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Crop production with limited irrigation: A review

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ABSTRACT

When water supplies are restricted, so that full evapotranspiration demands cannot be met, limited irrigation is practised. Management strategy of limited irrigation is to optimise production per unit of applied water rather than to maximise yield per unit of land. Principles that help to facilitate limited irrigation strategies can be broadly grouped into three: agricultural water management, crop considerations and agronomic options. When anticipating low water year, choose crops which maximise production with limited water. In decreasing order of efficiency, short season indeterminate and long season indeterminate crops should be chosen judiciously. Deficit irrigation practices, localised irrigation methods, reducing water losses,conjunctive use of water resources etc can help minimise yield losses due to soil moisture stress. Additional agronomic management options that can maximise production include conservation tillage, advancing or delaying planting dates in order to coincide the crop's critical period with water availability, decreasing plant competition byreducing seeding density and controlling weeds. Available options to address the challenge of limited irrigation have been briefly presented.

Key words: Conjunctive use of water resources, Deficit irrigation, Limited irrigation, Water productivity, Yield response factor.

Irrigated agriculture is the primary user of water globally, reaching a proportion that exceeds 70–80 per cent of the total in arid and semiarid zones. Globally, food production from irrigation represents >40 per cent of the total and uses only about 17 per cent of the land area devoted to food production (Fereres and Connor, 2004). Therefore, irrigation water management in an era of water scarcity will have to be carried out most efficiently, aiming at saving water and at maximising its productivity. Limited irrigation appears to be one of the strategies for sustained agricultural growth under irrigation water scarcity.

Simply stated, limited irrigation occurs when demand for irrigation water exceeds supply in a specified domain.

Limited irrigation = Excess water demand over available supply

Limited irrigation refers to situations where irrigation water is either managed or applied out of necessity in amounts, throughout the duration of the irrigation season, such thatthe total amount of water applied is less than that required to meet the potential evapotranspiration of the crop. The objective of limited irrigation, particularly in arid regions, has been to prevent water from becoming a limiting factor in crop production.

However, where water supply is inadequate in relation to the land area that can be irrigated, limited irrigation is often practised. Management strategy of limited irrigation is to optimise production per unit of applied water, rather than to maximise yield per unit of land. Major advantage of limited irrigation is increase of total farm yield and water use efficiency by reducing the area without irrigation (Stewart and Musick, 1982). The biggest advantage of using limited irrigation is that it maximises the productivity of water.

Reasons for limited irrigation (Schneekloth *et al*. 2009) include:

1) Limited capacity of the irrigation well – In regions with limited saturated depth of the aquifer, well-yields can be marginal and not sufficient to meet the needs of the crop.

2) Restricted allocation upon pumping – In some regions that have experienced declining groundwater levels, restrictions have been implemented to decrease the amount of pumping by farmers. In some instances, the allocations are less than what is required to fully irrigate the crops grown.

3) Reduced surface water supplies or storage – In regions that rely upon surface water to supply irrigation needs, droughts and water transfers can have a major impact on the amount of water tshat is available to farmers for irrigation.

A major advantage of limited irrigation is the increase of total farm yield and water use efficiency by increasing the area under irrigated cropping (Unger, 1972). Principles that help to facilitate limited irrigation strategies can be broadly grouped into three: 1) Agricultural water

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management, 2) Crop considerations, and 3) Agronomic options (Jones and Gains, 1941).

AGRICULTURAL WATER MANAGEMENT

Crop yield is linearly related to water use. However, each unit of irrigation does not return the same amount of grain yield as the previous unit of irrigation. Crops have critical time periods when water is more critical to the grain yield. When water allocation cannot meet full crop ET, water should be saved for the reproductive stages where it will have the most impact.

Deficit irrigation practices: Irrigation is applied to avoid water deficits that reduce crop productivity. Reducing the ET without reducing crop productivity is difficult. Until now, the paradigmatic irrigation strategy has been to supply sufficient water so that the crops transpire at their maximum potential and the full ET requirements are met throughout the season. This approach requires large amounts of water for irrigation.Under such situations, farmers often receive water below the maximum ET needs and either have to concentrate the supply over a smaller land area or have to irrigate the total area with levels below full ET. Deficit irrigation is an optimisation strategy in which irrigation is applied during drought sensitive growth stages of a crop (Fereresand Soriano, 2007). Outside these periods, irrigation is limited or even unnecessary if rainfall provides a minimum supply of water.

Deficit irrigation (DI) is one way of maximising water use efficiency (WUE) for higher yields per unit of irrigation water applied. The expectation is that any yield reduction will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. Irrigation supply under DI is reduced relative to that needed to meet maximum ET (English, 1990). Recently, emphasis has been placed on the concept of water productivity (WP), defined as the yield or net income per unit of water used in ET (Kijne *et al.* 2003). The WP increases under DI, relative to its value under full irrigation, as shown experimentally for many crops (Zwart and Bastiaansen, 2004 and Fan *et al.* 2005).

Small irrigation amounts increase crop ET, more or less linearly up to a point where the relationship becomes curvilinear because part of the water applied is not used in ET and is lost (Fig. 1). At one point (I_M), yield reaches its maximum and additional amounts of irrigation do not increase it any further. Location of that point is not easily defined and thus, when water is not limited, irrigation is applied in excess to avoid the risk of a yield reduction. Amount of water needed to ensure maximum yields depend on the uniformity of irrigation. In the simulation of Fereres *et al.*(1993), the seasonal irrigation depth required for maximum yield increased from 1.3 I_M to 2.0 I_M, when the coefficient of uniformity decreased from 90 to 70 per cent. Under low uniformity, irrigation efficiency decreases and water losses are high. By contrast, in DI the level of water application is less than I_M and the losses are of much less magnitude. Thus, under the situation depicted in Fig. 1, WP of irrigation water under DI must be higher than that under full irrigation.

In addition to the factors associated with the disposition of irrigation water, WP is also affected by the yield response to irrigation. Yield responses to irrigation and to ET deficits have been studied empirically for decades (Stewart and Hagan, 1973; Stewart and Nielsen, 1990 and Howell, 2001). It is not only biomass production that is linearly related to transpiration, but the yield of many crops is also linearly related to ET as shown in Fig 1. Design of DI programme must be based on knowledge of this response but the exact characteristics of the response functions are not known in advance. Many crops have different sensitivities to water stress at various stages of development and the DI programme must be designed to manage the stress so that yield decline is minimised.

Deficit irrigation is largely implemented through three approaches: 1) Growth stage based deficit irrigation, 2) Partial root zone based deficit irrigation, and 3) Subsurface deficit irrigation (Chai *et al*. 2016).

Growth stage based deficit irrigation: Before implementing deficit irrigation programme, it is necessary to know crop yield responses to water stress, either during defined growth stages or throughout the whole season (Kirda and Kanber, 1999). Crops and cultivars that are most suitable for deficit irrigation are those with a short growing season and are tolerant of drought (Stewart and Musick, 1982). Success with deficit irrigation is more probable in finely textured soils (Kirda, 2002).

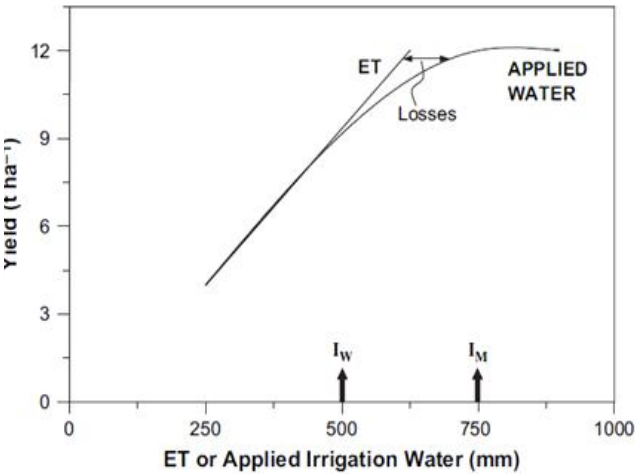

Fig 1: Generalised relationships between applied irrigation water, ET and grain yield. $\mathbf{I_W}$ indicates the point beyond which the productivity of irrigation water starts to decrease and $\mathbf{I_M}$ indicates the point beyond which yield does not increase any further with additional water application.

Yield response factor (Ky) describes the reduction in relative yield according to the reduction in crop evapotranspiration (ETc) caused by soil-water shortage. FAO (Doorenbos and Kassam, 1979) addressed the relationship between crop yield and water use in the late seventies proposing a simple equation where relative yield reduction is related to the corresponding relative reduction in evapotranspiration (ET). Specifically, the yield response to ET is expressed as:

$$\left(1-\frac{Ya}{Yx}\right)=Ky\left(1-\frac{ETa}{ETx}\right)$$

where,Yx and Ya are the maximum and actual yields, ETx and ETa are the maximum and actual evapotranspiration and Ky is a yield response factor. The equation is a water production function and can be applied to all agricultural crops (Allen *et al*. 1998).

This approach and the calculation procedures for estimating yield response to water were published in the FAO Irrigation and Drainage PaperNo. 33 (Doorenbos and Kassam,1979) are used widely worldwide for a broad range of applications. To get fully acquainted with the original procedures, the Ky use and related applications, the reader is referred to the original FAO IDP No. 56 (Allen *et al*. 1998). Actual crop yield (Ya) and yield reduction based on the estimated Yx and the actual yield (Ya) may be determined using yield-moisture stress relation equation. Yield reduction is expressed in relative terms, e.g. as a fraction or percentage (1-Ya/Yx) rather than absolute (Ya) as shown in Fig. 2. The Ky values are crop specific and vary over the growing season according to growth stages.

Based on the analysis of the available literature on crop yield and water relationships and deficit irrigation, Ky values were derived for several crops (Table 1). As illustrated for maize in Fig. 2, yield response will differ largely depending on the stage the water stress occurs. Typically, flowering and yield formation stages are sensitive to stress, while stress occurring during the ripening phases has limited impact, as in the vegetative phase, provided the crop is able to recover from stress in subsequent stages. Flowering and yield formation stages of groundnut are most sensitive to stress, while stress during ripening phase and vegetative phase has limited impact on yield (Reddy and Reddy, 1992). In the case of limited water supply, water savings should be made during periods other than flowering and yield formation stages.

Partial root zone based deficit irrigation: Partial root zone irrigation (also called partial root zone drying) is the second most popular approach of DI (Chai *et al*. 2016). Essentially, half of the root system is irrigated with full amount, while the remaining half is exposed to drying soil (Fig. 3). Typically, this approach includes two types as follows:

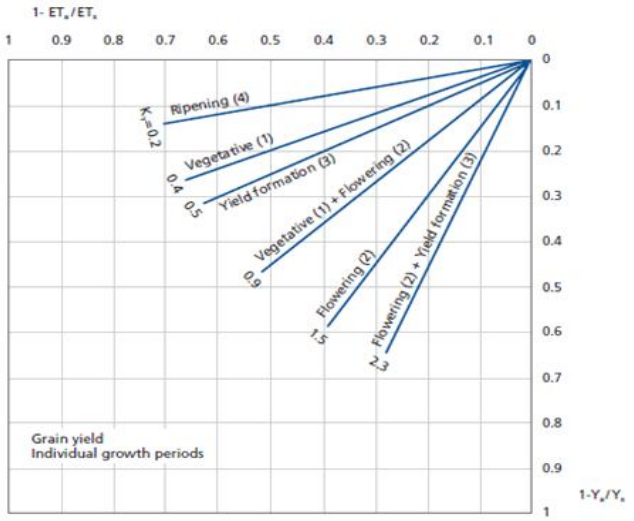

Fig 2: Linear water production functions for maize subjected to water deficits occurring during the vegetative, flowering, yield formation and ripening periods. The steeper the slope (i.e. the higher the Ky value), the greater the reduction of yield for a given reduction in ET because of water deficits in the specific period.

1. Alternate partial root zone irrigation (Fig. 3a): Watering and drying of root zone are alternated in a pre-set frequency that allows the previously well-watered side of the root zone to dry down while fully irrigating the previously dried root zones. The drying–wetting frequency is typically decided according to water requirements of the crop species, growth stages and soilmoisture retentive capacity at the time of irrigation. Irrigated and partially dried sides of the root zone are interchanged in subsequent irrigations.

2. Fixed partial root zone irrigation (Fig. 3b): During the entire growth period, approximately half of the root system is irrigated in a normal amount each time when irrigation is applied and the remaining half is always exposed to drying soil.

In both the approaches, it is assumed that: 1) the fraction of the root system under drying soil may respond to drying by sending a root-secured signal to the shoot where stomata may close to reduce water loss through transpiration (Liu *et al*. 2006) and 2) by reducing the amount of water applied to crop, a small narrowing of the stomatal opening may occur which helps reduce water loss with little or no impact on plant photosynthesis (De Souza *et al*. 2005).

Table 1. Seasonal Ky values from FAO IDP No 33.

Crop	Ky	Crop	Ky
Banana	1.2 to 1.35	Sorghum	0.9
Cabbage	0.95	Soybean	0.85
Cotton	0.85	Wheat	1.05
Groundnut	0.70	Sugarcane	1.2
Maize	1.25	Sunflower	0.95
Onion	1.1	Tomato	1.05
Peas	1.15	Watermelon	1.1
Potato	1.1	Beans	1.15
Safflower	0.8	Pepper	1.1

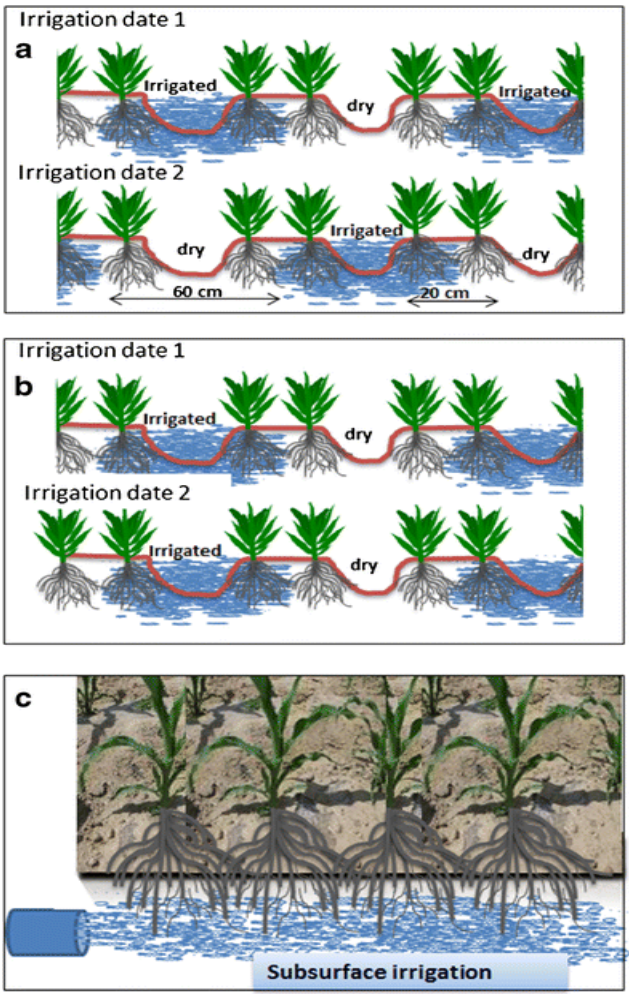

Fig 3: Sketch of the deficit irrigation approaches, including **'a'** alternate partial root zone irrigation where the two neighbouring plant rows in every four rows are irrigated and they are shifted in consecutive irrigations, **'b'** fixed partial root zone irrigation where the two neighbouring plant rows in every four rows are irrigated every time and the remaining two rows of plants kept in drying soil and **'c'** subsurface irrigation where irrigation is applied in the lower part of the root zone.



Fig 4: Sketch of the other deficit irrigation approaches, including the following: **'a'** dripper systems are used to provide supplemental water under plastic film cover at critical growth stages, **'b'** some of the plant rows are irrigated and the other plant rows left without irrigation are mulched with plastic films, and **'c'** alternate plant rows are irrigated and the other plant rows left without irrigated are mulched with crop straw.

Subsurface deficit irrigation: Subsurface deficit irrigation (infiltration movement) is the third most popular DI practice. Irrigation water is supplied to plants by capillary movement from the bottom (Fig. 3c). Root zone air space is not immediately filled by water, in contrast with traditional irrigation where water is supplied directly overhead and water first fills the air space in the soil. Infiltration movement induces plant hardening or internal physiological regulations caused by mild water stress. A false signal of water deficit is transduced to the internals of the cell, where it induces apparent xerophytophysiological regulation with internal adjustment from the gene level to physiological levels. Research shows that subsurface irrigation increases crop productivity and product quality (Xu *et al*. 2011).

In some regions, supplementary irrigation is applied to crops in combination with soil surface covering. At the critical growth stages, dripper systems are used to provide supplemental water under the cover of plastic film (Fig. 4a). In other cases, some of the plant rows are irrigated and the other plant rows are left without irrigation but mulched with plastic films as in Fig.4b (Hu *et al*. 2015). In areas with crop straw readily available, straw is used to cover the soil surface of plant rows with alternate rows irrigated (Fig. 4c). All these techniques add benefits such as reduced soil evaporation and soil erosion, increased topsoil temperature with plastic cover in the early spring when soil temperatures are low and improved soil nutrient availability to crops (Gan *et al*. 2013).

Supply enhancement: Increasing the availability of water for agriculture can be done at different scales. At the river basin scale, dams for the storage of irrigation water, either for single or multipurpose use, represent major capital intensive solutions. At a much smaller scale, individual farmers are able to dam rivers, store and harvest water for the benefit of their own operations. At farm level, in rainfed conditions, farmers can practice on-farm water conservation to reduce runoff and encouraging the infiltration and storage of water in the soil. At this local level, increasing the availability of water is highly decentralised and involves huge numbers of farmers involved in pumping groundwater and developing small scale water harvesting (FAO, 2012).

Water re-cycling and re-use in irrigation: In large scale contiguous irrigation projects, excess water returns to the system through drainage or infiltration and is re-used within the same system or further downstream.

Although, it is of minor global significance, the re-use of urban wastewater in agriculture is of potential importance at several situations. Although, the major concern about the use of untreated wastewater in agriculture is about the possible hazards to human health, the enforcement of water quality standards is often complicated by ambiguous lines of authority and poor capacity for enforcement (FAO, 2010).

Reducing water losses: There has been much controversy and debate about the engineering concept of water use efficiency – the ratio between the amount of water evapotranspired by plants for productive purposes and the amount of water withdrawn or diverted from its source (Reddy and Reddy, 2016). It is now widely accepted that, while irrigation losses appear high, with on average about 40 per cent of the water supplied to agriculture reaching plant roots on average, a large part of these 'losses' return to the river basin in the form of return flow or aquifer recharge and can be tapped by other users further downstream or serve important environmental functions. Measures to reduce losses upstream, while maintaining existing levels of withdrawal, will increase the productive efficiency of water use, but, at the same time may deprive downstream water users who depend on return flow in rivers or groundwater aquifers fed from these returns.

Basin development can improve the availability of water for farmers in semi-arid areas, but this often leads to intensification of water usage that reduces its availability in downstream areas (Batchelor *et al*. 2003). Many studies of the application of precision irrigation have shown that water conservation through extensive adoption of highly efficient drip irrigation can increase local consumptive water use and reduce downstream flow. These practices may increase the productivity of water but do not necessarily increase the amount of water available for other farmers.

In the case of rice, excess seepage into the underlying groundwater is already being recovered in many areas through pumping (Frederickson, 2009). Water that is 'lost' through leakage may eventually be used just as productively as that retained in the irrigation system even when associated with the extra costs of its recovery through pumping and treatment to obtain water with quality of acceptable standards.

Effective interventions to reduce losses in irrigationrequire careful evaluation of all the elements of the water balance over a given hydrological system, identifying in particular the share of water supplied that is lost through evaporation, the part that returns to the river or the aquifer and is or can be re-used downstream, the part that is put into beneficial use through evapotranspiration by crops and the part which is not consumed and is not recoverable (Molden, 1997 and Hsiao, *et al*. 2007). Only under such conditions can conservation measures be designed in an effective way.

In rice based canal systems in Asia, unbalanced and uncoordinated storage, together with internal distribution problems, has led to 'artificial' water scarcity in many irrigation schemes. Lack of understanding of water balances, of linkages between surface water and groundwater and of the difference between beneficial and non-beneficial uses of water have usually resulted in poor effectiveness of water saving approaches (AIT, 2009). Nevertheless, water saving practices such as alternate wetting and drying, soil compaction and intensive puddling can contribute to water saving and increased water productivity (Reddy and Hukkeri, 1979; Reddy and Hukkeri, 1980; Reddy and Hukkeri, 1983).

Most widely promoted conservation measures include canal lining and conversion from gravity to pressurised irrigation (Reddy and Nagamani, 2016), in particular localised irrigation (microirrigation). Canal lining in large surface irrigation schemes are among the most widely promoted approaches to reduce losses in irrigation, in particular in South Asia. When designed for areas with large, continuous unconfined aquifers, such as the Ganges basin, such interventions may be designed to improve water control and may reduce local leakage, but will not necessarily induce significant water saving across the whole command area. Further, in current conditions, with increasing importance of conjunctive use of surface water and groundwater through the digging of shallow groundwater wells in individual farm plots, gravity irrigation systems with poor conveyance efficiency play an increasingly important role in terms of aquifer recharge.

Re-allocating water fromlower to higher value use in irrigation: Scope for increasing value per unit of water use in agriculture (economic water productivity) varies considerably, but in some cases it may be a more promising

avenue than increases in physical water productivity. There is no correlation between crop water requirements and economic return. In water scarce areas, it makes sense to use water for crops providing a high economic return, rather than for staple crops with lower economic returns.

Where market conditions exist and staple production can be substituted from other sources, farmers can be encouraged to shift from lower value to higher value crops and increase the productivity of water in agriculture. However, higher value crops usually require more flexible and reliable water supply systems than what many large scale public irrigation schemes can offer. High value crops are usually very capital intensive and sensitive to market conditions and more risky for farmers for these reasons. Shifting to higher value crops requires access to inputs including seeds, fertilisers and credit, as well as technology and knowhow.

Engineering options: Engineering options include improvements to reduce irrigation water losses. Most obvious way for increasing irrigation efficiency for improving water use efficiency is to reduce losses in irrigation water conveyance, distribution and application to as small as possible (Reddy and Reddy, 2016). A list of possibilities is given below:

1. Significant conveyance losses in an open channel can be reduced by channel lining, channel realignment or installing a closed pipeline.
2. Improve application uniformity to reduce deep percolation.
   - For surface systems, quicker flow advance to reduce the differences in infiltration opportunity time along a furrow. Options include land levelling, surge irrigation, furrow irrigation etc.
   - For sprinkler systems, options include changing sprinkler types, re-nozzling the system or changing nozzle spacings to improve the overlap between heads.
3. Modify the timing and amount of irrigation to match the water holding capacity of the soil profile better, thereby reducing percolation and runoff losses.
4. Convert to a more efficient irrigation system (e.g. flooding to furrow to sprinkler) to reduce application losses. If the new system is well-designed and managed, applications are more uniform reducing deep percolation and runoff.

Localised irrigation methods: Localised irrigation (microirrigation) is widely recognised as one of the most efficient methods of irrigation(Reddy and Reddy, 2016). A well-maintained drip irrigation system can save irrigation water up to 50 per cent. With micro-sprayer (micro-sprinkler) irrigation water is sprayed over the part of the soil surface occupied by the plant with a discharge rate of 12 to 200 l h^{-1}. The aims of localised irrigation are mainly:

1. Application of water directly into the root system under conditions of high availability.
2. Avoidance of water losses during or after water application, and
3. Reduction of the water application cost (less labour).

Managing soil moisture: Irrigation scheduling is critical for managing soil moisture before, during and after the growing season. Knowing the water holding capacity (WHC), crop water use and growth stage, farmers can determine optimum timing and amount of irrigation water application. Such irrigations apply sufficient water to meet crop water needs and replenish depleted moisture within the crop's active root zone, while minimising loss to deep percolation and runoff.

ubsurface drip irrigation (SDI) systems, which reduce surface evaporation, runoff and deep percolation, work well for high value crops and fields too small for advanced irrigation systems like sprinklers. However, since very little water percolates below the root zone to carry away salts, such systems require good quality water, which often becomes a commodity when supplies run short.

More practical step for improving irrigation efficiency is to keep track of soil moisture. Knowledge of the soil available water holding capacity determine how much water the crop root zone can hold and apply water adequate to fill the profile.

Reduced yields due to water stress can occur when the crop depletes most of the available soil moisture (Reddy, 2016). Therefore, maximum allowable depletion (MAD, frequently expressed as a percentage of available soil moisture) is the amount of soil moisture depletion that causes no yield loss. Recommended MAD by crops are given in Table 2.

Conjunctive use of water resources: Management of multiple water resources in a coordinated operation such that the total water yield of the system over the period of time exceeds the sum of water yield of the individual components of the system resulting from uncoordinated operation.

Conjunctive use of surface and groundwater resources leads to optimum ulilisation of water resources under situations of limited irrigation. Saline and good

Table 2: General maximum allowable depletion (MAD) for some commonly irrigated crops.

Crop	MAD (%)
Potato	25
Sunflowers, beans	45
Cotton	60-70
Pulses	50-60
Sorghum	55-60
Pearlmillet	55-60
Barley	45-50
Maize	35-40
Wheat	45-50
Groundnut	40-45

quality of irrigation waters may be applied separately or mixed at times of water scarcity. Mixing of waters to acceptable quality for crops appears ideal under several situations. Allocation of these two water resources separately can be done either to different fields, seasons or crop growth stages such that high salinity water is not applied to sensitive crops or at sensitive growth stages (Reddy, 2016).

Pre-irrigation: Pre-irrigation includes water applied to have adequate moisture in the soil for crop seed germination, irrigation with the object of weed seed germination and incorporation of germinated weeds into the soil and frost protection. It also includes irrigation given to fill the soil profile to field capacity for *rabi* crops on receding soil moisture, especially, on Vertisols during the years of deficit rainfall.

Under Indian conditions, generally, water will be available for irrigation in tanks, wells, canals etc up to January – February due to monsoon rains. During certain years, rains may be inadequate to fill the profile of Vertisols to field capacity for sustaining*rabi*crops. Under such situations, a pre-irrigation may be given to fill the soil profile up to field capacity for a successful *rabi* crop on receding soil moisture.

CROP CONSIDERATIONS

When seeking to conserve irrigation water, farmers must be aware of specific crop water use characteristics and grow those crops which best utilise water at the time and in the volume in which it is available. While soil moisture depletion to the point of wilting reduces vegetative growth of nearly any plant, most crops have critical growth periods during which drought stress is detrimental to yield. This critical growth period often coincides with a crop's reproductive stage. Knowing this, farmers can conserve water during appropriate growth periods and apply water when it is most critical to yield or crop quality.

Determinate, indeterminate and forage crops: Crops are grouped into three general groups – 1) Determinate, 2) Indeterminate, and 3) Forages (Table 3). Determinate crops, including grain, cereal and oilseed crops, are grown for harvest of mature seeds and have a fixed growth period. They tend to be relatively tolerant of moisture stress during early vegetative stages and highly sensitive during seed formation, which includes heading, flowering and pollination. Removal of stress, once it has occurred during these critical periods, generally, does not lead to recovery of yield.

Tuber and root crops, such as potato, carrot and sugar beet are indeterminate crops. Because of their season-long, cumulative yield production, such crops can endure 4 to 5 day periods of moisture stress throughout the growing season with little reduction in quality or yield. While yield, generally, does not suffer from longer periods of stress, quality may decline. Because of their longer growing season, indeterminate crops, generally, require more water than determinate crops (Reddy, 2016).

Crops and cultivars: When faced with limited water supplies, substituting low water requirement crops, such as sorghum, pearlmillet, pulse crops, groundnut sunflower etc. for high water requirement crops, such as rice and sugarcane can conserve water while producing valuable crop.

Duration of crop is also an important consideration when water is limited. Short season crops use less water as they are harvested earlier. Thus, short season crops or short stature varieties can be a wise option when faced with limited water supplies (Table 3).

AGRONOMIC OPTIONS

Agronomic options for managing with limited water supplies are, generally, within the reach of farmers as they are only marginal adjustments for normal agronomy of crop production.

Reducing area under irrigation: Reducing irrigated area is one response to limited water supplies. When the irrigated area is reduced, the amount of irrigation per ha more closely matches full irrigation requirements and its corresponding per ha yield.

Ideally, the land that reverts to dryland production should still produce some level of profitable returns. This is the simplest management option for managing with limited irrigation water supplies. The easiest production option would be to look at a single irrigated crop with the remainder of production in either a dryland crop or fallow (Reddy and Reddy, 2016).

When the amount of water is less than adequate for maximum production, farmers must ask themselves whether the yield increase from increasing the amount of irrigation

Table 3: Critical moisture stress periods of determinate, indeterminate and forage crops.

Crop type	Examples	Critical period
Determinate	Cereal and oilseed crops (wheat, barley, maize, sorghum, sunflower etc)	Flower initiation, heading and seed development.
Indeterminate	Vegetable crop such as brinjal, tomato, capsicum floweringetc and tuber and root crops like potato, carrot, sugarbeetetc	Early growth stage (branching) and fruit development.
Forages	All grasses and crops grown for forage such as sorghum, maize, pearlmillet, pulses etc	No specific period. High production with adequate irrigation at vegetative growth stage.

to each acre will offset the reduction in irrigated acres and increased dryland production. Increasing the amount of irrigation to a crop reduces the total area under irrigation.

Conservation tillage: The goal when working with limited irrigation water is to capture, store and preserve every possible source of water in the production system. These sources include rainfall and irrigation water. Residue management can have a significant impact on increasing the availability of water (Bhattacharyya *et al*. 2008).

Conservation tillage or reduced tillage refers to the practice of utilising tillage methods and equipment that strive to retain crop residue that provides a minimum of 30 per cent soil surface coverage at all times, which includes both during crop growing periods and fallow periods (Jat, 2011; Bhattacharyya *et al*., 2013). Conservation tillage and the resulting changes in soil physical properties often lead to increased infiltration rates, which can be a benefit to irrigated soils with low and medium intake rates (Calegari,2006 and Reddy, 2016).

PLANT POPULATIONS

Recommended plant populations for dryland production are less than that for irrigated production. Low plant population reduce ET by the crop to better match precipitation/irrigation and stored soil moisture. However, when considering population reduction for irrigated crops such as maize, populations must be reduced to less than 40,000 plants ha^{-1} to reduce ET. Maize grain yields, generally, increase as plant population increase from 50,000 plants ha^{-1} to 80,000 plants ha^{-1} for varying irrigation capacities. Yield loss at higher plant populations will be small compared to lower populations when minimal irrigation is applied.

CROP ROTATIONS

Crop rotations can have a major impact upon the total water needs by irrigation. Crop rotations that have lower water use crops such as sorghum, pearlmilletetc can reduce irrigation needs.

With low capacity wells, planting the acreage with multiple crops with different peak water need periods allows for water to be applied at amounts and times when each crop needs the water. The net effect of irrigating fewer acres at any one point in time is that ET demand of that crop can be better met. Irrigation management can be as needed, rather than in anticipation of crop ET. With low capacity systems, farmers, generally, begin to irrigate early to keep the soil moisture as close to field capacity as possible in anticipation that their system cannot meet crop water needs later during peak water needs.

COMPUTERISED DECISION AIDS

Computerised decision aids (models) can help farmers determine how much water to apply. In such programs, farmers can input variables in order to reflect the conditions of their fields (U.S.D.A, 2012). Following are some of the models used for limited irrigation prescriptions:

- **Crop water allocator** (http://mobileirrigationlab. com/crop-water-allocator).

It calculates the net economic return for each combination of variables. It answers the questions of what the best/worst crop rotation would be and how much of the available water supply should be given to each crop in the rotation.

- **Crop yield predictor** (http://mobileirrigationlab. com/crop-yield-predictor).

It helps the farmer determine irrigation scheduling before growing season by predicting yield potential of crops and net economic return. It determines whether pre-season irrigation would be justified and when irrigation is started and stopped throughout the growing season.

- **The water optimiser** (http://agecon.unl.edu/wateroptimiser).

It is another decision support tool that predicts the profit maximising cropping strategy and the amount of water that goes along with it. It was developed to assist farmers deal with water shortages created by drought and interstate water rights litigation.

SUMMARY

When irrigation water is not available to meet crop demand, farmers need strategies to achieve the highest possible economic return with limited water. Such strategies include fine tuning irrigation scheduling to optimise crop water use efficiency, taking steps to capture and store precipi-tation and growing crops well-suited to limited irri-gation. The following list provides some strategies for dealing with limited irrigation water in either case:

1) Reduce irrigation during non-critical growth stages.

2) Use soil moisture and evapotranspiration (ET) measurements to schedule irrigations. Do not rely on crop appearance. Understand ET and how sea-sonal water use requirements vary by crop type, short term weather and length of growing season.

3) Deficit irrigation, localised irrigation methods (microirrigation), reducing water losses, water recycling and re-use minimises irrigation needs.

4)Under furrow irrigation, optimise row lengths and slope to shorten surface irrigation set times and increase uniformity. This increases uniformity and decreases set times.

5) Manage soil-water depletion carefully. Allow soil to reach its maximum allowable depletion (MAD) before completing the next irrigation.

6)In situations where good quality water is unavailable, farmers may consider using marginal quality water for irrigation. Conjunctive use of poor and good quality water may be used alternately or mixed. Care must be taken to avoid irrigating with poor quality water at critical stages for salinity.

7) Increase residue, reduce tillage and manage weeds with best available herbicide, crop technology and plant population reduction. These measures help capture and store precipitation, reduce runoff and evaporation and maximise water use efficiency.

8) Make equipment upgrades to improve irrigation system efficiency and unifor-mity of application.

9) Switch to shorter season crops which can tolerate moderate soil moisture stress considerably.

10. Forage crops are a good way to take advantage of precipitation when it occurs and accommodate drought conditions, while high value or quality driven crops are not good choices for limited irrigation.

11. Reduce irrigated acreage. Revert some land to dryland crops or grass.

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