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Soil Management for Optimising Dryland Crop Production

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In their combined report submitted in 1987, the visiting dryland farming team and the economics team working under the auspices of the Indo-US Sub-commission on Agriculture expressed thus "India's drylands are now a source of 45% of country's total crop production. By the year 2000, it is expected that 60% of food for her growing population may come from dryland cultivation." This underscores the importance of dryland agriculture and calls for developing improved technology for optimising crop yields on drylands. The present productivity of these lands is quite low, but experiments have shown that there is considerable potential to improve it.

While giving an overview of dryland agricultural systems at the International Conference on Dryland Agriculture at Amarillo, TX in 1988, Dr. N.P. Clarke made two important remarks, viz., (i) systems approach was appropriate for all levels of technology, and (ii) we are merely caretakers of precious soil and water resources and while using them for production we must also protect them for future generations. This implies that we have to evolve sustainable crop production systems with high productivity

Key Factors in Crop Production

The economic (grain, tuber, pod, etc.) yield is a product of dry matter production (DMP) and harvest index (HI), the ratio of grain yield to total biomass, i.e.,

$$GY = DMP \times HI$$

where, GY is grain yield. While the DMP is a linear function of transpiration (T) by the crop, the HI is determined by time of occurrence and magnitude of transpiration deficits during the life cycle of the crop. This means the final yield is a function of total transpiration of crop and its time pattern. The constant relating DMP with T, called transpiration efficiency (TE), is influenced by crop nutrition, i.e.,

$$DMP = TE \times T \text{ ; where, } TE = f\text{ (crop nutrition)}$$

Further, the transpiration and transpiration deficits are dictated by the transpiration demand and water uptake by crop. While the demand is governed by the atmospheric evaporativity (E_o) and leaf area index (LAI) of the crop, the uptake is a function of soil water status and root development. Whereas E_o is an independent parameter, both LAI and root development are affected by crop nutrition and soil water supply.

Hence, in the final analysis, the crop performance in the absence of pests and diseases is determined by the availability of water and crop nutrition under given climatic environment. To secure increased productivity with sustainability, soil management must ensure the most efficient utilization of water and nutrients by the crop and minimum soil erosion, loss of organic matter, compaction, water logging, salinization and acidification of soil and pollution of groundwater.

Analysis of Dryland Crop Production System

The dryland crop production system shown schematically in Fig. 1 can be split into soil water subsystem and crop production subsystem.

A. Soil Water Sub-System

Water received at the surface of soil as rain or run-on from contiguous area is partly lost as runoff and partly infiltrates into the soil. The

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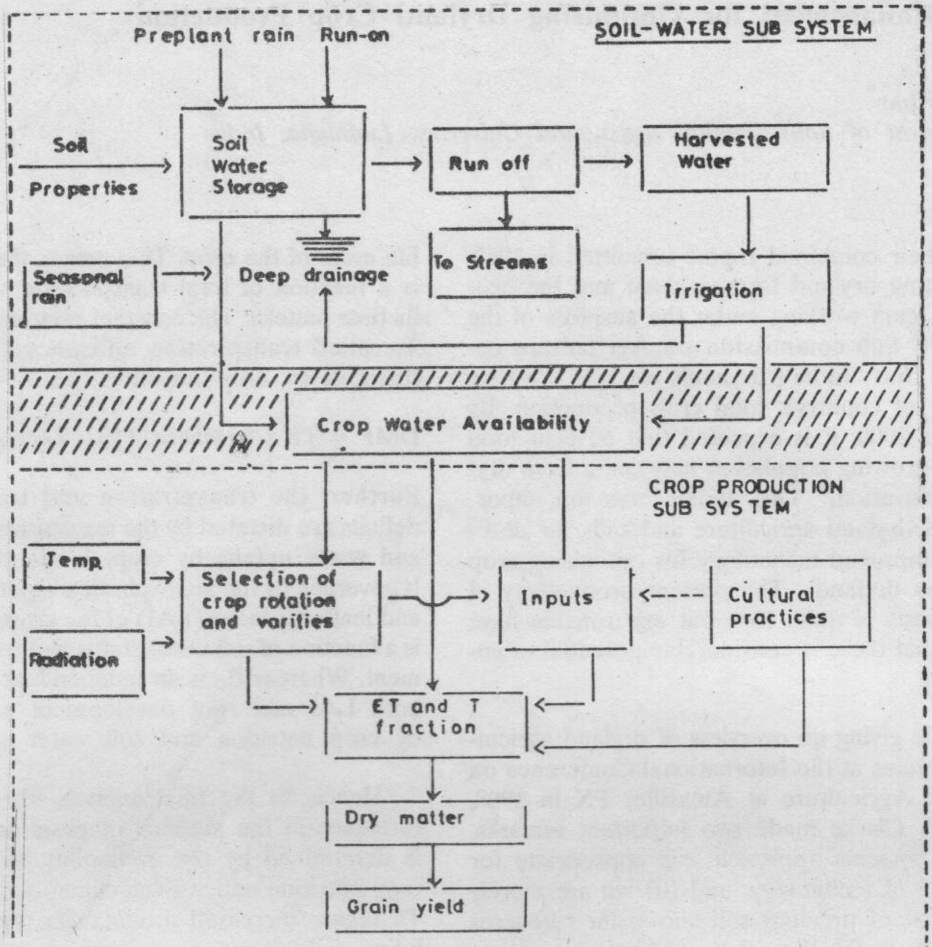

Fig 1 Dryland crop production systems

runoff is either lost to the streams or can be stored in suitable reservoirs for use during dry spells and post rainy season. The water infiltrated into the soil is partly retained in the potential root zone of the crop and is partly lost as deep drainage to lower layers. This water may ultimately join the groundwater and, if conditions permit, may be lifted for irrigation. Water retained in the root zone is lost as direct evaporation (E) from the bare soil and as evaporation and transpiration (T), collectively called evapotranspiration (ET), from vegetated soils. For enhancing crop growth and yields, soil management should aim at enhancing infiltration of rain water into the soil, maximising its retention in the root zone and reducing its loss by direct soil evaporation. The water stored in the root zone together with the seasonal rain and limited irrigation (if available) constitutes the crop water supply.

B. Crop Production Sub-System

The crop production system comprises of the interaction of the crop with the available water, the inputs, the cultural practices and the climatic conditions. The inputs and agronomic practices determine the LAI and root development and hence ET losses. The T part of ET determines DMP and yield. Thus, the soil management for dryland crop production relates to (i) soil and water conservation, (ii) seedling establishment and root development, and (iii) nutrient management.

Soil and Water Conservation

To most people, dryland farming connotes the management of water deficits for crop production. But in essence it includes the management of both shortage and excess of water for plant life processes. Many parts of India receive heavy and or high intensity rains which produce runoff and cause water congestion in crop. The water washes away the top soil and causes floods and sedimentation of streams, canals and fertile lands in lower reaches. It is estimated that 150 m ha of the 328 m ha total area of India suffers from erosion (National Agriculture Commission 1976). The problem of water conservation is actually that of soil and water conservation. Reduction of erosion losses must be considered along with increasing soil water storage.

A. Reducing Water Erosion

First step to control water erosion is to reduce runoff by increasing surface detention and infiltration. The velocity of surplus water should be lowered to reduce its cutting action and carrying capacity. The loss of water stored in the root zone through evaporation and deep percolation should be minimised.

Surface water detention : Rough soil surface and depressions caused by tillage determine the amount of water that can be held on sloping lands before runoff occurs. This effect was convincingly demonstrated by the studies of Burwell *et al.* (1966) on infiltration as affected by differential tillage of Barnes loam. In the case of rough mouldboard, surface cumulative infiltration approached a value equal to the sum of pore space and surface roughness retention before runoff began and exceeded their sum before 25 mm runoff had occurred. For the other treatments, the potential storage volume was not filled even when 50 mm runoff had occurred. The nature and extent of surface roughness is likely to differ with soil type, implements used, number of passes and the pre-tillage moisture conditions. The effec-tiveness of rough surface also depends upon other factors such as intensity and amount of rain and stability of aggregates. Unger & Stewart (1983) cited many such studies from USA in their review on soil management for efficient water use.

Adverse effects of roughness include rapid loss of small showers from exposed clods through faster evaporation. There is also considerable risk of enhanced soil loss if on sloping soils, the accumulated water exceeds the capacity of the system and the system fails. Diked and level fields are free from such a risk. In addition to surface roughness and micro-depressions, surface water detention is also promoted by loosening of surface, contour tillage, tie-ridging, bunding and terracing.

Infiltration : Infiltrability of soil can be manipulated by tillage including conservation tillage, protection by surface covers against beating action of rain and use of soil amendments and crop rotations.

Tillage : Water infiltration into soil is influenced both by surface and sub-surface conditions. Tillage disrupts dense soil layers, decreases bulk density, increases porosity and water conducting pores (Chaudhary *et al.* 1985) and thus, influences water entry into the soil. A sandy loam soil, with a compact layer of sandy clay loam, tilled 23 cm deep exhibited substantially greater infiltration than when tilled 15 cm deep (Vittal *et al.* 1983). One day after 18.2 mm rain, water front had penetrated 19.2 cm deep in the former against 15 cm in the latter. Khan (1985) found that compared with undisturbed soil, 15 cm deep tillage increased both the initial and final infiltration rates of a laterite: Acharya & Bhagat (1984) reported similar results with an alfisol. Henderson (1979) stated that for infiltration rate to increase, tillage must penetrate the limiting layer, otherwise, only detention storage is increased. Chiselling (Lindstrom *et al.* 1974) and profile modification (Eck & Taylor 1969) have been reported to enhance infiltration and soil water storage in deeper layers.

The association of traditional tillage with increased risk of structural degradation and loss of organic matter, and recent hike in the costs of fuels and labour, and availability of weedicides have given birth to the concept of conservation tillage (Mannering *et al.* 1987). It is defined as the tillage and planting system that maintains at least 30% of soil covered with residue after planting. Rockwood & Lal (1974) reported much lower runoff from no-tillage "residue on" plots compared with bare fallow and ploughed plots. Papendick *et al.* (1991) reported that even small quantities of residue are quite effective in reducing runoff losses. Most research on conservation tillage has been done with dryland crops in the temperate regions where cost-effective means to kill weeds are available. But in the tropics and sub-tropics herbicides are either not available or are too costly.

Surface covers : Crop residues at the surface in reduced tillage systems also act as straw mulch which, in addition to soil erosion by water, also affects wind erosion and evaporation loss from soil. While there has been very little work on conservation tillage in India, the role of extraneously applied straw mulch on various aspects has been studied under controlled (Jalota & Prihar 1990a, Prihar *et al.* 1994) and field conditions (Prihar & Arora 1980).

Straw mulch increases infiltration and reduces soil loss by erosion in three ways. Firstly, it increases the roughness of soil surface which reduces the velocity of water flow. Secondly, surface cover dissipates the energy of the falling rain drop and it does not hit the surface directly and the splash erosion is eliminated. Thirdly, the cover protects the soil aggregates from disruption, thus preventing surface sealing which reduces infiltration rate. Verma *et al.* (1979) studied the runoff losses from a sandy loam soil with one percent slope with and without 6 t ha^{-1} wheat straw mulch. For all the runoff producing storms, the runoff from the mulched (field) plots was lower than that from the bare plots.

Runoff reduction with surface covers is accompanied by reduced soil loss by erosion. In fact, the effect of mulch on soil loss is much greater than that on runoff. For example, Lattanzi *et al.* (1974) showed from their controlled experiments with Russell silt loam that water and soil loss were affected differently with increasing mulch rates. While 2 t ha^{-1} straw mulch reduced the runoff only slightly the soil loss was reduced drastically (Table 1). Elswafy (1988) also reported large reduction in soil loss by water erosion with increasing mulch cover. On a 10% slope gradient, 40% cover reduced soil loss to less than 50% and 80% cover to less than 20% of the unprotected soil.

Table 1 *Runoff (water) and Soil loss during initial and wet runs from 1.2m x 1.2m trays under a simulated rainfall of 6.4 cm hr^{-1} on Russell silt loam*

Rain applied	Mulch rate (t ha^{-1})	Water loss (kg m^{-2})	Soil loss (g m^{-2})
Initial run, 60 min	0.0	49.3	950
	0.5	50.9	600
	2.0	43.5	240
	8.0	2.5	7
Wet run, 30 min	0.0	28.6	410
	0.5	29.9	260
	2.0	27.7	90.
	8.0	2.5	2

Amendments and crop rotations : Soil physical properties including infiltration are influenced by the application of amendments and cropping systems. The common amendments used for improving soil conditions include bulky organic manures, crop residues, gypsum, lime and synthetic soil conditioners. Webber (1975) reviewed literature concerning the use of bulky organic manures for improving soil physical conditions. Gypsum in often applied for improving the permeability of sodic soils. The Ca ions released from gypsum replace exchangeable Na ions which enhances soil permeability to water. Bridge & Kleinig (1968) reported increased soil water storage following application of 10 t ha^{-1} gypsum to a sandy loam soil underlain by an impervious sandy clay loam B horizon below 12-18 cm depth. Gypsum decreased exchangeable sodium percentage and increased hydraulic conductivity of the B horizon from 0.0017 cm to 0.17 cm hr^{-1}. Synthetic soil conditioners help stabilize soil structure and, thus, decrease soil and water loss. Kijne (1967) reported that the soil conditioners PVA and Krillium sprayed on clay loam soil increased infiltration rates.

Crops affect physical properties of soil by pro-tecting it from erosion by canopy effects and modifying structure by root action. Grasses are accredited with improving soil structure through their dense rooting. They create large, stable and continuous pores that aid infiltration. Carrekar *et al.* (1968) reported that after eight years of cropping the terminal infiltration rate of Cecil sandy loam under continuous alfalfa was 5.1 cm hr^{-1} against 2.3 cm hr^{-1} for clean-cultivated corn. Inclusion of grasses and clover in rotation and leaving residues at the surface generally improved infiltration. In a 28 year (long term) study in Ohio (Lal *et al.* 1994) total aggregation in corn-soybean rotation was 27% higher than in continuous corn and 111% higher than in corn-oats, meadow rotation.

B. Soil-Water Retention

Storage of crop-available water can be increased either by increasing soil water retentivity or increasing the reservoir of crop water extraction or both. Under dryland conditions, it is important to maximise soil water storage such that it lasts till the next wetting. While the soil volume available to the crop for water extraction can be manipulated by manipulating root development, the soil water retentivity depends upon textural composition and organic matter content. Mixing of clay with low retentivity and excessively permeable sandy soils was found useful at several research centres in India. For example, in studies at the Jobner centre of the All India ICAR Coordinated Research Project on Improvement of Soil Physical Conditions, mixing of fine soil (40% clay) with sandy soil (6% clay) to increase the clay content of sandy soil by 2% and 5% increased the grain yields of pearl millet, wheat and barley. Unfortunately, the effect on soil water characteristics were not reported. Mixing of fine material from extraneous source in sufficiently large quantities to appreciably influence soil water retentivity may not be practical. However, mixing of finer material from lower layers with coarse textured surface layers can be easily accomplished. In a study by Miller & Aarstad (1972) (cited by Unger & Stewart 1983) 100 cm deep moldboard ploughing of Hezel soil, sandy loam to 46 cm depth, increased the texture of 0-15 cm layer to silt loam and 15-30 cm to loam. The available water holding capacity of 0-30 cm layer increased from 36 mm to 61 mm with the tillage treatment.

Compaction of excessively permeable soil with rollers at optimum moisture context has also been reported to increase soil water retention in the surface layers. The report from Jobner showed that after 24 hours of irrigation, 0-10cm layer of the compacted soil had 2.1% higher water content, compared with the uncompacted. Addition of organic matter and inclusion of a (leguminous) green manure crop in the rotation have also been shown to increase soil water retentivity. Although the gains with organic matter addition may be small, but they are important in dryland crop production. Unger (1975) (cited by Unger & Stewart 1983) showed that available water increased by 1.8% (V/V) with one percent increase in organic matter content of the soil.

Erickson *et al.* (1968) reported increased after-rain water content in the sub-surface layers of sandy soil when impervious asphalt layers were spread at 55-60 cm depth with a specially designed mechanical device. A few years later, J.P. Gupta demonstrated this phenomenon with hand laid layers in small plots at Central Arid Zone Research Institute, Jodhpur. But, because of their high cost and risk of getting ruptured, and hence ineffective, this technique has not become popular.

C. Reducing Evaporation Losses

As already stated, water retained in the soil profile is lost by evaporation and evapotranspiration. The stored water must be conserved by reducing the wasteful losses. Evaporation from soil can be reduced by a number of means of which, mulching with crop residues (Bond & Willis 1969, Jalota & Prihar 1990a) and shallow tillage (Jalota & Prihar 1990b) are within the realm of practicability. Mulching reduces the constant-rate stage evaporation by intercepting the solar radiation and reducing wind speed close to the surface. With time, the rate of evaporation from mulched soil equals and eventually exceeds that from the unmulched. Hence, the cumulative evaporation reduction (CER) increased with time upto a certain period and decreased thereafter (Prihar *et al.* 1994) depending upon mulch rate, E_o and soil type. Under an E_o of 10 mm day^{-1} and 3 Mg mulch ha^{-1} CER peaked at 9 days after wetting at 30 mm in silt loam and 18 mm in sandy loam. With 6 Mg mulch ha^{-1} CER peaked at 38 mm after 15 days of wetting in silt loam and at 34 mm at 18 days in sandy loam. For the given mulch rates, peaks were smaller and appeared later under lower E_o of 2.5 mm day^{-1} than under 10 mm day^{-1}.

Shallow tillage hastens the development of a dry layer at the surface which reduces further loss of water on responsive soils. The benefits of tillage for moisture conservation depend upon soil type, climatic conditions and depth and type of tillage (Jalota & Prihar 1990b). Benefits are generally larger on fine textured soils and under low evaporativity. Aujla & Cheema (1983) reported that one shallow cultivation of bare soil after cessation of monsoon rains in September resulted in 2-3 mm more water in 0-15 cm layer and 18-22 mm higher storage in 0-180 cm layer (Table 2) at seeding of wheat in late October.

Table 2 *Tillage effects on soil moisture storage at seeding time in 0-15 cm and 0-180 cm layers of a loamy sand*

Treatment	Soil water storage (mm)			
	1976		1977	
	0-15 cm	0-180 cm	0-15 cm	0-180 cm
No tillage after rains	9	176	11	217
Tillage 20 days after cessation of rains	12	194	13	239

Seedling Establishment and Root Development

A. Stand Establishment

Achieving an optimum crop stand, which is essential for utilization of stored water, poses the greatest problem in several dryland situations. The basic requirements for seed germination and seedling emergence, in terms of soil physical environments, are adequate supplies of moisture and oxygen, optimum soil temperature and freedom from mechanical stress. Under most dryland conditions, availability of adequate water in the seed-zone is the major limitation to stand establishment. This is particularly true for winter crops in northern India. The monsoon rains recede much earlier than the optimum seeding time and the seed zone gets dried out. Carry-over of moisture in the seed zone can be achieved by surface mulching or shallow tillage. Mulch keeps the surface soil layers more moist for variable lengths of time, depending upon soil type, evaporativity and rate of mulching. Prihar *et al.* (1981) applied straw mulch in maize growing on loamy sand and sandy loam soil a few weeks before its harvest and determined the profile water distribution at harvest time. Water content in 0-15 cm layer was 1.1 to 2.3% higher in the mulched compared with unmulched plots on loamy sand and 0.7 to 2.8% on sandy loam during the four years of study. Mulching with weeds @ 6 t ha^{-1} in growing dryland cowpea at Jodhpur increased moisture content of the surface 15 cm layer and benefitted crop growth (Gupta & Gupta 1986).

Shallow tillage creates a two-layered system with a loose dry layer at the surface underlain by relatively more moist firm layer. Gill & Prihar (1983) showed that 0.15 and 0.18 cm^3 cm^{-3} moisture content fronts advanced linearly with time in the untilled soil, but in the tilled soil, it moved rapidly in the loosened layer and very slowly in the consolidated soil below. Shallow tillage, maintained higher moisture content in the seed zone, over a longer period. In later experiments, Gill & Prihar (1989) studied the effect of seeding depth and placement of seed in relation to the interface of the two layered system on the emergence of wheat, barley and gram. Wheat seeds were generally more sensitive to adverse conditions than gram and barley. Under limited soil moisture in the surface layers, deeper seeding in order to place the seeds in direct contact with moist soil, was recommended. Water absorption by seed and coefficient of rate of emergence showed a strong soil water x temperature interaction (Gill & Prihar 1988). Whereas, at 23°C and 28°C, the emergence of barley seedlings was 100% under both wet and moist seed zone but at 18° and 33°C, the emergence was 90%

in wet and zero in moist seed zone. The management implication of this observation is that if one of these factors is limiting the adequacy of the other must be ensured for optimum seedling emergence.

Crusts at the surface, caused by rain or irrigation, after seeding and subsequent drying cause mechanical impedance to emerging seedlings and adversely affect crop stands. Retardation of rate of seedling emergence by increased mechanical impendance, deep placement of seed or other adverse seed environment, increases the risk of crust damage. Some practical measures to reduce the adverse effects of crusting on seedling emergence include, mechanical breaking of crust, keeping the surface moist with wetting or by keeping a mulch at the surface (Mehta & Prihar 1973), spreading organic materials, including farm yard manure at the seed rows. A firm soil below the seed increases the force of emergence of seedling (Prihar & Aggarwal 1975) and is likely to help stand establishment.

B. Root Development

Potential access of the crop to soil stored water and nutrients is directly related to the size of root system. The adequacy or otherwise of a given root system depends upon the water and nutrient supplying power of soil. On nutrient rich soils in humid or irrigated areas, a relatively small root system may be sufficient to meet the crop needs. But, on low fertility soils, and in arid and semi-arid areas, a deep and well developed root system is necessary to alleviate nutrient and water stress to the crop. Soil management practices, such as tillage and mulching, amount and time of wetting and fertilizer application have been observed to affect root development.

Tillage and mulching : Root follows the path of least resistance. If continuous pores, larger than the diameter of the root tip are available, root can grow into a rigid matrix (Russell 1977, Weirsum 1957). But where such pores are not present, the root penetrates by pushing aside the soil particles. In general, the root elongation rates are inversely related with mechanical resistance of soil (Taylor *et al.* 1966). Mechanical impedence and oxygen deficiency are reported to have additive effects on retarding root growth (Gill & Miller 1956).

Tillage promotes root growth by lowering mechanical resistance of soil (Arora *et al.* 1991, 1993) and improving air and water movement in the root zone (Hamblin 1985). Gajri & Prihar (1994) reviewed the Indian literature concerning tillage effects on root growth. Rooting depth and root proliferation were found to vary with soil type, depth of tillage, soil water regime, mulching, fertilization and manuring.

Chiselling of sandy loam and loamy sand soils to 40 cm depth, 35-40 cm apart, increased the silking-time rooting depth of unirrigated corn by 30 cm on loamy sand soil. Chiselling also increased the rate of extension of wheat roots in loamy sand (Gajri *et al.* 1991); the effect was more pronounced in drier years. Deep tillage not only increased root proliferation but also the length to mass ratio (cm mg^{-1}) in 65-day old corn on a sand soil (P.R. Gajri, personal communication). Compaction caused by heavy machinery has an adverse effect on root growth (Trouse 1979). Interrow compaction was observed to reduce rooting densities mid-way between rows of corn (Chaudhary & Prihar 1974a). Prihar & Vanoren (1967) and Chaudhary & Prihar (1974a) reported more symmetric root growth with shallow cultivation in standing maize than with no-cultivation. Straw mulching in growing summer crops has been observed to promote lateral rooting and increase root densities in the surface layers (Chaudhary & Prihar 1974a). This phenomenon is attributed to more optimum hydrothermal regime in the inter-row space under mulched than on unmulched soil. Relatively meagre data on the effect of tillage on root development does reveal that root system can be manipulated by proper choice of tillage and mulching.

Water management : Profile water distribution at seeding and time and extent of wetting by rain or irrigation have profound effect on rooting depth and root proliferation of crops. In their early experiments with dryland wheat on a sandy loam soil in north India, Singh *et al.* (1975) found that rain during early growth of wheat on a deeply wetted profile followed by dry spell, resulted in depletion of the top 180 cm to below 15 bar value. This provided an indirect evidence of deeper rooting with early wetting. More direct evidence on the effect of wetting episodes on root growth pattern came from field experiments of Gajri & Prihar (1985), Uppal *et al.* (1986), Gajri *et al.* (1989) and Gajri *et al.* (1991). Higher water storage at seeding, achieved with rain or through presowing irrigation, gave higher root proliferation of wheat (Jalota *et al.* 1980) and barley (Uppal *et al.* 1986). Wetting of soil during early growth, generally caused deeper rooting in dryland wheat on loamy sand and sandy loam soil.

The early post-sowing wetting stimulates deeper rooting by eliminating water stress and invigorating crop growth, through greater availability of applied nutrients. Also, wetting of soil layers ahead of the root system, located at shallow depths during early growth decreases soil strength, thus facilitating root extension into deeper layers. Deeper rooting resulting from early irrigation of 5 cm resulted in greater profile water depletion by wheat on loamy sand and sandy loam soils (Gajri *et al.* 1991) (Table 3).

In all years on both soils, irrigated wheat extracted more water from the profile which corresponded with root development. The differences were larger in relatively drier years of 1987-88 and 1988-89.

Nutrient application : Nutrient application affects root growth by invigorating the above ground growth, thus, making more photosynthates available for underground growth. Nitrogen (N) is the major limiting element in most dryland areas. Studies by Singh *et al.* (1975) with dryland wheat showed that application of N increased soil water extraction from deeper layers (Table 4).

Table 4 *Profile water extraction by unfertilized and fertilized dryland wheat*

Profile depth	Water extracted (mm)	
	No fertilizer	80 kg N ha^{-1}
0–90 cm	108	112
90–180 cm	45	87

This provided an indirect evidence that fertilized crop developed a deeper and more prolific root system. Direct evidence to this postulation came from the field studies of Gajri *et al.* (1989). They determined on two soils, the rooting depths and root distribution of wheat at various periods, after seeding as affected by N application at 0, 40, 80 and 120 kg N ha^{-1}, with and without 50 mm irrigation (I), 30 days after sowing. Logistic function gave excellent fit for both depth of rooting and root length index, RLI (km root per m^2 surface area in the rooted profile),

$$Y = a/(1+b \exp ct)$$

Where, Y is the RLI or depth of rooting at time t, a is the maximum value of the given parameter and b and c are regression coefficients. Smooth curves for RLI on the two soils constructed from the fitted coefficients are shown in Fig. 2. Both rooting depth and RLI were affected by both N and I on both soils. Root development was more extensive and rapid in sandy loam than in loamy sand soil. The increases in root growth, with early irrigation and applied N, were comparable in sandy loam; but irrigation had larger effect than N on loamy sand. Better root growth with N caused greater water extraction

Table 3 *Limited irrigation effect on (wheat) harvest-time water storage in 0-180 cm layer of two soils*

Irrigation	Residual extractable water (mm)				
	Loamy sand			Sandy loam	
	1987-88	1988-89	1989-90	1988-89	1989-90
None	47	38	38	142	134
5 cm, 30 days after sowing	15	16	25	101	124

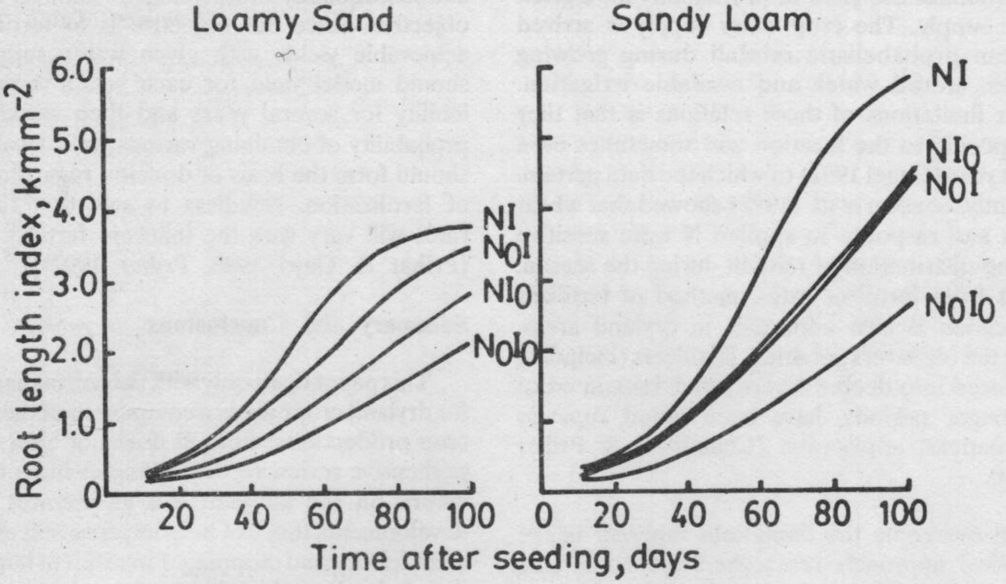

Fig 2 Progressive root length index as affected by N-fertilization and 50 mm early irrigation

from the profile. For most of the growth period, the effect of 40, 80 and 120 kg N ha^{-1} did not differ significantly. Earlier, Comfort *et al.* (1988) also reported that root growth of spring wheat increased with 67 kg N ha^{-1} and remained the same or decreased with further increase in N rate.

Nutrient Management

Yields of dryland crops are limited, not only by availability of water, but also of nutrients of which N is the most common. Therefore, it is necessary to add adequate fertilizer N to take advantage of available water supply. Application of excessive N to dryland crops not only increases expense, without increasing returns, but also reduces yields and increases the pollution hazard (Jackson *et al.* 1983). As a general rule, response of applied N increases with increase in water supply. At a given water supply the yield increases with increase in N rate upto a threshold value and declines thereafter; this threshold increases with increase in water supply (Prihar *et al.* 1989). Within certain limits water supply and N act synergistically. For example, Prihar *et al.* (1981) showed that increase in water supply from 300 mm to 450 mm, without N application, increased the four years' average yield of wheat from 2.2 to 2.7 Mg ha^{-1}. Similarly, addition of 80 kg N ha^{-1} at 300 mm water supply increased yield to 3.0 Mg ha^{-1}. But, when 80 kg N ha^{-1} was added with 450 mm water supply, the yield shot up to 4.5 Mg ha^{-1}. More recently, Gajri *et al.* (1992) have shown that N-use efficiency and marginal productivity of N were related to seasonal water supply in wheat. These observations and several others suggest that for each water supply situation, there is an optimum fertility level that must be ensured to realise maximum yield and nutrient use efficiency.

The rationalization of fertilizer application for dryland crops poses a big challenge to agricultural scientists. This is because heavy doses of fertilizer may cause accelerated depletion of profile-stored water, leaving little water for crop use towards maturity. Optimum fertilizer rate for dryland crops can be arrived at either through purely empirical or model-based systems approach (Prihar 1992). In the empirical approach, yields recorded with variable rates of applied nutrients, at various sites and different years, are multiply regressed over applied nitrogen and available water (e.g., Prihar *et al.* 1989). The ensuing equations are employed to compute N-rates to maximise yield or profitability for a given water supply. The crop water supply is arrived at from probabclistic rainfall during growing season, stored water and available irrigation. Major limitations of these relations is that they are specific to the location and sometimes even to the year (Engel 1991) to which the data pertain. Recently, Sandhu *et al.* (1992) showed that wheat yields and response to applied N were sensitive to time-distribution of rainfall during the season. Apart from fertilizer rates, method of fertilizer application is also important in dryland areas. Since the top layers get dried, fertilizers (including N) placed into deeper layers which remain moist for longer periods, have been found superior to broadcast application (Chaudhary & Prihar 1974b).

To overcome the limitations inherent in the empirical approach, researchers are advocating the use of simulation models (Uehara 1994). In the context of dryland agriculture, this approach can be used to either directly simulate the crop growth on daily basis, or to simulate transpiration from the crop and then relate it with yield assuming optimum fertility (Arora & Gajri 1995). The minimum input data to operate these models consists of daily weather information, including maximum and minimum temperature, rainfall and solar radiation, pan evaporation, soil characteristics, including particle size distribution, bulk density and growth and development characteristics of the crop cultivar (Uehara 1994). Additional requirements are the initial moisture profile and wetting episodes by rain and or irrigation. The fertility is assumed to be optimum and the achievable yield is computed either directly, if crop growth is simulated, or by using water production function. Rao & Rao (1992) summarised the Indian attempts at modelling yield of dryland crop for identifying efficient zones for crops and constraints analysis.

Dewit & Vankeulen (1987) cautioned that the use of average weather data to calculate production, where the weather varies considerably among years, may lead to under-estimation or over- estimation of yield. This bias can be avoided by calculating first the production for a number of years, on the basis of actual weather data, and subsequently interpreting the same for desired objective. Since our objective is to fertilize for achievable yields with given water supply, we should model yield for each year's water availability for several years and then workout the probability of obtaining various yield levels. This should form the basis of decision regarding rates of fertilization. Needless to say, that fertilizer rates will vary with the inherent fertility of soil (Prihar & Gajri 1988, Prihar 1992).

Summary and Conclusions

This paper deals only with the soil management for dryland cropping as a component of the overall crop production system. It does not offer a comprehensive review of work done in India or elsewhere on the subject; but enunciates useful developments that can help improve soil management for dryland cropping. First step in improving the dryland crop yields is the conservation of rain water which can not be separated from soil conservation. Runoff and erosion can be reduced by increasing infiltration of water through proper tillage, use of surface covers and amendments and following suitable crop rotations. Increase in opportunity time with ponding, surface detention, contour tillage, contour hedge rows, tie-ridging, etc., also helps infiltration. The excess water is drained off at non-erosive velocities or is stored in suitable reservoirs for use during dry spells. The retention of infiltrated water in the root zone can be enhanced by increasing soil water retentivity, by applying fine soil material to coarse soil or by mixing the fine layers in the subsoil with coarse layers at the surface and application of organic manures, including green manuring. Sub-surface barriers to downward movement of water have also been used to increase soil water retention in low retentivity, excessively permeable soils. Water stored in the soil must be saved from wasteful losses, such as direct evaporation from soil and transpiration from weed-foliage.

Soil management practices that help stand establishment and root development, are necessary to optimise the use of stored water by the crop. Shallow tillage and straw mulching help carry over of moisture in the surface soil layers that constitute seed zone. Deep tillage and proper water management and rational fertilization also help alter root systems to regulate crop water uptake. Recent field determinations of roots have provided direct evidence of these practices on root development. Early irrigation, followed by dry weather on deeply wetted soils, stimulates deeper rooting. Fertilized crops developed better root systems and extracted more water from deeper layers.

Rational fertilization for dryland crops is another crucial aspect of soil management. Excessive fertilization not only adds to cost, but also may reduce yield and increase pollution. There is a need to adjust fertilizer rates to achievable yields permitted by available water. Estimation of achievable yield required quantification of crop water use and water use-yield relationship.

It is being increasingly realised, that location specific crop production technology cannot be generated for each of the existing large number of agroecological units through conventional field experiments. Fortunately, simulation modelling with computers permits the screening of effects of various technological options in short periods. However, the modelling process required certain minimum input data, which needs to be generated through process-based field experiments.

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