 1976). The Ferruginous Tropical Soil is the most important soil type of the wetter part of the West-African savannah, between the 500 and 1200 mm isohyet, while the Brown and Reddish Brown Soils occur in the dryer Northern zone (Jones and Wild, 1975, based on the soil map of Africa after D'Hoore).
On the Indian Deccan plateau, Alfisols (Red Soils) and Vertisols (Black Soils) are the predominant soil orders with a longstanding rainfed cropping history (Spratt and Chowdhurry, 1978), with widespread deficiencies in the main nutrients nitrogen and phosphorus (Krantz and associates, 1975).

Fertility problems are further aggravated by unfavourable soil physical properties, in particular for the more sandy soil types. The inherently low water holding capacity is a serious constraint for overcoming periods of prolonged drought. Often, roots fail to penetrate the deeper layers, further limiting the chances of a continued moisture supply.
The top soil conditions are important as these largely determine the rainfall infiltration and the capability to store temporarily rainfall in excess of the infiltration rate. Unstable top soils break down under the considerable impact of raindrops and rapidly develop a surface seal causing runoff and erosion.
Upon drying, this seal develops into a hard crust, which may well prevent crop emergence. When dry, the soils become extremely hard to cultivate with the means and power available to the majority of farmers.

2.1.3 Traditional Cropping Systems

2.1.3.1 Major Crops -

The crops or crop combinations usually grown are largely climatically determined. The amount of rainfall and its distribution over the rainy season are the major indicators of the potential length of growing season, unless the temperature starts becoming a limiting factor.
The soil profile and surface characteristics largely determine the actual length of the growing season.
A deep profile with good waterholding capacity, favourable conditions for root proliferation, and surface conditions capable of maintaining high infiltration rates, has the highest potential for safe cropping during the rainy season. It will provide a fair water supply far into the dry season.
Conversely, in a shallow profile with physical properties impeding rooting and infiltration the period of cropping is limited to the rainy season itself. Moreover, the chances of a serious yield reduction or even complete crop failure are much larger because longer drought-stress periods may occur.
Crop substitution and soil management can greatly improve crop production for

a given rainfall and soil profile.

Important rainfed crops in India are discussed by Krantz and associates (1975), Krishnamoorthy (1975) and Chowdhury (1975). Sorghum and pearl millet are the major cereals, grown on respectively 22.9% and 11.6% of the total cropped area. The grain legumes chickpea and pigeonpea are the most important, occupying 6.3% and 2.3% of the area, respectively; groundnut and cotton are the most prominent cash crops, taking each 9% of the area (Chowdhury, 1975).
Important subsistence crops in the West African semi-arid regions are millets ,sorghum, maize and cowpeas (Cocheme and Franquin, 1967). Norman et al. (1979) presented similar data from a study in a North-Nigerian region ecologically similar to areas in many of West African countries. They found sorghum and millet occupying 30% and 25% of the land respectively, while cowpeas, groundnut and cotton accounted for 10%, 9% and 3% of the area, respectivily. Kassam (1976) presented a detailed account of the ecology, cultivation techniques, pests and diseases of major food, fiber and cash crops in the West-African semi-arid tropics. A comprehensive review of the main dry crops grown in the world, their economic significance, crop management practices, pests and diseases, etc. is given by Arnon (1972).

2.1.3.2 Intercropping -

Intercropping is the practice of growing two or more crops together in time and space. Andrews and Kassam (1976) distinguish four patterns of intercropping: mixed intercropping which lacks any row arrangement; row intercropping with a definite row pattern; strip intercropping with crops grown in strips wide enough to permit independent cultivation but sufficiently narrow for the crops to interact agronomically; and relay intercropping with successive crops planted in standing crops.

The reasons for practicing intercropping are many, higher gross return being the most important, with security and tradition other reasons given by small farmers (Norman et al., 1979). The same authors observed in a number of selected villages in Northern Nigeria a 27% higher annual labour input per hectare in crop mixtures, but also an alleviated labour bottleneck. The value of the crops was 35% higher, giving 28% higher returns per man-hour and a higher, more dependable net return between 32% and 41%.
Jodha (1979) summarised data on intercropping drawn from village-level studies conducted since 1975 by ICRISAT in six villages representing three agroclimatic zones in peninsular India. Interregional differences in the extent of intercropping depend on factors as irrigation facilities, type of crops and soil management systems. To the extent that intercropping reduces the weather-related risks, intercropping is a more popular system, in particular with farmers who try to satisfy profit, subsistence and security needs from a small parcel of land.
A multitude of crop mixtures is used, Jodha (1979) classified them into six categories. Based on their share in total area, the three most important categories are: mixtures of different maturity length to distribute labour requirements evenly; mixtures of drought-sensitive and drought-resistant crops to insurance against drought, with the option of benefitting from good rains; and mixtures of cash crops and food crops to satisfy cash and

subsistence requirements.

From the same study Jodha (1979) reported that the practice of intercropping covers 35% to 73% of the gross cropped area, with 84 crop combinations found in one village. Usually combinations of two crops were found, but patterns involving five to eight crops were not uncommon.
Norman et al. (1979) observed that only 26% of the area involved single cropping, the remainder intercropping with as much as 230 crop combinations.

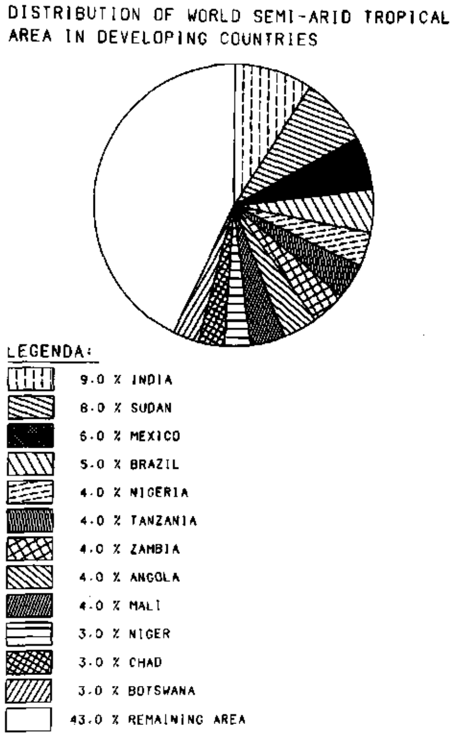
2.2 SOCIO-ECONOMIC ASPECTS

2.2.1 Populations In The Area

Ryan and associates (1975) delineated countries, or areas within countries, lying within the semi-arid tropics as defined by Troll. Semi-arid tropical regions are spread over four continents with an estimated total area of 19.6 million square kilometer and a total population of 512 million.
As much as 48 countries or parts of their territories fall into the semi-arid zone. The largest aggregate area is in Africa, where 157 million people or 30% of the total population live on 58.7% of the semi-arid area. The largest area within a country is in Australia with 10% of the total area, but with a mere 0.2% of its population. India, on the other hand, occupies 9% of the total semi-arid area, which is inhabited by 260 million people or 51% of the total population of the semi-arid tropics. Fig. 1 lists the most important countries in terms of their population and size of semi-arid areas. These figures reveal the tremendous population pressure on the resource base in significant parts of the semi-arid tropics.
In India, the geographical area per head has dwindled to 0.6 ha; in Nigeria, the most populous and densily populated country within the African semi-arid area, it is 1.5 ha. In fact, the population pressure on the land (marginally) suitable for agriculture is even more serious since in the semi-arid regions of India the average fraction of cropped area is estimated at only 57.2% of the total area (Chowdhury, 1975). In the Sholapur and Bijapur districts on the Deccan plateau, as much as 81% and 84% of the geographical area is cropped, respectively (Ryan, 1976).

2.2.2 A Wide Range In Resource Endowments

The huge differences in population pressure on the land has serious implications for the type of technology envisaged to increase agricultural production. For densily populated areas, as found in India, technology should be designed to increase land and labour productivity and make better use of the ubiquiteous draft animals, while taking into account the capital scarcity. On the other side of the spectrum are areas in semi-arid Africa where land is still relatively abundant, but where animal traction is not traditionally practiced and cannot be assigned a role in prospective technologies because of prevailant diseases. In this situation, there seem to be opportunities for labour-saving techniques and possibly mechanical innovations.
Whatever technological changes are considered, for their implementation the infra-structural facilities which need to support them, have to be taken into



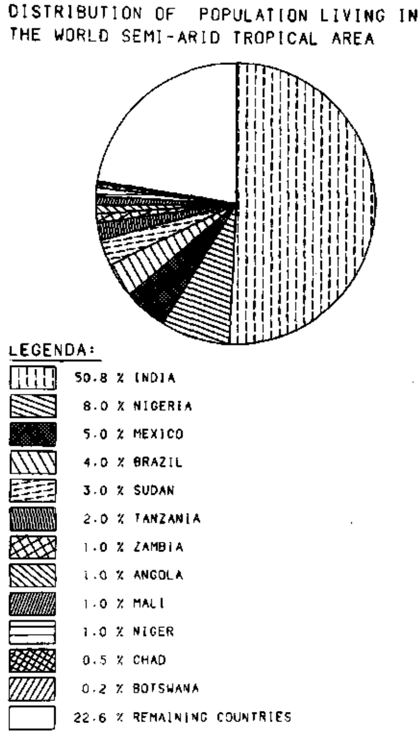


Fig. 1. Developing countries in the semi-arid tropical area, listed in order of area and population. Adapted from Ryan and associates (1975).

consideration. A densily populated country, such as India, has a widespread transport and communications network, large-scale fertilizer and pesticide manufacturing capabilities and a sophisticated agricultural research network (Ryan and Binswanger, 1980). The problems of access to fertilizers, pesticides and repair facilities are much less urgent compared to the situation in much of the African semi-arid tropics. African semi-arid countries are much less densily populated and do not have such facilities, which would require a much higher capital expenditure per head for expansion or maintanance .

2.3 THE CHALLENGE

2.3.1 The Deterioration Of The Resource Base

During the last 30 years populations in many semi-arid tropical areas have doubled and, because little increase of yield per hectare occurred during this period, the necessary production increase was realised by expansion of the cropped area. As a result ever steeper and more erodable lands were put under the plow, and were frequently overcropped and overgrazed by an increasing number of cattle. Forest lands were denuded at the expense of the productive potential of the land (Krantz et al., 1977).
The accompanying, continuing fragmentarisation of holdings tends to decrease the average gross and marginal return on a per hectare base (Ruthenberg, 1975). Accelerated soil erosion rates aggravate the problems of low and unstable yields and decrease the production capacity of the resource base. To keep production levels up with the increased demands of a still fast-growing population, expansion to even more marginal areas seems to continue unabated, thus further eroding the production potential of the resource base (Kampen and associates, 1975; Krantz et al., 1977).

2.3.2 Past And Present Dryland Research In India

In India, the earliest attempt to improve dryland farming on a scientific basis dates back as far as 1923, when a dry-farming research center was set up near Pune. In 1933, this center was transferred to Sholapur, the first of a chain of four more centers which would follow. Thus, research was carried out on soils representative of vast semi-arid tracts of the Deccan (Raychaudhuri et al., 1963).
The so-called 'Bombay Dry-Farming Method' evolved from research focused on two major facets: soil and water conservation, and agronomic practices. Recommendations included practices such as contour bunding to conserve soil and water, deep plowing for enhanced water infiltration and storage, the use of farmyard manure, limiting plant populations and adopting wider row spacings, and interculturing (Joshi et al., 1980). In spite of governmental support in the form of subsidies and grants for the contour bunding, the technology package was rejected by the farmers.
First of all, the maximum attainable return that would accrue from the recommendations was a meagre 10-20% increase over the low average yield plateau of 200-400 kg/ha, so that understandably, the technology failed to catch the farmers imagination. Secondly, the construction of the bunds was such that existing field bounderies were cut (Randhawa and Venkateswarlu, 1980 ;ICRISAT, 1978).
The interest in dry-land research faded away, the attention was shifted to irrigated agriculture.

During the sixties the 'green revolution' was triggered off with the introduction of input-responsive varieties of wheat and rice. The yield potential of these modern varieties was enormous, and the pace of adoption was such that targets set by the government were overshot. In 1968-69, a target of 2 million hectares was exceeded by 2.5 million hectares (Swaminathan,1970). The quantum jump in wheat production effectuated in areas having an assured water supply was a big step towards self sufficiency in India (Borlaugh, 1970); by 1971 a national reserve of food grain totalling 11 million ton had been built up (Joshi et al., 1980).

The mood of optimism to be able to become self-sufficient in food requirements caused some concern in governamental circles (Swaminathan, 1970). It was realised that the hitherto followed strategy to concentrate efforts to increase crop production in water-assured areas, had been highly effective in the endeavour to meet the nations food requirements. But an unchanged policy would cause serious socio-economic problems, as it would further widen the gap with incomes of dry-land farmers and would continue to 'create pockets of plenty and islands of prosperity' (Krisnamoorthy, 1971).
Furthermore, the rapidly growing population and the existence of a physical limit to the expansion of irrigation facilities, made a diversification of research and development to include dry-land areas a necessity.
No less than 60% of the arable land, producing 42% of the nations food, will continue to depend solely on rainfall (Krishnamoorthy, 1971). So, unless crop production in these areas is improved both in terms of yield and stability, one or more poor monsoons could still seriously deplete the nations food reserves (Cummings, 1976).

In 1965, short duration hybrids and varieties of major dryland crops became available for extensive field testing, and already large yield increases were realised, also under rainfed conditions (Randahwa and Venkateswarlu, 1980). For the first time, a real breakthrough in dryland farming seemed within reach. The yield potential of the new varieties provided a good basis for a renewed effort in the research and development of a dryland farming technology that would be really attractive for the farmers.
Unfortunately the 'high-yielding' varieties did not spread beyond the more assured rainfall areas in the semi-arid regions of India. The main reason was that the standardized technological packages (ICRISAT, 1978), neglected the need for a more flexible approach to counteract the adverse effects of less predictable environments. Secondly, the new varieties did not fit well into the traditional cropping system, which for risk-minimizing rely on crop diversification, particularly intercropping.
Thus, a lesson had been learned not to rely solely on improvements of management or crop aspects , but to design a mix. In 1970, the All India Coordinated Research Project for Dryland Farming was launched. The primary objective was to develop cropping systems that would substantially improve and stabilize crop production in various agro-ecological zones, within the constraints and limitations specific for each zone (Spratt and Chowdhury, 1978). Twenty-three research units, partly existing centers at universities and governmental institutions, were established throughout India. Recently, a summary of ten years of experimentation was published (ICAR, 1982).

2.3.3 ICRISAT and the farming systems research program

Parallel to the developments in India, and based on similar motives, the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) came into being in 1972.
Its initial mandate was to serve as a world center for crop improvement of the cereals sorghum (*Sorghum bicolor* Moench) and pearl millet (*Pennisetum americanum* Leake), and the pulses chickpea (*Cicer arietinum* L.) and pigeonpea (*Cajanus cajan* L.). In 1976, the legume groundnut (*Arachis hypogaea* L.) was added. ICRISAT's mandate further includes: development of farming systems; research to identify socio-economic constraints and means to alleviate them;

the communication of information; transfer of generated technology.

The recognition that a suitable technique was lacking for soil and water management and crop production systems as primary constraints to agricultural development in the non-irrigated semi-arid tropics, led to the inclusion of the farming systems research component. The Farming Systems Research Program (FSRP) was set up and formulated its major goals as follows:

-to generate economically viable, labour intensive technology for improving, utilizing and conserving the productive potential of natural resources.

-to develop technology for improved land- and water management systems that can be implemented and maintained during the extended dry seasons, resulting in additional employment for people and better utilization of available draft power.

-to contribute to raising the economic status and the quality of life for the people of the semi-arid tropics by developing farming systems that increase and stabilize agricultural output (Krantz et al., 1977).

Attempting to attain these objectives, the various disciplines working within the FSRP are engaged in many activities. These include the assembly and interpretation of 'base line' data; the organisation of an international communications network to disseminate research results and obtain the necessary feedback on its performance; research on management techniques at the ICRISAT research center and selected 'benchmark' locations; training activities; etc. An organizational chart is given in Fig. 2.
The concepts and rationale underlying the program's structure and approach, are more extensively discussed by Binswanger et al. (1976).
Here, a brief reference will be made to the framework of research activities on the ICRISAT center itself, because the tillage experiments were conducted within this framework.
These research activities fall into two phases:

a. Research on production factors.

b. Watershed-based resource utilization research.

Production factor research involves applied or basic studies of isolated parts of the farming system. Experiments in this category take place in all seven subprograms and are mostly discipline-centered, but can involve more disciplines. When positive results have been obtained, the improved part enters the second research phase.

Watershed-based research is of an interdisciplinary nature, involving investigation of concepts of improved farming systems on an operational field scale. In rainfed agriculture the only water available to the ordinary farmer comes from rain falling on a given area. Therefore, small natural watersheds, catchments, or drainage basins comprised of several field scale units, are the focus of this type of research. The central theme is how to make the best possible use of the seasonal rainfall. Resource development, field scale land management trials, detailed water balance, etc. are studied. The watersheds also form the testing ground where promising alternative soil-, water- and

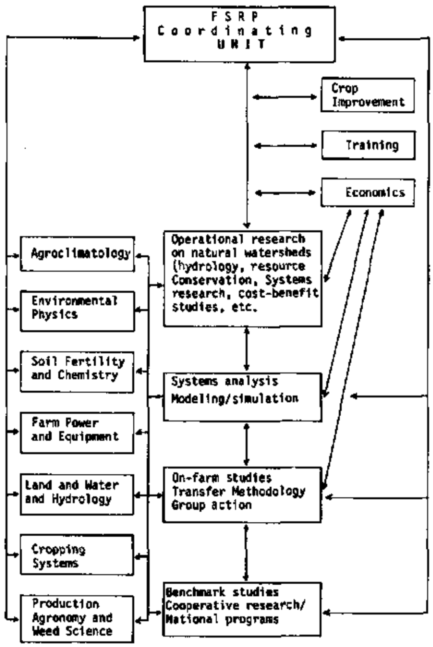


Fig. 2. Organizational chart of the Farming Systems Research Program.

crop management technologies are integrated into improved farming systems and simulated on an operational scale, using animal power. The systems are closely monitored, gathering extensive data on waterbalance , crop growth, pests and diseases, inputs of human labour, power utilization, fertilizer and pesticides. At the end of each season, the input-output data are assembled and reviewed for technical and economic evaluation.

The tillage experiments must be seen in the context of the achievements of the various improved soil and water management systems that were being developed. Their succes and shortcomings, as related to tillage, form the starting point of the experiments.
The tillage experiments were carried out within the Farm Power and Equipment Sub-program, and fall in the category production factor research.

CHAPTER 3

THE ROLE OF TILLAGE

3.1 DEFINITIONS AND OBJECTIVES

A soil cultivation system can be defined as the complex of recurrent tillage operations performed to create and maintain optimal conditions for crop production. The creation of optimum conditions can be considered a short-term objective concerning the present crop, while maintaining those refers to the long-term objective of conservation of the resource base. It is difficult to draw a line between tillage operations that serve the long-term and short-term objectives, because they are strongly interrelated and may partly overlap. Climate, soils and topography are important physical, environmental aspects having a bearing on the cultivation system adopted. Of course crops, and cropping systems that potentially can be grown, are also major determinants. Since cropping systems are largely associated with the type and size of production unit, a cultivation system and the ways and means to operate it, in turn, depend on the technical options available within the unit.

To create and maintain optimal conditions for crop production raises the question: which are those conditions that affect crop production, when are those optimal, and how does tillage create those conditions? Obviously, this is a complex matter. For convenience, the objectives of tillage are subdivided into three broad groups: crop requirements, management purposes, and weed control.

The generally short-term objectives of tillage for crop requirements are the most complicated and difficult to determine and evaluate. Tillage changes soil structure and aspects such as apparent bulk density , aggregate-size distribution and soil strenght, can objectively be assessed. However, to assess the beneficial effect of related transport processes of water, heat and gases on crop growth, is much more difficult. Let alone to know when optimal conditions prevail and how to maintain these. Also, the soil structural conditions are transient, because the soil is continuously subjected to climatologically induced forces. Moreover, optimum requirements for a plant are very likely to change substantially during its life cycle from a tiny seed to a mature plant. So, in the daily practice of farming, one is satisfied to establish the critical levels of soil conditions. For instance, crusts may prevent crop emergence, or rooting may be restricted by compacted layers.

THE ROLE OF TILLAGE

A good example in the category of tillage for management purposes, is the seasonal levelling or ridging of the land to facilitate irrigation and harvesting. Whereas these short-term measures are clearly taken for single-purpose technical reasons, their enhancing effect on soil and water conservation is less clear. Where water erosion poses a threat, certain tillage methods may enhance the infiltration characteristics of the surface layer. The long-term objective is served if runoff is reduced and, thereby, the chances of erosion damage. As for the short-term objective, the practice may be beneficial for crop production because more water becomes available, but yields may also be reduced due to waterlogging.

Last, but not least, is the importance of tillage for weed control. Mechanical weeding in a standing crop is a tillage operation with a sharply defined objective and a clearly visible result, but weed control cannot be regarded separate from the other tillage operations. Especially when chemical weeding is not feasible, the number and kinds of weeds deppends to a large extent on the type and sequence of tillage operations normally executed during the year.

Obviously, the broad, time-dependent objectives of tillage for crop requirements, management and weed control cannot be met by a single intervention. In practice, five groups of interrelated tillage operations are distinguished (Kuipers, 1974). In the usual chronological order these are:

a. Stubble tillage , to take care of crop residues and weeds.
b. Primary tillage, the deepest tillage, performed to prepare the land for the next crop.
c. Fallow cultivations, to keep the land in optimum conditions for benefitting from the period in which the land is free of crops.
d. Seedbed preparation, to create soil conditions which facilitate planting and provide optimum conditions for plant establishment.
e. Husbandry, post-planting tillage, to facilitate crop growth (e.g., weed control) and harvesting (e.g., earthing up).

These basic tillage operations can be regarded as building blocks of a cultivation system. In general, not all operations are executed in one crop rotation. Rather, some may be skipped, or some may be combined.
A schematic diagram according to Kuipers (1974) is presented in Fig. 3a. The generally practiced sequence of operations, their relative depth, and objectives are projected against a single crop's life cycle. Weed control plays a dominant role for all tillage operations executed between crops.

It is rather interesting and elucidating to consider how these groups of tillage operations fit into a typical semi-arid cropping season. Franquin and Cocheme (1967), who use monthly, mean evapotranspiration- and rainfall data to delineate availability-of-water periods relevant for crop production, designate various crucial periods on the basis of the intersection of the rainfall curve with those of the potential evapotranspiration (reference crop evaporation) (ET), ET/2, and ET/10 curves (see Fig. 3b). The following periods with their agronomic meaning are distinguished:

-the preparatory period, with a rainfall period between ET/10 and ET/2; in this period rainfall is sufficient for seedbed preparation.
-the first intermediate period with the precipitation period falling

between ET/2 and ET; this period is used for sowing and establishment of the crop.
-the humid period with rainfall exceeding ET.
-the second intermediate period between ET and ET/2, when the crop matures.
-the extension of the previous period (depending on the water stored in the profile), during which the harvesting takes place.

Franquin and Cocheme discuss how the growth cycle of various crops is adapted to the location-specific duration of these periods.
Here, the concept will be used to demonstrate the agronomic meaning of these periods and, by overlaying the concept of Kuiper's crop phase-tillage relationship, to help explain the tillage related problems of the semi-arid tropics.

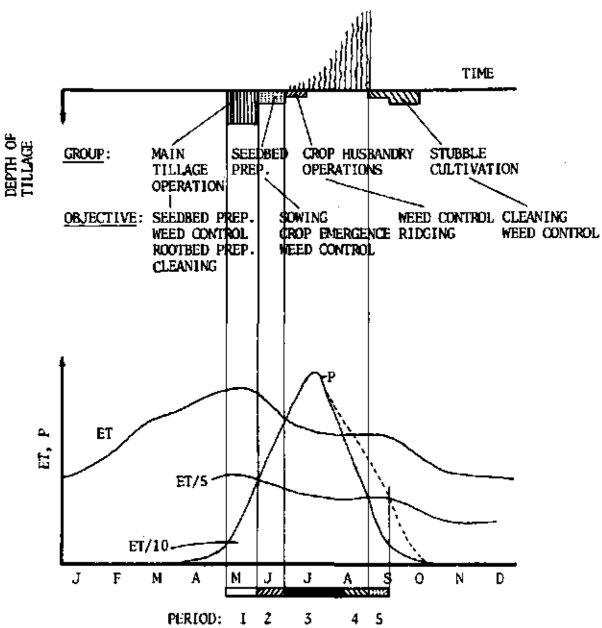


Fig. 3. Different groups of tillage operations, their objectives and timing (after Kuipers, 1974) in relation to a typical water balance situation (after Cocheme and Franquin, 1967).

3.2 CONSTRAINTS

The seasonality of the climate and vagaries of the weather impose severe limitations and restrictions on traditional agricultural production. Technical improvements, such as planting at the right time in optimal densities, better weed control, soil- and water conservation measures, etc. are prerequisites for improved cropping systems.

For the majority of farmers, even a few of these basic and well known principles are difficult to put into practice because, for their basic field operations, they have to make use of simple muscle-powered tools. The lack of power is not only the immediate source of timeliness problems, but can also lead to unsatisfactory quality in the execution and results of the following operations. Subsequent, secondary timeliness problems may be triggered off. In particular, soil cultivation constitutes a power peak which, when not met, may be felt until the crops are fully established.

During the dry season soils tend to become very hard. Only after pre-monsoon rainfall has softened the soil to a sufficient depth, can preparatory tillage begin. The first rains come in aggressive showers on unprepared fields, often sparsely covered and thus unprotected. Rainfall intensities are often much higher than the maximum infiltration rates, resulting in runoff.

By the time the fields have been prepared and sown, considerable quantities of precious water may, as runoff have been lost for crop production. In general, the erosive action threatens to affect the long-term productive capacity of the resource base ,because soil and water conservation measures are usually not taken. This presents a dilemma to the farmer, whose immediate concern is to get his crops established. Many crops require early planting for maximum yields, but preceding tillage is often needed to promote root development and provide a properly clean seeded to keep ahead of the weeds. Late planting can mean that the crop's sensitivity to drought, as it depends on growth stage, does no longer match the expected rainfall pattern. In Senegal, plowing payed off on a range of soils in 800 mm-rainfall areas, if sowing was not postponed by more than two to three weeks (Nicou, 1970).

The establishment of a crop is a critical phase. The quality of seeding, in terms of consistent metering and placement, leaves much to be desired in traditional systems. In addition, on structurally weak soils a drought period following planting often results in crust formation, impeding crop emergence and contributing to wastefull runoff.

In the humid period, rainfall may well exceed potential evapotranspiration for a longer period. Even on light slopes this may cause erosive runoff, whereas in local depressions crop yields are likely to be depressed as a result of waterlogging.

The time available for post-harvest tillage is limited strongly by the power constraint. When crop residues or manure have to be incorporated, there may be too little time, before the soil surface layer dries out.

To sum it up, the farmer never seems to be able to keep pace with the sequence: soils are hard; tillage is needed to plant a crop, but takes too much time ; delayed planting on haphazardly prepared fields depresses yields and increases weed problems; postponement of the earliest harvest date makes post-harvest cultivation, in time for the following year, impossible. All the while, the productive potential of the resource base is threatened as the lands are exposed longer to erosion.

New ways must be employed which use the farmers present resources more effectively. It must be realised that semi-arid, rainfed farming is limited by water and cannot economically support costly practices (Henderson, 1979). In addition, the farm holdings are small. The average holding size, sampled from six representative villages in the semi-arid tracts of India, ranges from 2.8-7.7 ha, with a high percentage operating on smaller than average size holdings (Jodha et al., 1977). The very size calls for 'yield-increasing mechanisation' (Giles, 1975); for instance, use of a simple seed and fertilizer drill combination in trials on farmers fields increased wheat and maize yields by 12.5% and 40%, respectively, irrespective of the power source. Giles estimated that in India 26%, 62% and 12% of the energy for agricultural operations comes from human, animal and mechanical power sources, respectively.

Economic tillage operations probably will be relatively shallow, in particular where hard abrasive soils may cause excessive wear and tear of tools.

Improved time- and energy-saving tillage systems have been developed for capital-intensive farming. In particular, the zonal tillage concept is promising in this respect, while it would also allow a more effective and efficient use of the rainfall.

3.3 TOWARDS SOLUTIONS

3.3.1 From Conventional Tillage To Zonal Tillage

Larson (1964) suggested the zonal tillage concept for row crops, defining a seedling environment (row) zone and a water management (inter-row) zone, each with its own functions and requirements, depending on the climate, soil type and crop. For the inter-row zone, soil parameters included micro-relief (relevant to potential water storage capacity in micro surface depressions) and plow layer storage (air-filled porosity at field capacity). Tillage influences positively these parameters which largely determine cumulative infiltration (Burwell and Larson, 1969; Johnson et al., 1979; Lindstrom and Voorhees, 1980).

Johnston and van Doren (1967) added a third zone by introducing a traffic zone. In particular controlled traffic, e.g., fixed pathways across the field, is receiving growing attention in modern mechanised agriculture, when soil compaction is reducing yields. Randomly breaking up soil pans by subsoiling will not improve rooting and infiltration, unless later traffic is controlled (Trouse, 1979). Traffic control is very easily accomplished in a bed and furrow system (Williford et al., 1974; Batchelder et al., 1974; Parish et al., 1974). The beds are maintained at the same location each year and remain uncompacted. In such a soil management system a considerable amount of energy for primary tillage is saved each year, because less area is tilled and less force is required to break the soil in the uncompacted area.

As Williams (1967) has put it: 'Before the advent of the tractor we had a form of minimum tillage,... We have come almost full circle in these days of modern technology. Now we are trying to get back to the principle of planting the seed and getting it up with as little disturbance of the soil as possible'.

The present situation in much of the semi-arid tropics is such that there is no option but to disturb the soil to a very limited extent. The necessary power for doing so is simply lacking. The controlled traffic concept, originally meant to save plentifull but costly power, has great potential for increasing the effectivity and efficiency of the use of the limited power available to the majority of small farmers.

3.3.2 The ICRISAT BBF-system

At ICRISAT a watershed-based approach of soil and water conservation is advocated. The focal point of the watershed-based approach is the land on which the rain falls. Contour bunding for soil and water conservation purposes is common practice in India. Undoubtedly, well maintained bunds deserve a place, as soil erosion is decreased on a watershed level. Often the land is not levelled, resulting in substantial erosion and sedimentation between bunds. Large quantities of water collect at the lower bund, which may cause waterlogging problems in monsoon cropping systems. Besides, infiltration of this water would benefit only a small portion of the land and would, therefore, hardly contribute to attaining higher and more stable crop production levels (Kampen and associates, 1975). Improved soil and water management systems aim at better utilization of the precipitation. This is attempted in three stages:

a. Improving the infiltration of rainfall in the soil;
b. Conducting the runoff safely from the fields, possibly collecting and storing it for future use;
c. Recovery from wells after deep percolation.

The first two stages have the highest priority, both from a crop production and in-situ soil and water conservation point of view. Through the option of the third phase, one enters the twilight zone between rainfed farming and irrigation farming, though use of the water for supplemental or life saving irrigation can still be considered to fall within the scope of rainfed farming.

The objectives of the first and second stage, being contradictory in a way, are both extremely important, although their relative importance changes in the course of the season.

At the beginning of the rainy season and during the preparatory period, the profile is dry and the average expected quantity and dependability of the rain is still low. Therefore, maximum infiltration of the precipitation during this period is highly desirable.

The rainfall intensity may exceed the maximum intake rate of the soil, which will inevitably lead to runoff on sloping lands. In order to prevent runoff from becoming dangerous, soil and water conservation measures have to be taken.

Later in the season, rainfall may well exceed the evapotranspiration of the crop, while the root zone is saturated. In this situation, not maximum infiltration, but controlled and safe disposal of the excess water is needed to prevent adverse effects of waterlogging on crop production.

Because of the erratic rainfall, there is not a gradual transition from the period when maximum infiltration is desirable to the period in which surface drainage becomes important. This means that a soil management system should have built in both capabilities for most of the season.

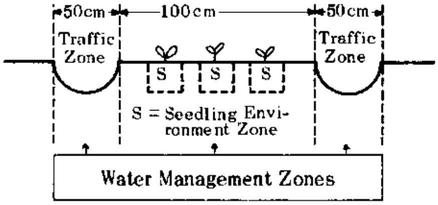


Fig. 4. Three managent zones associated with the broad bed and furrow (BBF)-system of cultivation.

Maximum infiltration and safe disposal of excess water each require different soil conditions that cannot easily be obtained through conventional cultivation systems over the entire field. A cloddy, rough surface is needed to catch the water and hold it temporarily, while channels to convey the excess water need to be present.
The Broad Bed and Furrow system of cultivation (BBF-system), as developed at ICRISAT, combines these two functions. The system is a special case of the zonal tillage concept. It is schematically presented in Fig. 4. The raised beds are layed out permamently at a 0.4-0.8% grade. The beds act as micro catchment areas. The excess water drains into the 1.50 meter spaced furrows, from where it is slowly and safely guided to a grassed waterway.
Clearly, this system is a compromise in that a balance is reached between conservation of water and runoff. Where exactly this balance should be, depends on the weight that should be given to either infiltration or drainage. Factors such as expected rainfall characteristics, soil type, crops, etc., will have to be considered.

The BBF-system resulted from early experience in the watersheds. Up to 1974, standard 75 cm-spaced ridges were included as soil and water conservation treatments. These ridges tended to slake down with the disastrous cross-furrow erosion occurring during high-intensity storms. Runoff had been higher than from flat cultivated fields. Similar disadvantages of ridges are reported by Kowal and Stockinger (1973).
The BBF-system was first introduced in 1975 to replace the ridge system in the Alfisol watersheds. Its performance proved highly satisfactory, breaching no longer occurred and soil erosion was reduced to acceptable levels. Because of the additional advantages, in particular the greater freedom it offers in plant row arrangements, it was decided to adopt the BBF-system for the Vertisol watersheds as well.

Initially, the beds were made and maintained with the available animal-drawn equipment. A single furrow opener, chained to a yoke which kept the animals at a 3 meter distance, produced 1.50 meter spaced furrows. Uniformity of the beds was poor and, as a result, planting and fertilizer application operations were difficult.
Alternative machinery, better adapted to the soil management system, and improved cropping systems were identified. The tool carrier concept seemed a very attractive proposition. Various of such machines were evaluated at the ICRISAT center. A review on the history of animal-drawn, multipurpose tool bars, their adoption, development and impact on agricultural development throughout the world, is discussed by Bansal and Thierstein (1982). The

'Tropicultor' (Fig. 5) was found to be the most versatile and reliable multipurpose machine (Thierstein, 1979).

All field operations done in the tillage experiments were carried out with the 'Tropicultor' tool carrier. Its use and performance in improved farming systems is described by Bansal and Srivastava (1981). The tool carrier consists of a frame on two pneumatic wheels, of which the track can be adjusted infinitely within a 60-180 cm range. The beam can be adjusted with a screw-type pitch adjustment, allowing for varying heights of draft animal pairs. A variety of implements can be clamped on the rear-mounted, square-sectional toolbar. Its height is easily adjustable in 5 cm steps. Within this range, shanks for cultivator shovels and planter furrow openers are infinitely adjustable, individually, so that the desired working depth can be obtained. Lateral spacing is virtually free.
The toolbar with attached implements can be lifted and put into work with a mechanical spring-assisted lifting mechanism. A locking mechanism holds the toolbar in either position.
The frame can accomodate two sitting persons, particularly usefull for operations that require constant attention, such as inter-row weeding or planting.
In addition, a cart body can be mounted and dismounted quickly, making the machine suitable for transportation as well. This feature seems important, because with it more work can be done on an annual basis. The economic aspects of the necessary yield increase to pay for the machine, the utilization rates, and its implications for the costs of depreciation, are discussed for Indian conditions by Binswanger et al. (1979).

Operational research has shown that the BBF-system satisfies the overriding soil and water conservation requirements, having many additional advantages as well. Positive aspects of the BBF-system have been summarised by Kampen (1979). He stated that the system:

a. reduces soil erosion,
b. provides surface drainage,
c. is adaptable to supplemental water application,
d. reduces soil compaction in the plant zone,
e. concentrates organic matter and fertilizer in the plant zone,
f. is adaptable to many row spacings,
g. can be layed out on a permanent basis,
h. is easily maintained with minimum tillage,
i. facilitates land preparation during the dry season,
j. reduces power and time requirements of agricultural operations,
k. provides furrows for the animals to follow,

The items f through k in particular, are relevant with respect to tillage operations. In the following sections, some of these advantages will be discussed.

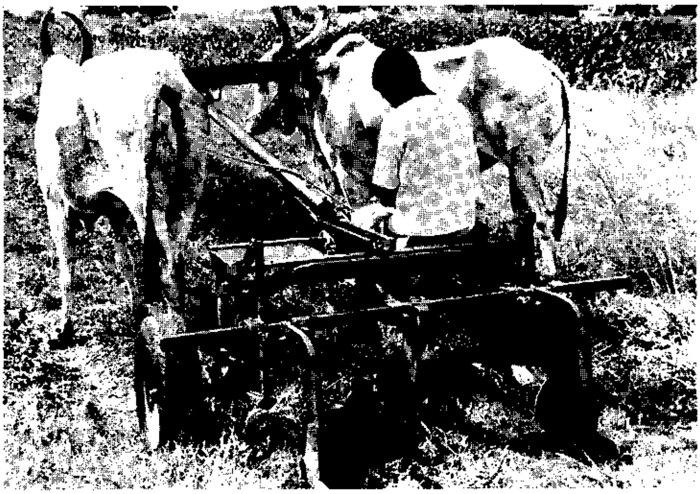


Fig. 5. The 'Tropicultor' multi-purpose toolbar, fitted for primary tillage in the BBF-system.

3.4 PERFORMANCE OF BBF-SYSTEM IN DEEP VERTISOLS

3.4.1 Production And Soil And Water Management Aspects

It is estimated that 15 to 20 million hectares of deep Vertisols in India are presently kept fallow during the rainy season (Krantz and associates, 1975). Important reasons for this are related to the physical behaviour of these clay soils. The Vertisols at the research center have a clay percentage ranging between 50% to 64%, with montmorillonite as the predominant clay mineral.
Drying is accompanied by shrinkage; deep cracks develop during the dry season. Cultivation demands much energy under these conditions; on the other hand, when thouroughly wet, the accessibility of the land becomes a problem and the stickiness of the soil virtually prevents any field operation.
Extremely low terminal infiltration rates, averaging 5 mm/day, have been measured (ICRISAT, 1977).
The poor drainage, the difficulty to cultivate, and the resulting weed control problems force the farmer to adopt the traditional rainy season fallow. During the rainy season, as often as dry spells permit, the fields are shallowly cultivated for weed control, using the traditional 'Bakhar' or blade harrow. As the rains recede, a post-rainy season crop is planted on relatively clean fields and grown on a secure soil moisture storage, which may be as high as 250 mm of available moisture.
Simulation of the traditional practice on part of the 'black' watershed has shown, that it leads to considerable runoff and erosion. For instance, during the 1975 rainy season it was estimated that only 25% to 30% of the rainfall was effectively used by the crop. A runoff loss of 25% was measured and around 30% of the rainfall was lost as evaporation and transpiration by weeds (Krantz, Kampen and associates, undated). Yields of cereal food grains range between 200-600 kg/ha under this system.

THE ROLE OF TILLAGE

The performance of improved systems facilitating double cropping contrasts sharply with the results of the traditional system. It was recognised early that, in areas having a rainfall exceeding 750 mm, the introduction of more effective land management techniques, in combination with short duration crops, could make double cropping possible (Krantz and associates, 1975).
In many years, sufficient moisture is available for intercropping, or sequential cropping of a short-duration, rainy-season crop and a dry-season crop. Examples are the intercropping of sorghum and pigeonpea, and the sequential cropping of maize and chickpea.
After seven years of experimentation and experience on watersheds of various soil management and cropping systems, a review was made by Binswanger et al. (1980). The general conclusion was that crop cover reduces soil erosion often to less than one quarter of that under fallow treatment.
The BBF-system reduces runoff under fallow conditions. Under improved cropping systems, the BBF-system reduces runoff by at least 30% compared to flat cultivated fields, giving a 15% higher gross return, and an additional Rs. 600.- profit per hectare. Aggregate yields can be in excess of 5 tons/ha (ICRISAT, undated).

Double cropping is possible only when the first crop is planted in time. As soon as the soil becomes wet, entering the field becomes difficult and the opportunity to establish the first crop may be lost for a considerable period of time.

Through the powerfull combination of improved soil management systems and appropriate machinery much of the traditional management problems are avoided. The BBF-system is particularly succesfull in this respect. The soil of the beds remains comparatively friable because of the controlled traffic, so that primary tillage can be executed after harvesting the second crop. The otherwise slack period can thus be used for tillage far into the dry season, when draft animals are still in good condition. Occasional pre-monsoon showers cause breakdown of the clods, contributing to making the seedbed. Thus, little effort and time is needed to prepare and shape the final seedbed. In anticipation of the start of the monsoon, only fertilizer application and planting will have to be carried out. This is done separately, swiftly and easily under dry conditions. Succesfull dry planting is subject to certain conditions. Firstly, the seeds will have to be planted sufficiently deep to prevent premature germination as a result of small early showers. Secondly, rains that cause germination must be followed by sufficiently dependable, life-sustaining rains. The seedling should be tolerant to early drought stress. Thirdly, the damage caused by rodents should be within acceptable limits (Krantz et al., 1977).

3.4.2 Tillage And Management Aspects

3.4.2.1 The Seedbed And Dry Planting -

As far as timeliness and ease of operations is concerned, experience in 1977 during the planting of rainy season crops clearly showed the advantages of the dry planting technique. Anticipating the onset of the monsoon, a total of 23.6 ha dry soils were planted during the first one and a half day. This was accomplished with four 'tropicultors', each operated by two man from 6 a.m. to 7 p.m. The workrate amounted to 3.5 ha/day/machine. Bullock pairs were refreshed after 6 hours. Rains delayed subsequent planting; to complete the rest of the 60 ha, five more days were required in which the average work rate was reduced to 2.2 ha/day/machine, because of the frequent stops needed to clean press wheels and unplug furrow openers of the planters. It was observed that, compared to flat cultivated fields, the BBF-system could be entered earlier and planted more easily because of the surface drainage provided.

The minimum seed depth for succesful dry planting in Vertisols is considered to be 6 cm. As untilled soils can be very hard when dry, during planting the seedbed should be sufficiently deep to make insertion of the seed physically possible.
The experienced superiority of the BBF-system, over flat cultivation and standard ridges, to provide an adequate seedbed with a minimum of energy and time, was quantified during the dry season between 1977 and 1978. These were the first aspects investigated in preparation of the tillage research later commenced on Alfisols.
Tillage for seedbed preparation, and its results in terms of thickness and its uniformity, clodsize distribution and apparent bulk density of the seedbed, were compared and evaluated in the replicated field-scale management trials on deep Vertisol of the black soil watershed BW-5.
In spite of the widely different implements used at different dates for primary tillage and seedbed preparation, the seedbed aggregate composition measured before planting time was not different among the three soil management systems. Apparently, the alternate drying and wetting of the topsoil as a result of pre-monsoon showers, was much more efficient in breaking down the clods than any tillage operation in this selfmulching soil.

The thickness of the seedbed and its variation must be evaluated in the direction of the planter path. For the flat cultivated fields the precise location of the plant rows is unknown; consequently, the seedbed characteristics can be evaluated at randomly choosen locations in the field. For the oriented tillage systems, the location of the future rows is predetermined, subject to slight lateral variations arising from steering inaccuracies.
This was taken into account in evaluating the seedbeds. The BBF-system may accomodate four rows spaced at 30 cm; therefore, the seedbed was measured over a width of 100 cm. On the standard ridge only 1 row is planted; here, a width of 30 cm was considered.
Shape and depth of the seedbed layers are presented in Fig. 6. The average depth of the seedbeds was measured from three samples per treatment with the help of the soil surface relief meter. The relief meter is described in Chapter 5 on primary tillage.
Average depth and standard error for the BBF-, ridge-, and flat cultivated system were 4.05±0.26, 4.72±0.66, and 3.80±0.83 cm, respectively. Seedbed depth did not differ much and was less than the desired depth of seed placement of 6 cm in all treatments.

During planting in the flat cultivated fields, it was observed that the planter furrow openers were frequently hitting the hard, unyielding soil beneath the loose layer. This caused severe planter vibration, resulting in premature ejection of the seed from the inclined seed plate. In the other systems the planter furrow openers could penetrate much more easily. This can be explained by the reduced soil strength under the uncompacted zone. Where seeds could be placed sufficiently deep without planter metering malfunction, considerably higher emergence percentages of maize were realised (Fig. 7).

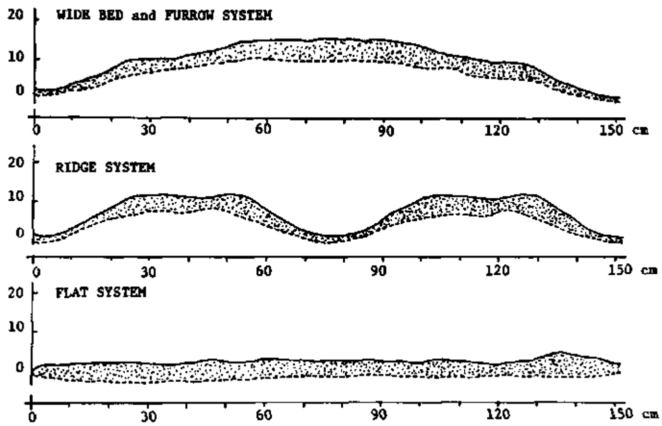


Fig. 6. Thickness and variability of the seedbeds of various soil management systems in deep Vertisols.

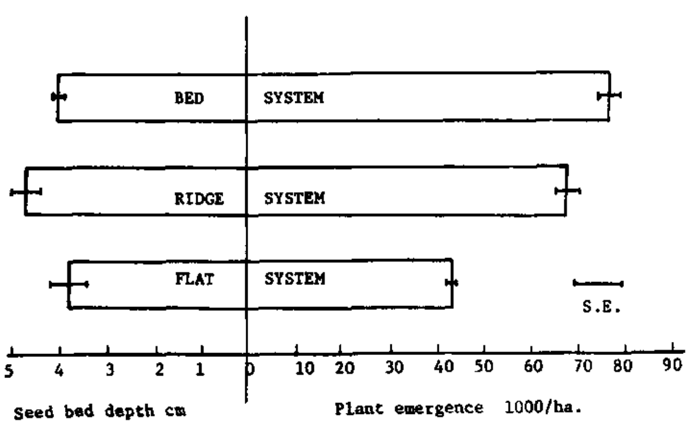


Fig. 7. Depth of seedbeds in relation to plant emergence of maize, with standard errors, for three soil management systems in a deep Vertisol.

3.4.2.2 **Shear Strength Measurements Of The Seedbed -**

Serious penetration difficulties occurred while planting the second crop in the flat cultivated fields. The establishment of a sequential crop often falls in a critical period. Soil moisture may already be decreasing, so that planting should follow the harvest of the preceding crop without delay.
To accomplish this, the second crop is planted without interfering with the old stubble rows. Precious time and energy is saved by cultivating only small strips at the location of the future plantrows for weed control.
If the surface layer has dried out, the seed and fertilizer must be placed somewhat deeper into moist soil. Planter furrow openers were set accordingly, but often failed to penetrate sufficiently deep on flat cultivated fields. Occasionally, the tool carrier was lifted completely while resting on the openers. A large proportion of the by vibration reduced planter output was placed too shallow for immediate germination. As a result, crop establishment was poor and only later rainfall, which is undependable, caused a second flush of emerging plants. Again, such difficulties were hardly experienced in the BBF-system. The reason for this was the apparent difference in soil strength between the two systems.

The soil strenght of both the BBF- and flat cultivation system was evaluated during this critical transition period by means of extensive shearvane measurements over the depth of the relevant layer. A multiple regression was performed on the shearvane and corresponding soil moisture data. From Fig. 8 it is evident, that shear strength generally increased with depth and the loss of moisture, but for the BBF-system only at a reduced rate in the uncompacted bed zone.

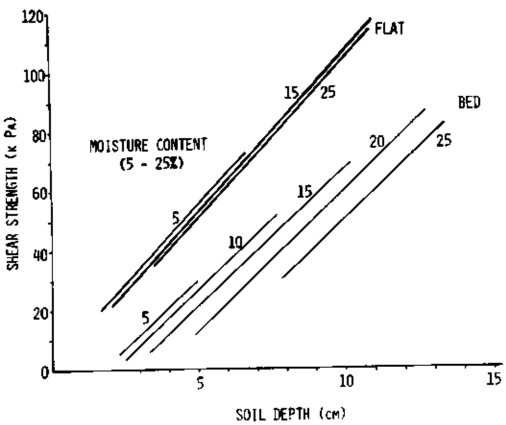


Fig. 8. Influence of soil management on soil shear strength of a deep Vertisol in relation to depth and moisture content.

3.4.2.3 **Primary Tillage Method For The BBF-system** -

A rather special method of primary tillage was developed for use with the BBF-system. This method has been used since 1975 on ICRISAT's research watersheds.
One right hand and one left hand plowbody are clamped onto the toolbar. The plows are set laterally to plow up each a strip from the outside edges of the bed towards the center. The distance from landside to landside is set at approximately 1 meter. Thus, in one single pass the stubble of the outside rows are plowed up and deposited over the center of the bed. To uproot the stubble of a center row to prevent regrowth, a duckfoot shovel or chisel tine may be attached at the center of the toolbar. This method of plowing has the soil-inverting characteristics of conventional plowing, except that only two slices are taken over the whole bed, while the inversion is less complete because of the mutual interference of the colliding plow slices.
The furrow areas are tilled separately with two furrowers, spaced at 1.50 meter. The highly compacted soil in this traffic zone is tilled after occasional pre-monsoon showers for weed control, and to shape the furrows to maintain the drainage capacity.

Post-harvest measurements on soil strenght, depth of tillage and volume of soil displaced were initiated in 1977.
During the cropping season, cultural operations and alternate wetting and drying tend to flatten the beds. A typical shape of beds, prior to and after tillage, is given in Fig. 9.
Prior to tillage, soil shear strength measurements were taken at four depths. The lines in Fig. 10 represent shear strength at constant depths below the soil surface.
The friability of the bed zone is clearly demonstrated: up to the tillage depth the values below the furrows are approximately twice as high. The average strength, however, increases rapidly with depth.
The power requirements for primary tillage are kept low by limiting tillage depth and width and by restricting tillage to the friable bed zone.

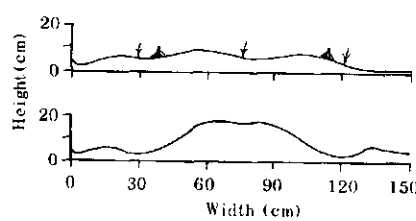


Fig. 9. Soil surface profile of a BBF-system before and after plowing.

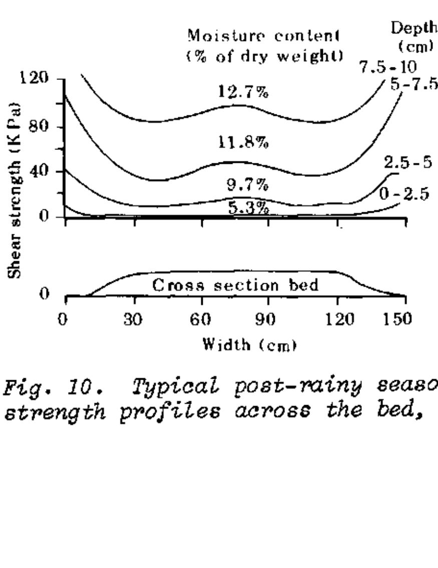


Fig. 10. Typical post-rainy season (December, 1977) soil (Vertisol) shear strength profiles across the bed, as function of depth.

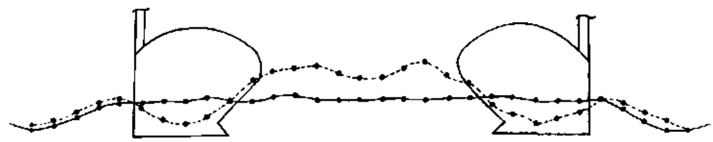


Fig. 11. Plow setting for standard primary tillage method of ICRISAT BBF-system, and its effect on bed shape.

The depth of tillage and resulting soil displacement were measured during tillage on the operational watersheds (Fig. 11). The distance from landside to landside between the two plow bodies is 104 cm, and the plow width is 22 cm. The measured depth varied from 4 cm to 6 cm at the landside to 9 cm to 11 cm at the sharepoints, and proved much shallower than estimated by eye.
Observed workrates in the operational watersheds showed considerable variation, ranging between 0.11 and 0.22 ha/hr (ICRISAT, 1978). No doubt, the strongly reduced need for timeliness and the reduced level of supervision are reasons for these much lower work rates than accomplished during planting.

The comparative ease of cultivating these soils far into the dry season never failed to surprise those who were only too aware of the difficulties in handling Vertisols.

3.5 PERFORMANCE OF BBF-SYSTEM IN ALFISOLS

Since its introduction in the Alfisol watersheds, the BBF-system has performed satisfactorily as a replacement for the unstable narrow ridges. The previous breaching of the standard 75 cm-spaced ridges did not occur anymore, while serious soil erosion was prevented.
Contrary to the situation of the deep Vertisols, the advantages of the BBF-system over improved flat cultivation, in terms of gross returns and profit, were much less clear and consistent. Unlike the deep Vertisol situation, the BBF-soil management system could not provide a real breakthrough. In the deep Vertisols, the basis for succes was the removal of the soil management bottleneck, enabling full use of the rainy season. An economically viable, double-cropping technology could replace the hitherto followed rainy season fallow practice.

THE ROLE OF TILLAGE

Alfisols have an inherently lower waterholding capacity; therefore, crops can only be grown during the rainy season. The productive potential is lower, because crops will more frequently be subjected to moisture stress during breaks in the rainy season.
Sequential cropping is not feasible without supplemental irrigation, but intercropping of a short and long duration crop is feasible.
Typical for the Alfisol watersheds, the seasonal runoff, expressed as a percentage of the rainfall, has been appreciably higher than from the deep Vertisol watersheds. Average runoff percentages from watersheds cropped during the rainy season under the BBF-system of cultivation, were (runoff from deep Vertisols in parentheses): 25%-30% (15.5%) in 1975 from narrow ridges; 21.7%-27.8% (10.6%) in 1976; a low 8% (2%) in 1977; 22.8%-33.2% (24.3%) in 1978; and 14% (8%) in 1979 (ICRISAT, 1976; 1977; 1978; 1980; 1981).
An important cause for this difference is the totally different infiltration characteristic. A comparison between an Alfisol and a Vertisol showed equally high initial infiltration rates of 75 mm/hr under dry conditions, and a terminal rate of 7.7 mm/hr and 0.2 mm/hr, respectively. In spite of the lower final infiltration rate, the vertisol water intake capacity at the onset of the monsoon remains high because of the cloddy receptive surface, the dense pattern of deep cracks, and the large water holding capacity.
Runoff occurs late in the season, when the soil profile is recharged.
Alfisols behave totally different in this respect. The reasons for this are related to a number of problems caused by some soil physical characteristics of Alfisols.
The loamy sand texture of the top soil and the predominance of Kaolinite among the clay minerals, make these soils structurally 'inert' (Charreau, 1978).
During the dry period, the noncracking top soil layer becomes compacted and extremely hard with a very smooth soil surface. Tillage and seedbed preparation will have to wait until pre-monsoon showers have infiltrated in sufficient quantities .
Therefore, tillage and seedbed preparation cause a potentially higher labour and power peak than in Vertisols.
Due to the lack of a receptive soil surface layer and the absence of deep cracks, the effective infiltration rates are moderate and during initial showers a substantial proportion of the precipitation may run off, even when the soil profile is not saturated. Later in the season, the rainfall tends to flatten the by tillage roughened more receptive upper soil layer.
The general observation in Alfisol watersheds is, that the BBF-system increases the total rainy season runoff, compared to the full field flat cultivation system (Binswanger et al., 1980). This suggests the importance of the soil surface layer characteristics. In the BBF-system of cultivation, only part of the total area is plowed, while the smooth and compact traffic lanes, conducive to runoff, occupy a considerable portion of the area.
Alternative, more intensive, primary tillage systems to be used with the BBF-system seem to have potential in this respect.
Timely plant establishment is critically important to keep ahead of the build-up of weeds, pests and diseases and to make maximum use of the growing season. It also guarantees the earliest possible full canopy closure, which protects the soil surface from the beating action of the rain.
Seeding is done after monsoon showers have sufficiently wetted the soil profile, and when the prospects for a continued rain supply are good.
The low waterholding capacity of the soil makes the plant establishment phase a difficult one. Not only may early drought periods set back the crop, poor stand establishment has also been a problem in the watersheds. Especially the

small-seeded, usually shallow planted crops such as pearl millet and to a lesser extent sorghum, are difficult to establish. Crust formation resulting from a dry sunny period after planting is believed to be a major cause (ICRISAT, 1978).

CHAPTER 4

THE TILLAGE EXPERIMENTAL SETUP

The role of tillage, the advantages of the BBF-system, its succes in the deep Vertisols, and factors which limit its efficiency in Alfisols, have been discussed in the previous chapter.

It was felt worthwhile not to abandon the BBF-concept, but to try to improve its performance in Alfisols by adapting the tillage component. A long-term tillage field experiment was set up with the general objective to evaluate alternative tillage practices and their effect on crop production in terms of soil reaction to tillage tools, plant and soil interaction during plant establishment and early growth, and to evaluate seed bed requirements.
Alternative primary tillage methods were designed to suit the existing BBF-system, as operated with the animal-drawn multipurpose toolbar.
Four primary tillage methods were envisaged which differed with respect to working depth and principle of operation. ICRISAT's 'standard' primary tillage method was included. The four treatments are, in descending order of soil volume displaced:

- T1: Split the bed through its center with a furrower, and rebuild the bed by successive plowing with a set of two opposite plow bodies.
- T2: Plow up the bed with a set of two opposite plow bodies. (ICRISAT's standard primary tillage method).
- T3: Chisel future crop rows.
- T4: Superficial cultivation with sweeps.

For clarification of these tillage methods see Fig. 12. Only tillage treatment T1, being the most intensive form of tillage, requires three separate passes over the field.
For convenience, the tillage treatments will be designated by their code T1, T2, T3, or T4 throughout the following chapters.

Weediness levels were expected to be lower with increasing levels of primary tillage, which in turn would reduce the need for weeding measures, or render these more effective.
The different primary tillage methods were also expected to affect seed bed properties, thereby influencing the effect of different planting methods being considered.

THE TILLAGE EXPERIMENTAL SETUP

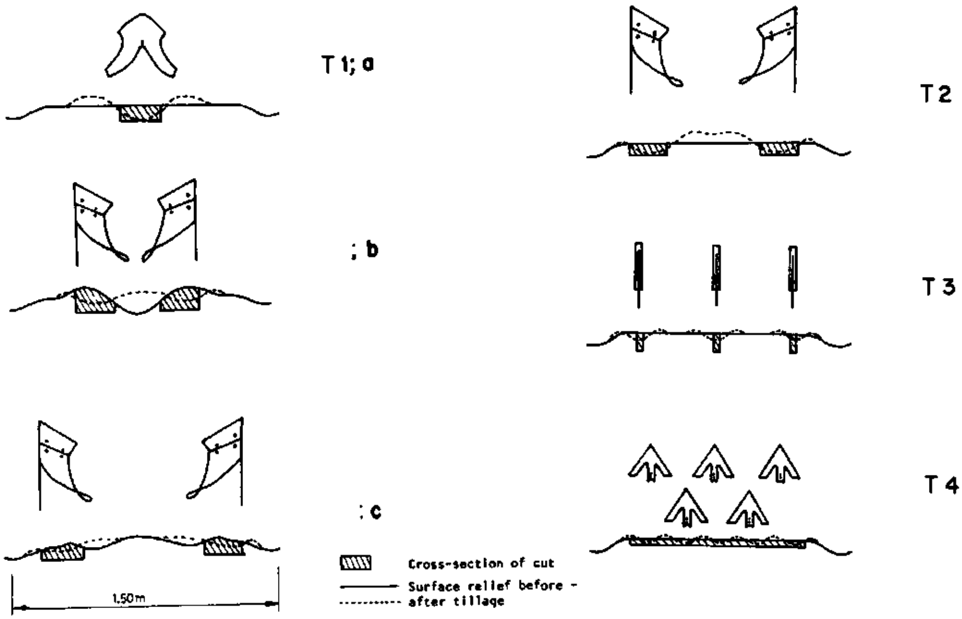


Fig. 12. Four primary tillage methods of the tillage field experiment, T1,T2,T3 and T4, in descending order of soil volume displaced.

Thus, a split-plot statistical design was used with main plots in a randomized complete block design.
The primary tillage methods were assigned to main plots and were kept on the same location for all years. The main plots were divided into sub-plots to which each year the particular weeding and planter treatments were reassigned randomly.

The experiment started in 1978 on RA-14 (Red Area No. 14). Part of the experimental field is shown in Fig. 13. Beds were prepared in 1977 and have been on the same location since then. During the first cropping season, the T1 treatment was not yet in use. With its introduction in 1979, the main plots had to be reassigned, but remained in place during the following seasons.
Prior to the 1979 rainy season part of the more clayey Alfisol Red Watershed No. 2B (RW-2B) was added to repeat the experiment during the 1979 and 1980 rainy season.
For practical reasons, to avoid peak demands for field operations, sampling and other observations, the planting dates for each of the fields were scheduled at least one week appart. The mere distance (approx. 1.5 Km) between the fields often resulted in spectacular differences in the occurrence and quantity of rainfall, overriding the peak demand consideration anyway. So, five more or less individual cases were studied during three years on two fields:

THE TILLAGE EXPERIMENTAL SETUP

1978, RA-14
1979, RA-14
1980, RA-14
1979, RW-2B
1980, RW-2B

The layout of the two experimental fields is given in the annex, along with general information on Alfisols at the ICRISAT center and a soil texture analysis. For crop observations, 1.5 to 2 m long plant rows were pegged out systematically on each bed of each subplot immediately after planting. This facilitated easy and accurate data acquisition on related variables, such as plant emergence, changes in plant population, plant height and ultimate crop yield.

Standard agronomic recommendations, as adopted for improved cropping systems and evaluated on the research watersheds, were followed. For fertilizer application this meant that, prior to planting, a basal dose of 100 Kg of Di-Ammonium Phosphate (18.46.0) was band placed at a depth of 5 to 6 cm slightly offset from the crop rows to be planted. Some two to three weeks after planting, a side dressing of 75 Kg/ha of Urea (48.0.0) completed the recommended fertilization. Recommended crop varieties and seed rates were used; details follow in the appropriate sections.
No chemicals were used for weed control, or against pests and diseases.

In the next chapter on primary tillage, the observations and results obtained from the experiments on RA-14 and RW-2B will first be discussed. In the following chapter on weed control, a review on the impact of weeds is given as well as the results of the various weed management treatments tried on the tillage experimental fields.

Complementary, small plot experiments to study the effect of seed bed compaction by planter press wheels on crusting, seed germination and seedling growth were conducted on an Alfisol plot (No. ST-2). Details of the setup of these experiments are described in the chapter on plant establishment.

THE TILLAGE EXPERIMENTAL SETUP

Fig. 13. Tillage experimental field RA-14, two weeks after planting.

CHAPTER 5

PRIMARY TILLAGE EFFECTS

5.1 TILLAGE MANAGEMENT ASPECTS

5.1.1 Energy Expenditure In Semi-arid Lands

Energy expenditure for tillage is often expressed in Mega Joules per hectare. An example may serve to illustrate this. Suppose a force of 1000 kg (10,000 N) is needed to pull an implement with an effective width of 1 meter. A total distance of 10 km is required to complete 1 hectare in this case. The total energy expenditure for 1 hectare is then:

$$
\begin{aligned}
E &= 10{,}000(N) \times 10{,}000(m) \\
&= 100{,}000{,}000 \text{ J} \\
&= 100 \text{ MJ}
\end{aligned}
$$

The force required to move a tillage implement through the soil depends on many factors, of which the most important are soil type, moisture content and speed of operation.
From specific plow resistance figures, the energy expenditure on a hectare basis can be estimated from:

$$E = r \times d \times w \times (10{,}000/w)$$

in which;

r= specific plow resistance
d= depth of tillage
w= effective width of operation

Common energy expenditure levels can be derived from an ASAE graph (NN, 1975), in which specific plow draft is plotted as a function of speed for various soil types. Energy expenditure may vary from 40 MJ/ha for low speed plowing (2 mph) in sandy soils, up to 210 MJ/ha for high speed plowing (6 mph) in a clay soil, assuming a plowing depth of 20 cm.

In dryland agriculture the energy levels are generally higher, likely because tillage is performed at lower soil moisture levels. In Botswana, Willcocks et al. (1976) measured draft forces for tillage and calculated energy expenditure on sandy loam soils. The reported levels range from 22 MJ/ha for shallow sweeping, up to 158 MJ/ha for 25 cm deep moldboard plowing. Hillel (1969) measured high values of 420 MJ/ha and 1000 MJ/ha for

40 cm and 50 cm deep plowing, respectively, in a clay loam in Israel. Excessively high energy values are given by Wolf and Luth (1977); 30 cm deep chiseling in a dry soil required 2200 MJ/ha.

When draft animals are used for tillage, energy expenditure levels must be necessarily lower, if tillage is to be completed within a reasonable time. For a given soil, there are only two ways to reduce the energy level. Obviously, the most important way is to reduce the depth of tillage, while controlled traffic allows for a reduced area to be tilled on a hectare basis. Nevertheless, energy expenditure for tillage can be still quite high. Using data on plowing depth and specific draft from a comparative study on traditional wooden country plows (Hussain and Sarker, 1978), energy levels would vary between 34.5 and 42.6 MJ/ha for 3 inch deep stirring of the soil. Willcocks et al. (1977), reported energy expenditure levels ranging from 14 MJ/ha for 10 cm deep sweep tillage, up to 75 MJ/ha for 20 cm deep plowing, using oxen pulling improved implements. Similar energy levels emerge from draft measurements of improved ox-drawn equipment, reported by Matthews and Pullen (1977): 8 cm and 20 cm deep mouldboard plowing in a sandy loam would require 21.6 MJ/ha and 60.8 MJ/ha respectively.

The BBF-system of cultivation uses comparatively little energy for primary tillage. On the basis of draft measurements (see section on draft) the following average values apply:
The shallow T4 tillage method requires a mere 7.7 MJ/ha, followed by T3, T2 and T1 requiring 9.6 MJ/ha, 11 MJ/ha and 28.2 MJ/ha, respectively. These are flattering values, since they do not account for the necessary cleaning out of the furrows.
This operation can be regarded as an 'auxiliary' tillage operation, which requires another 6 MJ/ha.

5.1.2 Available Draft Power And Time Requirements

The energy available from draft animals is composed of three components:tractive force, working speed and hours worked.

The tractive force that bullocks can exert is, as a rule of thumb, about 10% of their weight (Hopfen, 1969). The power available from different breeds of bullock pairs ranged between 0.44 KW and 0.97 KW (FAO, 1972). When assuming an average working speed of 1 m/s these power levels would correspond to a tractive force of 440 N and 970 N, respectivily. The estimates were based on duration tests in typical farming situations.
At ICRISAT, bullock pairs were able to exert a force of 2250 N while plowing during a 6-hour working day. At first sight, this would correspond to a very high power level of 1.9 KW, assuming a walking speed of 3 km/h sustained over the 6-hour period. It must be realised, however, that in the BBF-system of cultivation the bullocks are intermittently loaded, as turning time at the end of the bed may exceed 1 minute under heavy loads. This may have reduced the actual plowing time by 2 hours; moreover, the operation took place in the cool season, in which the animals are in top working condition.
Tests in which bullock pairs were continuously loaded, (ICRISAT, 1981) showed that 5.9, 5.7, and 5.7 hours could be worked on average under a draft regime of 490 N, 780 N, and 1070 N, respectively. The average initial and final

power level were 1 KW and 0.77 KW. The speed of the bullocks, weighing from 370 to 550 Kg, was initially 3.4 Km/h and decreased by 12% only when draft increased from 490 to 1070 N.

Thus, to make each operation as time-efficient as possible, the load should conform to the maximum sustainable tractive power. Therefore, the width of shallowly working implements should be wider than that of the deeper working plow.
The relative importance of the three components, tractive force, working speed and hours worked, and their interdependence are discussed in detail by Viebig (1982) for many kinds of draft animals.

Primary tillage operations are the most time consuming, because of the highest tractive force needed per cross sectional area. Hussain and Sarker (1978) reported 32-59 hr/ha (bullock-pair hours) for plowing with various traditional wooden plows, working at a depth of approximately 7 cm in a clay loam soil. The effective width of these 'breaking' plows was 20 cm, which for the necessary criss-cross plowing requires 100 Km travel per hectare.
The working rates of soil-inverting moldboard plows are higher, since one pass is sufficient. Wevers and Dibbits (1977) reported bullock-pair time expenditures of 19.1 h/ha for plowing at a depth of 15 cm with a small 'Ariana' multipurpose toolbar, and 18.7 h/ha when a 'Polyculteur' wheeled tool carrier was used. In both cases the walking distance is reduced to less than 50 Km/ha.

A drastic reduction in time expenditure is achieved in most of the tillage methods used in the BBF-system. The effective working width of 1.5 m reduces the distance travelled per hectare to 6 2/3 Km. Admittedly, this can be achieved only by reducing tillage depth, and thus force, and by tilling the beds only partially, thus reducing area per hectare.
The earlier mentioned 'auxiliary' tillage, in which the furrows are cleaned out, is an operation with an effective width of 3 meter, since it is not necessary to return in the same furrow. It is recommendable, however, to do so only when a large draft is available, so that a high degree of parallelity can be maintained.

5.1.3 Draft Requirements In BBF-system

5.1.3.1 Measurement Techniques -

The force needed to pull the tool carrier with the various implements attached, was measured either mechanically with a simple spring dynamometer, or electronically with a strain gage load cell. In either case, the load was picked up by a specially constructed sliding telescopic beam, so that rolling resistance of the tool carrier was included in the measurements.
Depending on the traffic path conditions, the rolling resistance varied between 50 to 150 N.

5.1.3.2 **Post Harvest Tillage** -

A late harvest or early receding of the monsooncan make post-harvest tillage operations very difficult, because of extreme hardness of the top soil. This was demonstrated in 1978 on the RA-14 experimental field after the harvest of pearl millet. The soil moisture content of the top layer was below the wilting point, and the soil proved very hard as evaluated by a penetrometer. On many spots on the bed, penetration was impossible; elsewhere the maximum measurable soil resistance of 5000 kPa was quickly reached (Fig. 14). (Features of the penetrometer used are described in the section on soil compaction).
Irrespective of the adverse soil conditions, tillage was desirable to kill the sometimes ratooning stubble, and to control established weeds that thrive on residual soil moisture. A spike-tooth harrow consisting of a frame with two banks of spikes was tried. Even though the average load per spike amounted to 17 Kg (due to the combined weight of the toolcarrier and its operator), the surface was scratched only ineffectively. This operation required excessive draft and caused much vibration (Fig. 15).
A small shower of 7.2 mm, and a 10.6 mm rainfall 10 days later brought the soil moisture content in the upper 15 cm to field capacity, making post-harvest primary tillage possible. Prior to tillage, vane shear measurements made in the stubble rows up to tillage depth, revealed a significant difference in shear strength due to the pre-monsoon primary tillage (Fig. 16).

The effect of primary tillage on weed control was disappointing (only T2, T3 and T4 were used at that time). No doubt, this was due to the delay of tillage, which allowed the bulk of established weeds to grow beyond the level that could effectively be managed.
Therefore, in the course of the dry season, four additional shallow tillage operations had to be executed to keep weediness at an acceptable level for primary tillage prior to the rainy season.

From then on, the post-harvest tillage strategy was altered. Only shallow cultivations were performed, which were more succesfully due to a two-stage approach.
The beds were tilled as soon as possible after harvest, using five narrow chisel points to break the soil surface. The first operation prepared the usually hard bed surface to facilitate the shallow cultivation with duckfoot shovels, which from a weed control standpoint is much more effective.
The draft required for the breaking operation averaged 1800 N, the five duckfoot shovels 1500 N.

5.1.3.3 Primary Tillage -

Draft measurements were made through the years; typical values are presented in Table 1. The cross sections of the tillage cut were estimated from the depth of cut, measured with a reliefmeter, and the width of the implement itself.

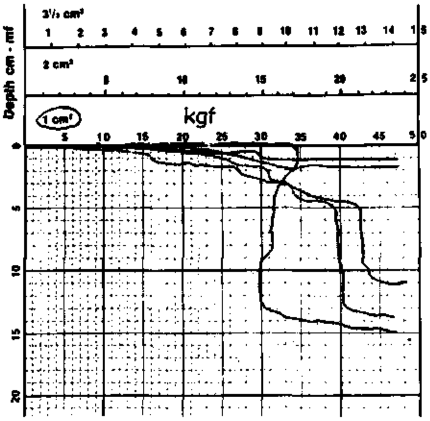


Fig. 14. Penetrometer measurements after harvest, October 1978, in hard RA-14 Alfisol.

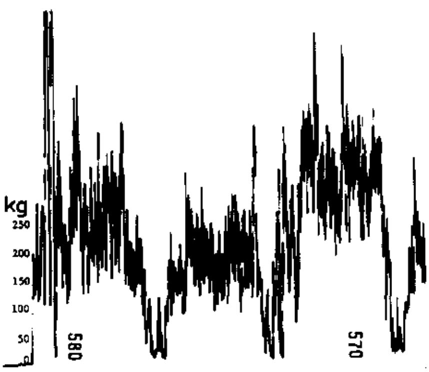


Fig. 15. Excessive vibration and high draft requirements of a spike tooth harrow during an attempt to uproot sorghum stubble and kill weeds.

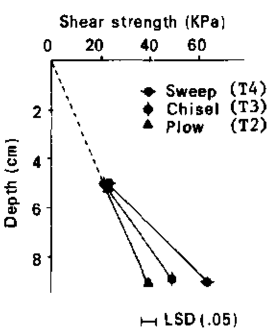


Fig. 16. Residual tillage effect of the T4, T3 and T2 tillage method on soil shear strength in RA-14 as measured in the crop row area.

Table 1. Draft requirements for primary tillage on RA-14, May 1978.

treatments	T1(*)	T2	T3	T4
draft (N)	1550 1600 1350	1850	1500	1150
depth (cm)	8-7-7	7	12	2-4
cross section (cm2)	190 310 310	310	140	250

* draft, depth and cross section values for respective implements used for the T1 method.

The draft values must be regarded rather arbitrary, since in practice draft is very sensitive to depth, particularly for the 'deep' tillage treatments. The average depth of tillage is about 7 cm for plowing in T1 or T2; increasing this by as little as 1 cm increases the cross section by 14%. Draft increases by more than 14%, often around 50%, because soil strength increases strongly with depth. The soil strength profile obtained from vane shear measurements in the RW-2B experimental field (Fig. 17), clearly illustrates the impact of zonation and the rapid increase of soil shear strength with depth. The soil moisture content was at field capacity.

From the data on draft and depth of tillage, the specific plow resistance can be calculated; for the T2 plowing this was 60 kPa. Similar data from the more clayey RW-2B Alfisol yield a specific plow resistance of 71 kPa. These data indicate a much higher draft requirement for tillage in this type of soil, than reported in the literature for comparable ox-powered shallow cultivation. Willcocks (1980) reported a specific plow resistance of 40 to 46 kPa and Matthews and Pullen (1977) established resistance values of 27 to 30 kPa, both for sandy loam. Nicou (1977) found 30 to 40 kPa for plowing in loamy sands and sandy loams.

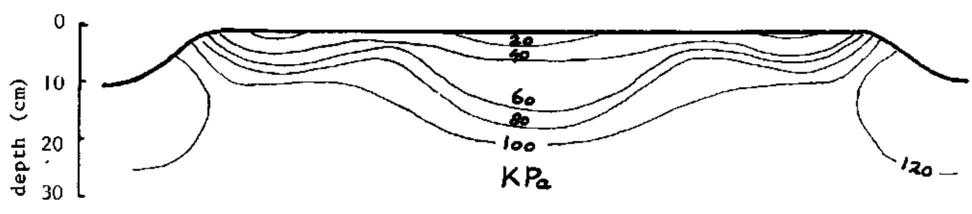


Fig. 17. Soil shear strength profile of RW-2B at field capacity.

5.1.3.4 **Other Field Operations** -

The draft required for the remaining operations averaged:

Furrow cleaning (2 furrowers)	1700 N
Fertilizer application (3 chisel type openers)	1000 N
Pre-sowing cultivation (spring tine or spike tooth harrow)	900 N
Bed shaping (2 furrowers and spring tine harrow)	2000 N

5.1.4 **Operational Experience**

The use of a wheeled tool carrier in conjunction with the controlled traffic BBF-system provides maximum comfort for the operator, while ensuring a high and consistent quality level of operations. A smooth ride is ensured and steering problems are minimal with the animals easily following the compacted smooth and flat furrow bottom.
All tillage methods use implement settings with a neutral (T3 and T4) or a compensated side draft component (T1 and T2). This is advantageous because time-consuming implement setting adjustments, as would be needed for conventional mould board plowing when encountering different soil conditions, are not necessary, nor is the skill required. Furthermore, it contributes to effortless steering, and lateral accuracy of the operations. It is, therefore, possible to concentrate the available power accurately in small strips at predetermined locations on the beds. This feature made the T1-treatment feasible. Also, the uprooting of the sometimes ratooning crop stubble for sanitary reasons, could easily be accomplished with three narrow tines, one for each row. This operation was the first in a number of shallow post-harvest operations to keep the weediness levels low during the dry period, until primary tillage could start before the next rainy season.

A high degree of depth control is achieved, because 'biting' of the implements in locally soft spots is prevented by the tool carrier wheels supporting the implements. The depth control aspect was quantified in the planting method experiments.

With the sweeps used for the T4 tillage method, penetration problems occurred in spots where grassy weeds were concentrated.
The soil-inverting tillage methods could cope adequately with surface trash and rootclumps remaining from the post-harvest tillage. Occasionally, this caused problems with the T4-tillage method. The sweeps are fixed on two rows of shanks. Despite a longitudinal spacing of the shanks of approximately 40 cm and a lateral spacing of 25 cm blockages could not always be prevented. The implement tended to clog, thereby loosing its capability to penetrate. As a result, much of the collected plant residue ended up at the end of the beds, where it was removed.

5.2 TILLAGE-SOIL INTERACTIONS

5.2.1 Soil Surface Relief Meter

Generally, tillage breaks up, shatters and rearranges a consolidated soil layer, thereby increasing its total porosity. The degree of 'coarseness', or 'roughness', and mean surface upheavel as a result of tillage were evaluated by means of a soil surface reliefmeter.
Kuipers (1957) introduced a soil surface relief meter and a computational method to quantify 'soil surface roughness'. The reliefmeter consisted of a horizontal beam with twenty vertically sliding pins of equal length, spaced 10 cm apart, which are made to rest on the soil surface. Kuipers defined a soil roughness index, 'R', as:

$$R = 100 \log s$$

where s= the standard deviation of heights in cm.

The soil roughness index was estimated from measurements at 20 locations, thus from a total of 400 height data.
Burwell et al. (1963) obtained 400 height measurements over a 40x40 inch area on a 2 inch grid. They defined two types of roughness: the one caused by the tool, such as ridges and furrows, and a so-called random roughness, obtained by mathematically removing the variation due to tillage. Random roughness is then defined as the standard deviation of the logarithm of the heights. In bedded fields, Gayle and Skaggs (1978) distinguished between macro storage due to undulations of the furrow, and micro storage or roughness.
Other workers used similar devices for height measurements, but calculated slope distributions (Dexter, 1977; Lutrell et al., 1964). Dexter also calculated auto-correlation functions, and concluded that Kuipers' index of roughness provides the most easily obtained and interpreted measure of soil roughness.

In more recent developments, soil roughness based on height measurements are used to predict micro-relief surface storage (Mitchell and Jones, 1976). These data are used for rainfall infiltration-runoff models (Mitchell and Jones, 1978; Moore et al, 1980; Linden, 1979).

The relief meter can be used to measure changes in mean surface level. On the basis of bulk density determinations, further changes in total pore space can be estimated from mean surface upheaval or consolidation (expressed in unit of length).
Initially, the total pore space in a particular layer is approximated from data of undisturbed core samples as follows:

$$P(0) = (1/n) \sum_{i=1}^{n} ((1 - Db(i)/2.65) \times d(i))$$

where n=the number of layers
Db(i)= the dry bulk density of layer 'i'
d(i)= thicknes of layer 'i'.

Subsequent changes in pore space due to tillage or weathering can then be calculated from:

$$P(t)= P(0)+h(t)-h(0)$$

where $P(0)$= previous pore space
$P(t)$= actual pore space
$h(0)$ and $h(t)$= average height at times 0 and t.

The advantage of this procedure is that the core samples necessary for the bulk density determinations need be taken only once. This is done, preferably, when the soil conditions are optimal for sampling.

Summarizing, reliefmeter measurements provide data from which plow layer storage and micro-relief can be estimated. In addition, lateral soil displacement can be described and depth of tillage measured.

A relief meter was constructed to suit the needs of the BBF-system cultivation studies. Thirty one pens, spaced at 5 cm are held in a horizontal beam to cover the width of one bed and half of each of the two adjacent furrows.
The beam rests on a frame, which straddles the bed. A series of 31 height measurements are made using a ruler. Then, the pins are lifted, the beam is advanced 5 cm in the direction of the bed and a new series of measurements are made. Sixteen series complete the survey, covering a 150x75 cm area in a 5x5 cm grid. The 496 height data are recorded systematically to enable height and roughness calculations for certain areas of the bed, as required. For instance, the roughness of the furrow bottom and the side slope are interesting from the hydrological point of view, while for seed bed evaluation the elevated part of the bed is particularly relevant.

Roughness calculations have been made on the basis of the standard deviation of 16 height data in the direction of the bed. Otherwise, a perfectly smooth but sloping area would produce high roughness values. As none of the primary tillage methods affect the furrow area, only those height series that include the width of 1.10 m of the bed were used for comparative evaluation of tillage.
Thus, roughness is calculated as the average of 23 standard deviations, each obtained from 16 height data.

5.2.2 Bed Shape And Roughness After Tillage

The average height of the beds, or depth of the furrows, depends on the depth to which the two furrowers have been set. As explained earlier, draft increases rapidly over depth, in particular in the compacted furrow bottom of the traffic zone. The usual cleaning-out operation only removes the rather loose material from the sloping furrow sides, left from planting and weeding or deposited by erosion, and does not work below the initially cultivated plane.
The typical shape after the cropping season was a flattened, rather smooth bed (roughness of 0.70 cm) of a modest height of 8 to 10 cm. Rainfall, handweeding and hand-harvesting all contributed to the consolidation of the bed, so that shape and heigth did not differ much anymore between tillage methods. The height data are plotted in fig. 18.

PRIMARY TILLAGE EFFECTS

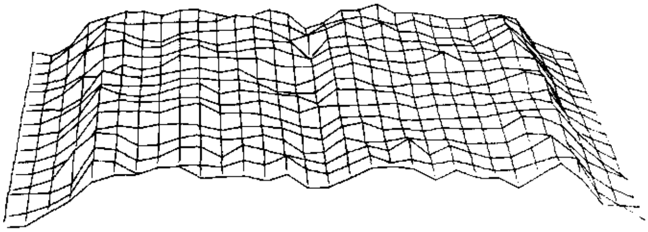


Fig. 18. Typical soil surface profile of BBF-system at the end of the dry season prior to primary tillage. Plotted from 496 height data in a 5x5 cm grid.

In Fig. 19 the soil surface of the T1 tillage method is seen after the passage of the single furrower set to work in the center of the bed. The furrower cuts a 24 cm wide, flat bottom, thereby severing all roots in its path. The adjacent strips on the bed are covered by the semi-inverted soil, while part of it rolls back. The soil surface roughness (based on the 1.10 m wide production zone) equals 1.31 cm.
After dessication of the uprooted plant material, two more passes, each with the opposite plows set subsequently at a wider distance, achieve an almost full undercutting of the soil of the bed (24 cm+2x22 cm+2x22 cm). In particular the edges of the beds, which in all other tillage methods escape agressive tillage are adequately tilled.
Though the T1 tillage method requires three separate passes over the field, weed control was effective and initial weed regrowth was visibly slower. This reduced the necessary number of seed bed operations by one to two, compared to the other tillage methods, depending on the pre-tillage weediness level.

In the T2 tillage method, two slices of the bed, each 22 cm wide, are plowed up and deposited temporarily on the center of the bed. Roughness is higher at 1.70 cm (Fig. 20). Subsequent shallow cultivation, such as needed for seed bed preparation, redistributes the soil over the bed as a first step towards its desired shape.

The T3 treatment shows the least effect as far as soil movement and shape of the bed is concerned (Fig. 21). Only three V-shaped marks, made by the three chisels, can be distinguished: one in the center of the bed, the others at 45 cm distance close to the edge of the beds. A fairly high roughness of 1.49 cm was measured, because this deepest tillage method, be it only in the plant rows, brought up the biggest root clumps compared to the other tillage methods. The following seed bed preparation operations were most difficult in this case, especially in the grassy patches which remained intact between the chisel's path.

The T4 tillage treatment shares with the T3 treatment its non-inverting character. The shape of the bed is little changed, unlike the T1 tillage method (Fig. 22). The full width of the bed is tilled, which resulted in a roughness of 0.99 cm. Where weeds were present, in particular grassy weeds forming a tough mat, penetration caused some problems.

PRIMARY TILLAGE EFFECTS

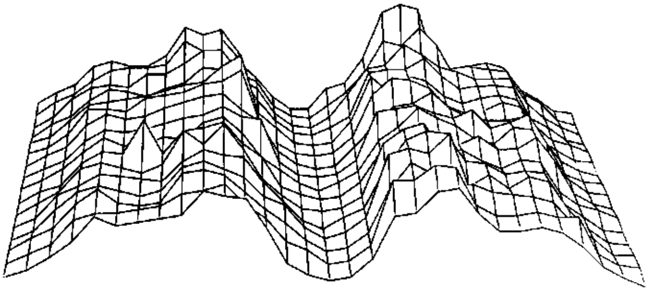


Fig. 19. Soil surface profile of BBF-system after passage of furrower through center of bed, first of three passes of T1 tillage method.

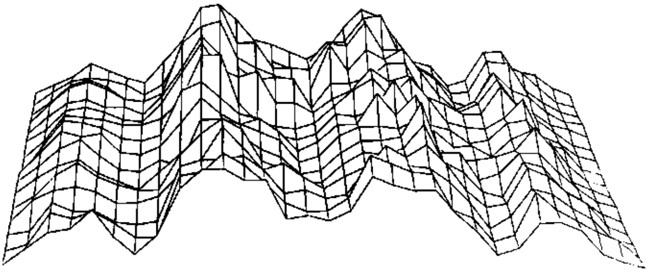


Fig. 20. Soil surface profile of BBF-system after passage of the opposite plows of T2 tillage method.

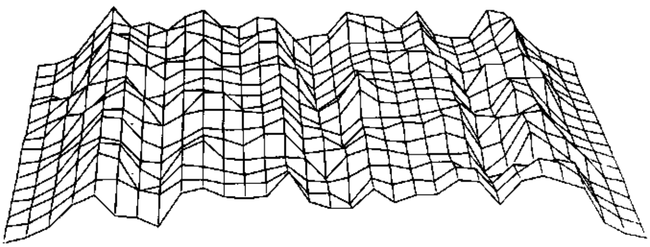


Fig. 21. Soil surface profile of BBF-system after passage of three chisels of T3 tillage method.

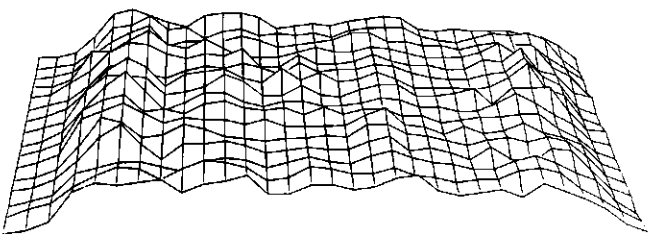


Fig. 22. Soil surface profile of BBF-system after passage of five duckfoot shovels of T4 tillage method.

The visual impression obtained from the plotted height data agrees well with the calculated roughness values. The data apply to the RA-14 field. On the RW-2B field, which tended to form clods, roughness values were slightly higher at 2.19 cm, 1.86 cm, 1.74 cm and 2.00 cm for the T1, T2, T3 and T4 tillage methods, respectively. In both fields, further seed bed preparation operations reduced the roughness levels, especially the initially high levels.

5.2.3 Plow Layer Storage Measurements

In order to measure accurately soil surface upheaval as a result of tillage, part of the RW-2B field was set aside. On either side of the beds of each measuring location, four support pins for the relief meter frame were driven into the soil of the adjacent beds. These provided a permanent and accurate benchmark for the frame, while allowing complete freedom of tillage on the central bed and its adjacent furrows. Previously, surveying techniques were used, but these proved too time-consuming and were a source of error.

Only tillage method T1 and T2 were evaluated. Bulk densities were determined at field capacity, prior to tillage.
The initial bulk density in the 0-5 cm and 5-10 cm layers averaged 1.40 gcm-3 and 1.52 gcm-3 respectively. The average tillage depth with respect to the initial surface level, was 8 cm.
The initial pore space, in terms of length can be calculated as explained in section 5.2.1.

P(0)= ((1-1.40/2.65)x5-(1-1.52/2.65)x3)/2=3.6 cm

This corresponds to a total porosity of 3.6/8=45%.
The tillage method T1 raised the mean level by 2.6 cm, thereby increasing the pore space to 3.6+2.6=6.2 cm, which amounts to an increase in pore space from 45% to 6.2/(8+2.6)=58%.
The T2 tillage method, while working as deep, tills only two strips, resulting in an average mean surface upheaval of 0.7 cm this amounts to a pore space increase from 45% to 50%.

Though not quantified on the tillage experimental fields, the effect of the increased plow layer storage on the infiltration of rainfall was clearly visible during rainfall shortly after plant establishment. Water could be seen collecting on the beds' surface, while on the beds tilled according the T1 method, it was still infiltrating (Fig. 23).
In all probability, more rainfall infiltrates under the T1 tillage method for at least part of the season. The porosity decreases with time, certainly during harvesting under moist conditions. Yet, prior to harvest a difference in bulk density between tillage method T1 and T2 still existed. Core samples were taken in the 2.5-7.5 cm soil layer, beyond the weeding cultivation depth. Bulk densities and pore space were 1.43+0.011 gcm-3 (46% pore space) and 1.52±0.015 gcm-3 (43% pore space) for T1 and T2, respecively.

Fig. 23. Effect of primary tillage on rainfall infiltration in RW-2B before plant emergence. On the left, 8 cm-deep tilled beds (T1); on the right, 2-5 cm shallow cultivated beds (T4).

5.2.4 **Tillage And Runoff Measurements On RW-3C, 1980**

The measured increased plow layer storage in beds cultivated with the 'intensive' tillage method T1 at RW-2B, seemed to be related with the visibly enhanced capacity to intercept and infiltrate more rainfall.
This assumption is supported by the increased yields from the T1 cultivated beds in 1979 on RA-14, and on RW-2B in 1980.

A small field experiment was set up by the Land and Water Management Sub-program in the RW-3-C Alfisol watershed, to evaluate the differences in soil and water conservation aspects between the T1 and T2 tillage method. The beds in RW-3C are layed out at a 0.8% grade.
In an unreplicated trial the T1 and T2 tillage methods were assigned to two adjacent plots, each having the size of four bed widths and 80 m long. The performance of the two tillage methods was evaluated by measuring runoff and soil loss, and by estimating of the plow layer storage at harvest. Evaluation of the agronomic results was restricted to grain yield.
Results are summarised in Tables 2 and 3. Conform the expectation, less runoff was collected from the beds under the T1 tillage method. The total runoff obtained from the measured storms amounted to 16% and 20% for the T1 and T2 method, respectively. The grain yield of the pearl millet crop was for the T1 tillage method 1840 Kg/ha, or 22% higher compared to the T2 treatment. It appeared that the increased plow layer storage due to tillage persisted throughout the season. Bulk density measurements at harvest in the 2-7 cm soil layer (beyond the depth of the by weeding loosened soil) yielded a significantly higher pore space for the T1 (1.48 gcm-3) than the T2 tillage method (1.55 gcm-3).

Table 2. Effect of primary tillage on runoff and soil loss, as measured in RW-3C in 1980.

date		rainfall (mm)	T1 tillage method runoff (mm)	T1 tillage method soil loss (Kg/ha)	T2 tillage method runoff (mm)	T2 tillage method soil loss (Kg/ha)
July	30	23.6	1.1	13	1.2	8
Aug	14	16.4	2.2	5	3.1	6
	19	114.8	22.1	137	27.4	118
	20	72.6	17.2	172	21.8	87
Sept	3	22.5	1.4	3	1.5	4
	6	31.1	4.4	6	5.2	9
	24	14.7	0.3	nr	0.3	nr
total		295.7	48.7	336	60.5	232

nr= not recorded

Table 3. Effect of primary tillage on grain yield and pore space at harvest, on RW-3C in 1980.

treatment	grain yield (Kg/ha)	dry bulk density (gcm-3)
T1	1840	1.48
T2	1500	1.55
SE	±79	±0.019
CV(%)	17	4

5.2.5 Crust Strength

The volume and depth to which the soil is tilled, varies among the tillage treatments. But, more importantly, the soil reaction caused by the different tools is widely different.

Plows or a plowbody type of ridger, are used in the T1 and T2 tillage method. In both cases, the soil is inverted and subjected to shearing forces which tend to pulverise it; only the volume of tilled soil differs. Plant material is buried, exposing a bare soil surface with freshly tilled soil.
The T3 and T4 tillage methods, on the other hand, use non-inverting tools which only break up the soil, with far less lateral displacement and mixing. Little fresh soil is brought to the surface, so that crop residue and weeds continue to provide surface protection against the erosive action of rainfall.

In so far all this would affect soil structure degradation, in terms of aggregate stability, it could possibly be reflected in the tendency to form a soil surface crust (Lal, 1979).
Extensive soil crust measurements were made during the crucial plant establishment period. A pocket penetrometer was used to evaluate the soil resistance in the plant rows. The measurements were part of the stand establishment studies , a more detailed discussion on crusts is given in Chapter 6. Here, only the effect of tillage on crust strength will be given.

Little difference in crust strength occurred due to tillage with varying results, see Table 4.

Table 4. Effect of primary tillage on soil crust strength. Penetration resistance in $kgcm^{-2}$ measured during crop emergence.

Treatment	79-RA-14	79-RW-2B	80-RA-14	80-RW-2B
T1	2.8	2.6	4.2	2.2
T2	2.9	2.7	5.2	1.4
T3	2.8	2.5	5.0	1.2
T4	2.7	2.6	5.0	1.9
SE	±0.16	±0.28	±0.16	±0.24
CV(%)	26	33	14	43

Statistically significant differences in soil crust strength occurred in 1980 on RA-14 and RW-2B at the 1% and 10% probability level, respectively. A comparison between the results of the two fields is not conclusive. Tillage method T1 yields the highest as well as the lowest crust strength. However, the texture of both soils is different, with a higher clay percentage present in RW-2B. In this field, the penetrometer probe frequently registered the resistance of a clod embedded in the soil surface layer. This was particularly so for the T1 treatment, in which the two outer strips of the bed are plowed up. Also in case of the T4 method, the outer edges of the bed are tilled. Apparently, the more compacted soil of the edges produces more clods. The chisel used in the T3 method always worked in the previously made slots, transporting little soil from the uncompacted crop production area and resulting, seemingly, in lower crust strength levels.

The negligible effect of primary tillage on the formation of crusts does not support the hypothesis of differential soil degradation, and no claim can be made of a particular tillage method being superior in this respect. Whatever differences in crust strength may have arisen from primary tillage, these were masked by the ensuing seed bed operations, fertilizer application and planting. These operations cause additional soil disturbance in the plant rows, where the crust were measured.
The effect of tillage on the formation of crusts did not affect plant stands by mechanical impedance to the emerging shoots.
The crust strength levels varied between years, because of the different soil moisture conditions prevailing at the time of emergence when the measurements were made.

5.2.6 Compaction In BBF-system

The permantly located furrows are subject to numerous cycles of compaction, due to the weight of the animals and the tool carrier from season to season. The influence of this compaction over depth and across the beds was estimated in RW-2B, which is free from stones, by measuring soil resistance to a penetrometer. Penetrometers are particularly convenient to evaluate relative changes of a soil profile due to compaction (Freitag, 1968).

A commerciably available, hand-operated, recording soil penetrometer was used to record a continuous force-depth relationship on a reusable chart, up to a depth of 60 cm. It was tried to maintain a constant rate of penetration of approximately 6 cm/s. Soil resistance is expressed in force per unit area. A 60-degree cone with a 1 cm2 base area was used.
For each primary tillage treatment, one bed was surveyed from the center of the furrow to the center of the bed, in 10 cm lateral steps between measurements. Three replicates were made at each interval, from which a smoothed single force-depth relationship curve was obtained. From the eight curves soil resistance values were read at 5 cm depth increments; these were used to plot iso-resistance curves.

The penetrometer was not particularly suitable to detect soil resistance differences due to primary tillage methods. This could be expected, as not one of the tillage treatments exceeded a depth of 8 cm. The zero-setting of the penetrometer could not be controlled sufficiently. The first 3 cm of penetration are subject to inaccuracy resulting from premature sinkage, while also the card drive did not always engage immediately. Therefore, all data of the four tillage methods were grouped for plotting. The obtained soil penetration resistance profile clearly shows the for BBF-systems inherent effect of permanently located different management zones (Fig. 24).

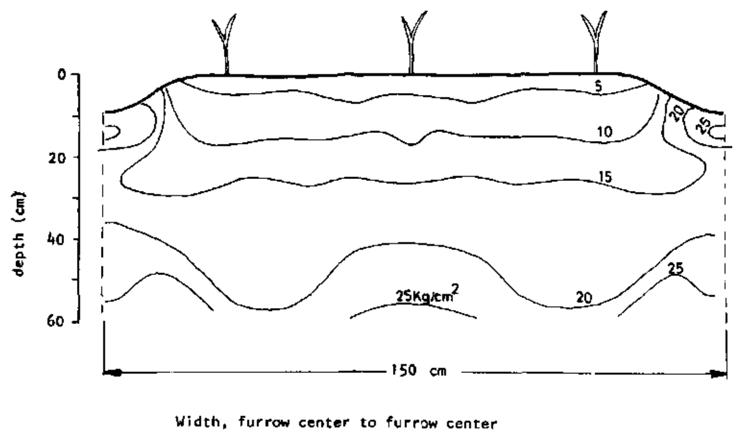


Fig. 24. Soil strength profile of RW-2B at field capacity obtained from penetrometer measurements.

PRIMARY TILLAGE EFFECTS

Traffic compaction is evident up to a depth of 25 to 30 cm. Notable are the two dips in soil resistance underneath the side rows; this phenomenon was also noted in the strength profile taken in the vertisol watershed. In all probability, the increased friability, as indicated by the dips, results from the growth of fibrous rooted crops (Danielson, 1972), which in the history of RW-2B were sorghum and pearl millet, mostly planted in the outer rows.
According to Schlebecker (1977), the early settlers in the USA recognised the 'soil breaking' action of the roots of maize. Charreau and Nicou (1971) reported active root action of millet, maize, sorghum and upland rice, in descending order. Kemper and Derpsch (1981) reported a much more friable soil because of the 'biological' loosening by the root system of cowpeas. This effect can be used to advantage in crop rotations; Willcocks (1980) found that maize and sorghum could benefit from the soil loosening effect achieved by the root system of a previous cowpea crop.

5.3 AGRONOMIC RESULTS

5.3.1 **Primary Tillage Effect On Crop Establishment**

By and large, primary tillage has shown little effect on crop establishment. Generally, seed beds with the least clods seemed to provide the most favourable conditions for a rapid and complete germination and emergence of crops, particularly in the absence of rainfall.
Secondly, the time span between primary tillage and planting played a role in such dry conditions. In 1979 on RW-2B, primary tillage preceded planting by a short two week period, which may have been to short for proper consolidation of the loose, cloddy soil. This is corroborated by the significant effect of 'deep' tillage on the early plant stand of sorghum, in particular on the cloddier side rows, as can be seen in table 5.

Table 5. Effect of primary tillage on crop establishment of sorghum on RW-2B in 1979 (x1000/ha).

	4 days after planting			7 days after planting		
	s	c	a	s	c	a
T1	96	145	120	171	206	189
T2	79	150	115	189	211	200
T3	156	133	144	204	220	212
T4	159	131	145	205	211	208
SE	+12.7	+7.1	+5.6	+7.7	+4.9	+4.6
CV(%)	41	20	17	16	8	18

s=side row, c=center row, a=average ((s+c)/2)

The plant stands in the side (outer) rows both of tillage method T1 and T2 lag significantly behind, the difference cancelling out to a large extent 7 days after planting. Depth of seeding may have played a role, though always care was taken to plant side and center rows equally deep.
Because crusting did not play a role in impeding shoot emergence, the delay in crop establishment in the absence of rain likely resulted from the soil moisture supply to the seed becoming a limiting factor. Evaporation rates

from rough, cloddy and loose soil surfaces (such as resulted from the T1 treatment) are reported higher (Holms et al., 1960; Papendick et al., 1973; Allmaras et al., 1977).
A less intimate seed-soil contact may have contributed further in limiting the moisture supply. These assumptions were not evaluated in the tillage field experiments, but in many instances emerging shoots visibly had to bypass clods, which accounts to some extent for the delay.

In RA-14, which has a sandier texture and less tendency to form clods, lower plant stands were associated with the shallow tillage method T4 (table 6). Instead of the generally observed delay in maximum crop emergence, here stands were already lower 5 days after planting and became significantly lower t 10 days after planting. Apparently, the limited soil moisture supply caused more seedlings to die.
The relative decline in plant stands between day 5 and day 10 was 4.2%, 4.5%, 1.7%, and 8.1% for the T1, T2, T3, and T4 tillage method, respectively (significant at the 10% probability level). These figures suggest an advantage for the chisel treatment, perhaps due to a more rapid downward root growth of seedlings subjected to drought stress.

Table 6. Effect of primary tillage on crop establishment of sorghum on RA-14 in 1979 (x1000/ha).

	4 days after planting			7 days after planting		
	s	c	a	s	c	a
T1	193	173	183	186	162	174
T2	185	182	184	170	179	175
T3	175	184	179	169	184	176
T4	166	162	164	154	153	153
SE	±7.6	±6.6	±5.7	±7.5	±6.9	±5.3
CV(%)	25	22	19	26	24	19

5.3.2 **Primary Tillage And Weediness**

It was expected that a thorough primary tillage operation carried out at the beginning of the rainy season, would result in appreciably lower initial weediness levels.
This would be desirable not only from a crop establishment point of view, but an important additional advantage would be that the first weeding could be delayed. This would relax, somewhat, the timeliness problems of planting and weeding.
The subjective assesment of weed regrowth (estimated visually) soon after primary tillage did indeed show a less quick and vigourous reestablishment of weeds on the beds after soil-inverting tillage. Because the first weediness measurements were made only after crop emergence, a time span ranging from 3 to 8 weeks masked the effects of tillage. The sampling method and procedure is explained in detail in the chapter dealing with weed management.
Once, in the case of a T1 tillage method in which the last plowing operations

were 1 to 2 weeks later, than for the otherwise less thorough tillage treatments, a difference could be detected, be it only at the 10% probability level.
This was in 1980 on RA-14, when the weediness levels of T1 were lower 11 days and 22 days after planting, while later the difference ceased to be statistically significant (Fig. 25).

Weed development late in the season hardly depended on the level of primary tillage. An exception occurred on RW-2B; in 1980 initial weediness levels were virtually the same for all treatments. But here a highly significant difference with the T1 tillage method developed, yielding the highest weediness level (Fig. 25). As crop yields in T1 were among the highest, the difference cannot be explained in terms of stronger weed competition. Apparantly the T1 treatment provided a better growth environment which was beneficial to the weeds.

The little and temporary effect of tillage on initial weediness levels, is problably due to the fact that the differences in depth and volume of tillage were rather modest. The biggest possible contrast is that between T1 with full width, soil-inverting tillage at a depth of 8 cm, and the soil-stirring tillage of T4 at a depth of 2.5-5 cm.

The difference in weediness levels between years have been considerable; on RA-14, the wet year 1978 produced much higher weediness levels than the rainy year 1980. Also for the RW-2B field, enormous differences were noticed.

5.3.3 **Primary Tillage And Crop Yield**

5.3.3.1 **Field RA-14, 1978 -**

The seasonal rainfall from June to October 1978 was 1077 mm, or 56% above average (ICRISAT, 1980). The rainfall was well distributed, with an exceptionally high amount of 273 mm from 13 to 15 August. Not surprisingly, pearl millet did not suffer from drought stress; to the contrary, part of the crop was affected by ergot, a fungal disease (*Claviceps fusiformis* Lov.), which reduced the quality of the grains due to the prolonged humid conditions in the canopy, which lasted until harvest.
Crop yield differences, therefore, are not likely to result from seasonal differences in soil moisture supply, when drainage is taken care of properly. In this respect, it was notable that in all tillage treatments the center row on each bed was taller and gave higher yields than the adjacent side rows. This effect was most pronounced in the T2 tillage method (Fig. 26).
A possible explanation is the flush of Nitrogen mineralisation that occurs with the first rainfall after a prolonged dry period. This phenomenon is discussed by Jones and Wild (1972), who reviewed the work of many authors on factors that play a role in the so-called 'Birch' effect.
In the T2 tillage method, crop residue and weeds are plowed up at the end of a prolonged period and deposited in a concentrated manner on the center of the bed. The subsequently formed, readily leachable nitrate-N may have moved down in the center of the bed before the final bed shaping, in which the soil is redistributed over the width of the bed. This aspect was looked at in 1980 on RA-14.

PRIMARY TILLAGE EFFECTS

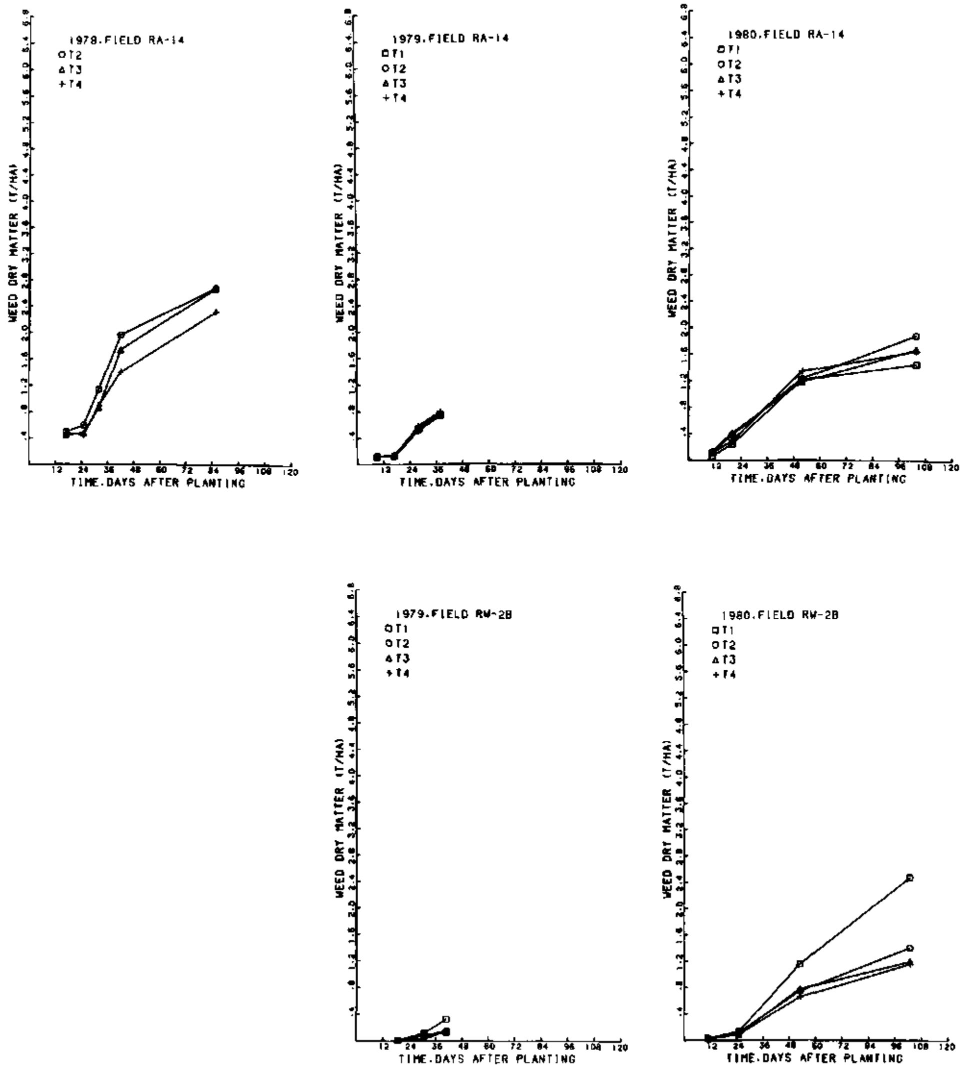


Fig. 25. Primary tillage effect on the growth of weeds in the crops on the two tillage experimental fields in the 1978-80 seasons.

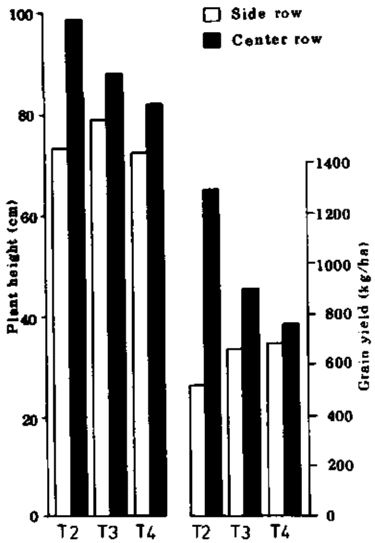


Fig. 26. Primary tillage effect on plant height 39 days after planting, and final pearl millet yields for side and center rows, on RA-14 in 1978.

Talati and Metha (1963) reported higher soil nitrogen mineralisation rates after mouldboard plowing than in fields plowed with the traditional soil-stirring wooden plow.

Taking side and center rows together, the most intensive tillage method T2 (T1 was not yet applied in 1978) had somewhat higher yields, but not significantly so. Pearl millet is reported to respond well to tillage, especially in sandy soils (Etasse, 1977).

5.3.3.2 Field RA-14, 1979 -

In 1979, 630 mm rain fell in the rainy season between 20 June and 1 October, which is marginally short of the normal amount of 690 mm in this period.
Drought periods occurred during the first two weeks after planting. A severe intra-seasonal drought period fell between 26 and 50 days after planting, in which only 6 mm rainfall was received in one shower. The drought stress caused an early senescence of leaves, particularly where weeds were competing for soil moisture. Increasing tillage resulted in correspondingly higher yields, as can be seen in Table 7. The T1 tillage method outyielded the other methods by 300 to 500Kg/ha of sorgum grain. A clearer picture emerges from Fig. 27, where crop yields are related to number of heads at harvest and their average weight. The T4 treatment, with its initally lower stands, had the lowest number of heads but, compared to T3, this was completely compensated by higher individual head weights.

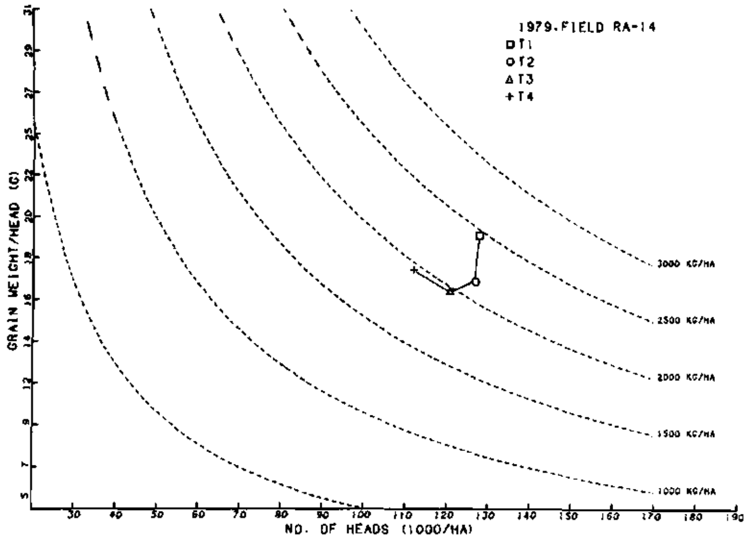


Fig. 27. Effect of primary tillage on sorghum crop yield components, on RA-14 in 1979.

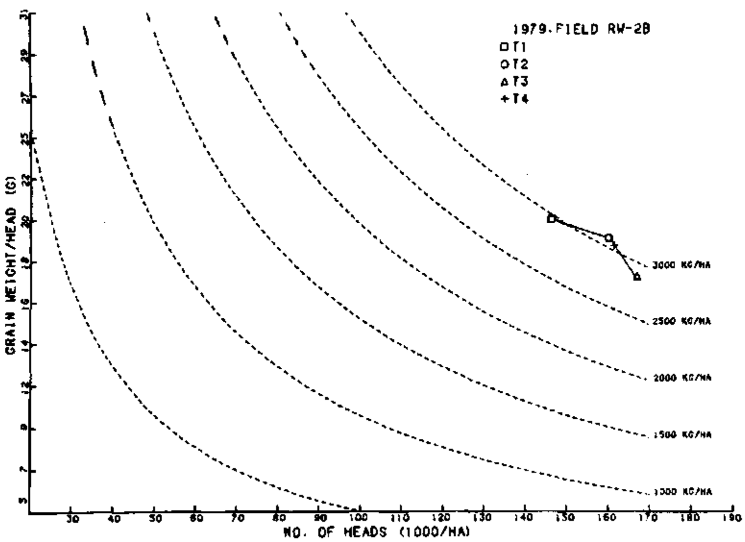


Fig. 28. Effect of primary tillage on sorghum crop yield components, on RW-2B in 1979.

The other two methods, T1 and T2, combine a higher head weight (significant at the 10% level) and a higher population (not significant).
Because there were no significant differences in weed growth among the primary tillage methods, it was assumed that yield responses can be explained to a large extent by treatment differences in the soil moisture availability.

As in the previous year, but much less pronounced, yields were higher from center rows than from side rows, except for the newly introduced T1 tillage method for which the reverse was true. This seemed consistent with the hypothesis that increasing tillage results in higher production of Nitrate-N from buried decomposing crop residue and weeds.
In the case of the T1 treatment, after tillage the tilled soil is concentrated on the edges of the bed , which might explain the increased yield of the side rows.

5.3.3.3 Field RW-2B, 1979 -

In RW-2B the crop was planted three days earlier than in RA-14. The same drought periods were experienced but, contrary to the RA-14 situation, crop yields did not respond to the level of primary tillage. The obtained yields were much higher, around 3000 Kg/ha, for all treatments (Table 7).
Apparently, possible differences due to tillage did not express themselves in differences in crop moisture stress levels.
There are two possible explanations; first hardly any weeds could compete for soil moisture; second, the probability of a soil moisture deficit was much lower in this deeper, more clayey Alfisol.
The numbers of heads at harvest were significantly lower for the T1 tillage method, but these were individually compensated by higher head weights (Fig. 28).

5.3.3.4 Field RA-14, 1980 -

The rainfall received between 1 June and 1 October amounted to 603 mm, which is 90 mm short of the long-term average in this period.
Between planting and harvesting of the crop, a total of 537 mm of rainfall was received in a well distributed pattern. In the absence of serious drougth stress symptoms, the soil moisture supply seemed adequate for a reasonable yield.
Yet, average crop yields were 50% lower compared to those of the previous much dryer season.
No doubt, this was due to a sharp decline in plant stand of a well established crop early in the season. The decline in stands was caused by a shootfly attack (Atherigona soccata). This pest is a considerable problem with sorghum in the seedling stage.
Initial weed growth rates were high, probably because of the reduced competition effect of the thinned crop.

PRIMARY TILLAGE EFFECTS

Crop yields did not differ among the primary tillage treatments, though again yields tended to increase with amount of tillage.
The T3 tillage method resulted in the lowest plant population at harvest and the lowest head weight, but not statistically significant (Fig. 29).

In this season yield differences between side and center rows were not consistent with those observed during the previous years on RA-14. The possible influence of the tillage method on the seasonal Nitrogen flush over the width of the bed was quantified .
Soil samples were taken, prior to primary tillage in June, in the 0-15 cm layer from side and center rows. Four weeks later this sampling was repeated, also in the 15-30 cm soil layer.
The results of the analysis for the amount of Nitrate-N are given in Table 8. There were no significant differences prior to tillage, nor between tillage treatments nor between row locations. The tendency of the amount of Nitrogen to decline after the first rains was reported earlier (ICRISAT, 1978). Other suggestions are difficult to make; the average amounts of Nitrogen lost under the T2 and T3 method are significantly higher, than for the T1 and T4 treatment. Whether or not this resulted from a higher production of readily leachable Nitrate-N is impossible to conclude, since the amounts in the deeper layer were not known before tillage.

Table 8. Analysis for Nitrate-N (ppm) on RA-14 in 1980.

	2 June			30 June					
	0-15cm			0-15cm			15-30cm		
	s	c	a	s	c	a	s	c	a
T1	6.9	6.2	6.6	4.6	6.7	5.7	4.6	2.4	3.5
T2	6.3	7.6	6.9	4.2	4.6	4.4	3.6	2.6	3.1
T3	6.2	7.9	7.1	4.5	4.6	4.3	4.4	2.1	3.2
T4	5.5	5.4	5.4	6.1	5.4	5.7	3.4	4.8	3.7
SE	+1.57	+1.44		+0.52	+0.59		+0.71	+0.49	
CV(%)	71	60		30	31		55	47	

5.3.3.5 Field RW-2B, 1980 -

The rainfall pattern was very much the same as on RA-14, the crop was planted 4 days earlier.
Also on RW-2B, plant populations suffered a considerable set back due to a shootfly attack.

Compared to the previous season, weeds developed at a much higher rate, in particular for the T1 tillage method.

Crop yields did not differ significantly, though the T3 tillage treatment had appreciably lower yields, with the lowest sorgum head weight at harvest significant at the 1% probability level (Fig. 30).
Plant stands at harvest were significantly different at the 10% level.
Apparently the T1 tillage method provided the best growing conditions over the

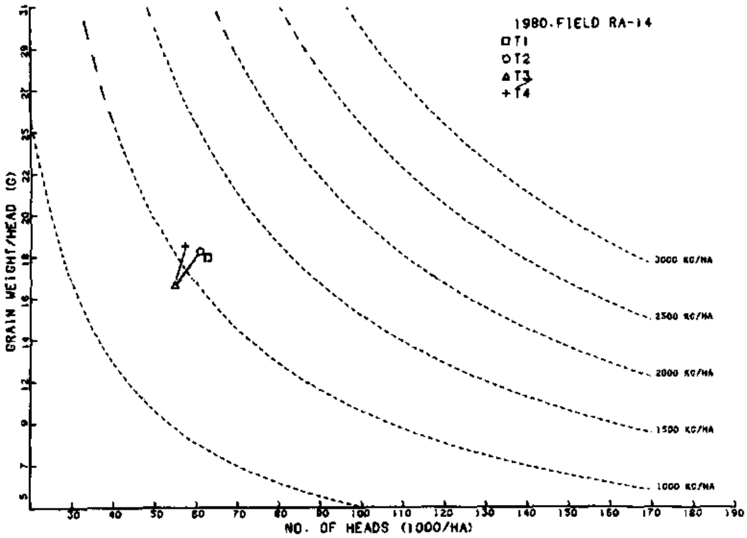


Fig. 29 Effect of primary tillage on sorghum crop yield components, on RA-14 in 1980

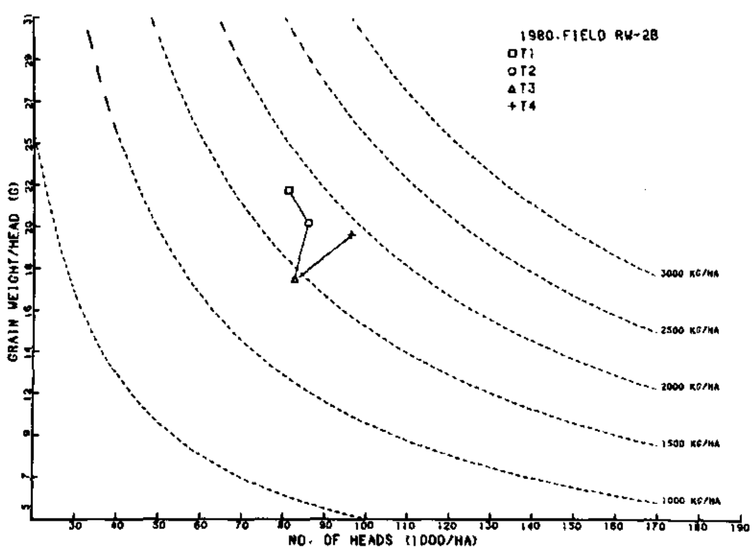


Fig. 30 Effect of primary tillage on sorghum crop yield components, on RW-2B in 1980.

season as the combined yield of sorghum grain and weeds were significantly higher.

Table 7. Effect of primary tillage on crop grain yield (kg/ha) of pearl millet in 1978, and sorghum in 1979 and 1980.

		RA-14 1978	RA-14 1979	RA-14 1980	RW-2B 1979	RW-2B 1980
	s	n.i.	2550	1190	3200	1695
T1	c	n.i.	2390	1020	2735	1900
	a	n.i.	2460	1135	2970	1800
	s	555	2025	1205	3155	2140
T2	c	1300	2360	940	2140	1375
	a	800	2140	1120	3080	1755
	s	660	1850	1070	3090	1670
T3	c	895	2215	590	2660	1230
	a	740	1970	915	2875	1450
	s	680	1935	1110	3260	2210
T4	c	770	2000	985	2820	1625
	a	710	1955	1065	3040	1915
	s	±66	±112	±153	±138	±183
SE	c	±235	±146	±156	±161	±175
	a	±92	±90	±116	±111	±120
	s	44	32	73	17	37
CV	c	101	38	97	22	44
(%)	s	52	25	60	14	27

s= side row
c= center row
a= average from 2s+1c rows(RA-14, 1978,1980)
a= average from s+c rows(rest)
n.i.= tillage treatment not included

5.4 DISCUSSION

The judgment on the different tillage methods obviously will rest on input considerations such as labour, power and equipment use, and ultimately on the effectuated crop yields.
Furthermore, there is the question to which degree the resource conservation was succesfull.

PRIMARY TILLAGE EFFECTS

Three years of experimentation on two fields provide a data set and experience on which to base such an evaluation of the range of tillage options tested for the BBF-system of cultivation.
In 1978 the tillage field experiment was started on RA-14, initially considering three tillage methods. Because of the tendency of crop yields to increase with amount of tillage, the experiments were repeated in 1979 on RA-14 and RW-2B, and the T1 method of tillage, the most intensive form of tillage, was also included.
Sorghum CSH-6 was the only crop used, because plant population differences, which can have a considerable effect, can be assessed easier in this non-tillering crop.
Moreover, it would facilitate comparing the effects of tillage between seasons and locations.

It is realised that conclusions, or even suggestions, as to which circumstances in a chain of environmental events led to differences in crop performance over the seasons, are difficult to make because each location and each season has its unique history of kind, duration and level of environmental stress acting upon the crop. The effects arising from the stress history are in some way integrated by the growing crop and may or may not be related to treatment differences.
In so far crop yields differed among the tillage methods, the yield responses are most easily explained in terms of stress limitations.

Naturally, a variety of environmental stress factors may become operative with many interactions between them; the soil moisture supply, nutrient supply, heat and light are important in this respect.

Limitations in crop performance due to moisture deficit is an important consideration in semi-arid rainfed cropping.
Primary tillage was expected to increase and stabilize crop production by relaxing the soil moisture stress limitations, directly by increasing the rainfall infiltration and indirectly by preventing its use by weeds. In Fig. 31, tillage-crop yield effects for both fields and both years are plotted in terms of crop yield and plant population at harvest.
Two strong effects on yields are at once noticable: a location effect and a plant population effect. The yield differences between tillage methods, years and locations are put into perspective with the help of the dotted curve. This curve is fitted through data points obtained from weedfree plots.
As such, the curve can be interpreted as a ceiling for yields, for which stress levels were minimal, in particular drought stress resulting from competing weeds in dry years.
In 1979 on RW-2B, yields between tillage methods hardly differed, all yields were very close to the ceiling. In contrast, on RA-14 in the same year yield levels were appreciably lower than the ceiling and a substantial and statistically significant tillage effect occurred. Apparently, soil moisture stress limited yields only on RA-14, with the crop responding well to the increased tillage, particularly for the T1 tillage method from which enhanced infiltration was expected. This assumption is corroborated by the fact that the weediness levels were much higher on RA-14 than on RW-2B, and were independent of primary tillage.
A similar, but reverse picture is seen in 1980. Yield data of RA-14 were lowest, but close to the ceiling, while on RW-2B a more diverse yield pattern existed below the ceiling. On RA-14 soil moisture stress did not play a major

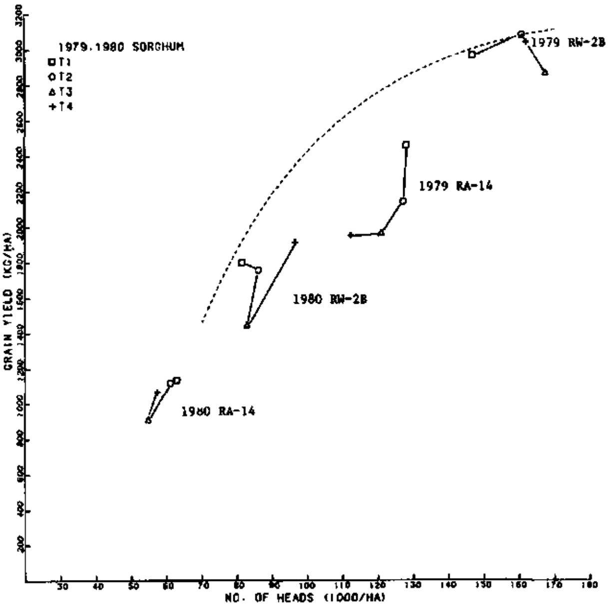


Fig. 31. Effect of primary tillage on plant stand at harvest, and sorghum yield from the two experimental fields in 1979 and 1980. The dotted line is fitted through data points of weedfree plots and represents the yield ceiling for relatively moisture-stress-free conditions.

role, so the extra amount of rainfall expected to infiltrate under the T1 method did not result in a yield increase.
On RW-2b yield differences were greater, certainly if the much larger weed growth on the T1 beds later in the season is taken into consideration. The crux of the matter is that, when there is little rainfall to conserve, differences between tillage treatments cannot be explained in terms of the enhanced rainfall infiltration mechanism. Two extreme situations can be visualised in which enhanced potential soil water conservation does not increase yields: one concerns a season with a prolonged drougth, the other is a season with a plentifull supply of well distributed rain.
Only in intermediate situations, tillage effects can be expected to bring about substantial crop yield increases, because of the improved soil water conservation capacity.

The tillage effect on the development of weeds was small. The T1 tillage method seemed to provide the most favourable conditions early in the season. This aspect is important because it gives crops an opportunity to obtain a head start over the weeds.
The significantly higher weed biomass developed later in the season in 1980 on RW-2B must not be seen as a disclaimer of this treatment. Rather, this fact works in support of the T1 method which apparently led to superior growing conditions and must be seen in the light of insufficient weeding measures.

PRIMARY TILLAGE EFFECTS

Crop yield was strongly dependent on plant population, even at the fairly high population levels.
Crop emergence differences due to tillage were small and were significant only once; the differences tended to narrow down with the progress of the season. In a few cases, small stand differences at harvest led to different crop yields between tillage methods.
The consistently lowest performance of the T3 tillage method can not be explained. The average individual head weight was the lowest in all cases, but this cannot be explained in terms of inferior weed control or plant population levels.

There was no evidence to support the view that more intensive, deeper tillage deteriorates the soil structure of the crop production zone. A likely explanation is that all tillage methods were essentially reduced-tillage methods, in which tillage depth did not exceed 8 cm, and this only for the crop production part of the zonal tillage system. Furthermore, no powered rotating tools with an aggresive action were used. In addition, tillage was followed quickly by complete soil cover by the crop, which is essential for preventing soil aggregates to break down under the impact of rain.

Increasing the amount of primary tillage enhanced infiltration in the crop production zone. The soil parameters micro-relief, or roughness, and plow layer storage, which affect the cumulative infiltration, were measured.
Higher soil roughness values indicate an increased water detention capability of the soil surface. Since seedbed preparation operations and rainfall decreased roughness levels, canceling tillage differences, the effect can have played a role only during the early season. But soil structural changes, as measured by shearvane and core sampling, indicated that tillage increased the total pore space, lasting all season. Apparently, increasing the plow layer storage by increasing depth and volume of tillage, enhanced rainfall infiltration during the whole season.
However, runoff rates measured for the T1 and T2 tillage method were still high. This is due to the fact that the drainage capability of the BBF-system is independent of primary tillage. The compaction profile (Figs. 15, 22) shows the increased compaction under the furrows. Arndt (1966) measured strongly reduced infiltration rates in the traffic zone of a clay loam, up to six-fold.

Runoff may be desirable in case of a limited moisture holding capacity and when runoff can be stored for future use to overcome drought periods. If runoff cannot be used or when in-situ storage is usefull, infiltration in furrows can be improved greatly by incorporation of straw, as reported by Aarstad and Miller (1981) for a sandy loam.

As far as input is concerned, energy and time requirements appear to differ widely. For the T4 tillage method, the lowest energy level needed is 7.7 MJ in one pass, while for the T1 treatment, 28.2 MJ/ha is expended in three separate passes. However, the initially higher energy and time requirements are fully compensated, because at least two fewer passes were required to arrive at the same low weediness level of the seed bed under fairly high pre-tillage weediness levels.
The soil-inverting tillage methods T1 and T2 were operationally most easy to perform, as blockage of the implements hardly ever occurred. Plant material was plowed under evenly over the field, while road sides and grassy waterways

bordering the fields remained free from trash, which occasionally collected in front of and between the shanks with the T4 method.

5.5 CONCLUSIONS

Yield increases are associated with increases of the plow layer storage. More rainfall infiltrated which is potentially beneficial under conditions of limited supply of soil moisture to the crop and thus contributes to stabilizing crop yields.
The T1 tillage method performed best in this respect and led to higher yields. The increase of the plow layer storage persisted over at least the growing season.
The T3 tillage method had the lowest yields.
There was no evidence supporting the hypothesis that increasing the level of tillage increases the rate of soil degradation, evaluated in terms of the tendency to crust. No doubt this was due to the fact that, in the range of tillage levels, even the T1 tillage method must still be regarded as minimal. This is also the reason why primary tillage hardly effected the weediness levels.
Although tillage method T1 required three passes, seedbed preparation was much easier, especially with increasing pre-sowing weediness levels.
Crop yields were strongly related with plant stands but, when stand differences due to tillage occurred, lower stands were to a large extent compensated by higher individual head weights, except for the T3 tillage method.

CHAPTER 6

WEED CONTROL

6.1 EFFECTS OF WEEDS

6.1.1 Weeds And Crop Production

The adverse effects that weeds have on crop production can be grouped broadly into two categories: yield reductions and direct costs.
The main adverse effect is that crop yields are likely to be reduced, depending on the degree of weed competition for water, nutrients and light. In addition, the net profit of crop production will be influenced negatively by the extra costs due to the interference by weeds. Mechanical harvesting operations may be hampered, much more bulk has to be handled requiring more energy and time. In combine harvesting operations, separation will be less efficient and quality of the produce impaired (Burnside, 1970). The decaying of unripe weed seeds may spoil the stored produce and seed stocks may be contaminated by weed seeds (Muzik, 1970).
In case of handharvesting, there is increased drudgery. Some weed species cause physical discomfort, ranging from irritation and burning sensation of the exposed skin, up to inflammation and infectious wounds (Holm, 1971).
Furthermore, when weeds are allowed to shed their seeds, harmful effects are to be expected in the production of future crops. Also, weeds can act as host for insects and fungi to survive between crops (Muzik, 1970). In the worst possible case, weeds may render land useless for crop production altogether; in India, 'Kans' grass (*Saccharum spontaneum*) forced farmers to abandon parcels of land (Arakeri *et al.*, 1962).

6.1.2 Potential Crop Yield Losses From Weed Competition

The magnitude of problems that weeds can cause was put into perspective by Furtick (1967), who compared for the USA annual crop losses due to weeds, insects and diseases, and cost of control. Weeds were found the number one cause for crop yield losses.
In India, potential crop losses as a result of weeds in food crops grown in the rainy season, are estimated at 36% (Gupta and Lambda, 1978). Because farmers practise some form of weed control, they give a more conservative estimate of actual losses of 10%.
But with the introduction of improved management techniques and varieties, crop yield losses from weed competition can be substantially larger. Burnside

and Wicks (1967) reported sorghum yield losses of 62% when weed control measures were omitted in dryland sorghum in the USA. Wiese et al. (1964) found yield losses caused by uncontrolled weeds of 8% to 40% also in dryland sorghum.
In India, 37% and 48% reductions in yield of sorghum and millet, respectively, were found in Hyderabad and Sholapur (Krishnamoorthy et al., 1974), whereas at the ICRISAT center yields of sorghum and millet were reduced by 70% (ICRISAT, 1976).

To what extent and by which mechanism weed competition may affect crop yield, depends on many interrelated factors.
In semi-arid regions, competition for water may be a critical factor in limiting crop yields. Davis et al. (1968) investigated the root moisture extraction profile of various weeds and sorghum. Some weeds were capable of an enormous lateral root spread, up to 14 feet, thereby drawing water from 44 cubic feet of soil compared to 36 cubic feet in the case of sorghum.
Phillips (1970) found that, in a sorghum crop growing under limiting soil moisture conditions, 1 weed per 61 cm row caused a yield reduction of 40%; increasing the weed population to one in every 30 cm of row decreased sorghum grain yield further to 50%. In one case , where the crop suffered from extreme drought conditions, grain production was prevented altogether.
According to Jordan and Shaner (1979), weed competition for plant nutrients is a major reason for crop yield losses in semi-arid environments. The competitive ability of some weeds in this respect was summarised by Gupta and Lambda (1978), who found appreciably higher contents of nitrogen, potassium and phosphorus in weeds than in crops. Competition for light can have a pronounced effect on the crop-weed balance. When conditions are favourable for early vigorous crop growth, the competitive advantage shifts to the crop, not only because more roots will increasingly enable the crop to compete succesfully for nutrients and water, but above all because the increased foliar canopy shades out the weeds.
Shading per se, reducing weed growth without the concommitant competition for nutrients and water, was quantified by the Agronomy and Weed Science Sub-program at ICRISAT. Seedlings of the four major weeds Cyperus rotundus, Digitaria ciliaris, Acanthospermum and Celosia argenta, were subjected to various levels of shading by using horizontal screens reducing the light transmission to 40%, 20% and 10% of the 1300 einstein/sqm/sec available.
All seedlings were sensitive to shading and the reduction in dry matter foliar production was considerable, though levelling off for all species at the 10% intensity, except for the very shade-sensitive Cyperus rotundus (ICRISAT, 1981).

6.1.3 Critical Competition Period

It is a well established fact that, in the crop-weed competition struggle, crops are particularly vulnerable during their early life. The time and duration of the period in which the crop is likely to suffer maximum damage, seems crop- and weed-specific.
Obviously, weather conditions determine which competition elements become operative, and to what degree. Nevertheless, a general picture emerges. Kasasian (1971) stated that, if a crop suffers competition from weeds in the first quarter of its life, crop yield reduction results. On the other hand,

if in this period the crop has been tended well, subsequent weed growth is unlikely to affect crop yields.
According to Muzik (1970), competition effects are most seriously felt within the first 6 to 8 weeks of the crops life. Parker et al. (1977) concluded from literature on worldwide experiments, that a critical time period exists, generally falling between 2 to 6 weeks after planting.
Furtick (1970) derived from many studies that the time of maximum competition falls some 3 to 4 weeks after planting.
As far as typical SAT crops are concerned, Burnside and Wicks (1967) reported that for dryland sorghum the first 4 weeks are particularly critical. When weeding was done at bi-weekly intervals but discontinued at 0, 2, 4, 6, and 8 weeks after planting, sorghum yields were reduced by 62%, 31%, 3%, 5%, and 2%, respectively. Krishnamoorthy et al. (1974) mentioned a case of pearl millet, for which delaying weeding by 10, or 20 days after planting caused a modest drop in yield from 1417 to 1379 kg/ha, but a further delay to 30 days reduced the yield sharply to a mere 538 kg/ha.
At the ICRISAT center, the highest crop yields of sorghum and millet were obtained when the crops were kept weed-free for the first 6 to 7 weeks. If in this period weeds were allowed to grow, each additional weed-free week from sowing yielded approximately 170 kg/ha more produce (ICRISAT, 1976).
Thus, there is a rather short period, almost immediately following sowing, in which weeds deploy their greatest damaging potential. This situation demands counter measures to be taken early, which presents a major obstacle in traditional crop production systems operating on low input levels.

6.1.4 Traditional Farmers Attitude

The onset of the monsoon is the beginning of a rather short period in which land preparation, planting, thinning and weeding have to be completed. The hope and expectations of the farmer are reflected in the allocation of his resources. For the sake of security, preference is given to food crops and, until those are established, operations for cash crops are delayed. Usually, late planting lowers the potential yield of cash crops and when attention is turned belatedly to food crops, these may be found in rather weedy conditions (Parker, 1974).
Druiff and Kerkhoven (1970) surveyed weeding practices of tenants in Eastern Kenya in an irrigated cotton scheme. They did not find much difference in total weeding effort, averaging some 28 mandays per acre spent on hand weeding. Yet, a striking difference in crop yield and weediness was noted. Farmers who initiated weeding early, obtained yields of 2400 lbs/acre. However, many farmers started their weeding much to late or in plots already infested beyond hope, resulting in dismally reduced yields down to 170 lbs/acre.
These were a few examples of African agriculture, where manual labour is still predominant for tillage and weeding (Herblot, 1974). In the semi-arid peninsular India, quite another picture emerges from a study of the economics of weed control practices. Much of the following is drawn from a study across locations in semi-arid India, done by the Economics Program (ICRISAT, 1977).
Contrary to the conclusions of Druiff and Kerkhoven (1970), one of the conclusions is that farmers act in a very rational way. The higher the crop value and the more vigorous the early weed growth, the more timely and intensive weed control activities become.

WEED CONTROL

The timing and frequency of weed-control activities in sorghum intercrop mixtures was such that on more than 85% of the farms, weeding was initiated 26 or more days after sowing. Weed control was carried out one time or two times on 65% and 35% of the farms, respectively.

Handweeding is traditionally done by females, mainly in cash crops, with a high proportion of the work done by hired females. In the Mahbubnagar area, which is agroclimatologically comparable to the Hyderabad area, dry crops are grown on red soils of shallow to medium depth. For inter-cultivation, a typical Indian blade harrow or 'Guntaka' is commonly used. Farmers also operate with two to three narrow-blade harrow-type implements, especially made for inter-row cultivation. In that case, two to three persons are required to guide individually the implements tied to the yoke of the pair of bullocks.

Thus, inter-row cultivation can be carried out with little investment in time, which is crucial for timely weeding. A field capacity of 0.1 ha/hr is easily achieved (Gupta and Lambda, 1978). The multiple-row blade harrow can work even faster.

The straight blade of the blade harrow makes it a very effective tool, since the weeds can not escape by lateral yielding, as sometimes happens when V-shaped hoes are used. At the same time, especially this property drops the efficiency when increasing weed loads necessitate frequent stops to turn over the implement and remove caught and trailing weeds. Krantz and Shetty (1977) reported that noxious weeds, as Cyperus and Cynodon, cannot be controlled by blade harrows.

6.2 IMPROVED RESOURCE BASE AND WEED CONTROL

6.2.1 Role Of Chemical Weed Control

In low input situations, the absolute losses due to weeds remain limited. This changes when improved soil management techniques and synthetic fertilizers are used. The latter, in particular, boost biomass production of crops and weeds alike. The competitive abilities of weeds will be enhanced and weeds will grow even more vigorously (Furtick, 1970). At the ICRISAT center, for instance, the amount of weeds found after harvesting sorghum were more than twice that on neighbouring fields where fertilizers were not used in this crop (Krantz et al., undated).

So, when fertilizer use does not go hand in hand with adequate weed control measures, the expected yield improvement will not be attained; even worse, fertilizer use in developing countries has often caused yield reduction due to the tremendous response of weeds (Furtick, 1967). Krishnamoorthy et al. (1974) also recognised that farmers may not gain anything at all from using fertilizers, if additional precautionary measures are not taken.

If the potential yield increases as a result of fertilizers are to be achieved, it is crucial that adequate measures be taken to check weed growth. This can be achieved by a combined application of chemical, cultural, mechanical and biological weed control principles. Apart from chemical weed control, these are somewhat loosely defined broad categories. Chemical weed control has great potential but its use in developing countries is questionable under many circumstances. This may be illustrated by a field experiment conducted in India. The experiment was designed to compare the relative costs of three alternative weed control systems for several typical food crops on farmer's fields in the Maharasthra State in peninsular India

(ICRISAT, 1978). The same level of weed control was achieved using:

- human and animal power only
- partial herbicide use and animal power
- herbicides only

Even partial herbicide use proved 2 to 4 times costlier than weed control with traditional means. This should not be surprising at the existing low wage rates. The average opportunity costs of female labour is slightly more than half of that of male labour at RS. 1.20 per day (approximately $ 0.15), (ICRISAT, 1980).
Only when existing wage rates of human and animal power would increase by 50%, partial herbicide use could become an economically viable proposition.
Concern is expressed that herbicide research and technology in semi-arid India has a great labour-displacing potential. It is feared that this could 'adversily affect the income earning opportunities of one of the most disadvantaged socio-economic groups, namely female labourers and in particular hired females from the landless and small farmers households'.
In this context, Miller and Burrill (1980) speak of a major dilemma for agriculture in developing countries evoked by modern weed control techniques. On the one hand, there is the advantage of a potentially considerable production increase through the relaxation of labour peaks and better control of noxious weeds. On the other hand, if land is scarce and labour abundant as is often the case, a labour displacement effect is to be expected, which not only hits landless labourers but also small farmers hiring out their labour. The authors conclude that weed control techniques should be tailored carefully to suit the local, physical and socio-economic environment, and this may not necessarily involve the use of herbicides.

6.2.2 Cultural Weed Control Aspects

Cultural weed control measures include the use of clean seed, the practice of crop rotation and the principles of crop competition. Whereas the first two measures have a long run impact on the general level of weediness and its nature, the mechanism of crop competition is relevant for the succes of a particular crop in a particular season.
Various measures can tip the scale of the crop-weed balance in favour of the crop. Row arrangement and crop density are important, relatively easily manageable factors. Generally, higher crop yields and reduced weed growth resulted from higher crop populations (ICRISAT, 1977; 1978; 1980; 1981). Similar and sometimes enhanced advantages result when intercropping provides an earlier and longer lasting canopy (Rao and Shetty, 1977).
The desirable degree of control over aspects such as row pattern and population level of different crops and combinations of crops, cannot be attained with traditional methods and tools. The introduction of improved planting equipment has greatly contributed to achieving target populations for a variety of crops.
A practice such as band application of fertilizers ensures a minimal area that can be used by weeds, thereby contributing to the crop gaining an early competitive advantage over the weeds. Through timing of fertilizer application, an unfavourable crop-weed balance can be restored in favour of the crop. Ennis et al. (1963) reported how early application of phosphates

stimulated Barnyard grass (Echinochloa crus-galli (L.)), other grassy weeds and broadleaved weeds. Rice yields were doubled by delaying application of phosphates, and also of nitrogen, until after the heading of Barnyard grass, because of a considerably reduced weed competition.

6.2.3 Physical Weed Control Aspects

When chemical weed control is excluded, only physical means of controlling weeds remain. Only mechanical weeding or inter-row cultivation and manual weeding will be considered here (burning, flooding or grazing by animals being other ways of physical weed control).
The use of a sickle for handweeding is a widely spread practice in India, with fairly high but constant labour requirements of 24-28 women days/ha for traditional dryland crops (ICRISAT, 1977), and 25 and 20 woman days/ha in rice and groundnut, respectively, asuming an effective 6 hour working day (Singh et al., 1978). In West Africa, upland rice requires 28 mandays/ha per weeding (Curfs, 1976). There is no doubt that hand weeding can be very succesfull if executed timely and repeatedly, but its tremendous labour requirements may still pose a bottleneck (Fig. 32). In this context, Pothecary (1970) points out the danger of overdependence on hired labour for weeding.
A judicious mix of mechanical inter-row weeding and hand weeding seems to have great potential in relaxing labour peak demands, while still maintaining an acceptable level of control.

Fig. 32. Handweeding involves high labour requirements especially when delayed.

WEED CONTROL

It must be realised that the basic weakness of a system fully dependent on inter-row cultivation, is the fact that a band of soil centered in the crop row cannot be cultivated. The proportional area of the remaining strip depends on the toolsetting and the row distance of the crop according to:

untouched area= (1-(w-2xs)/w)x100 (% of total area)

where w= row distance
s= the minimum distance of the tool edge to the crop row

Even when crop rows can be approached very closely, an area remains untouched by the weeding tool. This area can be quite substantial as the crop rows are planted narrower. Koch (1959) used a 12 cm wide hoe in 18 cm spaced wheat, leaving 33 % of the total area out of the tool path. In sugarbeets the possibility of getting within 1 inch of the seedlings is claimed under optimum conditions of straight rows and flat land (NN, 1960), which amounts to a 10% untouched area at the current row spacing.
In ridged cultivation systems for tropical crops, ridgers have been used succesfully for weeding in standing crops (Wevers and Kuipers, 1976), and may even replace one in-the-row handweeding (Nicou, 1981).
However, with ridgers a rather wide top of the ridge remains unscathed. Hechelmann and Boettcher (1962) reported a 10 cm wide strip on top of potato ridges, even when using furrowers with adjustable wings.
The fact that part of the area escapes the direct action of the weeding tools, does not necessarily mean that weed growth continues unchecked. Extensive research on mechanical weed control for wheat in Germany during the sixties may illustrate this.
In Germany, the usual tools and sequence for spring-sown wheat were pre-emergence 'blind' harrowing, harrowing after the 3rd leaf stage, and hoeing in later stages. Habel (1957) found that weed seedlings were killed by harrowing, not so much because the seedlings were pulled out and left to dessicate, but mainly by covering them with a loose layer of soil. The degree of succes in killing weeds by covering them depended on species and size of its seed, with the highest percentage killed when seedlings were not grown beyond the cotyledonuous stage. Too early blind harrowing stimulated too many weed seeds to germinate and develop, before the crop had grown to the stage where a next harrowing could be tolerated. This had a negative effect on weed control. Generally, not more than a 2 cm thick layer of loose soil was generated by harrowing. Koch (1959) confirmed these results and stressed the importance of timely harrowing in the standing wheat crop. Increasing the forward speed while harrowing had a positive effect on its efficiency, because it generates more loose soil, especially in light soils. In later stages, the harrow becomes increasingly less effective because the weeds are higher and, because of compaction, less material for coverage is available. Then, in the next stage of weed control, hoeing replaces harrowing. Also in this case the majority of the weed seedlings are killed by soil coverage, increasingly so as the hoeing depth increases towards the optimum working depth of 2-4 cm. Later, as the weeds grow taller, the cutting and uprooting action predominates. Thus, hoeing is effective for both small and taller seedlings and, therefore, less time critical than harrowing (Koch, 1964).
Usually, the wheat rows were spaced at 18 cm and 12 cm wide hoes were used, running at an optimum speed of 2.5-3 km/hr (Rademacher, 1962).
A recently renewed interest in mechanical weed control led to the development of a 'hybrid' weeding tool, combining characteristics of a hoe and a ridger

for more effective intra-weed control. Terpstra and Kouwenhoven (1981) studied this tool in a model experiment, using an indicator crop as a weed. The quantity and distribution of the soil thrown alongside the tool path was such that most of the 'weeds' were killed by coverage. The tool is expected to work satisfactory at row spacings up to 50% wider than the tool.

6.2.4 BBF-system And Weed Control

In Alfisols, the fields are accessible within 24 hours after even heavy rainfall, because the upper layer of the beds drain quickly and evenly. Because compaction does not occur on the beds, knives and shares of weeding equipment run through a friable top layer, thereby reducing the danger of breaking up larger soil segments which may damage the crop seedlings.
The tool carrier itself provides a clearance of 75 cm, from which the height of the beds of the BBF-system must be subtracted, because the toolcarrier straddles all the crop rows on the bed.
If necessary, the weeding equipment can be mounted in two banks, one in front on the main rear mounted toolbar, the other in a row behind it. For this purpose, L-shaped extentions or additional rectangular frames are clamped to the main toolbar to receive the second row of shanks. The shanks can be adjusted laterally to accomodate different row widths and size of implements.
The longitudinal spacing permits overlapping of the implements and easy passage of trash and weeds, thereby keeping blockage to a minimum.
A steerable toolbar is optional, but is hardly worthwhile in a bed system with inherently parallel rows.
The shanks of the shovels and duckfeet can be adjusted individually for depth to accomodate the bed shape. The angle of penetration can be altered by adjusting the pitch of the beam.
Only fixed tools such as sweeps, duckfeet, tines and ridgers, were used; rotary ground-driven type of implements generally require, for optimum effectivity, higher forward speeds than can be expected from draft animals. Typical speeds for rotary hoes range between 8-17 km/hr (Krause and Lorenz, 1979). However, Ogborn (1979) developed a single-row, animal-drawn rotary hoe for ridge cultivation systems, which is simple to manufacture and seemed to work satisfactorily, provided the soil was dry and sandy.
In the BBF-system of cultivation, weeding is performed swiftly because of the effective width of 1.5 m. When only one pair of bullocks is used, 1.8 ha can be weeded easily per working day of 6 hours.
In tall crops, such as millet and sorghum, inter-row cultivation can be carried out in the first five weeks only.
Generally, the traffic paths are relatively free from weeds because of the agressive action of the furrowers; in addition, compaction further discourages weed growth.

6.3 MATERIALS AND METHODS

The objective of the weed management part of the experiments was to provide data and experience necessary to evaluate the degree of succes of different weeding methods. Basically, input-output relations are sought; input in terms of frequency, timing and use of labour and equipment, output in terms of resulting effects on crop and weed growth.

Various ways of assessing the amounts of weeds are available: by number, height, age, weight, percentage of ground cover, or a combination of these (Druiff and Kerkhoven, 1970).

Throughout the experiments weed samples were taken by cutting and removing the top growth of the weeds from 0.5 square meter areas, demarcated by square frames. The collected material was put into muslin bags and dried for 24 hrs in a bin by forced circulation of air of approximately 60 degree Celsius. Weed yield was expressed in kg/ha of dry weight produced.

In all years the frames were placed identically on the beds, with one side parallel to the crop rows to include two crop rows. As a consequence, crop rows were overrepresented, because each frame included approximately 1.4 m of crop row against the expected 1 m of row on the basis of 20,000 m of row/ha.

The sampling commenced after crop emergence before the first weeding took place, at one end of the subplots. The RA-14 field had 140 subplots, yielding 140 composite samples from 2x0.5 sqm areas each. The RW-2B field had 60 subplots yielding 60 samples from 3x0.5 sqm areas. Thus, per observation date, 4.8% and 4.2% of the total area was sampled for the RA-14 and RW-2B field respectively. The amount of weeds was determined each time after weeding, and when deemed necessary. The successive sampling areas were spaced sufficiently apart to avoid possible border effects created by the open space of the previously sampled areas. The same precaution was taken with regard to the crop sampling area.

Each year the permanently located main plots (receiving the main tillage treatments) were divided into subplots, to which the weed management treatments selected for that particular season, were randomly assigned.

Two treatments were always included, one in which the weeds were allowed to develop freely from planting to harvest, the so-called weedy check. In the other treatment, plots were kept weedfree throughout by hand weeding regurlarly.

Thus, the degree of succes of any weed management treatment could be rated between the possible two extremes occurring in a particular season.

In some years, the amount of weeds between the rows, in the path of the weeding tools, was determined separately.

6.4 RESULTS

6.4.1 General Aspects Of Weeding Practice

To make mechanical weeding potentially succesfull a clean seed bed is of utmost importance to give the crop a maximum head start. A crucial aspect is the proper timing of the planting operation in relation to the last pre-sowing cultivation.

When the weather remains dry after the last pre-sowing cultivation, nothing can be done but wait for rains and hope that the emergence and growth of new weeds will be retarded. In this situation timing is not very critical, unless an excessive delay of sowing rains produces an unacceptable level of weediness and makes new pre-sowing cultivation necessary. One may then well be put into the same position as in the other case of extremely critical timing, namely when sowing rains follow the last cultivation. When this happens, planting should be started as soon as possible to give the crop maximum opportunity to keep ahead of the already germinating weeds.

During the experiments, the successive time lapses between the last pre-sowing cultivation and planting were 0, 6, 6, 10, and 10 days, respectively. Obviously, a 0 day time laps is not realistic when only one tool carrier unit is available.
A time lapse of 6 and 10 days between planting and cultivation gave rise to a peculiar phenomenon. While planting, numerous tiny weed seedlings about to emerge could be seen as thin white strands in the wake of the planter furrow openers. Apparently, the majority of these died while deposited partly on the sides of the furrow openers tracks, because weed growth in the crop rows was strikingly absent for some weeks, in sharp contrast to the untouched area on the bed between the rows (Fig. 33).
The first inter-row cultivation was executed as soon as possible after the crop reached a height of approximately 10 cm. Depending on the trafficability of the land -the bed top layer dried out quickly- and the outlook of the weather, inter-row cultivation could be started already 10 days after sowing. Pearl millet, being a slow starter, required 18 days.

6.4.2 Equipment

The crop row area of the bed was cultivated using two pairs of opposite, L-shaped shovels. The upright sides protect to a large extent the plant row from lateral soil movement, which makes weeding close to the crop rows possible at an early stage.
A uniform shape of the bed in the direction of travel is important and too-rough a seedbed is to be avoided. Only then, complete coverage can be accomplished at the necessary shallow average depth of 3 to 4 cm without the need for sophisticated equipment which follows soil surface undulations.
In Fig. 34 an average cross section of the beds after passage of the planters is sketched from soil surface relief meter data. The track left after passage of the planter furrow opener and press wheel show up clearly. The crop plants are particularly liable to be covered by soil rolling into the depression, unless use is made by the L-shaped shovels.
At the same time of weeding the crop row area on the bed, the bottom of the furrows and the sloping sides of the bed were cleaned using two furrowers having adjustable wings. After weeding a bed, the tool carrier returned in the same furrow to proceed on the adjacent bed. Thus each furrow was passed twice. Because the protection provided by the L-shaped shovels lacked on the furrow side of the two outer rows, side rows were more frequently covered by soil than the center row. This was expressed in the difference in plant stand decline following the first inter-row cultivation, as illustrated in Fig. 35.
A second inter-row cultivation usually followed within a week. By that time, the crop had reached sufficient height to allow a more aggresive weeding. To this end, two duckfoot shovels, approximately 31 cm wide, were mounted to weed between the rows on the bed, filling the crop row depression through the lateral soil transport.
In a few cases, extra attention had to be paid to the shoulder of the beds; for this, two additional shovels were mounted, each one to cut the outer side of the bed close to the crop row (Fig. 36). Sometimes, it was felt necessary cultivate the weeds growing outside the cutting and scraping range of the furrower, which had become to big to be killed merely by the soil covering by the furrowers. This operation tends to fill the furrows with some soil and weed plants, making an extra pass with the furrowers necessary only to reshape

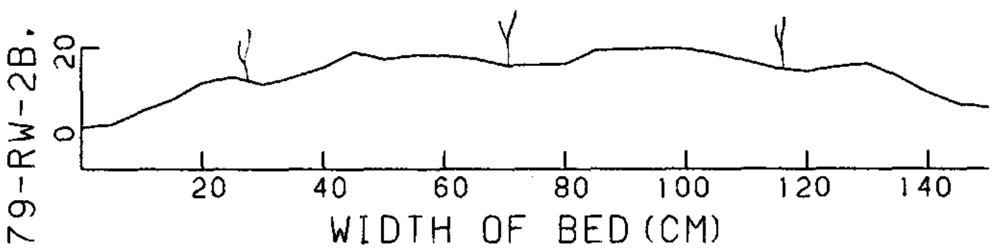


Fig. 34. Cross section of BBF-system after planting three rows.

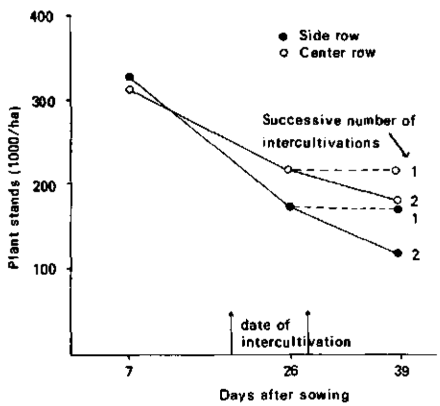


Fig. 35. Influence of inter-row cultivation on plant stands of side and center rows in pearl millet.

Fig. 33. Broadleaved weeds between sorghum rows two weeks after planting. In the planter track weed growth is delayed.

Fig. 36. Inter-row cultivation in sorghum.

the furrows. In this case the effective width of the operation increases to 3 m since there is no need to return in the same furrow.
Because the tool carrier straddles all the rows on the bed, inter-row cultivation is possible for a limited time span only, until the crop outgrows the maximum clearance provided by the tool carrier for sorghum and millet. In practice, this meant that mechanical inter-row cultivation was possible only upto 4 to 5 weeks after planting. In one case, a planned weeding had to be cancelled because of strong winds blowing perpendicular to the direction of the beds. Stems and leaves were blown sideways and caught underneath the joint of the axle and the main frame of the tool carrier; this knocked down most plants of the side rows.

On the whole, inter-row cultivation proved to be a fairly easy operation, with little that could go wrong. Use of the optional, steerable toolbar made the operation unnecessarily complicated. Steering proved tiresome on the long run and did visibly more harm than good, which is understandable in the typical BBF situation with its inherently paralellity of rows. Only when beds are laid out in a rather curvilinear pattern, additional steering is needed to compensate for the swaying of the shovels.

6.4.3 Power Requirements

Because of the limited working width and depth, weeding required little force. An average draft of 600 N was needed for the bed-engaging implements. With concurrent use of the two furrow openers, the draft requirement increased depending on the depth to 1300 N. The experimental fields, having a size of 0.33 and 0.45 ha, invariably were completed within 1 and 1.5 hour, respectively, which amounts to a field capacity of 0.3 ha/hr.

6.4.4 Aspects Of Handweeding

Hand weeding was done by female labourers using a handhold sickle sharpened at the point. The attitude during weeding depends on the degree and stage of weed infestation. During the first weeding, when many tiny weed seedlings were present, weeding was done in a stooped attitude by alternately pushing and pulling the sickle over the whole area, thereby breaking up a shallow layer of top soil. In a later stage of high level weed infestation, when the weed population was more thinly spread and taller, the weeds were cut individually in a squatting position.
It was noted that by intra-row hand weeding in the early stages, some root pruning occurred which set the crop back temporarily, as visible through wilting under drying conditions. For overall hand weeding, 150 hrs/ha were required on average.

6.4.5 Weed Management Results

6.4.5.1 Introductory Remarks -

For convenience, the various treatments involved will be abbreviated for use in graphs and tables as follows:

IRC: inter-row cultivation
SHW: supplemental handweeding of the weeds remaining in the crop row after inter-row cultivation
CHW: complete handweeding of the whole area

In addition, a two-digit number may be attached to indicate the days elapsed since planting.

6.4.5.2 Field RA-14, 1978 -

Weed management was accomplished exclusively by mechanical inter-row cultivation; treatments differed by the number of cultivations:

W1: no weeding
W2: inter-row cultivation 18 days after planting
W3: inter-row cultivation 18, and 27 days after planting
W4: inter-row cultivation 18, 27, and 39 days after planting
W5: weedfree

The excellent plant stands of pearl millet seemed to promise a good starting position in terms of early competitiveness of the crop in the crop-weed balance. But, being a slow starting crop, pearl millet could not be weeded sooner than 18 days after planting.
For the first inter-row cultivation, L-shaped shovels were used for weeding the 10 cm-high millet (Fig. 37).
In spite of the relatively narrow hoe setting, a considerable proportion of the width of the bed was covered by laterally moving soil, in particular by the furrowers burying some crop plants in the process. As a result, more plants from side rows died compared to plants in the center row. This did not happen during the subsequent weedings, because the crop was much higher at that time. The L-shaped shovels were then replaced by two 32 cm-wide duckfoot shovels working between the rows on the bed. A wider path between the rows was cut with the tool edges approaching the crop row to 6 cm; in addition, the tool had a much more agressive action and threw much more soil into the crop rows.

The effect of weed management treatments on weed growth during the crop life is shown in Fig. 38.
Weediness levels were reduced following each inter-row cultivation, but the effect was disappointingly small. For instance, the amount of weeds immediately after the last inter-row cultivation was only modestly lower compared to unweeded plots. The unweeded plots yielded 1961 kg/ha, whereas with each of the three additional inter-row cultivations weediness levels dropped to 1740, 1396 and 1384 kg/ha, respectively.
As a result, all weed management treatments produced unacceptably low yields

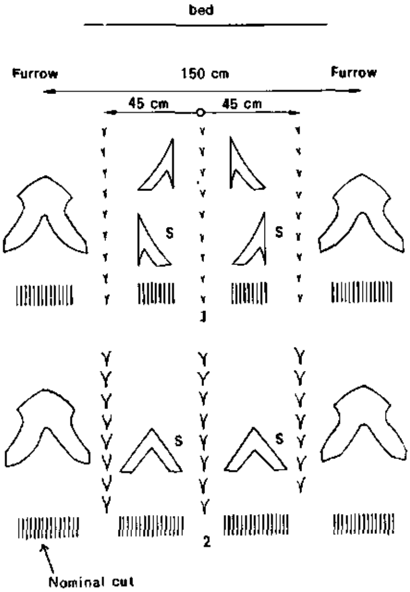


Fig. 37. Top view of 1st inter-row cultivation with L-shaped shovels, and of 2nd inter-row cultivation with duckfoot shovels. The furrower cleans the traffic zone.

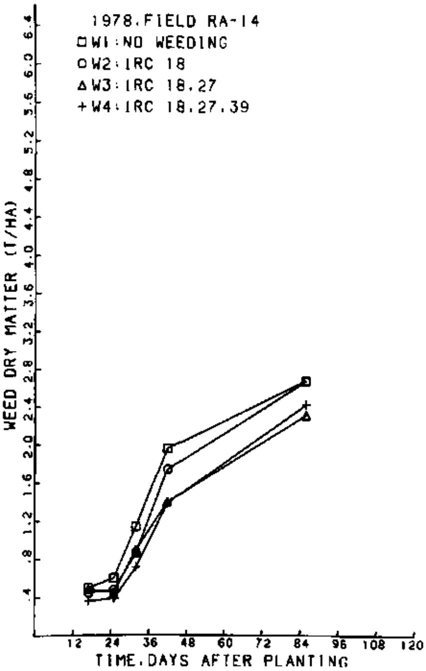


Fig. 38. Effect of various weed management treatments on weed growth in pearl millet on RA-14 in 1978.

which could have been much higher, as indicated by the yield obtained from the weedfree kept plots (Table 9).

Table 9. Effect of weed management treatments on pearl millet yield on RA-14 in 1978.

treatment	grain yield (kg/ha)	straw yield (kg/ha)	no. of heads 1000/ha
W1: no weeding	420	950	205
W2: IRC 18	370	1230	207
W3: IRC 18,IRC 27	490	1140	161
W4: IRC 18,IRC 27,IRC 39	690	1730	181
W5: weedfree	1830	4540	362
SE	±134	±364	±32
CV(%)	54	57	47

The reason why inter-row cultivation performed so poorly, was fully realized later in the season: where weeding had taken place, a distinct, rather clean track having the width of the shovel, could be seen. Even at harvest time , after pushing aside the foliage of the crop and weeds, weeds were predominantly growing in the crop row area. To quantify the distribution of weeds between and within the rows, weed samples were taken prior to harvest in the usual way, but also exclusively in 33 cm-wide strips between the rows coinciding with the shovel path.
The results are given in Table 10 and it is evident that weeding was effective between the rows in the cutting path of the shovel.

Table 10. Effect of inter-row cultivation on intra- and inter-row weed growth at harvest on RA-14 in 1978.

treatment	inter-row weediness (kg/ha)	intra-row weediness (kg/ha)
W1: no weeding	2478	3058
W2: IRC 18	1895	4164
W3: IRC 18,IRC 27	1344	4199
W4: IRC 18,IRC 27,IRC 39	1137	4926
SE	±178	
CV	40	

Apparently, weeds in the row, beyond the reach of the shovel, could not effectively be killed by soil coverage because crop and weeds emerged simultanuously. The weeds killed in the track actually gave rise to more vigorous growth of the established weeds in the crop row area, since these took full advantage of the light becoming available. This led to the surprising result of much more intra-row weeds after three inter-row cultivations than in unweeded plots.

It can be concluded, that weeding had a definite effect on the weed dry matter early in the season, and consequently on crop yield. However, the unchecked abundant intra-row weed growth detracted from the overall inter-row weeding effectiveness. A single complementary handweeding to destroy intra-row weeds would have great potential in boosting the overall weed control management effectiveness. Handweeding was, therefore, incorporated in some of the weed management treatments envisaged for the following seasons.

6.4.5.3 Field RA-14, 1979 -

The weed management treatments for the 1979 rainy season were:

- W1: no weeding
- W2: inter-row cultivation 10 days after planting, complete handweeding 39 days after planting
- W3: inter-row cultivation 10 and 17 days after planting
- W4: inter-row cultivation 10 days after planting, inter-row cultivation + intra-row hand weeding 17 days after planting, complete handweeding 39 days after planting
- W5: weedfree

Weeds developed less fast early this season (Fig. 39).
The first inter-row cultivation executed 10 days after planting reduced weediness considerably as measured 17 days after planting. A second inter-row cultivation performed from the same level of weediness proved less effective, however, basically because the weeds in the track were already treated adequately. In other words, the sharp increase can be attributed almost completely to the enhanced growth of the weeds in the row. This is corroborated by treatment W4 in which these weeds were removed by handweeding, thus keeping the weediness at day 28 essentially at the same low level as measured previously.
In the beginning of August, some five weeks after sowing, Celosia argenta started to develop. At harvest time, this weed was the single most present species, particularly were handweeding was omitted. Its time and duration may not have had consequences for crop yields but it surely made post-harvest tillage difficult because of its sheer volume and toughness of the stems.
The sorghum yield was significantly dependent on the reduction of weediness accomplished by the various treatments, as shown in Table 11 and Fig. 40.

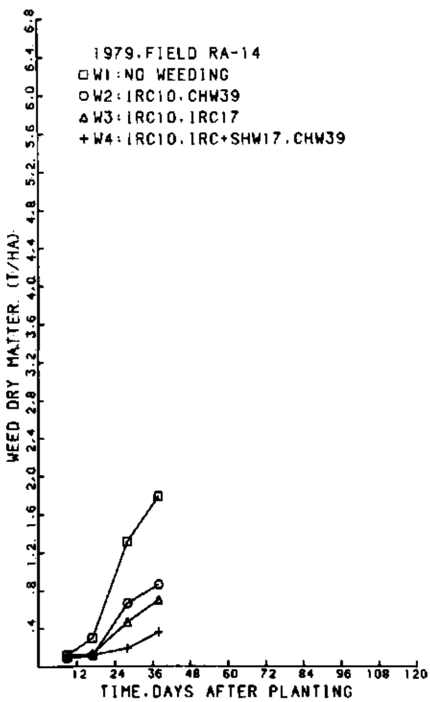


Fig. 39. Effect of various weed management treatments on weed growth in sorghum on RA-14 in 1979.

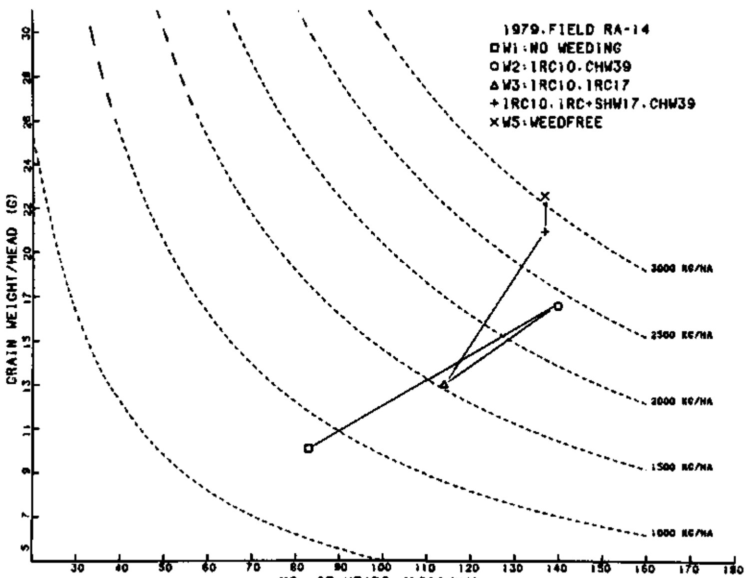


Fig. 40. Effect of weed management on sorghum crop yield components on RA-14 in 1979.

Table 11. Effect of weed management treatments on yield of sorghum CSH-6 on RA-14 in 1979.

weed management treatment	grain yield (kg/ha)	no. of heads 1000/ha	average head weight(g)
W1: no weeding	856	83	10.3
W2: IRC 10,CHW 39	2390	140	17.1
W3: IRC 10,IRC 17	1527	114	13.4
W4: IRC 10,IRC+SHW 17,CHW 39	2832	137	20.6
W5: weedfree	3056	137	22.3
SE	±123	±7.1	±0.65
CV(%)	31	31	28

The relationship between plant stands at harvest and crop yield as a result of weed management was interesting. Really good yields were obtained only when handweeding, either complementary within the row (W4) or as complete hand weeding, was part of the weed management system. The plant population of W3 was significantly lower compared to the treatments where weeds within the row were removed at some stage of their development. Apparently, the crop-weed competition in the intra-row area was so severe as to decline not only stands, in itself sufficient for reducing yields, but also grain weights per head. The difference in yield between the top ranking treatments W2, W4 and W5 is attributed solely to heavier heads, since the stands were equal.

6.4.5.4 Field RW-2B, 1979 -

In RW-2B the same treatments were envisaged as in the RA-14 field in the 1979 rainy season. However, weed regrowth was extremely slow and the highest levels of weed management treatments had to be dropped. The resulting weed management treatments reduced to:

- W1: no weeding
- W2: inter-row cultivation 20 days after planting
- W3: inter-row cultivation 20 days after planting, complete hand weeding 48 days after planting
- W4: weedfree

The weed management effect on weed dry matter is illustrated in Fig. 41.
Weed growth was extremely slow in this season. A possible explanation may be that by 1979 this field had been under the BBF-system of cultivation for four years. ICRISAT's standard primary tillage method had been performed following harvest of the previous crop. Prior to the 1979 rainy season, the field was reassigned and the primary tillage treatments imposed. This extra tillage probably contributed to the reduced weed growth.
As a consequence of the negligible weed growth early in the season, sorghum grain yields were high and did not differ significantly between the weed management treatments (Table 12 and Fig. 42). In fact, the yields of weedfree plots were not significantly higher than the yields of the unweeded plots.

WEED CONTROL

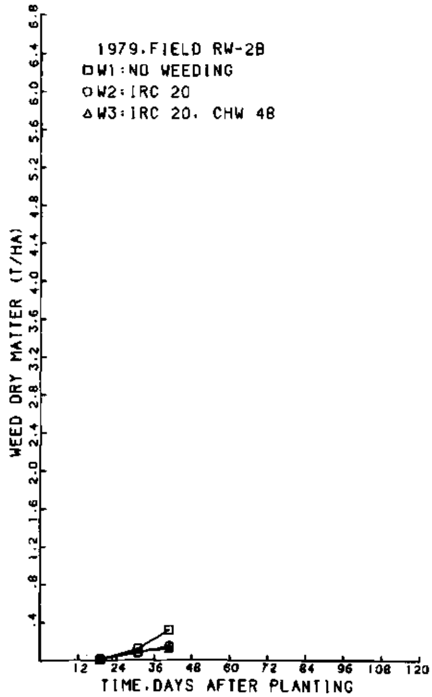


Fig. 41. Effect of various weed management treatments on weed growth in sorghum on RW-2B in 1979.

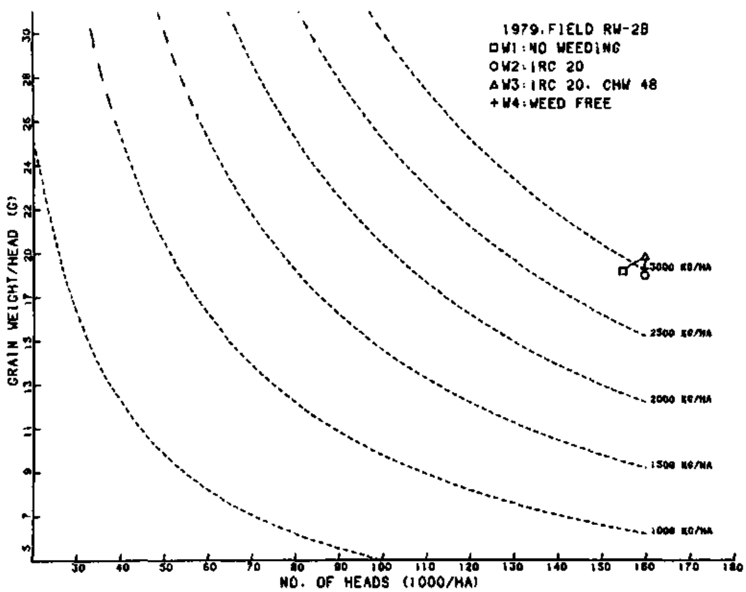


Fig. 42. Effect of weed management on sorghum crop yield components on RW-2B in 1979.

Table 12. Effect of weed management treatments on yield of sorghum CSH-6 on RW-2B in 1979.

treatment	grain yield (kg/ha)	no. of heads 1000/ha	average head weight(g)
W1: no weeding	2896	155	18.7
W2: IRC 20	2965	160	18.5
W3: IRC 20,CHW 48	3100	160	19.4
W4: weed free	3025	160	18.8
SE	±127	±5.7	±0.98
CV(%)	15	12	18

6.4.5.5 **Field RA-14, 1980** -

The weed management treatments were slightly changed to include a minimum of 2 inter-row cultivations, and a complete hand weeding late in the season, when inter-row cultivation is not possible anymore. The late hand weeding can be seen as a step taken to facilitate harvesting, particularly to prevent shedding of weed seeds, and to make post-harvest tillage possible. The treatments were:

W1: no weeding
W2: inter-row cultivation 13 and 21 days after planting
W3: inter-row cultivation+intra row handweeding 13 and 21 days after planting
W4: inter-row cultivation+intra row handweeding 13 and 21 days after planting, complete handweeding 53 days after planting
W5: weedfree

Weeds developed vigorously at an unprecedented rate of approximately 70 kg/ha of dry matter produced each day between 10 days after planting and harvesting 95 days later (Fig. 43).
However, the various weed management treatments were very effective in substantially reducing weed growth, particularly the intra-row hand weeding. The extra two supplemental handweedings in the row reduced the overall weediness considerably, from 1600 kg/ha to a mere 400 kg/ha as measured 9 weeks after planting. Subsequent weed growth remained limited, with weediness levels at harvest of 800 kg/ha of dry matter, a tolerable level from a post-harvest tillage point of view.
Fig. 44 shows that intra-row handweeding boosted yields by 57%, or 500 kg/ha of grain produced. Remarkable is the drop in yield in treatment W4, apparantly due to the extra complete handweeding given 53 days after planting. The drop in yield can not be explained in terms of a reduced number of harvestable heads. In all probability, the plants suffered a setback because of inadvertent root pruning and lodging of the crop. The grain weight per head was lower than that of the nearest W3 treatment.
On the whole, plant stands at harvest were approximately half the near optimum level attained in the previous year, due to a shootfly attack. The reduction

WEED CONTROL

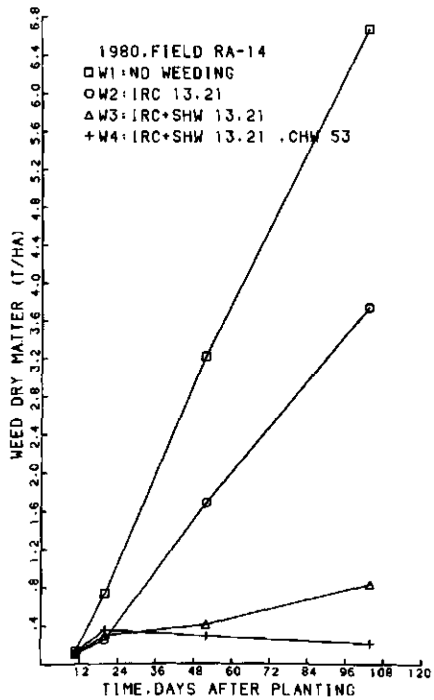


Fig. 43. Effect of various weed management treatments on weed growth in sorghum on RA-14 in 1980.

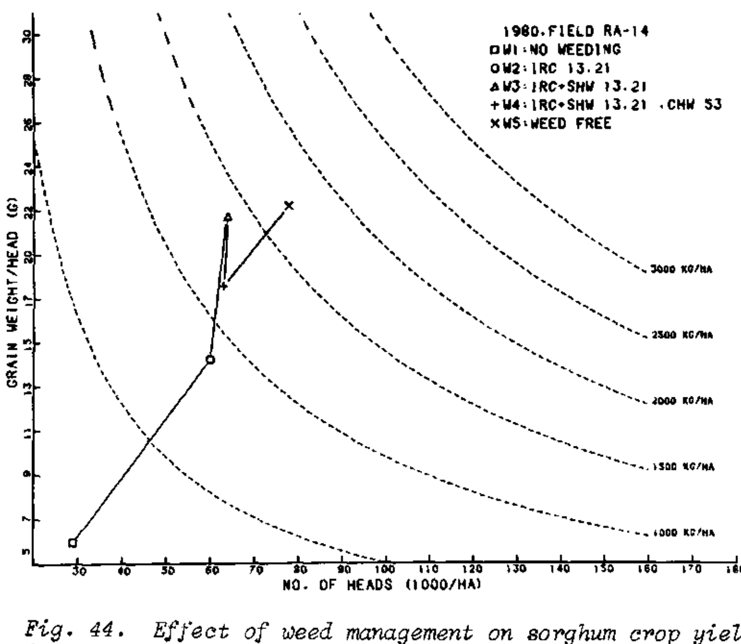


Fig. 44. Effect of weed management on sorghum crop yield components on RA-14 in 1980.

in population was not compensated by increased individual plant yield (Table 13 and Fig. 44). At harvest time weeds again were sampled exclusively in the inter-row area. The results are presented in Table 14. Note the enormous effect that the two extra intra-row handweedings exerted on the intra-row weeds, reducing levels to a mere 10% of that for inter-row cultivation alone.

Table 13. Effect of weed management treatments on yield of sorghum CSH-6 on RA-14 in 1980.

treatment	grain yield (kg/ha)	no. of heads 1000/ha	average head weight(g)
W1: no weeding	177	29	6.0
W2: IRC 13,IRC 21	877	60	14.6
W3: IRC+SHW 13,IRC+SHW 21	1375	64	21.4
W4: IRC+SHW 13,IRC+SHW 21,CHW53	1158	63	18.1
W5: weed free	1708	78	21.9
SE	±167	±6.3	±1.4
CV(%)	77	52	48

Table 14. Effect of weed management treatments on intra- and inter-row weediness levels at harvest on RA-14 in 1980.

weed management treatment	inter-row weediness kg/ha	intra-row weediness kg/ha
W1: no weeding	6263	7512
W2: IRC 13,IRC 21	1001	9094
W3: IRC+SHW 13,IRC+SHW 21	773	964
W4:IRC+SHW 13,IRC+SHW 21,CHW 53	113	416
SE	±251	
CV(%)	74	

6.4.5.6 Field RW-2B, 1980 -

The same weed management treatments as given in RA-14, were applied to the RW-2B field with slightly different weeding dates:

WEED CONTROL

W1: no weeding
W2: inter-row cultivation 12 and 26 days after planting
W3: inter-row cultivation+intra-row handweeding 12 and 26 days after planting
W4: inter-row cultivation+intra-row handweeding 12 and 26 days after planting, complete handweeding 54 days after planting
W5: weed free

Contrary to the last season, weed growth was very vigourous as can be seen in Fig. 45.
An appreciable reduction in weediness was achieved by inter-row cultivation alone, but when inter-row cultivation was supplemented by handweeding in the crop row, weediness was reduced markedly during the first 53 days and thereafter.
The effects of weed management on crop yields exibited the same pattern as on RA-14 in the same year, be it on a much higher average yield plateau. The same unexpected drop in yields resulted from the additional late, complete handweeding, in this case penalized with a loss of 400 kg/ha. Also in RW-2B, the crop suffered from a shootfly attack reducing the plant population far below its optimum level (Table 15 and Fig. 46). At harvest time, Celosia argenta was the predominant weed species where handweeding had not been part of the weed management method.
When comparing the W2 and W3 treatments the extra intra-row handweeding yielded 300 kg/ha more. In itself, this is not a spectacular reward for the extra labour involved; however, the handweeding again was a necessary prelimanary for succesfull post-harvest tillage. Additional to the normal sampling at day 104, weediness levels were again sampled in the row area; the results are presented in Table 16.

Table 15. Effect of weed management treatments on yield of sorghum CSH-6 on RW-2B in 1980.

treatment	grain yield (kg/ha)	no. of heads 1000/ha	average head weight(g)
W1: no weeding	747	81	9.2
W2: IRC 13,IRC 25	1772	93	19.0
W3: IRC+SHW 13,IRC+SHW 25	2076	90	23.1
W4: IRC+SHW 13,IRC+SHW 25,CHW53	1687	74	22.8
W5: weed free	2366	96	24.5
SE	±120	±6.6	±1.52
CV(%)	31	26	26

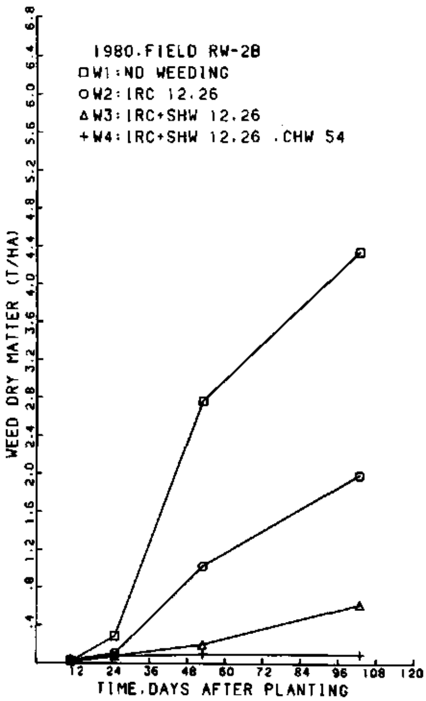


Fig. 45. Effect of various weed management treatments on weed growth in sorghum on RW-2B in 1980.

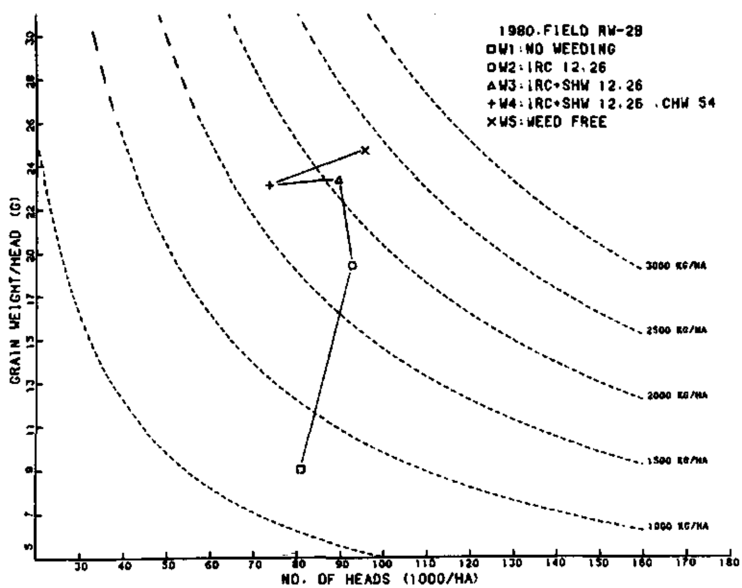


Fig. 46. Effect of weed management on sorghum crop yield components on RW-2B in 1980.

Table 16. The effect of weed management treatments on intra- and inter-row weediness levels at harvest on RW-2B in 1980.

weed management treatment	inter-row weediness kg/ha	intra-row weediness kg/ha
W1: no weeding	4420	4181
W2: IRC 12,IRC 26	636	4596
W3: IRC+SHW 12,IRC+SHW 26	227	1296
W4:IRC+SHW 13,IRC+SHW 26,CHW 54	26	238
SE	±485	
CV(%)	158	

6.4.6 Discussion

From the first experiment in 1978 on RA-14 with pearl millet, it became clear that intra-row weeds could not adequately be taken care off by inter-row cultivation only. In fact, more weeds grew on the intra-row area after cultivation. As a result, the positive effect of inter-row cultivation had on weeds between the rows was almost fully negated by the abundantly growing intra-row weeds.

There is an explanation for the failure to control the intra-row weed growth. There was no time between the only pre-sowing cultivation and planting, so that a wave of weeds stimulated by the cultivation germinated and emerged virtually in synchronisation with the crop. The problem of intra-row weeds that would normally arise was further aggravated by the slow establishment typical of pearl millet. Because, when this happens, the crop and intra-row weeds are equally vulnerable, weeding shovels had to be set to prevent soil transport into the rows. This is why handweeding became the only option left. Since then handweeding was consistently incorporated in at least one weed management treatment.

The results from that moment on proved that intra-row weeds prevented high crop yields. Except in 1979 on the RW-2B field with its exceptionally low weed growth, yields were disappointingly low, unless some form of handweeding was used. Handweeding, either exclusively intra-row or over the entire field, brought about substantial increases in crop yields.

In 1979, yields of sorghum grain from plots receiving handweeding were 863 to 1305 kg/ha higher. In 1980, the effect was less pronounced, with yields of 281 to 498 kg/ha higher than with inter-row cultivation. Where this additional yield did not cover the costs involved, the handweeding reduced the amount of weeds at harvest to sufficiently low levels for a potential quick turnover (eg. on a deep Vertisol), essential for the succesfull establishment of a sequential crop.

The potential yield reduction of uncontrolled weeds varied from 10% to 90% of the weedfree plots.

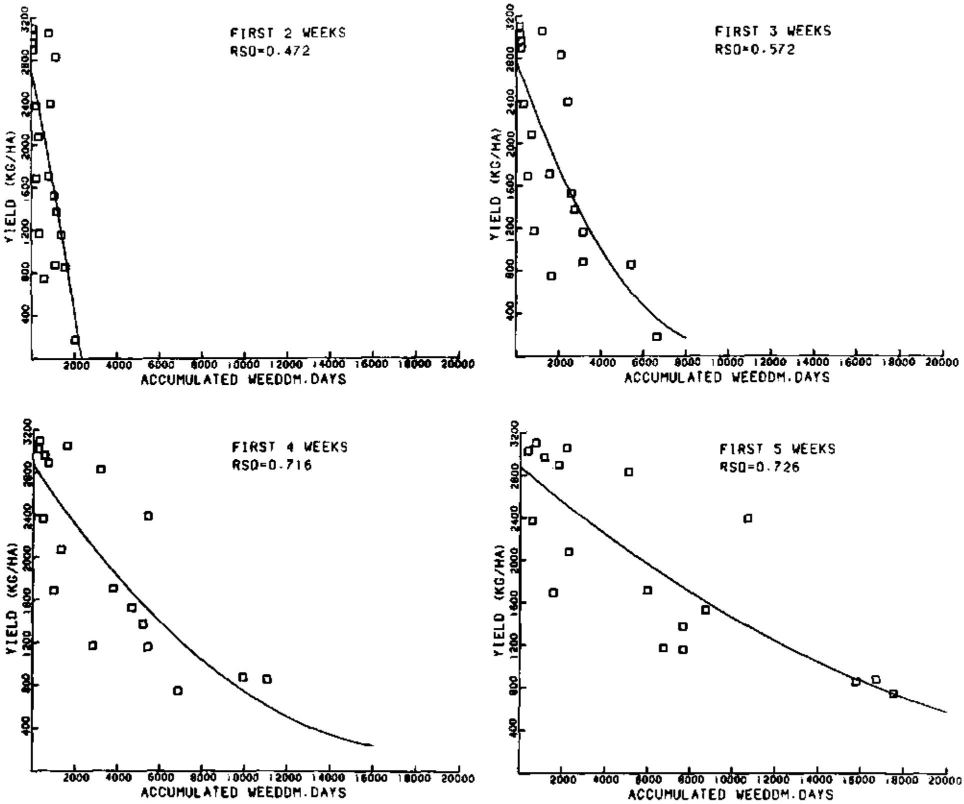


Fig. 47. Relationship between weediness integrated over increasing periods of time, from RA-14 and RW-2B in 1979 and 1980.

From 1979 onwards, sorghum CSH-6 was the only crop used. Obviously, this goes against the sound practice of crop rotation. Yet, this was done to facilate comparisons of weed growth and its effect on crop yields.
Complicating factors still remained, due to experimental planning and weather, treatments and dates of weeding, and inevitable sampling variations between years and locations. As a result, the amount of weeds observed at a particular date is not always indicative of the damage inflicted on the crop until that date. It would be meaningless, for instance, to compare the effect of weediness levels 30 days after seeding on crop yields, when in one case weeds were allowed to grow and in a second case a thorough handweeding shortly preceded that date. In the second case, the crop is not likely to recover and a poor relationship between weediness and yield would result.
To circumvent this complication, weediness levels were integrated over time from planting onwards for each weed management system, such as seen in Fig. 45, and compared with the ultimate crop yield. In fact, there is an analogy with crop yields, as the crop also 'integrates' the competition effect of weeds as these develop over time.
The outcome of such a procedure is presented in a series of graphs in Fig. 47, which show the relationships between the pressure of weeds (expressed as weed dry matter days accumulated) during the first 2, 3, 4 and 5 weeks after planting, and the resulting crop yield.
The plotted data show that, over the years and fields, crop yields were fairly closely negatively correlated with the presence of weeds during those early stages. Even as early as two weeks after planting, when weeding levels were still fairly low and close, the regression proved signifant.

6.4.7 Conclusion

The maximum clearance of the tool carrier permits inter-row cultivation in tall growing crops, such as millets and sorghums, only during the first five weeks.
The weeds between the rows could be controlled adequately during this period. But the soil covering mechanism was not reliable for controlling intra-row weeds, since in most cases too many weeds were present having reached the same stage of development as the crop.
Unless supplemental handweeding supported inter-row cultivation, intra-row weeds continued to grow unabated and high crop yields could not be realised.
A late handweeding is essential when a sequential crop follows. It spreads the labour peak of the post-harvest pre-sowing cultivation and planting, and permits a minimum turnover time.

CHAPTER 7

PLANT ESTABLISHMENT

7.1 INTRODUCTION

7.1.1 General Remarks

The field establishment of a crop is a yearly recurring critical phase in rain fed crop production. A good stand is essential to benefit to the full extent from a good season and, although it certainly does not guarantee good yields, uneven poor stands will definetely never produce them.
Poor and uneven stands is one of the major causes of low crop yields in the semi-arid tropics (ICRISAT, 1981; 1982). Erratic rainfall patterns are believed to have created emergence problems on Alfisols due to crusting (ICRISAT, 1978).

A host of factors are involved in the physical and physiological processes of the transfer of a seed to seedling. The scope of the experiments allows only a discussion of those external factors, which are related to the soil physical environment. Soil physical properties are believed to be the major factors for seedling growth up to emergence, since growth is sustained by the seed's nutrient reserves (Collis-George and Lloyd, 1979).
A planted seed requires adequate levels and quantities of water, heat and gaseous exchange to complete germination. Soil structural aspects are important not only in this respect, but also in providing a medium conducive to rooting and the emergence of the hypocotyl.

The above mentioned factors are interdependent, making a complete analysis extremely complicated. Roughly two complementary categories of experimentation are reported in the literature.
In the first category, a theoretical hypothesis underlies the mostly laboratory type of experiments. One, two or occasionally three factors are varied in a controlled way, while the remaining factors are kept constant. The effects of the variable factors on germination rate and percentage are quantified to establish their optimum range and critical limits for predictive use.
A second broad group of experiments deals with problems encountered in the field in obtaining adequate stands. Often, one of the germination and emergence related factors is found critical and is associated with a particular soil type or climate. Special soil management or planting techniques are sought to alleviate or remove the critical factor, and are evaluated in field experiments. The degree of succes is expressed in the

improvement of emergence rate and percentage, while in the more elaborate experiments relevant factors are monitored to explain explicitly possible improvements and shifts from the critical limit into the acceptable zone.

7.1.2 **Factors Influencing Germination And Emergence**

7.1.2.1 Water -

A seed passes through three stages to complete germination, as summarized by Hadas and Russo (1974a):

-imbibition: water uptake by the seed, a physical process.
-development or pause: enzymatic transformation and initiation of meristematic activities.
-growth: radicle elongation and protrusion through the seed coat.

Obviously, water conditions around the seed are important and many workers have tried to define and establish critical limits.
When soil moisture is controlled by matric potential (suction), the rate of germination declines already with small reductions in matric potential, such as from 0 to -100 cm of water (Collis-George and Sands, 1959; 1962, Collis-George and Hector, 1966). The seed-soilwater contact area was believed to play a role. This was verified by Collis-George and Hector (1966) who not only varied matric potential but, independently the seed soilwater contact area as well. They found that even at soilwater matric potentials close to free water, a reduced wetted area of contact retarded the germination rate. Also, they recognised the possibility of the matric potential acting as a mechanical restraint, since it may contribute to the isotropic effective stress in the soil matrix surrounding the seed. This was verified by Collis-George and Williams (1968), who reported that the influence of the soil water matric potential on seed germination could be attributed wholly to the isotropic stress and not to the energy content of the soil water, at least in the matric potential range of 0 to -400 cm water.
Hadas and Stibbe (1973) suggested that a species dependent critical soil water matric potential exists, below which germination stops. For sorghum, imbibition was completed within two days in a dry soil with a volumetric moisture content of 11%, corresponding to a soil water matric potential of approximately -2.5 bar. Reviewing these and other studies, Hadas and Russo (1974a) pointed out that the effects of matric potential, hydraulic conductivity and seed soil water contact were not fully independent. Capillary conductivity and seed-soil contact area affected water uptake rates in a soil water potential range as high as -0.02 bar to -0.55 bar. In a companion paper, Hadas and Russo (1974b) reported on germinating seeds in soil aggregate fractions of various sizes, subject to various soil water matric potentials. The coarser the soil structure, the smaller the relative wetted area for a given seed size and soil water potential. They argued that little water is needed for germination and that the limiting factor is the seed-soil water contact impedance. The latter can be influenced by seedbed preparation. A high number of contact points is preferable and, because little change in wetted area of contact occurs between a seed-particle size ratio of 10:1 and 5:1 (except at very low matric potentials), Hadas and Russo (1974b) concluded that a 5:1 ratio would suffice. Packing the soil, especially in case of small

seeds, would further contribute to germination, though care should be taken not to hamper root development.

7.1.2.2 Oxygen And Temperature -

The effect of temperature and oxygen supply was not considered in the above-mentioned studies. Sharma (1976) studied the effect and interaction of temperature and soil water potential on the germination of some arid species. Optimum temperatures were between 20-25 degree C, with one species germinating over a range of 5-40 degree C. Cumulative emergence dropped outside the optimum temperature range for all soil water potentials.

Eavis et al. (1971) grew pea seedlings in divided gas chambers. They reported progressively decreasing radicle elongation rates when the oxygen level in the root zone was reduced, while normal atmospheric conditions were maintained around the cotylodons and shoot. Hanks and Thorp (1957) observed reduced emergence when oxygen diffusion rates fell below 75 to 100x10E-8 g/cm2/min, corresponding with an air-filled pore space of 15%, 17% and 25% in a silty clay loam, silt loam and fine sandy loam, respectively.
Gill and Miller (1956) and Barley (1962) varied the oxygen supply to growing maize radicles under various mechanical stresses. The growth rate of unimpeded roots declined when the oxygen content fell below 10%; the combined effect of oxygen shortage and mechanical stress seriously reduced growth in this range.

7.1.2.3 Mechanical Impedance -

As a germinating seed continues to develop, its organs displace soil particles. The rate of elongation of root and shoot is controlled mainly by the soil strength over a range of commonly found field conditions (Barley et al., 1965; Taylor, 1962). Main types of soil deformation by volumetric growth of roots and underground shoots are shear and tensile failure, which are associated with the apparent cohesion and internal friction of the soil (Barley, 1968). These soil physical parameters depend on soil type, but are greatly influenced by moisture content and soil bulk density.
Penetrometer resistance is related to shear strength and measured easily (Freitag, 1968). Despite the poor analogy of a growing root finding its way through the soil with a generally much larger, rigid and comparatively fast penetrating probe, many investigators have attempted to correlate penetrometer readings with root growth and shoot penetration through soil surfaces. Vaughan and Bowen (1977) measured radicle elongation rates for various combinations of constant levels of moisture content, temperature and mechanical impedance for use in a simulation model. Depending on moisture content and temperature, the rate of elongation declined steadily with increasing mechanical impedance up to 10 kgf/cm2, as measured with a penetrometer.
For sandy loams, loamy sands and clay-sand mixtures, root elongation rates drop gradually until a critical soil penetrometer resistance of around 20 kgf/cm2 stops root growth completely under otherwise optimum conditions for sorghum (Hemsath and Mazurak, 1974), and cotton (Camp and Lund, 1968).

Many studies reported in the literature involve soil mechanical impedance as it affects shoot emergence. A huge body of literature is devoted to the study of the causes of crust formation, their effect on seedling emergence, and ways and means to overcome such problems. A complete bibliography on the subject covering the years 1880 to 1980 is given by Goyal (1982).
In the semi-arid tropics, crusts are formed by raindrop impact causing the breakdown of soil aggregates. The smaller detached particles are dispersed and settle down filling and blocking the larger pores of the soil surface. Soil properties related to soil structural stability which make a soil susceptible to crusting are low organic matter, high exchangeable sodium and high silt content (Ahn, 1977; Miller and Gifford, 1974; Gerard, 1965; Kowal, 1972). High silt contents are particularly important in providing maximum particle to particle contact. In crusting soils of the arid and semi-arid regions, amorphous silica is most likely the cementing agent (Uehara and Jones, 1974).
Similar difficulties as with root growth exist in measuring and relating soil strength with shoot emergence . Various methods have been used. Richards (1953) expressed mechanical impedance in terms of the modulus of rupture of briquets of pre-moulded and oven-dried soil. While this is a standardised method, its relationship with the yielding of a natural crust is remote. The application of this technique to field practices was improved by Hanks and Thorp (1957), who modified Richards modulus of rupture technique by compacting the soil to the crust bulk density and breaking the briquet when wet. Bowen (1966) measured the hydraulic pressure needed to rupture the soil surface by inflating balloons buried at seed depth. Page and Hole (1977) compared the modulus of rupture technique with fishline and shearvane measurements; the latter is preferred because of its smaller variance and ease of operation.
Arndt (1965a) proposed a classification of impedance mechanisms based on the interaction of seal cracking characteristics and seedling size. Because of the wide variations in crust strength characteristics, such as strength, thickness and cracking habits, and differences in seedling force and growth behaviour, a universal measure of impedance, such as the modulus of rupture has limited use.
Therefore, Arndt (1965b) adopted the much more realistic method of measuring directly the force required for the emergence of spherical tipped probes buried prior to seal formation. Morton and Buchele (1960) measured the emergence energy required for probes of various diameters, for a variety of compaction levels. Upward moving probes have also been used by Chaudhri et al. (1976), and Royle and Hegarty (1977). The latter reported that the downward force required to break through a crust is highly correlated with that of probes forced upwards.

7.1.3 Seedbed

7.1.3.1 **Seedbed Requirements** -

To ensure optimum conditions for germination of crop seeds and their emergence, it is usually necessary to create a seedbed. Depending on the soil tillage system, in most cases a stepwise approach is adopted; one or multiple seedbed preparation operations are executed to make a provisional seedbed, and finally the planting operation completes the seedbed.
Planting, being the last intentional intervention, gives the seed its location and immediate soil physical environment. From then on, the environmental conditions can change considerably due to the weather; for instance, rapid depletion of soil moisture in the seed zone or development of a crust.
Also, the relative seed position may change under the erosive action of rainfall. For instance, seeds sown on ridges may be exposed or, conversely, seed depth may increase by soil slaking when seeds are sown in a furrow.
Which major factors must be considered, in selecting the array of measures to be taken for the establishment of a crop?
Obviously, soil properties, seed characteristics, climate and weather are important, but equally important are the soil management system and the technical level at which the crop production is realised.
Particular cultivation methods for preparing a seedbed and planting result from trial and error during many years of field and location experience, rather than from exact knowledge of the optimum range of physical environmental conditions needed for crop establishment, and the ability to construct a seedbed accordingly.
Mostly, one is satisfied to alleviate or prevent the effect of a particular limiting factor in crop establishment; for instance avoiding a crust, breaking down big clods into smaller ones, or compacting of a draughty soil to improve the soil water supply to the seed.

The general growth behaviour of a developing seedling is such that its immediate interacting environment steadily increases in volume, with a main thrust in the vertical direction. For fairly closely spaced seeds of row crops, the seedbed merges into a strip of soil. The dimensions which this strip should have, depend on the limiting factor. For instance, if crusting is the main problem, special measures for seedbed preparation could be restricted to small strips overlying the seed row.
Not surprisingly, seedbeds are made by widely varying methods and have widely different dimensions. Batchelder and McLaughlin (1978) reported that a fluted coulter, preparing the soil in a strip in front of the planter furrow opener, provides an adequate seedbed of 3.8x10.2 cm (width x depth) for cotton in loamy sand and clay loam soils. Griffith et al. (1973) found 6x7.5 cm satisfactory for maize in a sandy loam. Larson (1964) suggested for maize a seed zone of 15x17.5 cm, necessary to accomodate most of the primary root system. Unger and Stewart (1976) associated the dimensions with species and environmental conditions and put these arbitrarily at 10x20 cm.
Seedling root and crop development may need special attention when rooting is mechanically impeded. Whiteley and Dexter (1982) reported for several crops in a red brown earth stand reductions of 10% with 3 cm deep slots and 40% with 3 cm deep planting holes, compared to integral tilling to a depth of 12 cm. The reduced early root growth of both seminal and lateral roots explained the reduced dry matter production and yield of the crops.
A rapid development of the root system is particularly important when periods of draught are likely to occur during early growth. Macartney and Northwood (1971) reported a crop failure for maize with a 1.3x5 cm seedbed, because of

the inability of the root system to penetrate the bottom of the cultivated strip. Northwood and Macartney (1971) also studied the effect on plant growth of various widths and depths of strip cultivation with a rotary tiller. Germination was delayed and growth retarded with a seedbed width of less than 20 cm. A depth of 9 cm was better than a depth of 5 cm, both for a 'red' soil and a Vertisol, while increasing width was increasingly important with shallow cultivation.

7.1.3.2 **Critical Factors** -

The difficulties in obtaining uniform stands in the semi-arid tropics are confounded. Limiting the problems to those of medium to coarse textured soils and disregarding aspects such as seed quality, major causes for poor stands are connected with deficient soil moisture in the seedling zone and soil surface crusting which hampers seedling emergence.
The soil moisture supply should be sufficient for the seed and seedling to support growth until the next rainfall occurs. Normally, the seeds are planted in moist soil at a time that the prospects for future rainfall seem good. The decision as to when and how deep to plant is based upon longterm experience with the weather, the weight of the risk of failure and the costs to replant or plant late. Even so, due to the inherently erratic weather in the semi-arid tropics, risks of failure remain high. An otherwise quickly germinating and emerging crop may be subject to prolonged draught stress killing many seedlings.

Rainfall and hot weather shortly following planting may result in the formation of surface crusts on vulnerable soils. Superimposed on these technologically neutral causes, which in itself can seriously reduce stands, are the technical constraints in which the farmers operate. Quickly changing soil moisture conditions require a high field capacity of planting to ensure that the bulk of the planted seeds will have the longest possible favourable period for germination and emergence. This is a quantitative aspect. Quality of planting deals with the proper placement of seed, for which aspects of seedbed preparation and methods of planting are relevant.

Seeding behind the country plow, the 'kera' method, is commonly practised in the red soils of the Deccan plateau in India. Women drop the seeds by hand in a furrow opened by the plow. A critical factor is the time span between opening and closing the furrow; an undue delay impaires the seed-soil moisture contact, since the soil underneath the seed becomes too dry for rapid germination. Depth of covering is variable under the best of circumstances.
In the 'pora' method, seed placement is improved. The seed is hand-metered via a seed tube with funnel on top, attached behind the country plow. As a result, the seed is placed in moist soil and covered immediately by soil falling into the furrow behind the plow. A following pass with a blade harrow kills the weeds and provides a more intimate seed-soil contact.
Three tined seed drills, such as the 'gorru', are also used. A divider funnel distributes the hand-metered seeds through three hollow bamboo pipes leading to the three furrow openers fixed on the cross head. The performance of these indigenous seeding techniques were compared with that of improved machinery with respect to the emergence and yield of sorghum (Gupta and Anderson, 1978) under various soil moisture conditions. The 'Pora' method and the improved

machine with press wheels performed best at 46% and 49% final emergence, respectively. Seed placement in moist soil and depth of seeding are critical. Anderson (1977) discussed the limitations of indigenous practices in this respect and found that the 'Pora' system is the best, but that mechanised drills will eventually be needed for consistent metering.
Field experience in Botswana indicated the importance of the use of seed firming wheels and positive maintanance of planting depth (Willcocks et al., 1977). A level seedbed also helps in this respect to improve plant establishment on farmers fields (Salmon et al., 1977). Seedling establishment problems are associated with high soil temperatures and crust formation (Willcocks, 1980).
In Mali, a quick germination and emergence of millet was observed with minimum tillage seedbed preparation, but later seedlings died for water shortage due to the combined effect of poor rooting, which was physically hampered, and decreased rainfall infiltration rates resulting from crusting (Hoogmoed, 1981).

7.2 FIELD EXPERIENCE OF PLANTING METHOD AND EMERGENCE

7.2.1 Materials And Methods

The four primary tillage methods used resulted in distinctly different seedbed 'foundations' in terms of shape, depth, volume and looseness. During planting, while inserting and packing the seed into the soil, the seedbed obtains its final shape. The different pre-sowing soil conditions may need different seed packing efforts under different environmental circumstances.
This aspect was studied in the tillage field experiments during the years 1977-1980 by evaluating the effect of tillage and planting method, and their interaction on the establishment of rainy season crops.
The experimental design was a split plot with tillage methods assigned to main plots and planting methods assigned to subplots. Planting methods refers to the use of different planter press wheels to obtain various degrees of soil surface compaction:

P0: a split rim wheel consisting of two 2.5 cm wide flat steel rims with a 4.5 cm gap in between and a wheel load of 8.2 kg. The seed-soil contact results from compacting the soil on either side of the seed row and leaving the center above the seed uncompacted.

P1: a band wheel with a 7 cm wide flat steel rim and a wheel load of 8.2 kg. The soil is compacted over the seed row.

P2: the same wheel dimensions, but with extra weights attached to obtain a wheel load of 11.6 kg.

The circumference of all wheels was 1 meter, corresponding with a diameter of 32 cm.

Three small unit planters with an inclined plate seed metering mechanism were clamped to the toolbar to cover the width of one bed.
The units were carefully prepared to keep the possible variation among them, arising from the metering and drive mechanism, to a minimum. Prior to

planting, the sets were calibrated under actual field conditions to obtain a reliable estimate of the average output and its variation. For sorghum, a typical output rate was 15+0.1 seeds per meter of row (95% confidence limits). The furrow opener was designed for low draft and for preventing loose dry soil to fall from the soil surface to below the seed so that seed placement was in moist soil.

Observations included crop emergence, when possible at various dates to assess the rate of emergence. Soil crust strength was measured during the period of emergence with a Soiltest 700 CL hand-held pocket penetrometer, designed to estimate the unconfined compressive strength of saturated soils. The flat cylindrical probe of 0.64 cm diameter is pushed 0.5 cm deep into the soil surface; a sliding ring retains the maximum displacment of the probe against the force of a calibrated spring. The readings were converted to point resistance values, expressed in kPa. When soil strength was too low to deflect the spring, it was assumed to be zero.

No attempt was made to detect the individual effect of surface compaction treatments on soil moisture dynamics. Instead, at one location the upper zone layers were sampled daily during emergence for general information.

7.2.2 Seedbed Management And Planting

After completion of the different primary tillage operations, the seedbeds were prepared identically. Basically, two requirements had to be met; the seedbed had to be clean, that is free from weeds, and it had to have an uniformly shaped bed surface.
Depending on the general weediness level after tillage, which varied between the years, one or two passes were made with duckfoot shovels, the same set as used for the T4-primary tillage method. While the emphasis of this operation is on obtaining a weedfree seedbed, shape, uniformity and physical conditions of the seedbed became important during the following operations. To this end, a special set of implements (deviating from ICRISAT's standard bed shaper, see Fig. 48) was used, which shall be referred to as the 'seedbed conditioner'. The seedbed conditioner consisted of two furrowers, mounted 1.5 meter apart, to clean and shape the furrow, with a spike tooth or spring tine harrow section, mounted behind and in between, to work on the bed. The tines would break the bigger clods, and redistribute and level the bed surface to an uniform height (Fig. 49). In addition, the teeth are reported to have a vertically segregating effect, leaving the bigger clods on the surface and packing the smaller clods closer underneath, guaranteeing a better seed-soil contact (Kouwenhoven and Terpstra, 1979). Also, small weed seedlings are killed during this phase.

Every season care was taken not to cultivate the beds after the last rainfall prior to planting, to avoid unnecessary soil moisture loss.
The depth of planting was set individually by the furrow opener which keeps a fixed position with regard to the tool bar, and thus also the tool carrier wheels. The planter furrow openers, being supported by the big tool carrier wheels, are prevented to sink in locally soft spots, but have the full benefit of the weight of the machine for penetrating until the set depth is reached. Depending on bed height, readjustment may be needed when going from one field

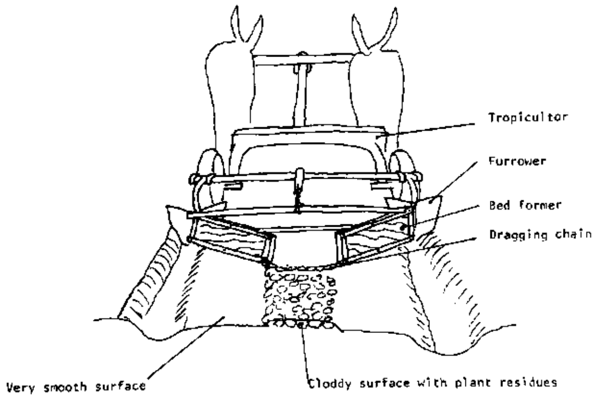


Fig. 48. Shaping broad beds prior to planting with two deflector boards hinged behind the furrowers with dragging chain in between.

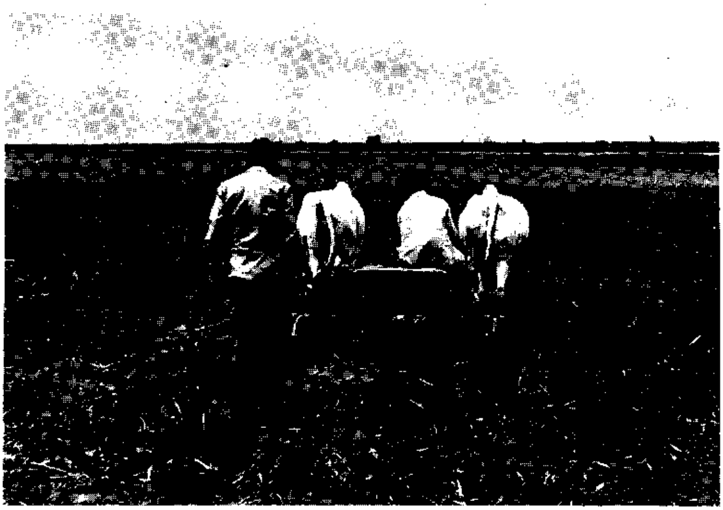


Fig. 49. The 'seedbed conditioner', an alternative implement for preparing a seedbed with uniformly shaped flat top and clods evenly spread over the bed. Field RW-2B.

to another.
Two men are needed to operate the machine while planting: one to guide the animals and tool carrier, the other to monitor the planter performance and to lift and lower the toolbar for turning at the end of each bed.

7.2.3 Plant Emergence Results

7.2.3.1 Pearl Millet On Field Ra-14, 1978 -

1978 was the first and only year that pearl millet was planted. The crop (PHB-14) was planted in a 3-row arrangement, spaced 45 cm apart, at a rate of 750,000 seeds/ha at a depth of 3 cm. Planting date was 1 July (day 182).
Soil strength was not measured. The weather conditions following planting were excellent; within 6 days after sowing, a uniform looking stand was obtained. Both tillage and press wheels influenced emergence percentage considerably, though statistically the tillage effect was insignificant. Increased stands were associated with shallow cultivation, and compaction effort by the planter press wheels of P0, P1 and P2 resulted in stands of 265,000, 318,000, and 354,000 plants/ha, respectively (SE=+19.3, CV= 18%, see Fig. 50). No interaction effect between tillage and planting method existed.
Pearl millet is a notoriously difficult crop to establish. Because of its small size, the seed must be planted at a shallow depth.

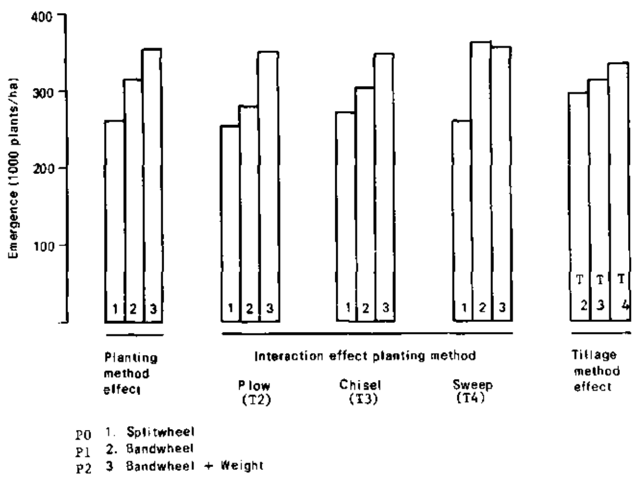


Fig. 50. Emergence of pearl millet as affected by planter press wheels and tillage method.

Apparently the success of establishment was partly due to the fact that the depth of seeding was maintained to a high degree. The same crop was planted on the same day on an adjacent field in roughly made beds and failed completely.
In the course of the season stands declined rapidly, possibly by 'selfthinning' resulting from severe seedling competition (Donald, 1963). Within two weeks the average population fell from 312,000 to 198,000 plants/ha.
When stands are much less dense, the crop has a high capability to compensate through profuse tillering. This was demonstrated when grain yield of three pearl millet cultivars remained unaffected over the broad range of 3 to 25 equally spaced plants/m2 (ICRISAT, 1977).

7.2.3.2 Sorghum Field Establishment -

7.2.3.2.1 Rate And Percentage Of Emergence -

During 1979 and 1980, sorghum CSH-6 was grown in the tillage experiments. The optimum plant population of sorghum alone is regarded to be 175,000 plants/ha under Hyderabad conditions. Three 45 cm-spaced rows were planted on the beds. In order to reach the target population 300,000 seeds/ha were planted in 1979, which was increased to 320,000 seeds/ha in the 1980 rainy season.

In no one year or experimental field was there the slightest indication of an interaction between the level of primary tillage and the level of soil surface compaction by the planter press wheels.
The effect of primary tillage, which was moderate, is discussed in the chapter on primary tillage.

The results of crop emergence rate and maximum percentage in relation to press wheel compaction are presented in Fig. 51.
In both years and on both locations emergence was swift, the first seedlings emerging two days after planting. Maximum emergence was reached around day 5 after planting in 1979, and between day 5 and day 11 in 1980.
Except for 1980 in RW-2B, differences in emergence due to compaction were modest and the average total emergence was slightly above the target of 175,000 plants/ha.
Soil surface compaction by planter press wheels benefited the final emergence, though not appreciably. There seemed to be a trend that, the dryer the soil conditions following planting, the greater the positive effect from compaction. Similar field experience was reported by Stickler (1964), Stickler and Fairbanks (1965) and Dasberg et al. (1966) for sorghum, and by Yadav (1977) for pearl millet. Rawitz and Hillel (1977) also report higher emergence percentages for sorghum following compaction, in spite of increased crust strength.

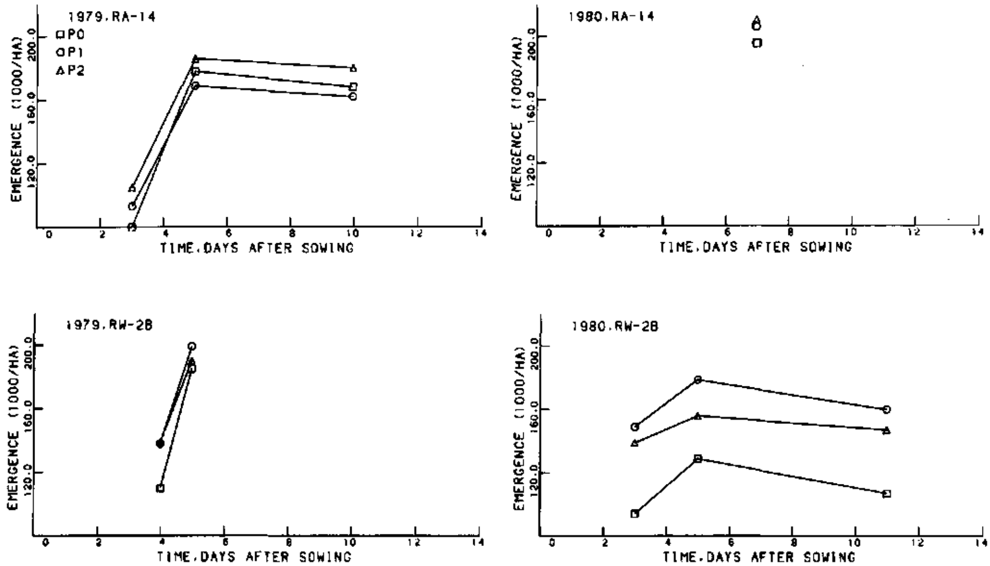


Fig. 51. Emergence (rate) of sorghum as affected by planter press wheels.

7.2.3.2.2 Crust Strength -

The sheer number of penetrometer readings involved (720 on RW-2B, 840 on RA-14) made a day to day monitoring of soil surface strength impossible. Therefore, the timing of crust measurements was chosen to fall as closely as possible within the period in which most seedlings were expected to emerge. This procedure facilitated a comparison between fields and years. The question as to how crusts develop over time from planting until emergence was studied in a separate experiment.

Table 17 presents the average emergence percentages for the various compaction treatments and resulting soil strength levels, along with the relevant dates of observation. Soil strength observations were made 3, 4 and 5 days after sowing, since most of the seedlings emerged then.

PLANT ESTABLISHMENT

It is noteworthy that in some cases where rainfall occurred after planting, planting treatment P0 with zero soil surface compaction led to higher crust strenght levels than planter treatment P2 which gave maximum soil surface compaction.

Table 17. Final emergence of sorghum and crust strength.

planting method	final emergence (1000/ha)	% of seeds sown	crust strength (kPa)
1979, RA-14. Date of sowing 9 July (day 190)			
	5DAS*		3DAS
P0	178	59	25
P1	169	56	367
P2	186	62	452
SE	±4.2		±18.7
CV(%)	12		35
1980, RA-14. Date of sowing 11 July (day 192)			
	7DAS		4DAS
P0	195	61	413
P1	210	66	519
P2	207	65	531
SE	±4.5		±12.8
CV(%)	11		13
1979, RW-2B. Date of sowing 6 July (day 187)			
	5DAS		4DAS
P0	185	62	214
P1	199	66	280
P2	190	63	283
SE	±5.8		±13.0
CV(%)	10		17
1980, RW-2B. Date of sowing 3 July (day 184)			
	11DAS		5DAS
P0	129	40	7
P1	179	56	203
P2	156	49	285
SE	±6.4		±18.2
CV(%)	14		32

DAS= days after sowing

Fig. 52 shows individually plotted relationships between maximum emergence percentages and soil surface strength levels caused by the planter press wheels.
The regression curves are drawn only to serve as visual reference aid; only the regression of RW-2B in 1980 is significant, the others are not having

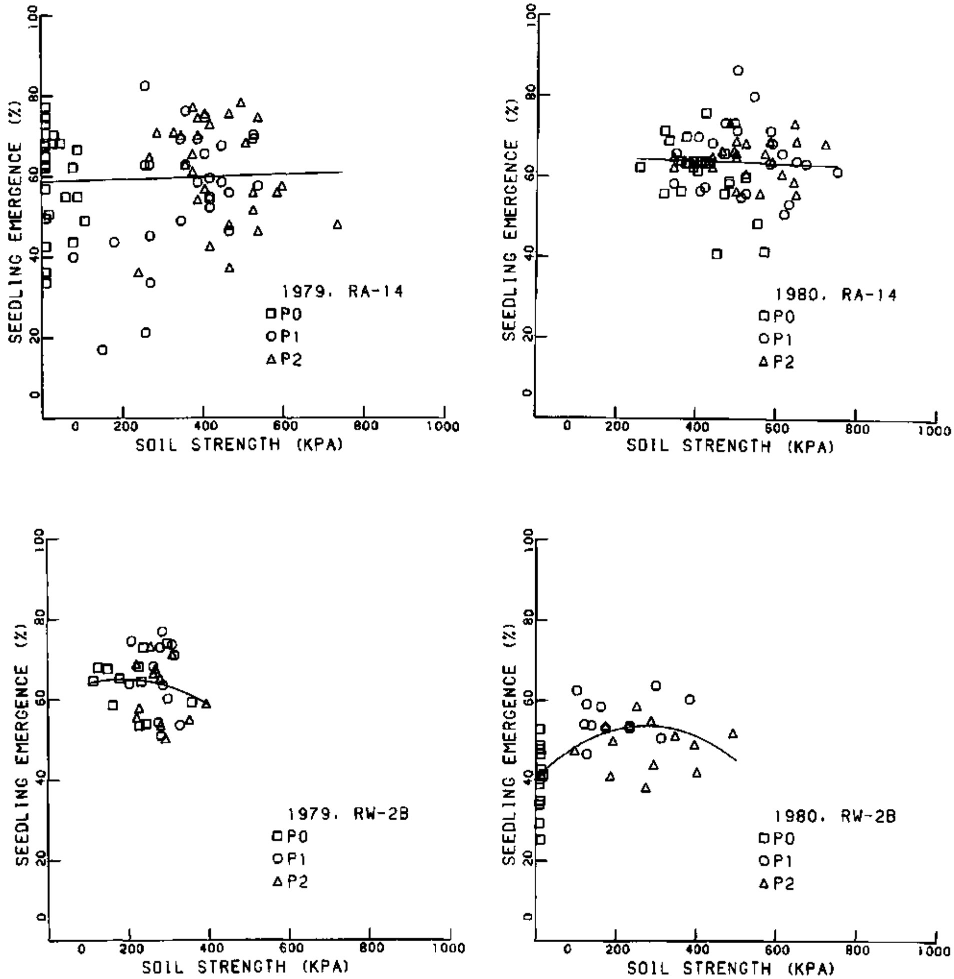


Fig. 52. Effect of planter press wheels on crust strength and final emergence of sorghum.

coefficients of determination less than 1%. The wide range of observed soil strength values, 0 to 780 kPa, is not reflected in a similar range of sorghum emergence percentages. To the contrary, increased compaction levels generally gave higher, be it only modestly, maximum emergence percentages. Thus, there was a positive relationship between pressure applied and crust strenght developed, but the emergence percentage was not affected. In interpreting Fig. 52, it must be realised that the soil moisture contents at which crust strength were measured differed between years and fields, influencing the results considerably. The soil moisture variation during the plant establishment phase is presented in Fig. 53.
Other sources that possibly influenced crust strengths are soil moisture content at the time of planting, and rainfall occurring between the dates of planting and crust measurements.
The following general observations can be made from the two sets of graphs in Figures 52 and 53. The zero soil surface compaction planter treatment result in zero crust strength in 1980 on RW-2B, and in 1979 on RA-14. In both cases, drying conditions without rainfall followed planting, so that a crust did not develop.
However, the zero compaction planting treatment resulted in crust strength levels close to those of the other treatments in 1979 on RW-2B and in 1980 on RA-14, when rain followed planting before crust strength measurement took place. This aspect will be investigated further in the section 'Crust strength versus time'.

By and large, the field experience showed that soil surface compaction increased soil strength substantially, but not with the detrimental effect on stand establishment expected. Apparently, the positive effects arising from seedbed compaction, such as enhanced seed-soil contact, were overriding under the field conditions encountered. The maximum crust strength measured was 780 kPa still below the level reportedly harmfull for sorghum. Parker and Taylor (1965), who used a similar penetrometer (0.48cm diameter probe pushed 0.5 cm into the soil), found that sorghum emergence ceased when the crust strength exceeded 18 kg/cm2. Taylor et al. (1966) used a different penetrometer (0.18 cm diameter) and reported only slightly reduced emergence percentages below 10kg/cm2. Above that level the percentage of emergence dropped off until no emergence occurred above 12 to 18 kg/cm2, depending on soil type. Other factors were not limiting in these experiments, which were conducted on soils with a sandy loam texture.

7.2.3.2.3 Effect Of Planting Method On Crop Yield -

On the whole, the effect of soil surface compaction on crop yield was moderate. In all cases increased compaction led to higher crop yields. Taking the split wheel (PO) treatment as basis, in 1979 on RA-14 and RW-2B and in 1980 on RA-14, yields increased with 5%, 19% and 11%, respectively. Only in 1980 on RW-2B, yields were statistically significantly higher by 43%.
Table 18 shows that the yield increase can be attributed to higher plant populations, except for RW-2B in 1979. In this case, the average weight of the heads was higher, although not statistically significant.

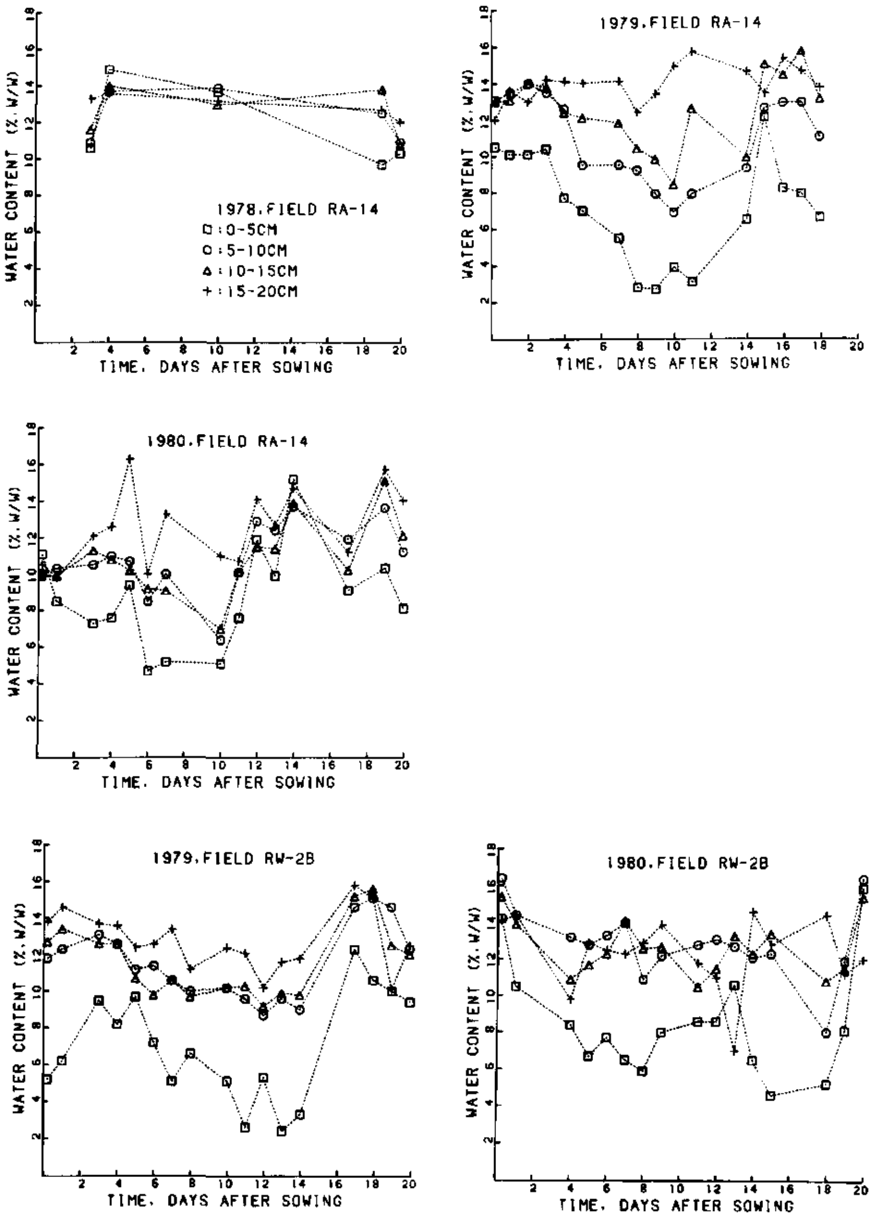


Fig. 53. Soil moisture variation in top 20 cm soil layer during plant establishment.

Table 18. Effect of planting method on crop yield components.

planting method	heads (1000/ha)	yield (kg/ha)	head weight(g)
1979, RA-14			
P0	119	2168	17.5
P1	122	2235	17.6
P2	126	2273	17.2
SE	±4.0	±72.8	±0.95
CV(%)	18	17	28
1979, RW-2B			
P0	162	2843	17.5
P1	162	2967	18.3
P2	153	3147	20.6
SE	±5.9	±154	±1.3
CV(%)	9	13	16
1980, RA-14			
P0	55	957	17.4
P1	61	1073	17.6
P2	61	1142	18.7
SE	±5.2	±149	±1.4
CV(%)	30	48	38
1980, RW-2B			
P0	62	1336	21.7
P1	102	1940	19.0
P2	98	1908	19.4
SE	±6.5	±132	±1.0
CV(%)	26	27	18

7.2.3.2.4 **Decline In Plant Population -**

Plant population seems to have been an important factor affecting yields, because in 1979 plant populations and yields were much higher than in 1980.
In the 1979 rainy season, average plant stands declined on both fields at an decreasing rate. Part of the decline can be attributed to soil covering the smallest seedlings during inter-row cultivation. Probably also competition between closely spaced seedlings played a role.
A dramatic decline in plant stands occurred during the much wetter 1980 rainy season. This was due to an attack of shootfly (Atherigona soccata) while also red hairy caterpillars (Amsacta albistriga), created some damage.

PLANT ESTABLISHMENT

The drop in average plant populations during each season is depicted in Fig. 54.
No difference in rate of decline was observed between tillage and planting methods.

7.2.4 Effect Of Weediness On Plant Stands

An important objective of seedbed preparation is to create an environment which is as free from weeds as possible. Such a seedbed will delay the unavoidable effects of competition with weeds, giving the seedlings a head start.
Secondly, the presence of fairly large quantities of undigested plant material badly interferes with technical requirements of the planting operations. Rhizomes are caught by the planter furrow opener, increasing the soil disturbance so that much wider furrows are formed with less soil to cover the seed. In addition, the soil surface of the bed becomes irregular making early mechanical inter-row cultivation difficult. Phillips (1968) observed reduced cotton stands because seeds were not covered due to interfering weeds.
The initial weed growth was most vigourous on the RA-14 field. Only in 1979 on RA-14, weeds affected plant establishment. Planting was followed by two rainless weeks. Severe moisture stress was visible in the field, particularly in grassy weed patches. Fig. 55 shows the regression of weed dry matter during the first 9 days after planting and plant stands 5 days after planting. This demonstrates the deleterious effect of even fairly low weediness on plant establishment.

7.3 EFFECT OF CRUST STRENGTH ON GERMINATION AND EMERGENCE

7.3.1 Experimental

The results of the tillage field experiments showed a positive effect of soil surface compaction by planter press wheels on the field emergence of pearl millet and sorghum, despite the accompanying increased soil surface strength. Crusts were stronger when rainfall followed planting and when compaction took place in relatively wet soils.
The tentative conclusion was that soil conditions in the seedling zone, particularly the soil-seed contact, were on average positively influenced.

A small plot experiment was set up to evaluate in more detail the effects of compaction on the soil physical characteristics in the seedling zone. It was hoped that crop response, in terms of germination and emergence, could be explained by the different soil physical conditions brought about by compaction.
The highest crust strength observed in the tillage experiments had been still below the level beyond which the ability of the crops to emerge decreased. Therefore, special attention was given to attaining higher maximum crust strengths.

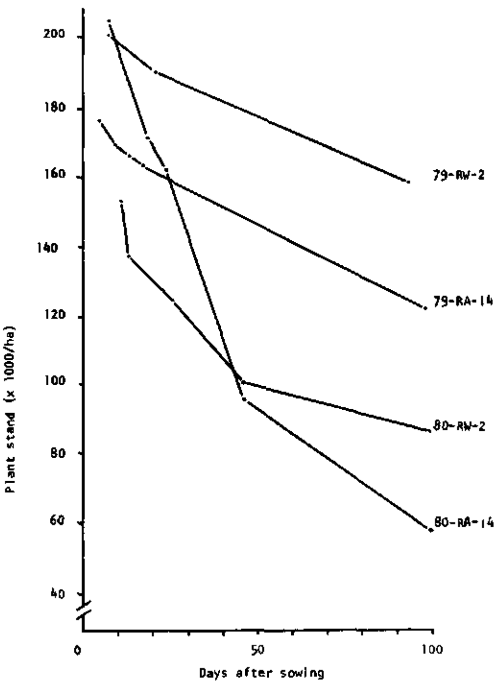


Fig. 54. Decline in plant stands up to harvest of sorghum during the 1979 and 1980 season.

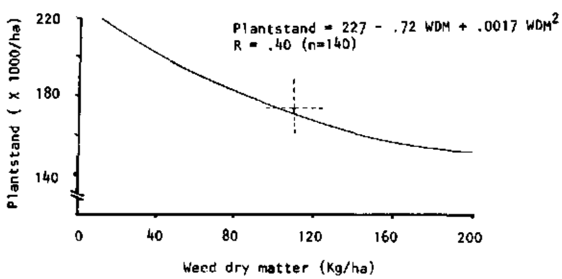


Fig. 55. Effect of weeds in seedbed on plant stand of sorghum five days after planting in RA-14 in 1979.

The experiment was conducted in part of ST-2, an Alfisol area known for its tendency to form crusts, during the winter season of 1978-79. The weather is then generally relatively cool, dry and sunny with a small chance of rain. This enabled simulating seedling emergence and growth during a rainy season under steadily receding soil moisture conditions.
The experimental area was given a good irrigation, followed by a standard seedbed preparation with the seedbed conditioner under optimum soil moisture conditions.
The same planters and press wheels as used in the field experiments, were used to plant sorghum CSH-5 at a rate of 14.4 seeds per meter of row, at an average depth of 5 cm into the moist soil.
Immediately after planting, crusting was induced by applying water from a tractor-mounted sprayer. The boom with the nozzles was set approximately 10 cm above the soil surface of the beds, such that strips of 5 to 7 cm width coinciding with the planted rows received 3 to 4 mm of artificial rain. This small amount of water did not contribute much to the soil moisture, so that main effects could be attributed to the mechanical impedance only. The slower drying rates in the winter season, in combination with the erosive action of the spray, was expected to yield higher crust strength levels (Hillel, 1960; Gerard, 1965).
The statistical design of the experiment was a split plot design in two replications, with crusts assigned to main plots and planter press wheels assigned to sub plots.
The following observations were included, most of them on a daily basis: seedling dry and wet weight, radicle and shoot length, emergence, soil moisture content, and penetrometer resistance. Each set of daily observations required the destruction of 1.5 meter of row to obtain at least 10 samples per treatment. Results of the 10 samples were averaged for the statistical analysis.

7.3.2 Mechanical Impedance And Crop Relations

Both the dry and wet seed weight taken at the third day after planting, did not significantly differ among treatments. Thus, there was no evidence that increasing the compaction level influenced the seed-soil contact such, that a differential beneficial effect on the rate of seed water uptake resulted.
The 3 to 4 mm of water, applied in small bands, in all probability did not increase soil moisture at the seed level; already one day after planting the difference in soil water content between 'crust' and 'non-crust' plots, and between planter press wheel treatments, could no longer be detected. The average soil moisture content in the seedling zone following planting, is given in Fig. 56.

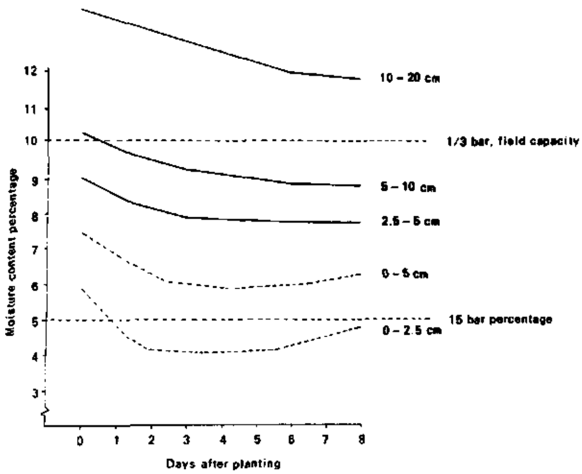


Fig. 56. Soil moisture variation in various soil layers during the establishment of sorghum in December 1978 on ST-2.

The soil moisture availability in all probability was adequate at a level where the oxygen supply was not limiting.

The seedling development, along with the changes in soil mechanical impedance in the seedling environment, is summarised in Fig. 57.
The mechanical impedance, as measured in the 0 to 5 cm top layer, increased as expected with the level of compaction and increased steadily as the soil moisture in this layer evaporated.
Similarly, soil crust strength as measured with the pocket penetrometer, depended on the initial compaction level and either leveled off or even declined as the surface dried out. There was no statistically significant difference in crust strength of the plots which received 'rain', except the crusts of the P2 treatment which were significantly higher four days after planting. A decline in crust strength was also reported by Arndt (1965b), Holder and Brown (1974), Hemsath and Mazurak (1974) , and Bilanski and Verma (1976). A possible explanation is the formation of micro cracks.

Plumule lengths were not statistically different among the treatments, though after four days, when the first seedlings were about to emerge, the plumule growth rate for the P2 treatment dropped, particularly when a crust was present. Plumule lengths five days after planting and crust strengths measured with the pocket penetrometer at day 4, correlated highly significantly at the 1% probability level ($r= -0.691$, with $n=24$).
The behaviour of the correlation looking at various dates with various time lags, is interesting (Table 19). At day 4 most plumules had reached the crust, thus during the next 24 hours (day 5) most seedlings were expected to

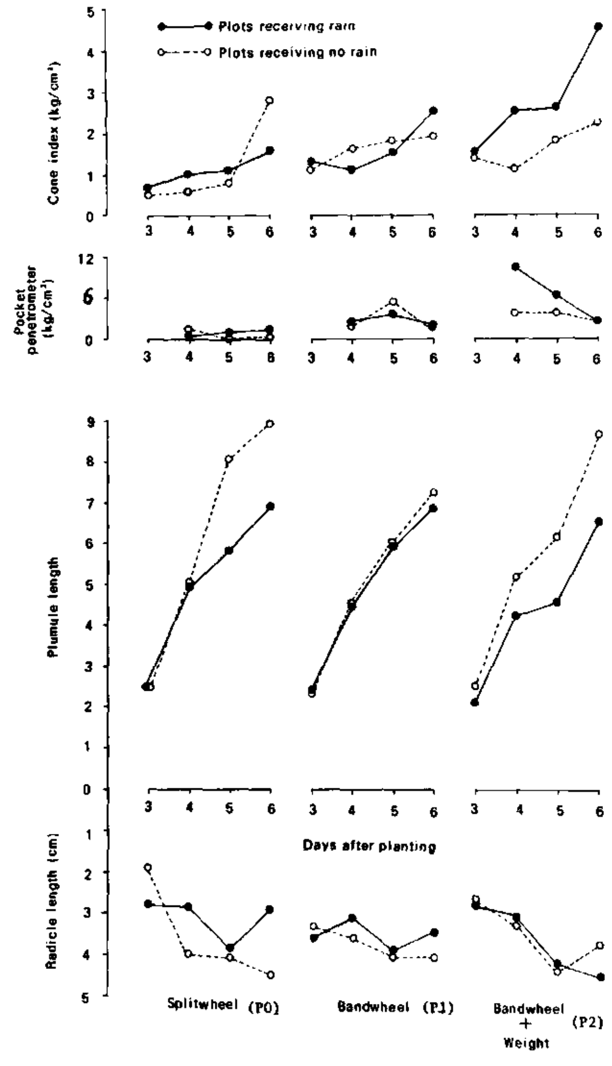


Fig. 57. Soil mechanical impedance, crust strength, and plumule and radicle elongation, as function of time.

emerge and this is probably why the correlation with crust strengths measured one day earlier (day 4) is the highest.

Table 19. Correlation between crust strength and plumule length when measured at various dates and time lags.

day-day crust emergence	r	significance
3-3	-0.353	-
3-4	-0.590	**
4-4	-0.507	*
4-5	-0.691	**
4-6	-0.615	**
5-5	-0.514	*
5-6	-0.496	*
6-6	-0.436	*

*, ** significant at the 0.05 and 0.01 probability level

Radicle growth rates were independent of the applied surface compaction and crusts, which was to be expected since the moderate compaction was of short duration and was applied from a small bearing area. The variability was higher than that of the plumule growth, probably because most of the root growth was in soil beyond the depth of seedbed preparation.

Seedling emergence rate and number were affected substantially by the presence of a crust. However, both in crusted and noncrusted plots, increased soil surface compaction by planter press wheels increased the total number of emerged seedlings, statistically significant, only five days after planting (Fig. 58).

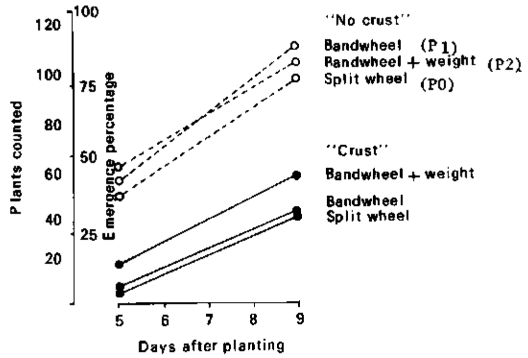


Fig. 58. Effect of planter press wheels on emergence of sorghum from crusted and noncrusted plots.

The effect of the small amount of simulated rainfall was rather surprising. In the P0 treatment, the resulting crust strength was hardly higher than in the untreated plots. Yet, plumule growth rate and number of emerged seedlings were substantially reduced. For the P1 treatment, crust strengths of crusted and noncrusted plots did not differ much either, but here differences in plumule growth rates were not seen.
Yet, emergence differences were quite high. Irrespective, of the different sorghum variety, absence of fertilizer in the root zone, the lower average temperature, and erosive rainfall in the more clayey Alfisol, similar relationships existed between the compaction, ensuing crust strength, and emergence performance as in the tillage trials. Though the maximum crust strength was higher, at 1400 kPa thus close to the level reported to prevent emergence, also in this case increasing compaction increased the emergence percentage.

7.3.3 Crusts Strength Versus Time

After arrival of the rains, Alfisols are planted as soon as possible when still relatively wet. Planting operations continue, in the absence of further rains, until the soil it is considered to have become too dry for succesfull plant establishment. A considerable difference in the soil physical environment then exists between the seeds planted first and those planted last.
The initial wet soil is sensitive to compaction, but soil moisture conditions on the average are better for seedling emergence. The last batch is planted in relatively dry soil, with chances that an erosive rainfall soon after planting creates a crust.
On ST-2, complementary experiments were carried out in which planting was simulated using the same planter and press wheels, but without seed, both in wet soil and in initially dry soil. In the latter case, 25 mm of water was applied in the planter tracks as before. The effects of the different press

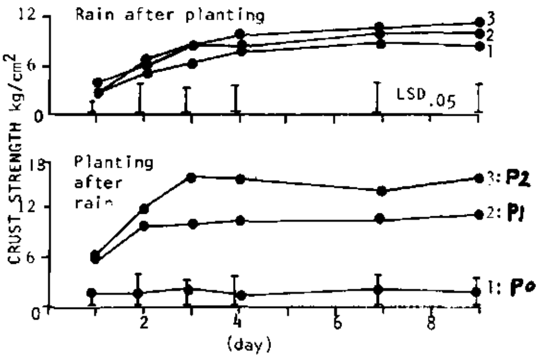


Fig. 59. Crust development under drying conditions for various press wheels in relation to soil moisture content before and after planting.

wheels were also studied and results are shown in Fig. 59.

Evidently, rain after planting created crusts, with strengths independent of the press wheel compaction level. Thus, if an erosive shower would occur immediately after planting, a split wheel would not prevent the buildup of a crust. On the other hand, compaction showed advantages in the absence of rain.

Under wet conditions during planting, large compaction efforts resulted in high crust strengths, though not at dangerous levels under the tillage experimental circumstances.

Unfortunately, crust strengths tended to reach maximum values when the soil moisture content in the upper layer leveled off, which was after three days. Even if shallow planting were feasible, at the time of emergence crust strengths would already be close to their maximum value, so that this would not provide a means to escape the possible harmfull effects of a crust.

7.4 DEPTH OF PLANTING

7.4.1 Introduction

The potentially rapid changes in soil moisture status of a seedbed dictate a high degree of planting depth accuracy to obtain uniform stands.

Under conditions of rapidly declining soil moisture, increasing the planting depth increases the time available until soil moisture is depleted to a certain level.

However, the ability of the seedling to emerge from greater depth is limited by the energy reserve stored in the seed. Even when seedling emergence is accomplished, the greater the depth from which the seedling emerges the weaker it will be as it reaches the soil surface. For average circumstances, these opposite effects yield an optimum range of planting depths. The smaller the seed, the narrower this range and, therefore, the more critical it is to place the seed accurately.

Obviously, the first requirement is that the roughness of the seedbed decreases as the optimum planting depth becomes shallower. But even when micro-roughness conditions for a seedbed are met, much depends on the uniformity of the surface and the functioning of the planters. As explained earlier, the planter furrow opener remains in a fixed position with respect to the tool carrier. Depth accuracy, therefore, will largely depend on the uniformity of the bed and furrow. When the toolcarrier rides over stones or rubbish in the furrow, the planter furrow openers will be lifted and the seeds will be placed too shallow or even on the soil surface.
At the time of the experiments, no data were available on the potential of the BBF-system of cultivation to maintain a set planting depth and its influence on plant establishment.

7.4.2 Measuring Planting Depth

7.4.2.1 Method -

Seed depth distributions were evaluated from soil surface elevation measurements in planter tracks, similar to a method used by Colwick et al. (1971). The instrumentation, diagrammatically presented in Fig. 60 enabled the continuous recording of the soil surface made by the planter press wheel.
A linear displacement meter was actuated by the up and downward movement of the hinged bracket in which the wheel followed compacting the seedbed. The displacement meter, essentially a straigth sliding potentiometer, was fed from a 12V car battery through a voltage stabilizing circuit. The output was recorded continously with a strip chart recorder.
The band rim press wheel of the P1 planting treatment was used in this case, because it left a distinct track without soil rolling back, so that the elevation measurement could be related directly to planting depth distribution.

During the planting of the 1980 rainy season crop on RA-14, one run over the 80 m long bed was monitored for each primary tillage method, while maintaining the usual forward speed. Later, seedlings were excavated from the same beds over 3 meter of row to measure the seed depths and their distribution for comparison with the depth distribution estimated from the recorded elevation data. In addition, dry matter of the seedlings were determined.

7.4.2.2 Seed Depth Distribution -

A section of a typical strip chart output of the continuous elevation recording is shown in Fig. 61.
Elevation point data were sampled by scaling the chart, every 2.5 mm corresponding to approximately 10 cm of forward travel in the field. This procedure yielded for each tillage method over 500 data points, from which histograms of the depth frequency distribution were constructed (Fig. 62).
Prior to planting, the usual visual check on the desired average planting depth of 5 cm was carried out by excavating the seed furrow. The furrow openers were set and remained in the same position during the elevation

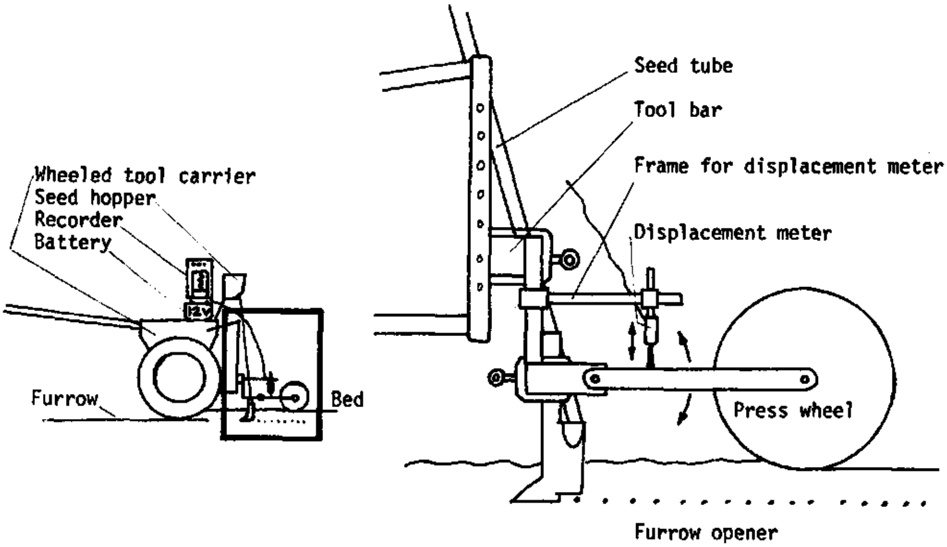


Fig. 60. Overview and details of instrumentation for continuous recording of soil surface elevation of seedbeds.

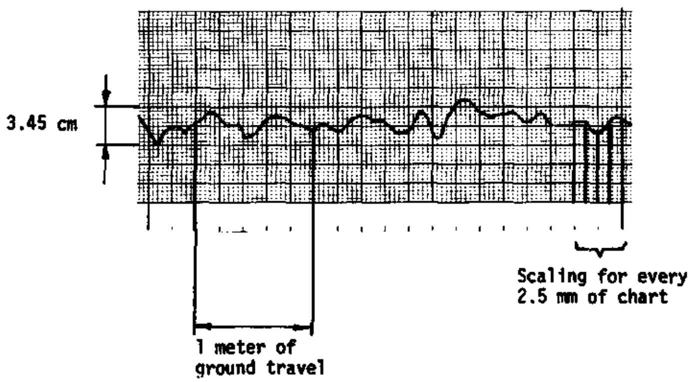


Fig. 61. Typical strip chart output of soil surface elevation measurement with band rim planter press wheel.

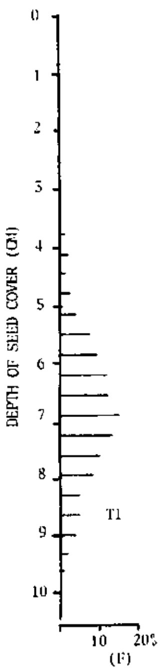


Fig. 62. Effect of primary tillage on seed depth distribution, based on soil surface elevation measurements.

measurements on all four beds. This caused a difference in average depth of planting, the greatest depth being expected for the T1 tillage method because the pre-sowing seedbed was loosened to a greater depth, thereby rising its mean soil surface level.

The four sets of data were tested statistically for normality; the details are presented in Table 20. Only in one case the frequency distribution departed significantly from normality. The uniformity of planting depth is expressed as the standard deviation of the elevation data from their mean.

Table 20. Average depth, standard deviation, kurtosis and skewness based on soil surface elevation data in cm.

	tillage method			
	T1	T2	T3	T4
average depth	6.7	4.1	3.7	4.0
standard deviation	0.95	0.93	0.81	0.77
kurtosis	2.88	3.48*	3.02	2.72
skewness	0.04	0.64**	0.48**	0.11
number of readings	678	642	587	739

* departs from normality
** significantly skewed

Heege (1973) reported a standard deviation of 0.6-1.1 cm obtained with a minimum tillage seed drill for cereals. A 'mere' 0.6 to 1.6 cm was reported by Estler (1978) for similar machines. Where these are examples of highly controlled and mechanised agriculture, Foster (1980) carried out research in Botswana on planting equipment suitable for animal draft. He reported typical standard deviations of 1.5 cm for contour-following planters, while planters with coulters fixed rigidly on a tool bar clearly performed less, yielding a standard deviation of 2.5 cm due to the variable compactibility of the soil underneath the tool bar wheels.
The low standard deviations measured in the BBF-system of cultivation compare well with those from the above-mentioned literature.

Outside the experimental area, a 3-m row of seedlings was excavated per tillage treatment for verification of the actual seed depths. The planting depth of individual seedlings was readily measurable with the seed coat still intact.
A limited number of 20 to 25 seedlings per tillage treatment was thus sampled. The average planting depth and standard deviation (in parentheses) for T1, T2, T3 and T4 were 5.2 cm (0.76), 4.1 cm (0.94), 5.4 cm (0.93) and 4.2 cm (1.06), respectively.
These results deviate only slightly from the displacement meter data, confirming the low standard deviations.

7.4.2.3 Seed Depth And Seedling Development -

The following observations deal with the small sample of seedlings excavated fourteen days after planting. The seedlings showed large individual differences in development (expressed in dry weight of the above ground parts). It appeared that seedlings originating from shallow placed seeds were considerably ahead of the more deeply placed seeds. Fig. 63 shows significant linear relationships between the depth of placement and the seedling dry weight for each tillage treatment and all taken together, except for the T1 primary tillage bed.
The heaviest seedlings were the tallest at 30 cm, while the laggards were only 7 cm high.
A reason may have been that the seedlings from shallow planted seeds benefitted more from the di-ammonium phosphate fertilizer placed only slightly

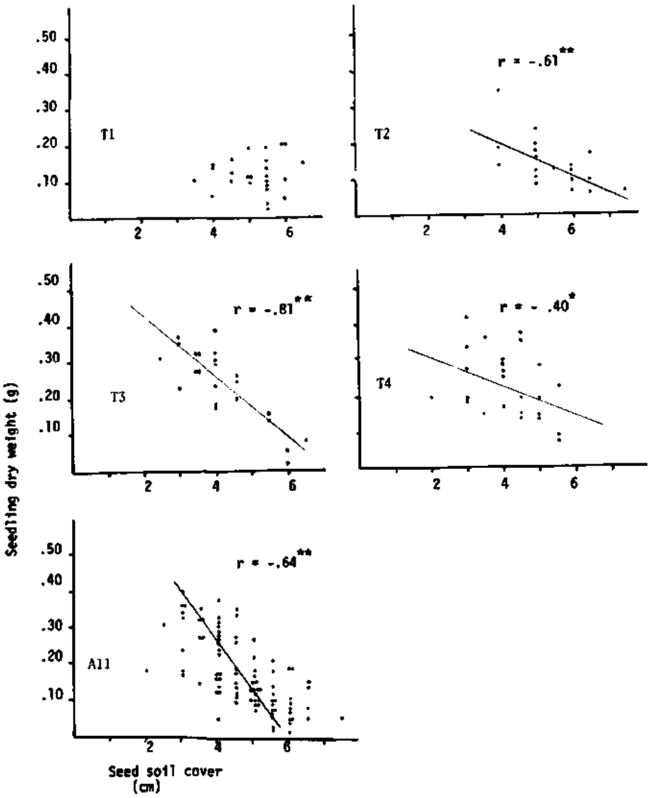


Fig. 63. Relationship between seed soil cover and seedling development of sorghum 14 days after planting in RA-14 in 1980.

deeper prior to planting. The substantial difference in development and height may have contributed to the rapid early decline in plant stands, in that seedlings having a favourable size were available to the shootfly for a longer period of time.

Also, the competition between crop plants and with weeds may have caused the death of the poorly developed seedlings. In addition, inter-row cultivation killed part of the smallest plants by soil coverage.

7.4.3 Simulation

Suppose a crop with a very narrow planting depth range for successfull emergence, is planted in a nonlevel seedbed. The total percentage of emergence then will be low, because a substantial part of the seeds is placed either too deep or too shallow.

PLANT ESTABLISHMENT

Assuming a normal distribution of soil elevation over the seed, the total emergence of a crop planted at a particular average depth can be calculated if the relationship of seed depth versus emergence is known.
This procedure would give insight into the potential benefit of the time and energy spent in seedbed preparation.
The model needs as input the seedbed property describing the standard deviation of surface elevations and the average depth of planting, as well as the relationship of crop emergence versus planting depth.
The model output gives information about the emergence of the seeds placed at varying depths around the average set planting depth.
Two steps carried out repeatedly are:

step 1: evaluate the probability of seeds falling within a choosen (small) interval starting at the set depth (D): for instance D+3s with s equal to the standard deviation.

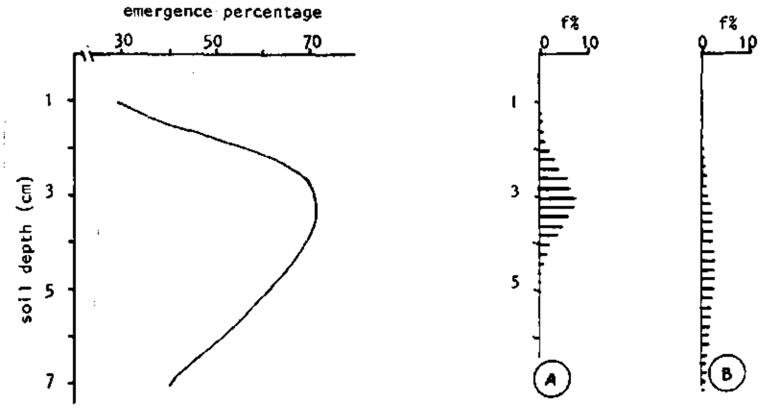
step 2: multiply the above probability with the average expected emergence over the interval.

Step 1 and step 2 must be repeated until the full range of planting depth (D+3s through D-3s) is covered.

The outcome of such a planting simulation is presented in Fig. 64 on the basis of a depth - emergence relationship of pearl millet obtained from experiments in Mali (Hoogmoed, 1981). The depth interval was chosen at 0.2 cm, so the contribution of successive 0.2 cm layers to the total emergence percentage can be seen.
It was assumed that the seedbed preparation and planting technique would result in an average planting depth of 3 cm, with a standard deviation of 0.7 cm. This describes a rather perfect situation, which results in a simulated total emergence percentage of 66%. A second case assumed a seedbed with a higher roughness of 1.7 cm and a planting depth of 5 cm. Not only drops the total emergence to 49%, a much greater time span between the first and last emergence results. As seen from excavated seedlings, the generation gap can have considerable consequences, since the latest emerged seedlings are more susceptible to competition, which may further reduce plant stands.

Emergence was simulated for a range of planting depths and standard deviations. Fig. 65 shows that the total emergence percentage drops when planting depth is not set accurately. Also, the total emergence percentage drops when the standard deviations (or seedbed roughness) increases. The optimum planting depth shifts as the standard deviation increases, a result of the asymetric depth - emergence relationship in this case.

The depth - emergence relationship as described integrates the effect of the particular initial condition of the seed environment and its ensuing conditions. As such, a whole family of relationships would exist.
However, it would seem feasible to select only a few of these relationships on the basis of average expected initial soil moisture conditions and subsequent evaporative demand. The simulation would then give an indication about the importance of the effect of seedbed preparation and planting depth on crop emergence.



Emergence of Pearl Millet in relation to planting depth (source W.B. Hoogmoed)

Frequency distribution of simulated plant emergence per .2 cm layer.

a. planting depth 3 cm, σ=.7 cm total emergence 66%

b. planting depth 5 cm, σ=1.7 cm total emergence 49%

Fig. 64. Simulated layerwise contribution of planting depth and seedbed roughness to the total emergence of pearl millet, based on an established planting depth-emergence percentage relationship.

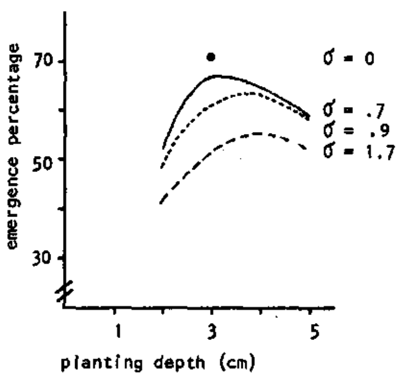


Fig. 65. Simulated effect of planting depth on emergence percentage of pearl millet, assuming seedbeds with different roughness values.

7.5 CONCLUSION

There was no evidence that soil crusting affected the establishment of the rainy season crops on the Alfisol during the tillage field experiments.
Increased levels of compaction of the soil covering the seed did result in stronger crusts, apparently still much below the levels which are harmfull. Contrary to general believe and expectation, positive effects of compaction prevailed as both plant populations and yields were generally higher.

Through which mechanism compaction was beneficial, could not be ascertained. The complementary trial on ST-2 did not provide evidence that seedlings developed faster because of improved seed-soil water contact. In this experiment, in which a crusting treatment was superimposed on the planting methods, crusts seriously retarded emergence over non-crusted plots, but in either case compaction increased stands.

No doubt, there are two prerequisites for a seedbed to obtain adequate stands. In the first place, it should be as free from weeds as possible, since weeds spoil the proper action of planter furrow openers, thereby affecting the seed placement. In addition, already small amounts of weeds reduced plant stands during a dry establishment period. Secondly, the seedbed must be capable to accept seeds at the desired depth. The seeding depth measurements showed that the BBF-system in conjunction with the seedbed conditioner can maintain the set planting depth within narrow limits.
Even then, the development of sorghum seedlings grown from the shallowest placed seeds was much ahead of that of the deeper placed seeds. This may reduce plant stands in a later stage because of interspecies competition; also, part of the smaller seedlings will be killed during the first inter-row cultivation. These effects will be more pronounced as the seedbed quality is lower.

The reported serious shortcomings in crop establishment during rainy season cropping on Alfisol watersheds is likely the result of inadequate seedbed preparation, both in terms of weediness and wider range of seed placement depth.

CHAPTER 8

SUMMARY

Tillage field experiments were conducted on Alfisols in a semi-arid tropical environment in India. The research was conducted within the framework of the Farming Systems Research Program of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

To put the experiments into perspective, a general review is given in chapter 2 on the environment of the semi-arid tropics, its problems and the research related to agricultural production. Rainfed agriculture has failed to provide a stable and sufficient food supply for the populations of many developing countries. An important reason is the severe physical constraint to agricultural production imposed by the harsh climate. Water is the key factor and though the average total precipitation appears to be sufficient for cropping, its distribution is highly erratic. Much of the rain falls in high intensity storms, resulting in uncontrolled runoff and erosion. Thus a high proportion of the water is lost for crop use.

The majority of as much as 500 million people living in the world's semi-arid tropics, depend on agriculture for income, food and shelter. During the last three decades, populations have doubled in many of the 48 countries which are at least partly located in the semi-arid tropics.

Since the indigenous production systems are characterised by stagnant yield levels, hitherto stable forms of agriculture came under immense pressure by the attempt to continue to provide sufficient amounts of food and fiber for the rapidly growing populations. The farmers were compelled increasingly to expand their agricultural activities to more marginal lands.

Consequently, the production potential of the resource base is threatened seriously and vast areas already have been damaged permanently further destabilizing agricultural production.

To improve a situation of recurrent food shortages, governments tended to concentrate their resources on improving agriculture in water-assured areas. With the advent of high yielding varieties of wheat and rice, this strategy proved succesfull.

In India it was realised that continuing such a policy would further widen the gap with dryland farmers, as it creates 'islands of prosperity in a sea of poverty'. Furthermore, there is a physical limit to the area that potentially can be irrigated. A high proportion of the nation's food requirements would still have to be met by rainfed agriculture. So, unless yield levels and stability are improved in this segment of farming, a few poor monsoons in succession would still lead to serious food problems.

Therefore, research on dryland agriculture was revived, but met with limited

and varying results. Either too much emphasis was given to genetical improvement of the seeds, or major attention was given to soil and crop management aspects. The proposed technologies did not fit well into the farmers traditional cropping systems, in which crop yield security is important.
In 1972, ICRISAT started to work on the improvement of dryland crops. From the outset, it was recognized that the lack of a suitable technology for soil and water management and crop production systems, was a primary constraint to agricultural development in rainfed farming. A farming systems research program was developed. A so-called watershed based research program evolved, with the underlying filosophy that the only water available to the common farmer comes from rain falling on a limited area. Therefore, small natural watersheds comprising several field-scale units, became the testing ground for promising new technologies.
During the first period, attention was focussed on developing improved soil and water conservation and cropping systems suitable for deep Vertisols.

In Chapter 3, the role of tillage is described generally , and specifically the zonal-tillage concept.
A 'broad bed and furrow' (BBF)-system, based on the zonal-tillage concept, provided a breakthrough for these soils, in which tillage operations are difficult both under wet and dry conditions. The indigenous practice of rainy season fallowing could be replaced by rainy season cropping, as new technology facilitated dry planting at the onset of the monsoon, while primary tillage could be executed after harvest of the second crop. As a result, the rainfall use efficiency increased tremendously and soil erosion was curbed. The BBF-system was fully operable with the use of a multi-purpose tool carrier drawn by a pair of bullocks.
Unfortunately, the system was less succesfull on Alfisols. These soils are structurally weak, the surface becoming smooth and sealing readily due to the impact of rain. At the beginning of the rainy season, substantial portions of the precious water run off even from yet unsaturated soil profiles. Plant establishment proved difficult and crusting was believed to cause poor, spotty plant stands.
Because the BBF-system features many advantages, it was felt worthwhile not to abandon the system, but to try to improve its performance by adapting the tillage component.

In Chapter 4, the experimental setup of the tillage field experiments is described.

In Chapter 5, the effects of primary tillage in terms of soil response and its effects on crop growth are discussed. By varying depth and principle of tillage on the beds, infiltration characteristics were expected to be influenced. Different soil surface conditions, in terms of soil surface roughness and storage provided by the increased pore space in the tilled zone, were thus created. In particular, the newly developed tillage treatment (T1) (Fig. 12), in which the whole width of the beds was tilled at the greatest depth, proved superior in intercepting rainfall. The increased soil roughness was shortlived but the effect on pore space lasted throughout the season. The latter aspect, therefore, seems important with respect to water conservation.
Yield increases were positively related to increasing levels of primary tillage, particularly so when soil moisture was limiting. The T1 tillage method performed best in this respect, thereby contributing in stabilizing

yields. The limiting moisture supply was partly due to the growth of weeds. Tillage played a pervasive role in weed control throughout the year. The soil-inverting primary tillage methods facilitated seed bed preparation. Weed regrowth after this type of tillage was delayed compared to the non-inverting methods, thereby providing a temporary advantage. By and large, the effect of primary tillage on the amounts of weeds had disappeared during the plant establishment phase. This is not surprising as all tillage methods were essentially at the minimum tillage level.

Weed management in the standing crop is essential. Chapter 6 gives a review on the impact of weeds on crop production. It appeared that chemical weed control is not an economically viable option in India for some time to come. Thus, only inter-row cultivation, handweeding and combinations of these were evaluated in the tillage experiments. The potential growth of weeds was tremendous. General weediness levels varied substantially between years and fields, independent from the tillage system. If allowed to grow, the highest measured weediness level at harvest was 6.7 t/ha. Throughout the experiments uncontrolled weeds reduced yields by 10% to 90%. Weed management could greatly reduce weediness levels in the crop. Where inter-row cultivation was practised, inter-row weeds were adequately controlled. However, intra-row weeds developed unchecked and these reduced crop yields considerably, especially in pearl millet. Handweeding proved to be a must for acceptable yields, a supplementary in-the-row weeding after inter-row cultivation being a satisfactory compromise. The effect of weeds on crop yields was partly due to plant population reduction because of competition, but remaining plants also performed less on an individual basis.
The toolbar system allows weeding in tall growing crops for a limited time of 4 to 5 weeks after sowing. When weeds develop after the period in which they affect crop yields, a handweeding may still be desirable; certainly when a sequential crop is considered, but also to prevent the weeds from shedding seeds and to facilitate post-harvest tillage.

In Chapter 7, plant establishment problems are discussed, as well as various planting method options tested in the field. Poor and uneven stands is one of the major causes of low crop yields in the semi-arid tropics. In Alfisols, crusting was believed an impediment to adequate stands. In the tillage field experiments, plant establishment was given attention but plant establishment was invariably succesfull in all tillage methods. There was no evidence that crusts developed such that crop emergence was hindered. Seed bed compaction by planter press wheels increased crust strength, but apparently it still remained below a harmfull level. In fact, increasing compaction effort increased plant stands and crop yields significantly in a number of cases. An explanation could not be given in terms of improved water supply to germinating seeds and developing seedlings.
But it appears that two aspects of the seed bed are extremely important. Firstly, the presence of weeds affect the proper functioning of the planter furrow opener, making seed placement less consistent. When a dry plant establishment period follows, even small amounts of weeds proved to reduce stands considerably. Secondly, the uniformness of the seedbed is important.
Evaluation of the consistency of seed placement depth following the various tillage methods revealed a high degree of control. Seed depth was normally distributed with standard deviations of less then 1 cm. The importance of placing the seeds exactly was demonstrated in that seedlings from deeper placed seeds were retarded, even within the narrow depth range achieved. As a

consequence, in the field inter-row cultivation must be delayed or part of the smaller seedlings must be sacrificed. Also, competition between crop seedlings may prevent the laggards to become productive.
The simulation of the effect of seed placement on emergence showed that the seed bed quality and planting depth have a profound effect not only on total emergence percentage, but also on the uniformity of seedling development.

In conclusion, the performance of the BBF-system of cultivation in Alfisols can be improved by increasing soil surface roughness and plow layer storage. A new technique of primary tillage, the T1 tillage method, proved best in this respect. In addition, the method features operational advantages as bigger amounts of crop residue and weeds can be handled without clogging the implements. Seed bed preparation is of crucial importance, particularly freedom from weeds and depth uniformity. Compaction of seed beds by planter press wheels contributes positively to plant stands and crop yields. Crusts did not hinder crop emergence at all.
Because none of the evaluated primary tillage methods exceeded the minimum tillage level, weeds developed vigorously soon after planting. For such conditions inter-row cultivation alone proved insufficient to keep weeds in the crop at acceptable levels. Then, supplemental handweeding was absolutely essential for good crop yields.

CHAPTER 9

SAMENVATTING

Grondbewerkings proeven werden uitgevoerd op Alfisolen in een semi-aride tropisch gebied in India. Het onderzoek werd verricht binnen het kader van het 'Farming Systems Research Program' van het International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).

Teneinde de experimenten in de juiste context te plaatsen wordt in Hoofdstuk 2 een algemeen overzicht gegeven van de natuurlijke omstandigheden van de semi-aride tropen, de problemen en het onderzoek ten behoeve van de landbouw. Met de van regen afhankelijke landbouw is het veelal niet gelukt de bevolking steeds van voldoende voedsel te voorzien. Een belangrijke oorzaak is de fysieke beperking waaraan de landbouw onderhevig is door de klimatologische omstandigheden. Water is de belangrijkste factor; hoewel de totale regenval vaak voldoende lijkt voor akkerbouw, is de verdeling ervan zeer onregelmatig. Veel regen valt in hevige buien die aanleiding geven tot oppervlakte-afstroming en bodemerosie. Op deze wijze gaat een groot deel van het water voor het gewas verloren.
Het overgrote deel van de 500 miljoen mensen die over de wereld verspreid in de semi-aride tropen leven zijn voor hun bestaan afhankelijk van de landbouw. Gedurende de afgelopen dertig jaar is de bevolking verdubbeld in vele van de 48 landen die deel uitmaken van de semi-aride tropen. Stagnerende niveaus van opbrengsten zijn kenmerkend voor de bevolkingslandbouw, en tot dusver evenwichtige produktie systemen kwamen onder zware druk te staan om te kunnen blijven voorzien in een voldoende aanbod van landbouwprodukten voor de snelgroeiende bevolkingen. Boeren werden gedwongen in toenemende mate hun bedrijfsactiviteiten naar meer marginale gronden uit te breiden.
Het gevolg is dat de natuurlijke produktie capaciteit van de grond ernstig in gevaar komt, uitgestrekte gebieden zijn daarbij al onherstelbaar vernield met als gevolg een toenemende instabiliteit van de landbouwproduktie.
Om herhaalde voedseltekorten een halt toe te roepen, hebben regeringen de hen beschikbare middelen vooral aangewend ter verbetering van de landbouw in die gebieden waar op water gerekend kon worden. Deze strategie bleek een succes, vooral door de introduktie van nieuwe varieteiten van rijst en tarwe.
In India realiseerde men zich dat het voortzetten van deze politiek de kloof met de boeren welke voor water uitsluitend van regen afhankelijk waren, verder zou verwijden en zou resulteren in 'eilanden van welvaart in een zee van armoede'. Bovendien is het areaal dat geirrigeerd kan worden, beperkt. De van regen afhankelijke landbouw zou nog steeds moeten voorzien in een groot deel van de nationale behoefte aan voedsel. Tenzij opbrengstniveaus en stabiliteit van de produktie in deze tak van landbouw worden verbeterd, kunnen

enkele achtereenvolgend tegenvallende moessons nog altijd tot ernstige verstoringen in de voedselvoorziening leiden.
Nieuw leven werd ingeblazen in het onderzoek ten behoeve van de 'droge landbouw', echter met geringe en wisselende resultaten. Soms werd teveel nadruk gelegd op het verbeteren van gewassen, in andere gevallen werd de aandacht beperkt tot cultuurtechnische en teelttechnische maatregelen. De gepropageerde technieken pasten niet in de traditionele landbouw systemen, waarbij opbrengstzekerheid voorop staat.
In 1972 begon ICRISAT met het verbeteren van droge landbouwgewassen. Reeds vanaf het begin werd onderkend dat het ontbreken van een geschikte technologie voor vocht- en bodemconservering, alsmede een geschikte gewassenkeuze een hoofdbelemmering was voor de ontwikkeling van de van regen afhankelijke landbouw.
Een Farming Systems Research Program werd opgezet. Hieruit ontwikkelde zich een zo genoemd 'watershed-based' onderzoeksprogramma. De onderliggende gedachte was dat de voor de gemiddelde boer beschikbare hoeveelheid water afkomstig is van regenval op een beperkt oppervlak. Om deze reden werden kleine drainage bekkens, met daarin kavels van veldafmetingen als proefgebied gekozen om veelbelovende technieken aan de praktijk te toetsen.
Aanvankelijk werd vooral aandacht besteed aan de ontwikkeling van een verbeterde vocht- en bodembeschermingstechniek en gewasrotaties, geschikt voor de zware, diepe Vertisolen.

In hoofdstuk 3 wordt de rol van de grondbewerking in het algemeen, die van bewerkingszones in het bijzonder behandeld.
Een system van permanente bedden, gebaseerd op het principe van grondbewerkingszones, vormde een doorbraak voor de behandeling van deze zowel in droge als natte omstandigheden zeer moeilijk bewerkbare gronden. De gebruikelijke methode, het land braak te laten liggen tijdens het regenseizoen kon worden vervangen door de verbouw van een gewas in de regentijd, dankzij een nieuwe techniek welke zaaien in droge grond juist voor de regens mogelijk maakt. De hoofdgrondbewerking wordt daarbij uitgevoerd na de oogst van een tweede gewas. Hierdoor wordt de regenval een stuk doeltreffender benut, terwijl de erosie binnen de perken gehouden wordt. Het bedden systeem kan met behulp van een door twee trekdieren voortbewogen werktuigraam volledig operationeel gemaakt worden.
Helaas werkte dit systeem minder goed op Alfisolen. Dit soort gronden hebben een zwakke struktuur, het oppervlak wordt door regenval vlak en de grond slaat dicht. Al tijdens de aanvang van de regentijd stroomt een aanzienlijk deel van het water af, zelfs als het profiel nog niet verzadigd is. De opkomst en stand van het gewas liet doorgaans te wensen over wat toegeschreven werd aan korstvorming.
Omdat het beddensysteem veel voordelen biedt leek het de moeite waard dit systeem niet zonder meer te verwerpen, maar te trachten de grondbewerkingsmethoden aan te passen voor Alfisolen.

In Hoofdstuk 4 wordt de proefopzet van de grondbewerkings veldproeven beschreven.

De effecten van de hoofdgrondbewerking op de grond die mede van invloed zijn op het gewas, worden behandeld in Hoofdstuk 5. Door verschillende diepte en wijze van grondbewerking van de bedden werd gepoogd de infiltratie van water te beinvloeden. Dit resulteerde in verschillende oppervlakte ruwheden en vochtberging van de bovenlaag.

SAMENVATTING

De ontwikkelde T1 grondbewerkingsmethode (Fig. 12), de diepste bewerking over de gehele breedte van het bed, bleek de regenval het beste vast te houden. Hoewel de grotere oppervlakte ruwheid kortstondig was, bleek het effect op de porositeit een seizoen lang stand te houden. Vooral dit aspect lijkt daarom van belang voor de vochtconservering.
Met het toenemen van de diepte en de intensiteit van de grondbewerking werden hogere opbrengsten verkregen, vooral bij vocht gebrek. De T1 methode had de beste resultaten en had zodoende een stabiliserend effect op de opbrengst. Het vocht tekort was voor een deel te wijten aan onkruidgroei. Grondbewerkingen spelen een belangrijke rol in het beheersen van onkruidgroei gedurende het hele jaar. Na de kerende bewerkingen was zaaibed bereiding eenvoudiger dan bij de niet kerende. De hergroei van onkruid was trager waardoor een tijdelijk voordeel werd verkregen. Over het algemeen was de invloed van de hoofdgrondbewerking op onkruidgroei niet meer merkbaar na de opkomst van het gewas. Dit is niet verbazingwekkend, omdat zonder uitzondering de beproefde methoden tot de 'minimale grondbewerking' gerekend kunnen worden.

Onkruidbestrijding tijdens de groei van het gewas is essentieel. Een overzicht van de invloed van onkruid op de gewasproduktie wordt gegeven in Hoofdstuk 6. Het bleek dat chemische onkruidbestrijding voorlopig economisch niet haalbaar is in India. Daarom werden uitsluitend mechanisch wieden, wieden met de hand, en combinaties hiervan betrokken in de proeven. De potentiele groei van onkruid bleek enorm. In het algemeen varieerde het onkruidbezwaar zeer sterk van jaar tot jaar, en tussen de velden, onafhankelijk van het grondbewerkingssysteem. Bij een onbelemmerde onkruidgroei werd als hoogste 'opbrengst' bij de oogst 6.7 t/ha gemeten. Onbelemmerde onkruidgroei reduceerde de gewasobrengst van 10% tot 90% tijdens de proeven. Door wieden werd de hoeveelheid onkruid in het gewas aanzienlijk gereduceerd. Bij mechanisch schoffelen tussen de rijen werd het daar aanwezige onkruid voldoende bestreden, maar de onkruiden in de rij groeiden onbelemmerd en veroorzaakten een aanzienlijke opbrengst derving, in het bijzonder bij gierst. Wieden met de hand bleek absoluut noodzakelijk voor een goede opbrengst, waarbij aanvullend wieden in de rij na mechanisch schoffelen een goed compromis was. De invloed van het onkruid op de gewasopbrengst was gedeeltelijk het gevolg van een door concurrentie verminderd aantal planten, maar ook de overblijvende planten brachten minder op.
Het werktuigraam systeem laat slechts een vijf- tot zestal weken lange periode na het zaaien toe waarin gewied kan worden. Wanneer onkruiden zich ontwikkelen na de periode waarbinnen ze nog een ongunstige invloed op de opbrengst hebben, kan hand wieden toch nog wenselijk zijn, vooral als aansluitend een tweede gewas gezaaid zal worden, maar ook teneinde uitzaaing te voorkomen en om de stoppelbewerking te vergemakkelijken.

Problemen, verbonden met de opkomst van het gewas worden besproken in Hoofdstuk 7, alsmede de verschillende zaaimethoden welke beproefd zijn in het veld. Een dunne en onregelmatige stand is een van de oorzaken van lage opbrengsten in de semi-aride tropen. Aangenomen werd dat korstvorming een goede opkomst belemmerde. Dit aspect werd bestudeerd in de veldproeven , in alle gevallen echter bleken opkomst en stand van het gewas zonder meer een succes. Er waren geen aanwijzingen dat korsten van voldoende sterkte ontstonden om de opkomst nadelig te beinvloeden. Het aandrukken van de grond met drukwielen van de zaaimachine deed de sterkte van de korst weliswaar toenemen, maar blijkbaar nog beneden het niveau dat nadelig werkt. In feite

werden hogere plantaantallen en opbrengsten verkregen bij toenemende belasting van het drukwiel, in enkele gevallen was dit significant. Hiervoor kon geen verklaring gegeven worden door bijvoorbeeld een verbeterde vochtvoorziening van zaad en zaailing.
Het blijkt wel dat twee zaaibed eigenschappen van bijzonder groot belang zijn. Allereerst heeft onkruid een ongunstig effect op het functioneren van de vorenopener waardoor het zaad op onregelmatige wijze in de grond terecht komt. Volgt dan een droge periode dan kunnen kleine hoeveelheden onkruid het aantal gewasplanten sterk doen teruglopen. Ten tweede is de gelijkmatigheid van het zaaibed belangrijk.
Bekeken werd in hoeverre de verschillende grondbewerkingsmethoden bijdroegen tot het nauwkeurig op diepte zaaien van het zaad. Een hoge mate van nauwkeurigheid kon worden bereikt; de zaaidiepte bleek normaal verdeeld met standaardafwijkingen kleiner dan 1 cm. Het belang van een exacte zaaidiepte werd aangetoond. Het bleek dat zelfs binnen de nauwe grenzen die bereikt werden, zaailingen voortkomend uit het dieper gelegen zaad aanzienlijk achterlagen in hun ontwikkeling. Een gevolg hiervan is dat mechanisch wieden uitgesteld moet worden tenzij men de vernietiging van de kleinste kiemplantjes op de koop toeneemt. Bovendien zal de concurrentie tussen de zaailingen de achterblijvers verdrukken.
De simulatie van het effect van de positie van het zaad op de opkomst liet zien dat de kwaliteit van het zaaibed en de ingestelde zaaidiepte een aanzienlijke invloed uitoefenen, niet alleen op de totale opkomst maar ook op de gelijkmatigheid in de ontwikkeling van de zaailingen.

Concluderend kan gesteld worden dat het bedden systeem voor Alfisolen verbeterd kan worden door de oppervlakte ruwer te maken en de bouwvoor te verdiepen. Een nieuwe grondbewerkingstechniek bleek hiervoor het meest geschikt. Bovendien bleek deze methode in de praktijk voordelen te bieden omdat gewasresten en onkruid gemakkelijker konden worden verwerkt zonder de werktuigen te verstoppen.
Zaaibedbereiding is van doorslaggevend belang; het zaaibed moet vrij zijn van onkruid en gelijkmatig van diepte. Aandrukken van de grond boven het zaad draagt bij tot hogere plantaantallen en opbrengst. Korstvorming bleek de opkomst niet nadelig te beinvloeden.
Omdat de verschillende hoofdgrondbewerkingsmethoden in principe alle tot een minimale grondbewerking behoren, ontwikkelden onkruiden zich zeer snel na het planten. Mechanisch schoffelen was daarom ontoereikend in het terugdringen van het onkruidbezwaar. Daarom bleek anvullende onkruidbestrijding in de rij met de hand noodzakelijk voor een goede opbrengst.

REFERENCES

Aarstad,J.J. and D.E.Miller. 1981. Effect of small amounts of residue on furrow erosion.Soil Sci. Am. J. 45(1):116-118.

Ahn,P.M. 1977. Soil factors affecting rainfed agriculture in semi-arid regions with particular reference to the Sahel zone of Africa.In: Proceedings of an int. symp. rainfed agr. semi-arid regions. Riverside: Univ. of California. pp 128-165.

Allmaras,R.R., R.E.Burwell, W.E.Larson, R.F.Holt and W.W.Nelson. 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USDA Cons.Rept. No.7.

Anderson, D.T. 1977. Soil tillage, methods of seeding and equipment. Paper presented for training program for agricultural officers from selected DPAP districts, April 10-17, held at ICRISAT training centre, Patancheru.

Andrews,D.J. and A.H.Kassam. 1976. The importance of multiple cropping in increasing world food supplies.pp. 1-10. In: Multiple cropping. R.I.Papendick, P.A.Sanchez and G.B.Triplett (Eds.). Am. Soc. of Agron. Madison, Wis.Special publication no. 27.

Arakeri,H.R., G.V.Chalam, P.Satyanarayana and R.L.Donahue. 1962. Soil management in India. Sec.rev. edition. Asia publishing House.

Arndt,W. 1966. The effect of traffic compaction on a number of soil properties. J. Agric. Engng Res. 11(3): 182-187.

Arndt,W. 1965a. The nature of mechanical impedance to seedlings by soilsurface seals. Aust. J.Soil Res. 3:45-54.

Arndt,W.1965b. The impedance of soil seals and the forces of emerging seedlings. Aust. J. Soil Res. 3:55-68.

Arnon,I. 1972. Crop production in dry regions. Vol 2. Systematic Treatment of the Principal Crops. Leonard Hill London, U.K.

Bansal, R.K. and K.L.Srivastava. 1981. Improved animal drawn implements for farming in the semi-arid tropics. Agricultural Mechanization in Asia, Africa and Latin America 12(2): 33-38.

Bansal,R.K. and G.E.Thierstein. 1982. Animal drawn multi purpose tool carriers. Agricultural mechanization in Asia, Africa and Latin America 13(4):27-36.

Barley, K.P. 1962. The effects of mechanical stress on the growth of roots. Journal of Experimental Botany 13(37): 95-100.

Barley, K.P. 1968. Deformation of the soil by the growth of plants. Transactions 9th Int. Conf. Soil Sci. pp. 759-768.

Barley, K.P., D.A.Farrell, and E.L.Graecen. 1965. The influence of soil strength on the penetration of a loam by plant roots. Aust. J. Soil Res., 3:69-79.

REFERENCES

Batchelder,P.G. and G.McLaughlin, 1978.Seed bed preparation for dryland narrow row cotton production.Transactions of the ASAE 21(3):451-459.

Batchelder,D.G., J.G.Porterfield and G.McLaughlin. 1974. Zone seedbed preparation for cotton production. Transactions of the ASAE 17(39):461-462.

Bilanski,W.K., and R.K.Varma. 1976. Effect of bulk density and moisture tension on corn shoot growth. Transactions of the ASAE 19(2):337-340.

Binswanger,H.P., R.D.Ghodake and G.E.Thierstein. 1979. Observations on the economics of tractors,bullocks and wheeled tool carriers in the semi-arid tropics of India. paper presented at the Workshop on Socio-economic Constraints to Development of Semi-aid Tropical Agriculture, ICRISAT, 19-23 Feb. 1979.

Binswanger,H.P., B.A.Krantz, and S.M.Virmani. 1976. The role of the ICRISAT in farming systems research. ICRISAT, Hyderabad, A.P., India.

Binswanger,H.P., S.M.Virmani, and J.Kampen. 1980. Farming systems research components for selected areas in India:Evidence from ICRISAT.Research bulletin No.2.

Borlaugh,N.E. 1970. Seed for the future. pp 70-88 in Proceedings of an international conference on mechanized dryland farrming, sponsored by Deere and Company under the auspices of the FAO, Aug 11-15, 1969.

Bowden,L.W. 1977. Geographic aspects of the world's semi-arid tropics. In: Proceedings of an Int. symp. on rainfed agr. in semi-arid regions. Riverside: Univ. of California. pp 60-71.

Bowden,L. 1979. Development of present dryland farming systems. In: Agriculture in semi-arid environments. (Eds: Hall, Cannell, and Lawton) pp:45-72. Ecological Studies v.34.Publ.: Springer Verlag, Berlin, New York, 1979.

Bowen, H.D. 1966. Measurements of edaphic factors for determining planter specifications. Transactions of the ASAE 9:725-735.

Buringh, P.1979. Introduction to the study of soils in tropical and subtropical regions. PUDOC, wageningen, The Netherlands.

Burnside,O.C. 1970. Progress and potential for nonherbicidal control of weeds through preventive weed control.In Present and potential contributions of weed control to solution of problems of meeting the worlds's food needs.Fao. international Conference on Weed control, Davis,Calif., June 22-July 1, pp 464-483. Weed Sci. Soc. Am. 1970, 668 pp.

Burnside,O.C. and G.A.Wicks. 1967. The effect of weed removal treatments on sorghum growth. Weeds, 15:204-207.

Burwell,R.E. and W.E.Larson. 1969. Infiltration as influenced by tillage-induced random roughness and pore space.Soil Sci. Am.Proc. 33(3):449-452.

Burwell,R.E., R.R.Allmaras and M.Amemiya. 1963. A field measurement of total porosity and surface micro-relief of soils. Soil Sci.Soc. Am. Proc. 27:697-700.

Camp,C.R. and Z.F.Lund. 1968. Effect of mechanical impedance on cotton root growth. Transactions of the ASAE 11,188-190.

Charreau.C. 1978. Some contraversial technical aspects of farming systems in semi-arid West Africa. In proceedings of an Int.Symp.Rainfed Agr. Semi-arid Regions. pp 313-360. Riverside: Univ. of California.

Charreau,C. and R.Nicou. 1971. L'ameriolation du profil cultural dans les sols sableux et sablo-argileux de la zone tropicale seche ouest-africaine et ses incidences agronomiques. Agron. Trop. 26,209-255; 531-565; 903-978; 1138-1247.

REFERENCES

Chaudhri,K.G., K.W.Brown, and C.B.Holder. 1976. Reduction of crust impedance to simulated seedling emergence by the addition of manure. Soil Science 122(4):216-22.

Chowdhury,S.L. 1975. Cropping systems in the semi-arid tropics of India. In proceedings, International workshop on farming systems. pp 375-384. ICRISAT, 18-21 Nov 1974, Hyderabad, India.

Cocheme,J. and P.Franquin. 1967. An agroclimatology survey of a semi-arid area in Africa South of the Sahara. Technical note no. 86 (WMO- No 210. TP. 110.), World Meteorological Organisation Geneva.

Collis-George,N., and Jocelyn E.Sands. 1959. The control of seed germination by moisture as a soil physical property. Aust. J. of Agr. Res. 10(19):628-636.

Collis-George, N. and Jocelyn E.Sands. 1962. Comparison of the effects of the physical and chemical components of soil water energy on seed germination. Aust J. of Agr. Res. 13(1): 575-584.

Collis- George N., and Jennifer B.Hector. 1966. Germination of seeds as influenced by matric potential and by area of contact between seed and soil water.Aust. J. Soil Res., 4:145-164.

Collis-George,N., and J.Williams. 1968. Comparison of the effects of soil matric potential and iso-tropic effective stress on the germination of Lactuca sativa. Aust. J. of Agr. Res. 6:179-92.

Collis- George,N., and Jocelyn E.Lloyd. 1979. The basis for a procedure to specify soil physical properties of a seed bed for wheat.Aust. J. Agric. Res., 30:831-846.

Colwick, R.F., J.W. Jones and F.E.Fulgham. 1971. Crop residue disposal-tillage- planting relationships. Transactions of the ASAE 14:114-120.

Cummings,R.W. 1976. New horizons for rainfed agriculture in India and the semi-arid tropics. Lecture held on the occasion of the Jennareddy Venkat reddy memorial lecture 1976.

Curfs,H.P.F. 1976. Systems development in agricultural mechanisation with special reference to soil tillage and weed control. Meded. Landbouw Hogeschool, Wageningen, Nederland. 76-5.

Danielson.R.E. 1972. Nutrient supply and intake in relation to soil physical conditions.In:Optimizing the soil physical environment towards greater crop yields. D.Hillel (ed.) Academic Press 1972.

Dasberg,S.D., D.Hillel and I.Arnon. 1966. Response of grain sorghum to seed bed compaction. Agron.J. : 58, 199-201.

Davis,R.G., Wiese, A.F.,Pafford,J.L. 1968. Root moisture extraction profiles of various weeds. Weeds 13: 98-100.

Dexter,A.R. 1977. Effect of rainfall on the surface micro relief of tilled soil.Journal of Terra Mechanics 14(1):11-22.

D'Hoore. 1968. The classification of tropical soils. In: The soil resources of tropical Africa. Moss, R.P. (ed.). pp 7-28.

Donald, C.M. 1963. Competition among crop and pasture plants. In Advances in Agronomy 15. pp 1-118.

Druiff,A.H. and G.J.Kerkhoven. 1970. Effect of efficient weeding on yields of irrigated cotton in eastern Kenya. Pans 16(4):596-605.

Eavis,B.W., H.M.Taylor, and M.G.Huck. 1971. Radicle elongation of pea seedlings as affected by oxygen concentration and gradients between shoot and root. Agron. J. 63:770-772.

Ennis,W.B., W.C.Shaw, L.L.Danielson, D.L.Klingman and F.L.Timmons. 1963. Impact of chemical weed control on farm management practices. Adv. Agron., 15: 161-210. Academic Press., New York, London.

Estler,M. 1978. Die Minimal-Besteltechnik: Verfahrenstechnik, Auswirkungen

REFERENCES

auf Boden und Pflanze. pp 457-480. Berichte ueber Landwirtschaft 56.

Etasse,C. 1977. Sorghum and pearl millet.In food crops of the lowland tropics. C.L.A. Leakey and J.B.Wills (eds.). Oxford Univ. Press 1977.

FAO. 1972. The employment of draught animals in agriculture. CEEMAT/FAO, Rome, Italy, 244p.

Foster,J.D.G. 1980. Design of animal draught planters for semi- arid conditions. In: Final scientific report of dryland farming research scheme phase 2, vol 4.Overseas Development Administration, London,UK, pp 42.

Freitag,D.R. 1968. Penetration tests for soil measurements. Transactions of the ASAE 11(6):750-753.

Furtick,W.R. 1967. National and international weeds for weed science. A challenge for WSA. Weeds 15:291-295.

Furtick,W.1970.Present and potential contribution of weed control to the world's food need.In:Present and potential contributions of weed control to solution of problems of meeting the world's food needs.FAO international Conference on weed control, Davis, Calif., June 22-July 1, pp 1-6. Weed Sci.Soc. Am. 1970, 668 pp.

Gayle,G.A., and R.W.Skaggs. 1978. Surface storage on bedded cultivated lands. Transactions of the ASAE 21(1):101-104, 109.

Gerard,C.J. 1965. The influence of soil moisture,soil texture drying conditions, and exchangable cations on soil strength. Soil Sci. Soc. Am. Proc. 29(6):641-645.

Giles, G.W. 1975. The reorientation of agricultural mechanisation for the developing countries. Part 1.Policies and attitudes for action programs. Agricultural mechanisation in Asia. 6(2): 15-25.

Gill,W.R. and R.D.Miller. 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. Soil Sci. Soc. Am. Proc.20:650-653.

Goyal,M.R. 1982. Soil crusts vs seedling emergence: review. AMA 13(1):62-78.

Griffith, D,R., J.V.Mannering, H.M.Galloway, S.D.Parsons, and C.B.Richey. 1973. Effect of eight tillage- planting systems on soil temperature, percent stand, plant growth, and yield of corn on five Indiana soils. Agron. J. 65:321-326.

Gupta,O.P., and P.S.Lambda. 1978. Modern weed science- (in the tropics and subtropics). Publ: Today and Tomorrows Printers and Publishers, TTP, Delhi, India.

Gupta,P.D., and D.T.Anderson. 1978. Effect of seeding methods on plant emergence. Paper prepared for presentation in the 16th annual convention of the Indian Society of Agricultural Engineers, held at I.I.T., Kharagpur, India Dec. 18-20 1978.

Habel,W. 1957. Ueber die Wirkungsweise der Eggen gegen Samenunkraeuter sowie deren Empfindlichkeit gegen der Eggvorgang. Zeitschrift fuer Acker- und Pflanzenbau. Band 104 heff 1, p 39-70.

Hadas,A.,and E.Stibbe. 1973. An analysis of soil water movement towards seedlings prior to emergence.In: Ecological Studies Analysis and Synthesis,vol 4 (Hadas et al.eds.) Springer Verlag Berlin. Heidelberg. New York. 1973.

Hadas,A., and D.Russo. 1974a. Water uptake by seeds as affected by water stress,capillary conductivity and seed soil contact 1. Experimental study. Agron. J. 66(5):643-647.

Hadas,A., and D.Russo. 1974b. Water uptake by seeds as affected by water stress,capillary conductivity and seed-soil water contact. 2. Analysis

of experimental data.Agron. J. 66(5): 647-652.
Hanks,R.J. and F.C.Thorp. 1957. Seedling emergence of wheat, grain sorghum, and soybeans as influenced by soil crust strength and moisture content. Soil Sci. Soc.Am. Proc. 21(4):357-359.
Hechelmann,H.G., and G.Boettcher 1962. Mechanische Unkrautbekaempfung in Kartoffeln. Landtechnik 17:202-203.
Heege,H.J. 1973. Getreidebestellung- Bodenbearbeitung, Saetechnik, Kombination von Arbeitsgaengen. DLG-Verlag, Frankfurt.
Hemsath,D.L., and A.P.Mazurak. 1974. Seedling growth of sorghum in clay-sand mixtures at various compactions and water contents. Soil Sci. Amer. Proc. 38:387-390.
Henderson,D.W. 1979. Soil management in semi-arid environments. In: Agriculture in semi-arid environments. (eds.; Hall, Cannell, and Lawton) pp224-256. Ecological Studies Vol.34 Publ.:Springer Verlag, Berlin, New York, 1979.
Herblot,G. 1974. La lutte contre les mauvaises herbes par des moyens mechaniques dans certaines cultures tropicales annuelles; cas particulier du riz. Machinisme Agricole Tropical 46 avril- june:31-42.
Hillel, D. 1960. Crust formation in loessial soils. in: transactions of the 7th int. congr. of soil sci., Madison, Wisconsin, USA. pp 330-339.
Hillel,D. 1969. Soil- Crop- Tillage interactions in dryland and irrigated farming. Final technical report submitted to the USDA, project No.A10-AE-3. Faculty of Agriculture, the Hebrew University of Jerusalem, Rehovot.
Holder,C.B.,and K.W.Brown. 1974. Evaluation of simulated seedling emergence through rainfall induced soil crusts. Soil Sci. Amer. Proc. 38:705-710.
Holm,L. 1971. The role of weeds in human affairs.Weed Sci. 19: 485-490.
Holms,J.W., E.L.Graecen, and C.G.Gurr. 1960. The evaporation of water from bare soils with different tilths. Trans. Intern. congr. of Soil Sci. 7th. , pp. 188-194.
Hoogmoed,W.B. 1981. Field experiments on infiltration, runoff, tillage and millet emergence in Mali. In: Rawitz,E., W.B.Hooggmoed and Y.Morin. 1981. Development of criteria and methods for improving the efficiency of soil management and tillage operations, with special reference to arid and semiarid regions. Tillage laboratory, Agricultural university, Wageningen and Hebrew university, Rehovot Israel , appendix 3: pp. 33.
Hopfen,H.J. 1969. Farm implements for arid and tropical regions. FAO Agric. Devel. Pap., 91.
Hussain,D., and R.I.Sarker. 1978. Performance studies of country ploughs in Bangladesh. AMA 9(3):55-60
ICAR. 1982. A decade of dryland agricultural research in India, 1971-80. Indian Council of Agriculturaal Research, New Delhi, India
ICRISAT. 1975. Annual report 1974-75, Hyderabad, India.
ICRISAT. 1976. Annual report 1975-76, Hyderabad, India.
ICRISAT. 1977. Annual report 1976-77, Hyderabad, India.
ICRISAT. 1978. Annual report 1977-78, Hyderabad, India.
ICRISAT. 1980. Annual report 1978-79. Patancheru, A.P., India.
ICRISAT. 1981. Annual report 1979-80. Patancheru, A.P.,India.
ICRISAT. 1982. Annual report 1981. Patancheru A.P., India
ICRISAT. 1979. Report of work 1977-1978, Farm Power Equipment subprogram. FSRP.
ICRISAT, undated. Annual report of the Farming Systems Research Program. June 1976- May 1977. ICRISAT, Hyderabad A.P., India.

REFERENCES

Jodha, N.S., M.Asokan and J.G.Ryan. 1977. Village level study methodology and resourrce endowments of the selected villages. Occasional paper 16, Economics Program, ICRISAT, Hyderabad, India.

Jodha,N.S. 1979. Intercropping in traditional farming systems. Progress Report 3. Economics Program. ICRISAT Patancheru, A.P., India.

Johnson,C.B., J.V.Mannering, and W.C.Moldenhauer. 1979. Influence of surface roughness and clod size and stability on soil and water losses. Soil Sci. Soc.Am, J. 43(4): 772-777.

Johnston,J.R. and C.E.VanDoren. 1967. Landforming and tillage for moisture conservation. In tillage for greater crop production. ASAE, St. Joseph, Michigan.

Jones,M.J.,and A.Wild. 1975. Soils of the West African savanna. Technical Communication No.55 of the Commonwealth Bureau of Soils Harpenden.

Jordan,L.S. and D.L.Shaner. 1979. Weed control.In: Agriculture in semi-arid environments. (eds.; Hall, Cannell, and Lawton) pp:266-296. Ecological Studies V. 34. Publ.: Springer Verlag, Berlin, New York: 1979.

Joshi,A.B., N.D.Patil, and N.K.Umani. 1980. The drought-prone areas of Maharashtra. pp 221-225 in Proceedings of the international symposium on development and transfer of technology for rainfed agriculture and the SAT farmer, 28 Aug-1 Sept 1979, ICRISAT, Patancheru, A.P., India.

Kampen.J. and Associates. 1975. Soil and water conservation and management in farming systems research for the semi-arid tropics.pp 3-43 In: Proceedings, International Workshop on farming systems,ICRISAT, 18-21 Nov 1974, Hyderabad.

Kampen.J. 1980. Farming systems research and technology for the semi-arid tropics. pp 39-56 in Proceedings of the international symposium on development and transfer of technology for rainfed agriculture and the SAT farmer, 28 Aug-1 Sept 1979, ICRISAT, Patancheru, A.P., India.

Kasasian,L. Weed control in the tropics. Publ. Leonard Hill Books. First published in 1971.

Kassam. 1976. Crops of the West African semi-arid tropics. ICRISAT, Hyderabad, A.P., India

Kemper,B. and R,Derpsch. 1981. Results of studies made in 1978 and 1979 to control erosion by cover crops and no-tillage techniques in Parana, Brazil. Soil and Tillage Research, 1:253-267.

Koch,W. 1959. Untersuchingen zur Unkrautbekaempfung durch Saatpflege und Stoppelbearbeitungsmassnahmen. Diss. Hohenheim.

Koch,W. 1964. Unkrautbekaempfung durch eggen, hacken und meisseln in Getreide. 1. Wirkungsweise und Einsatzzeitpunkt von Egge,Hacke und Bodenmeissl. Z.Acker- und Pflanzenbau 120(4): 369-382.

Kouwenhoven,J.K., and R.Terpstra. 1979. Sorting action of tines and tine-like tools in the field. J. agric. Engng Res. 24: 95-113.

Kowal.J. 1972. Study of soil surface crusts in the loess plain soils of Northern Nigeria. Nigerian Journal of Science 6(19): 93-100.

Kowal,J. and K.Stockinger. 1973. Usefulness of ridge cultivaton in Nigerian agriculture. Soil Water Conserv. J. 28:136-137.

Krantz,B.A. and associates. 1975. Cropping patterns for increasing andd stabilizing agricultural production in the semi-arid tropics. In: proceedings International workshop on farming systems, pp 217-248. ICRISAT, 18-21 Nov 1974, Hyderabad.

Krantz,B.A., J.Kampen, M.B.Russell, G.E.Thierstein, S.M.Virmani, R.W.Willey and associates. 1977. The Farming Systems Research Program. ICRISAT, Oct 1977.

REFERENCES

Krantz,B.A. and S.R.V.Shetty. undated. Progress report Production Agronomy,FSRP, report of work 1978-79.ICRISAT, Patancheru PO. Andrhra Pradesh, India.

Krantz, B.A., J.Kampen and associates. undated. Annual report of the Farming Systems Research Program. April 1975- March 1976. ICRISAT, Hyderabad, A.P., India.

Krause,R. and F.Lorenz. 1979. Bodenbearbeitung in den Tropen und Subtropen. Schriftenreihe der GTZ, Band 79. Deutsche gesellschaft fuer Technische Zusammenarbeitung (GTZ) GmbH, Eschborn, pp. 252.

Krishnamoorthy,C. 1975. Present cropping systems: trends of change and approaches for improvement.In: Proceedings, International workshop on farming systems.pp 277-286. ICRISAT, 19-21 Nov 1974, Hyderabad.

Krishnamoorthy,C. 1971. Review of dryland research in Andhra Pradesh. Indian Farming 21(2):9-13.

Krishnamoorthy,C., S.L.Chowdhurry and E.D.Spratt. 1974. New horizons for dry farming in the rainfed tropics-results of the all India coordinated Research Project on Dryland Agriculture.Fao,UNDP Expert consultation meetings,Hyderabad, India, Nov 24-30, 1974.

Krishnan, A. 1975. Some climatological features of the semi arid tropical regions of the world. In: Proceedings, International Workshop on Farming Systems. pp 53-91, ICRISAT, 19-21 Nov. 1974, Hyderabad.

Kuipers,H. 1974. The objectives of soil tillage. In: Report on the expert consultation meeting on the mechanisation of rice production. Jointly sponsored by IITA, FAO, and the Government of the Netherlands. IITA, 10-14 June 1974 Ibadan, Nigeria, 1975.

Kuipers,H. 1957. A relief meter for soil cultivation studies. Neth. J. agric. Sci. 5:255-262

Lal,R. 1979. Physical characteristics of soils in the tropics: determination and management. In: Soil physical properties and crop production in the tropics. (Eds.: Lal,R. and D.J.Greenland), pp 7-44. Wiley-Interscience Publication.

Larson,W.E. 1964. Soil parameters for evaluating tillage needs and operations. Soil Sci. Soc. Amer. Proc. 28:118-122.

Linden.D.R. 1979. A model to predict soil water storagge as affected by tillage practices. Ph.D thesis. Univ. of Minnesota. St. Paul, Minnesota 55108.

Lindstrom,M.J. and W.B.Voorhees. 1980. Planting wheel traffic effects on interrow runoff and infiltration.Soil Sci. Soc.Am.J. 44(1):84-88.

Luttrell,D.H., W.G.Lovely, and C.W.Bockhop. 1964. The effect of tillage operations on soil physical conditions. ASAE paper No. 64-103.

Macartney,J.C.,and J.P.Northwood. 1971. The effect of different cultivation techniques on soil moisture conservation and the establishment and yield of Maize at Kongwa, Central Tranzania. Trop. Agric. (Trinidad) 48:13-23.

Matthews,M.D.P. and D.W.M.Pullen. 1977. Cultivation trials with ox-drawn equipment in the Gambia 1973-75. The Agricultural Engineer, autumn 1977.

Miller,D.E., and R.O.Gifford. 1974. Modification of soil crusts for plant growth. pp 7-16. In soil crusts. Technical bulletin 214, Agricultural Exp. Station, Univ. of Arizona, Tucson, U.S.A. (Eds.: Cary,J.W., and D.D.Evans).

Miller,S.F. and L.C.Burrill. 1980. Weed control problems in Tanzania.A review team report.Publ.: International Plant Protection Center.Oregon State University, Corvallis, OR 97331, USA.

Mitchell,J.K. and B.A.Jones. 1976. Micro-relief surface depression storage

REFERENCES

Analysis of models to describe the depth-storage function. AWRA Water Resources Bull. 12(6):1205-1222.
Mitchell,J.K. and B.A.Jones. 1978. Micro-relief surface depression storage: changes during rainfall events and their application to rainfall-runoff models. AWRA Water Resources Bull. 14(4):777-802.
Moore,I.D., C.L.Larson and D.C.Slack. 1980. Predicting infiltration and micro-relief surface storage for cultivated soils. Water Resources Research Center, Bull. 102, Univ. of Minnesota Graduate School.
Morton, C.T. and W.F.Buchele. 1960. Emergence energy of plant seedlings. Agricultural Engineering 41:428-454.
Muzik,T.J. 1970. Weed biology and control.McGraw-hill Book Company.New York.
Nicou,R. 1981. Les techniques culturales du mais en Afrique de l'ouest. Agronomie Tropicale 36(4): 356-363.
Nicou,R.1970.Influence of tilage on the cultivation of sorghum in a dry tropical area.In: Proceedings of the seminar on sorghum and millet research in West Africa, Bambey, Senegal, Aug 31-Sept 4.
NN, 1960. Bulletin no. 153.Sugarbeet cultivation, Ministry of Agriculture, Fisheries and Food, UK. 2nd edition, March 1960, p 78-82.
NN, 1975. ASAE Yearbook. American Society of Agricultural Engineers, St. Joseph, 1975.
Norman,D.W., D.H.Pryor and C.J.N.Gibbs. 1979. Technical change and the small farmer in Haussaland, Northern Nigeria. African Rural Economy paper no. 21. publ. under AID contract with Mich. State Univ. (AID/afr-c-1260).
Northwood,PJ., and J.C.Macartney. 1971. The effect of different amounts of cultivation on the growth of Maize on some soil types in Tanzania. Trop.Agric. (Trinidad) 48:25-33.
Ogborn,J.E.A. 1979. Straddle ridge cultivation and equipment for the heavy lands of the African savanna.In: Proceedings of the appropriate tillage workshop.IAR, zaria, Nigeria, 16-20 Jan 1979.Publ.: London, UK; Commonwealth Secretariat.
Page,E.R. and B.J.Hole. 1977. Soil crust strength measurement. Commun. in Soil Science and Plant Analysis 8 (2),139-148.
Papendick, R.I., M.J.Lindstrom, and V.L.Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in Eastern Washington. Soil Sci. Soc. Amer. Proc., 37:307-313.
Parish.R.L., S.M.Brister and D.E.Mermound. 1974. Preliminary results of wide bed-narrow row cotton research.Transactions of the ASAE 17 (6):1073-1075.
Parker,C., R.R.Dryden, and S.R.Obien. 1977. Guidelines for ICRISAT weed research program, ICRISAT, Hyderabad.
Parker,C. 1974. Weed problems in the tropics.Meded.Fakulteit Landbouwwetenschappen Gent, 39(2):367-376.
Parker,J.J.Jr., and H.M.Taylor. 1965. Soil strength and seedling emergence relations. 1. Soil type, moisture tension, temperature, and planting depth effects. Agron. J. 57:289-291.
Phillips,R.E. 1968. Minimum seedbed preparation for cotton. Agron. J. 60:4337-441.
Phillips,W.M. 1970. Weed control methods, losses and cost due to weeds, and benefits of weed control in grain sorghum.In: Present and potential contributions of weed control to solution of problems of meeting the world's food needs. FAO International Conference on Weed Control, s, Davis,California,June 22-July 1, pp 101-108. Weed Sci. Soc. Am. 1970, 668 pp.
Pothecary,B.D. 1970. Mechanised weed control in the tropics. World Crops sept/oct 1970.

REFERENCES

Rademacher,B. 1962. Mechanische Unkrautbekaempfung im Getreide. Landtechnik 17:194-198.

Randhawa,N.S. and J. Venkateswarlu. 1980. Indian experiences in the semi-arid tropics: prospect and retrospect. pp 207-220 in Proceedings of the international symposium on development and transfer of technology for rainfed agriculture and the SAT farmer, 28 Aug-1 Sept 1979, ICRISAT, Patancheru, A.P., India

Rao,M.R., and S.R.V.Shetty. 1977. Some biological aspects of intercropping systems on crop-weed balance. ICRISAT, Hyderabad, India. Paper presented at the Weed Science/Workshop in India. Andrha Pradesh agr. Univ., Hyderabad Jan 17-20,1977.

Rawitz,E., and D.Hillel. 1977. Development of criteria and methods for improving the efficiency of soil management and tillage operations, with special reference to arid and semi-arid regions. Hebrew Univ. of Jerusalem, State Agr. Univ. of Wageningen, Ministry of Agr. Israel. Annual report.

Raychaudhuri,S.P., R.R.Agarwal. N.R.Datta Biswas, S.P.Gupta, P.K.Thomas. 1963. Soils of India. ICAR, New Delhi.

Richards,L.A. 1953. Modulus of rupture as an index of crusting of soil. Proc. soil Sci. Soc. Am. 17:321-323.

Richardson,H.L. 1968. The use of fertilizers. In: The soil resources of tropical Africa. Moss,R.P. (ed.) pp 137-154.

Royle,S.M., and T.W.Hegarty. 1977. Soil impedance and field emergence in calabrese. Journal of Horticultural Science 52:535-543.

Ruthenberg,H. 1975. From shifting cultivation to semi-permanent and permanent farming in the African savannas. In: proceedings international workshop on farming systems, pp 325-349. ICRISAT, 18-21 Nov 1974, Hyderabad.

Ryan,J.G. 1976. Resource inventories and economic analysis in planning agricultural development in drought prone areas. in proceedings of a training program for agricultural officers from selected DPAP districts at ICRISAT, Hyderabad Feb 9-14, 1976.

Ryan,J.G. and associates. 1975.Socio-economic aspects of agricultural development in the semi-arid tropics.In: International Workshop on Farming Systems,pp 389-431,Hyderabad, India: ICRISAT Nov 18-21 , 1975.

Ryan,J.G. and H.P.Binswanger. 1980. Socio-economic constraints to agricultural development in the semi-arid tropics and ICRISAT's approach. pp 57-61 in Proceedings of the international symposium on development and transfer of technology for rainfed agriculture and the SAT farmer, 28 Aug-1 Sept 1979, ICRISAT, Patancheru, A.P., India

Salmon,D.J., L.Labovitch, and D.Horspool. 1977. Evaluation of farming systems and agricultural implements project (EFSAIP), Botswana.

Sanchez,P.A. 1976. Properties and management of soils in the tropics. Publ.: John Wiley and sons Inc. New York, London, Sydney, Toronto.

Schlebeker,J.T. 1977. Tillage and crops on prairies and plains America 1830-1960. In: Les hommes et leur sols. pp171-183. Journal d'agriculture traditionelle et botanique appliquee, 24, no. 2-3.

Sharma,M.L. 1976. Interaction of water potential and temperature effects on germination of three semi-arid plant species. Agron. J. 68(2):390-395.

Shetty,S.R.V. and B.A.Krantz. 1978. Weed science annual report.Farming Systems Research Program 1976-77. Informal report ICRISAT, Patancheru PO., A.P., India.

Singh,S. and B.A.Krantz. 1976. A brief description of the soils of ICRISAT. ICRISAT 1976, an informal report.

REFERENCES

Singh,C.P., G.S.Randhawa, J.S.Samra, K.C.Dhawan, B.S.Panesar, B.S.Gill and Bhupinder Singh. 1978. Energy requirements in intensive agricultural crop production program. Annual report 1977-78. Dep. Farm Power and Machinery, Punjab Agricultural University, Ludhiana India.

Spratt,E.D. and S.L.Chowdhury. 1978. Improved cropping systems for rainfed agriculture in India. Field Crops Research 1(1978) :103-129.

Stickler,F.C. 1964. Stand establishment and yield of grain sorghum as affected by method of planting and use of press wheels. Agron. J. 57: 497-500.

Stickler,F.C., and G.E.Fairbanks. 1965. Grain Sorghum stands and yields as affected by tillage methods and use of press wheels. Agron. J. 57:497-500.

Swaminathan,M.S. 1970. The next step is dry land farming. Ceres, the FAO review 3(6):59-60.

Talati,M.R. and B.V.Metha. 1963. Effect of deep and shallow plowing on nutrient status of soil and uptake of nutrients by pearl millet on Gordu soil Anand. J. Ind. Soc. Soil Sci. 13:143-148

Taylor,H.M. 1962. Seedling emergence of wheat,grain sorghum, and guar as affected by rigidity and thickness of surface crusts. Soil Sci. Soc. Am. Proc. 26(5):431-433.

Taylor,H.M., J.Parker Jr., and G.M.Roberson. 1966. Soil strength and seedling emergence relations. 2. A generalised relation for Gramineae. Agron. J. 58:392-393.

Terpstra,R. and J.K.Kouwenhoven. 1981. Inter-row and intra row weed control with a hoe-ridger. J. agric.Engng Res. 26: 127-134.

Troll,C. 1966. Seasonal climates of the earth; world maps of climatology, eds.: E.Rodenwaldt and H.jusatz. Springer-Verlag, Berlin.

Trouse,A.C. 1979. Some advantages of under-the-row subsoiling. pp 321-324 in Proceedings of the 8th conference of the ISTRO, held at Univ. of Hohenheim W-Germany.

Uehara,G., and R.C.Jones. 1974. Particle surfaces and cementing agents. pp 17-28 in Soil Crusts.

Unger,P.W. and B.A.Stewart. 1976. Land preparation and seedling establishment practices in multiple cropping systems. pp 255-273: In multiple cropping Amer. Soc. of Agronomy Spec. Pub. No. 77.

Vaughan,D.H., and H.D.Bowen. 1977. simulation of cotton radicle elongation during emergence. Transactions of the asae ( ):810-812.

Viebig,U. 1982. Harnessing and use of implements. In: Munzinger, P (Ed.) Animal traction in Africa. Schriftenreihe der GTZ, Band 120. Deutsche Gesellschaft fuer Technische Zusammenarbeit (GTZ) GmbH, Eschborn, pp.133-221.

Virmani,S.M., J.Kampen and B.A.Krantz. 1977. Some aspects of the agricultural climate in relation to land evaluation for sorghum and millets in the semi-arid tropics. Paper presented at Expert consultation on land evaluation standards. FAO, 25-28 Oct., Rome.

Webster,C.C. and P.N.Wilson. 1971. Agriculture in the tropics. Tropical Agriculture series. Longman Group Ltd. London.

Wevers,J.D.A., and H.J.Dibbits. 1977. Landbouw mechanisatie in het noorden van Nigeria. Landb. Tijdschrift 89(7):233-241.

Wevers,J.D.A. and H.Kuipers. 1976. Tillage as a weed control measure in the tropics.Paper presented on the 7th. Conference of the International Tillage Research Organisation (ISTRO), Sweden.

Whiteley,G.M., and A.R.Dexter. 1982. Root development and growth of oilseed, wheat and pea crops on tilled and non-tilled soil. Soil and Tillage

REFERENCES

Research 2:379-393.

Wiese,A.F., J.W.Collier, L.E.Clark, and U.D.Havelka. 1964. Effect of weeds and cultural practices on sorghum yields. Weeds 12:209-211.

Willcocks,T.J. 1980. Scheme summary and semi-arid tillage studies. In: Final scientific report of dryland farming systems research scheme phase 2, vol 1,Overseas Development Administration, London,UK,pp 205.

Willcocks,T.J., J.M.Peacock, P.G.Lee,J.D.Foster and G.C. Johnson. 1977. Interim Scientific Report. DLFRS phase 2 ,Dryland Farming Research Scheme (DFLRS) Botswana.

Willcocks,T.J., J.M.Peacock, P.G.Lee , and J.D.Foster.1976.Initial scientific report,DLFRS Phase 2. Dryland farming research scheme, Botswana.

Williams,D.A. 1967. Tillage as a conservation tool. In conference proceedings Tillage for greater crop production. ASAE publication PROC-168.

Williford,J.R.,P.E.Fulgham and O.B.Wooten. 1974. Wide bed cultural systems for cotton production. Transactions of the ASAE. 17(6):1136-1138.

Wolf,D. and H.J.Luth. 1977. Tillage equipment for clodforming soils. ASAE paper 77-1008.

Yadav,R.C. 1977. Stand establishment of pearl millet in relation to seed drills.AMA winter 63-65.

APPENDIX

A.1 SOILS OF THE EXPERIMENTS

In the following some general information on Alfisols on which the experiments were conducted is given. The source is a note: 'A brief description of the experiments of the soils of ICRISAT, compiled by Sardar Singh and B.A.Krantz (undated).

The soils are shallow (RA-14 being an example) to moderately deep (RW-2B). The soils have a 5-12cm thick Ap horizon underlain by a clayey subsoil which in turn is underlain by a gravelly subsoil (murrum).
The clay is predominantly of the kaolinite type. The soils are moderately well drained. The soils are normally weathered, leached and low in nitrogen, phosphorus and sometimes zinc. The pH ranges from 5.5 to 7.0. Some chemical properties of two Alfisol series at ICRISAT are:

field no.	depth (cm)	organic carbon	pH (1:2.5)	exchangeable base Ca	Mg	Na	K	CEC (me/100g)
shallow	0-15	0.9	6.3	2.6	0.6	0.4	07	4.4
red soil	15-27	0.2	6.2	4.8	0.7	0.4	0.7	8.6
RA-18	weathered parent							
medium	0-18	0.2	6.7	6.7	1.5	0.4	0.7	10.0
red soil	18-35	0.3	5.8	10.6	2.8	0.5	0.6	16.4
RC-1	35-62	0.3	6.1	12.7	2.8	0.5	0.6	18.8
	62-105	0.3	6.4	14.3	2.7	0.6	0.8	19.8
	105-145	0.1	6.6	17.2	2.6	0.6	0.6	22.2

Chemical properties have not been determined of the tillage experimental field except for available nitrogen in RA-14.

The results of the soil texture analysis is seen in Figs. a1, a2 and a3.

APPENDIX

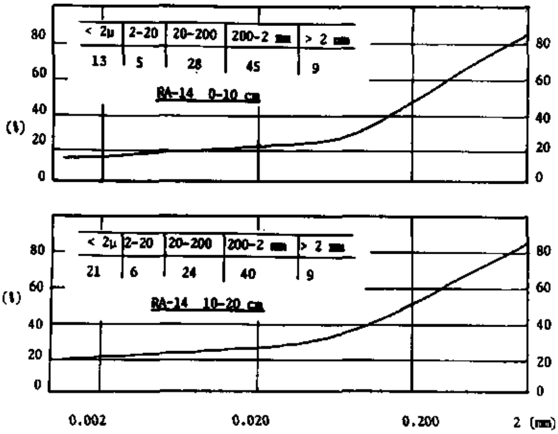


Fig. a1. Soil texture analysis of the RA-14 Alfisol.

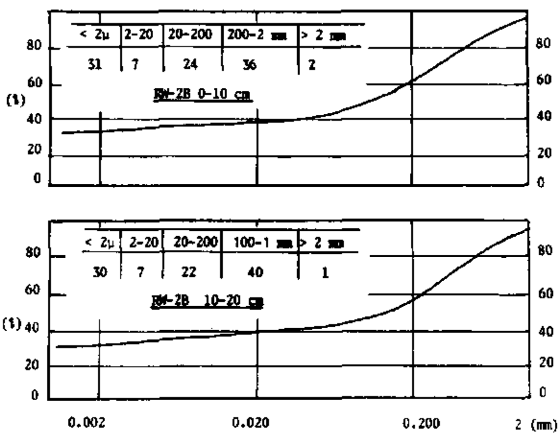


Fig. a2. Soil texture analysis of the RW-2B Alfisol.

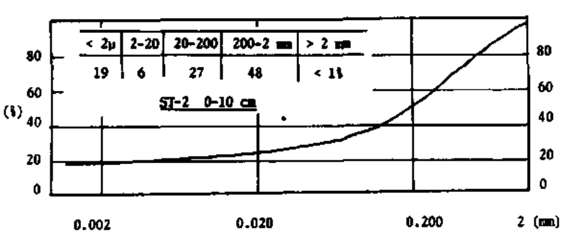


Fig. a3. Soil texture analysis of the ST-2 Alfisol.

APPENDIX

A.2 CLIMATE

Daily rainfall during the experiments is presented in Fig. a4. The rainfall in the dry season was taken from the ICRISAT weather station. Some general characteristics are presented in Fig. a5.

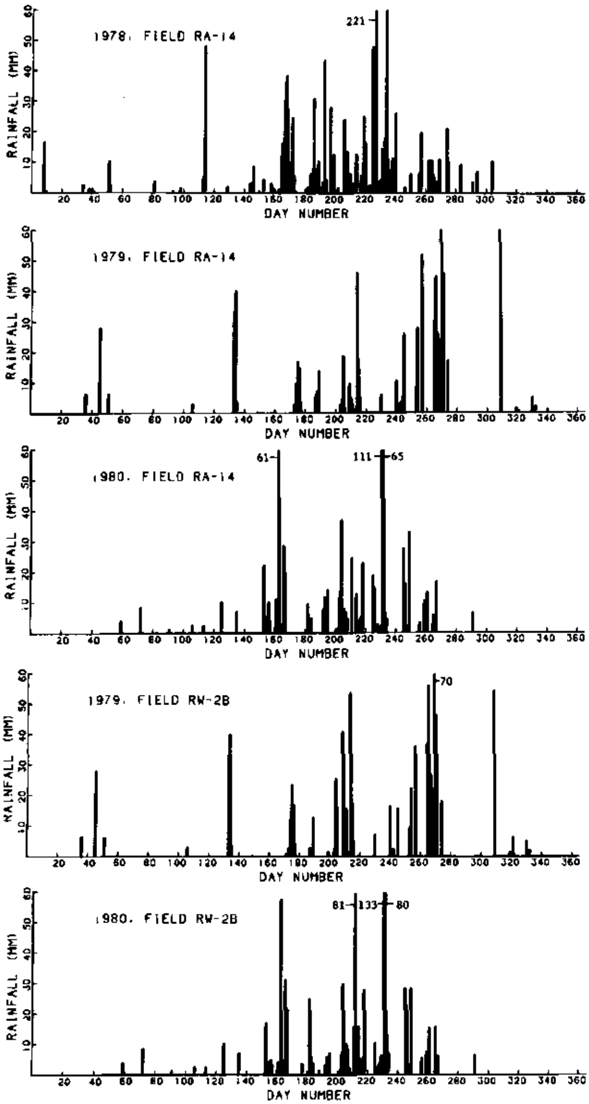


Fig. a4. Daily rainfall at the tillage experimental fields during 1978 to 1980.

APPENDIX

Latitude: 17°27'N Longitude: 78°28'E Altitude: 545 M

Annual mean temperature - Max: 31.7°C; Min: 20.0°C.

Annual mean relative humidity - AM: 69%; PM: 48%

Monsoon rainy season: June to October; Total Annual Rainfall: 761 mm; Seasonal Rainfall: 654 mm

Frequency Groups of Precipitation[1]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0/	0	0	0	0	0	29.5	41.1	26.2	61.0	1.8	0	0	481.3
1/	0	0	0	3.7	4.8	54.3	114.8	77.0	87.0	24.0	0	0	627.7
2/	0	0	1.1	11.8	14.1	77.7	143.7	118.7	106.8	52.5	0.8	0	725.8
3/	0	2.8	4.8	21.9	33.7	99.8	176.5	143.7	162.9	87.3	15.5	0	800.0
4/	0	20.6	28.5	32.5	45.9	153.8	223.4	194.8	257.1	109.9	39.7	2.9	886.3
5/	25.9	96.0	114.3	162.8	116.1	323.6	312.7	333.8	361.7	269.2	229.1	69.3	1158.0

Climatic classification: Semi-arid[2].

Productivity classification[2]: Production possible for crops requiring a 3 to 4 months growing season.

[1]Source: Climatological Normals (Clino) for climate and climatship stations for the period 1931-60. WMO No. 117, TP 52 (1971).
Monthly and annual frequencies groups are given for the lowest (0/) and the highest (5/) observed values of precipitation. Groups 1/, 2/, 3/, 4/ are 20%, 40%, 60% and 80% probability levels.

[2]Hargreaves, G.H. (1975). Climatic zoning for agricultural production in NE Brazil. Utah State University (75-D158), 40p.

Fig. a5. Some generalised climatic characteristics of Hyderabad (India).

APPENDIX

A.3 LAYOUT

Particulars on the statistical design, the number of plots and plot size are drawn in Fig. a6.

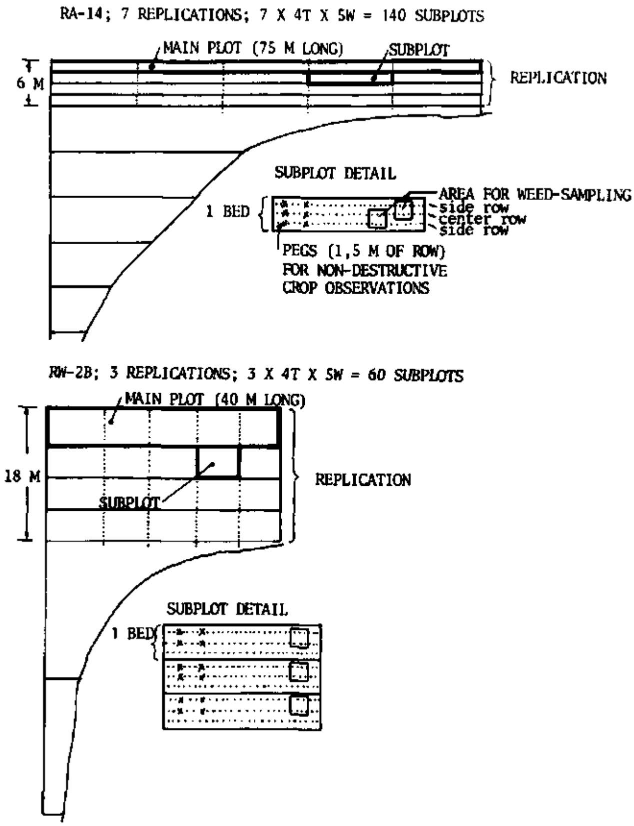


Fig. a6. Experimental plan of the tillage field experiment on RA-14 and RW-2B.

CURRICULUM VITAE

De auteur werd op 3 april 1946 te Arnhem geboren. Na het behalen van het HBS-B diploma aan het Marnix-College te Ede begon hij in september 1965 met de studie aan de Landbouwhogeschool te Wageningen.
De studie werd onderbroken voor het vervullen van de militaire dienst. In januari 1976 behaalde hij het ingenieursdiploma in de studierichting 'Landbouwtechniek'. Als verzwaard hoofdvak werd de Grondbewerking gekozen en als bijvakken de Wiskunde en de Industriele Bedrijfskunde.
Na het afstuderen werkte hij een half jaar in dienst van de voormalige Directie Internationale Technische Hulp, gedetacheerd bij het Internationaal Agrarisch Centrum te Wageningen, in afwachting van de voorbereiding voor zijn uitzending in 1977 als bilateraal assistent-deskundige ten behoeve van het International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) te India.
In 1981 keerde hij terug naar Wageningen, alwaar dit proefschrift voltooid werd bij de vakgroep Grondbewerking van de Landbouwhogeschool.
Per november 1983 heeft hij een functie aanvaard bij het ICRISAT Sahelian Center te Niamey in Niger.