Enhancing Agricultural Water Productivity Using Deficit Irrigation Practices in Water-Scarce Regions

11

Truptimayee Suna, Arti Kumari, Pradosh Kumar Paramaguru, and N. L. Kushwaha

Abstract

As the world grapples with climate change concerns, particularly changes in temperature and precipitation, modifying these climate variables as a result of global warming leads to a water scarcity crisis in the country. Water scarcity is defined as annual water availability per capita is less than 1000 cubic metres, according to a World Bank assessment. Following the Falkenmark Index, water shortage exists in more than half of the country's 20 river basins, with availability of less than 1000 cubic metres per capita per annum (Singh and Kaur, India's water crisis: challenges, solutions and barriers, working paper, Rajiv Gandhi Institute for Contemporary Studies, 2019). Along with this India has endowed only 4% of the world's *freshwater* resources despite of 17% of world population clearly highlights the need for its sagacious use. The country's water availability has worsened as a result of the disproportionate availability of freshwater and the delayed monsoon as a consequence of climate change. The situation extensively affects the country's agricultural productivity which is the mainstay of Indian economy and principal livelihood for over 58 percent of the rural households. However, an ever-increasing population puts a strain on food supplies. As a result, scientific water management in agricultural practice is widely recognized

---

T. Suna (✉)
Water Technology Centre, ICAR-Indian Agricultural Research Institute, Pusa, New-Delhi, India

A. Kumari
ICAR-Research Complex for Eastern Region, Patna, India

P. K. Paramaguru
ICAR-National Institute of Secondary Agriculture, Ranchi, India

N. L. Kushwaha
Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, Pusa, New-Delhi, India

© The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2023

A. Naorem, D. Machiwal (eds.), *Enhancing Resilience of Dryland Agriculture Under Changing Climate*, https://doi.org/10.1007/978-981-19-9159-2_11

as critical to long-term agrarian reform in water-stressed situations, which necessitates a paradigm shift away from maximizing productivity per unit of land area and towards maximizing productivity per unit of water. Keeping these facts, potent irrigation water management in a future of water shortage must be required, with the goal of conserving water and optimizing its output. In addition, a new management paradigm based on maximizing net benefit rather than yield must be implemented. This can be accomplished by lowering irrigation water demand and diverting the saved water to irrigate greater area while maintaining a relatively high water yield. To deal with this, the most important intervention is deficit irrigation, which involves purposely under-irrigating crops by applying water below the evapotranspiration requirements (English and Nuss, J Am Soc Civil Eng 108:91–106, 1982). As a result, this chapter has discussed a methodical and plausible strategy for increasing water productivity through deficit irrigation.

Keywords

Arid agriculture · Deficit irrigation · Water use efficiency

11.1 Introduction

Dryland farming is often defined as crop production in areas subjected to annual rainfall of less than 500 mm and specially practised in arid and semiarid regions in which annual precipitation is about 20–35% of potential *evapotranspiration*. Drylands account for 44% of the world's cultivated area and endowed with one-third of its population. It possesses only 8% of the global renewable water supply, whereas in India dryland agriculture occupies 68% of India's cultivated area and supports 40% of the human and 60% of the livestock population. It contributes 44% of food requirements, which highlights it plays a critical role in India's food security. The substantial development in drylands has been impeded due to immense pressure from the burgeoning populations, land degradation, and climate change impacts. Along with this nowadays water scarcity is the most prominent challenge that drylands face which implies the need of begin to see the lights in efficacious management of water resources. As the competition for water resource swells due to certain anthropogenic concerns and the insufficient attention paid for its management, the access of agriculture to this crucial source is no longer guaranteed for dryland condition. The chronic water scarcity scenario, worsened by the above explained reasons, leads to an imbalance between supply and demand for water (Seckler et al. 1998; Kushwaha et al. 2016). Therefore, in a stage of water scarcity, water management needs to be rationalized in a scientific manner to ensure efficient water saving and maximized productivity.

Apart from this in water-scarce areas releasing of water to other sectors with maintaining the productivity to meet the demands raised is a complicated picture. However, Food and Agricultural Organization (2012) estimated that to meet the demand of future 80% of the additional production is required which can be fulfilled by intensification and enhancement of yield. Hence there has been a paradigmatic shift of increasing productivity per unit land towards increasing productivity per unit water consumed which heightened by limited possibilities for extension of more irrigated areas (Shanan 1992a, b; Kushwaha and Kanojia 2018). The strategy of supply irrigation with abundant water up to the maximum ET requirements to enhance the yield becomes challenging in water-scarce region. Therefore, a plausible and robust strategy is mostly needed to limit the available water supply with insignificant reduction in yield. In this situation rather than covering the whole land, small area should be concentrated, or irrigate the total area below full ET requirements.

Taking these above said concerns in account deficit irrigation is an assuring solution to lessen the supply-demand gap of water in dryland regions. Below ET-based application of water is termed as deficit irrigation (English et al. 1996). This strategy differs from the traditional one by actively managing the crop water stress during the growing season (Klocke et al. 2007). Though producers can obtain maximum profit by propitiating entire crop water requirements, practicing deficit irrigation as a consequence of limited water supply can increase the irrigated area by saving considerable amount of water. Application of water on the right time can galvanize the enhancement of water use efficiency for most of the crops. During growing season a rationalized irrigation management should be allowed to double the area covered by crops with minimum decrease in yield loss and substantial fetching of economic return considering the economic standpoint, whereas according to Zhang et al. (2018), the optimization of irrigation water application revolves around the estimation of crop water use, determination of irrigation scheduling, and proper management of agronomical measures.

Nevertheless, on the basis of these background information, the focus of this chapter is on providing a clear-cut understanding about deficit irrigation, intervention of new techniques to enhance water use efficiency with limited water supply, management of soil and water in deficit irrigation, and its economic analysis which will definitely provide new avenue for the betterment of DI practice in water-scarce situation.

11.2 Definition and Feature of DI

Deficit irrigation (DI) is a reasonable and manageable depletion of water to enhance water use efficiency (WUE) for higher yields per unit of consumed water. As stated by English, DI can be defined as “methodical and systematic under-irrigation of crops” (English 1990; English et al. 1996) integrated with development of methodical framework to maximize the profit with restriction of water availability. Behind this approach a certain level of water stress is allowed during a particular period or for the whole growing season. Apart from this Chai et al. (2016) defined water deficit for different level of field capacity:

- Severe water deficit—soil water $<$ 50% of the field capacity.
- Moderate water deficit—soil water $=$ 50 to 60% of the field capacity.

- Mild water deficit—soil water = 60 to 70% of the field capacity.
- No deficit or full irrigation—soil water > 70% of the field capacity.
- Over-irrigation—amount of water application > optimum crop water requirement.

This irrigation strategy is considered with an expectation that benefits gained from the conserved water should be greater than insignificant reduction in yield (Fan et al. 2014; Pereira et al. 2012). Despite of reduction in yield, this strategy has opportunities of maintaining considerable quality of crop compared to full irrigation condition. However, the response of crop yield to water stress at critical growth stages or throughout the growing season and maximum allowable with minimum reduction in crop yield is necessary to be known before adopting deficit (Kirda and Kanber 1999). Along with this pertinent knowledge of crop ET, identification of critical crop growth periods, and the economic impacts of yield, reduction strategies are needed for the adaptation of DI. However, the soil salinity consequence of limited water used by DI raised due to lack of leaching and its impacts on sustainable water management have been considered as greater risk (Schoups et al. 2005). In spite of certain limitation, DI can contribute to (i) reducing overall water demand, (ii) reducing declination of productivity of land, (iii) decreasing operation and maintenance cost, (iv) fixed amount of water increase in areas under irrigation, and (v) upliftment of economic return and food security (Geerts and Raes 2009).

There are certain factors that need to be considered before adopting deficit irrigation. Sensitivity of crop growth to water deficit is an essential factor in this strategy. Hence it is preferred to select crop having high water resistance. In deficit irrigation, short-growing and drought-tolerant crop varieties are more suitable (Stewart and Musick 1982). Generally, high-yielding varieties (HYVs) are more water-sensitive than low-yielding varieties. For example, new maize varieties show poor result in deficit irrigation compared to the traditional verities (Food and Agriculture 1979). Apart from this to achieve blooming and robust deficit irrigation strategy, soil parameter also plays an important role. To ensure this concept, soil water retention capacity should be considered. In sandy soil crops may be exposed to water stress very quickly compared to those in fine-textured soil. Low soil matric pressure can be easily maintained in fine-textured soil without affecting the soil water content. Therefore, successful deficit irrigation is more relevant to fine-textured soil.

11.3 Types of Deficit Irrigation

PRD and RDI strategies are the most important types of DI which involve enhancement of crop water use efficiency by manipulating in irrigation water application and deficit of moisture within the root zone. On the basis of maximum crop ET-based water supply level, each DI situation can be defined. In this chapter two major types of deficit irrigation have been discussed.

11.3.1 Regulated Deficit Irrigation

According to English et al. (1990), regulated deficit irrigation modified as controlled deficit irrigation is a conscious restriction of irrigation water which may be a justifiable management during certain crop-growing phases to manipulate crop water use (Chalmers et al. 1981). At different crop development stages, RDI (RDIC) is a standardized approach where critical growth stages (most sensitive growth stages) are supplied by full irrigation and noncritical growth stages are restricted by limited water application. This practice imposes water stress during insignificant yield reducing crop-growing phases with considerable maintenance plant water status below the permissible limits of deficit to control vegetative and reproductive growth (Chalmers et al. 1981; Li et al. 1989; Girona et al. 1993; Kriedemann and Goodwin 2003). RDI has been often demonstrated to be an optimized tool for water use efficiency (WUE) for different crops such as citrus, grapes, pears, (Romero et al. 2013; Cui et al. 2008; Panigrahi et al. 2014; Chalmers et al. 1981; Matthews et al. 1987; Mitchell et al. 1989; Girona et al. 2006). sugar beet (Miller and Hang 1980; Fabeiro Cortes et al. 2003), cotton (Snyder 1992), and tomatoes (Hsiao 1993). Precision irrigation strategies are the paramount for a successful application of RDI by taking into account the timing control and soil water level monitoring. According to Kriedemann and Goodwin (2003) in regulated deficit irrigation, size and quality of fruit and vegetative growth can be controlled fruit size and quality, vegetative growth can be achieved.

11.3.2 Partial Root Zone Drying

Partial root zone drying (PRD) is where half of the root system is irrigated, while the remaining half is exposed to drying soil. The principle behind this approach is considering a frequency at which previously well-watered side of the root zone should be dried down while the previously dried side is fully irrigated and the alternate partial wetting and drying of the root zone is done. In this strategy alternate plant sides are imposed by a percentage of crop evapotranspiration which is ensured by allowing partial wetting of root system. However partial root zone drying is based on two assumptions: (1) dried partial root zone tends to send root-shoot signal (induced by Abssisic ABA) to limit the stomatal aperture for limited transpiration (Dry and Loveys 1999), and (2) with limited availability of water, a partial closing of stomatal aperture may be effective in reducing loss of water substantially with insignificant impact on photosynthesis (Dry and Loveys 2000). The concept of PRD depicted in Fig. 11.1 is hypothesized for water use efficiency enhancement and reduced vegetative growth, stomatal conductance by root to shoot signalling induced by abscisic acid (ABA) during alternative drying and wetting of root zone (Wang et al. 2012). In this strategy the crop growth and development are not affected as the decrease in leaf water potential has no effect on decrease in irrigation to the part of the root zone, and instead the protective process of plant may be stimulated by PRD. PRD has been represented as a potential technique in saving water and enhancing water use efficiency (Wang et al. 2012; Kang et al. 2001; Guang-Cheng

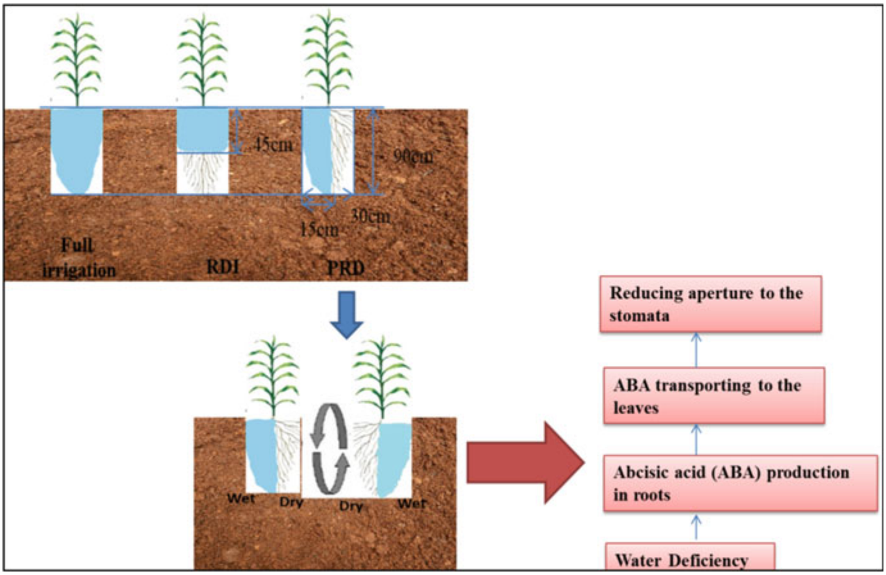

Fig. 11.1 Schematic diagram of partial root zone drying method

et al. 2008; Wakrim et al. 2005; Savic et al. 2008; Stikic et al. 2003. The nature of the confined soil moisture and crop water status conditions (Ruiz-Sanchez et al. 2010) makes PRD to be differed from RDI.

11.4 Water Productivity and Deficit Irrigation

At present, the consequence of global expansion of irrigated areas and the restricted availability of irrigation water compel to adopt appropriate water management to achieve efficient use of water. Increase net economic return per unit consumed water should be concentrated instead of per unit land when limited water supply is concerned. Recently, water productivity concept has been emphasized which is defined as the yield per unit of water used in evapotranspiration (Kijne et al. 2003a, b). This leads to reduce ultimately maximum investment returns and production costs and simultaneously supports the sustainability under frequently occurring situations of deficit irrigation. Oweis et al. (1998) and Zhang et al. (1998) stated that the concept of water productivity revolves around optimal irrigation schedules when multifactorial field trials derive different strategies for deficit irrigation. When specific crop development period is exposed to water deficit, there is a variation in yield response based on sensitivity of crop at different growth stage. Therefore, in order to minimize the yield loss, controlled time of irrigation is appropriate tool for scheduling irrigation. According to Kirda (2002), careful evaluation is needed in irrigation scheduling to ensure enhanced efficiency in limited water supply condition.

Moutonnet (2002) further stated that when there is a maximum reach of evapotranspiration, then the yield approaches to the maximum value. Generally, a significant reduction in soil water storage affects the crop water availability which ultimately affects the actual yield and evapotranspiration. A standard formulation represents a relative yield decrease to relative evapotranspiration deficit including the yield response factor (Ky), (Food and Agriculture Organization 2002) earlier used by Stewart et al. (1977) which is given below:

$$\frac{Y}{Y\mathrm{m}} = 1 - k\mathrm{y}\left[1 - \left(\frac{\mathrm{ETa}}{\mathrm{ETm}}\right)\right] \tag{11.1}$$

Here Y is actual yield (kg/ha).
Ym is maximum yield (kg/ha).
ETa is actual evapotranspiration (mm).
ETm is maximum evapotranspiration (mm).
Ky is yield response factor.

A crop yield response factor is known as water production function (k_y) which depends upon several factors such as species, variety, irrigation method, management, and growth stage when deficit evapotranspiration is imposed. It indicates the unit change in yield as there is a unit change in evapotranspiration. When its value exceeds 1, it indicates that the relative decrease in evapotranspiration is proportionality lower than expected relative yield decrease for a given evapotranspiration deficit (Kirda et al. 1999a, b), and it is vice versa for when its value less than unity. Nevertheless it has been experimented that relative to under full irrigation, WP increases under DI for many crop (Zwart and Bastiaansen 2004; Fan et al. 2005; Ozbahce and Tari 2010; Kumar et al. 2018) and the regression analysis for WP increment and yield reduction versus saved water represented higher values, which indicates that DI could be an option for enhancement of WP and increasing overall yield by expanding irrigated area and applying the saved water in water-scarce region.

In Table 11.1 yield response factors for different crops where there is a less yield reduction compared to relative evapotranspiration deficit have been presented (Kirda et al. 1999a, b).

Elias and Soriano (2007) has stated that limited irrigation amounts increase crop ET; the relationship between ET and yield is found to be linear up to a certain point where it turns curvilinear because some fraction of water applied is not contributed in crop evapotranspiration and is neglected. After hitting the peak point where yield approaches its maximum value, then further addition of water does not have any effect on yield increase. However, the uniformity in irrigation is needed to approach the maximum yield for given amount of water. According to Elias and Soriano (2007), it is also important to highlight the need of irrigation systems of high application uniformity under DI so that the over-irrigated area should be restricted

Table 11.1 Crop response factors for different crops

Crop	Specific growth stage	k_y	Reference
Cotton	Flowering and yield formation	0.99	Bastug (1987)
	Whole season	0.86	Yavuz (1993)
	Bud formation; flowering	0.75 0.48	Prieto and Angueira (1999)
	Boll formation; flowering, vegetation	0.46; 0.67; 0.88	Anac et al. (1999)
	Flowering	0.74	Ahmad (1999)
Maize	Whole season	0.74	Craciun and Craciun (1999)
Soybean	Vegetative	0.58	Kirda et al. (1999a, b)
Sugar cane	Tillering	0.40	Pene and Edi (1999)
Wheat	Flowering and grain filling	0.39	Waheed et al. (1999)

by limited supply and under-irrigated area should be irrigated to deficit level to enhance the water productivity.

According to Kirda et al. (1999a, b), water use efficiency at deficit ET is 1.09 times higher than at full irrigation. This indicates that there is a compensating effect between the increased irrigated area by saved water and the yield loss. Throughout the season if the planned ET is imposed, then the total irrigation water saved can be calculated on the basis of crop water requirement. However, it is crucial to know the water requirement of crop if the stress is presumed during a specific growth stage, to quantify the water saved. This concept is very much important to select crops which have lower crop yield response factor ($k_y < 1.0$) to achieve significant irrigation water savings with an considerable increase in water productivity. Where as it has been studied that at high yield level water productivity decreases i.e., enhancing water production tends to lower yields. Example in Northern Syria, Oweis et al. (1998) reported that 10–15% yield will be reduced when 50% of full supplemental irrigation requirement is satisfied.

However, there is a lack of precession in knowing the yield function and the water use cost. Due to this fact, there is an uncertainty associated with this type of irrigation system. There is a difficulty in estimation of water losses which is contributed by different components when there is a variability related to weather, soil, and topography; the yield function tends to be uncertain. It is also difficult to predict, for a given amount of root zone stored soil water, what yield would be produced which ultimately contributes to economic risk (English et al. 1990).

11.5 Deficit Irrigation Scheduling

Deficit irrigation can be successfully applied when there is a better understanding about when and how to irrigate. According to Goodwin and Boland (1998), scheduling has been relied on pan evaporation (Epan), soil moisture measurement, and plant response before taking management decision. Pereira (2001) reported that through validation and calibration of simulation models, the irrigation scheduling strategies for deficit irrigation have been generated. This modelling approach includes the yield-water function by which the yield impact of water deficit can be evaluated. El Amami et al. (2001) concluded from this study that when there is ten times reduction in available water, it decreases the yield per unit surface cropped land, but the yield per cubic metre of water applied is increased. Therefore, for each irrigation strategy, land should be allocated to crop based on balance between economic return and cropped area; for a low deficit irrigation, the water productivity increases and decreases afterwards when there is a severe deficit. Therefore, according to Kirda et al. (1999a, b), cropping only a fraction of land rather than the full land is the best option for deficit irrigation. It implies scheduling of deficit irrigation requires not only knowledge of crop but also the yield response to water. However, controlling time of irrigation and crop water stress identification are the best approach to for scheduling the deficit irrigation. According to Goodwin and Boland (1998), in the case of drip irrigation, for scheduling RDI the time of run can be calculated by a standard formula based on E_{pan} which is

$$\text{Run time} = ((\text{Epan} - \text{Rain}) * \%\text{Replacement} * \text{Row spacing} * \text{Plant spacing}) \big/ _{\text{Emitter rate per plant}} \tag{11.2}$$

Where, run time is in hour, rainfall is in mm, plant spacing and row spacing are in m, and emitter rate is in litres/h.

Apart from estimation of run time, determination of irrigation interval is also important for scheduling deficit irrigation for system other than trickle. According to Mitchell and Goodwin (1996), the formula for calculation of irrigation interval based on average daily pan evaporation is the following:

$$\text{Interval (days)} = \frac{\text{Volume of water in root zone(litres)}}{\text{Average daily ater use}\left(\frac{\text{litres}}{\text{day}}\right)} \tag{11.3}$$

Precise determination of crop water stress based on different strategy enhances the proportion of water saving. According to Carmen et al. (2018), in water stress condition, water stress threshold can be determined by different water stress detection technologies such as physiological sensor, dendrometry, thermography, and soil water content measurement depicted in (Fig. 11.2) which is related to yield and fruit quality, nutritional status, and water saving. By water production function, the amount of water saved can be estimated and water use efficiency which decrease in case of over irrigation. Based on these two factors, plausible strategy can be determined for deficit irrigation.

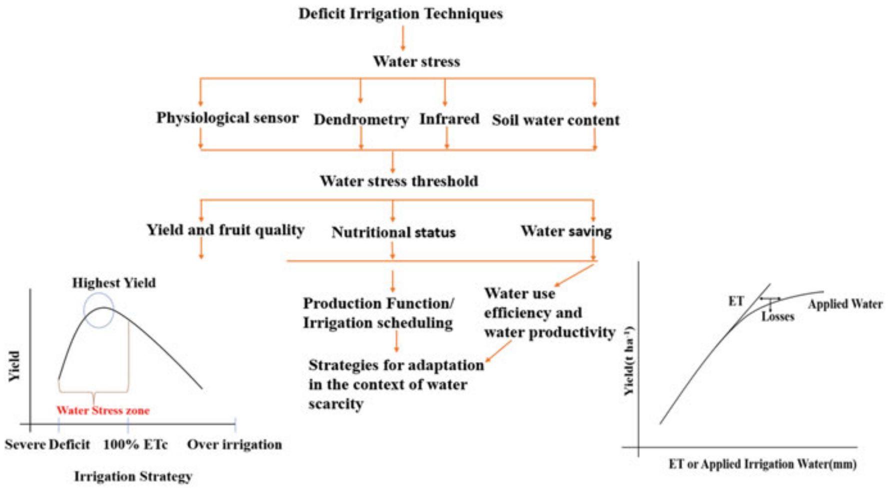

Fig. 11.2 Schematic diagram on irrigation strategy based on water scarcity scenarios

11.6 Techniques for Enhancing Water Use Efficiency

Dryland farming, which is common in semiarid and arid regions, is basically crop cultivation process where water supply is a key limitation. According to ACIAR (2002), dry land farming can be defined as agricultural areas in which the average water supply of the crop limits potential production to less than 40% of full production (without water). Various factors like soil erosion by wind and water, depletion of organic matter content (OMC), salinity and chemical deterioration, etc. contributed to soil degradation in dry environments. Apart from it, the water availability for crop use, as well as its spatiotemporal distribution, is a major challenge in dryland agriculture. Desertification also occurs in the worst circumstances. Despite of it, degradation mechanisms are often considerably more prevalent than soil conservation techniques in dryland environments, allowing the soil resource base to swiftly erode. As soil quality deteriorates, infiltration rates and water-holding capacity decline, making an already scarce water resource increasingly less efficient, resulting in a negative twist in soil-water quality and crop productivity in dryland agriculture. Processes of soil degradation and conservation practices have a complex relationship with soil quality (Fig. 11.3).

To enhance agricultural production and improve water use efficiency, suitable tillage and residue management strategies, well-adapted varieties of crops, and fertility management are required. Water harvesting, which concentrates/collects runoff water from non-cropped regions and applies it to neighbouring agriculture, is another method for improving productivity in specific circumstances. Generally, the options to improve water use efficiency in dryland regions are categorized into two major sections: agronomic and engineering practices. Detailed description of

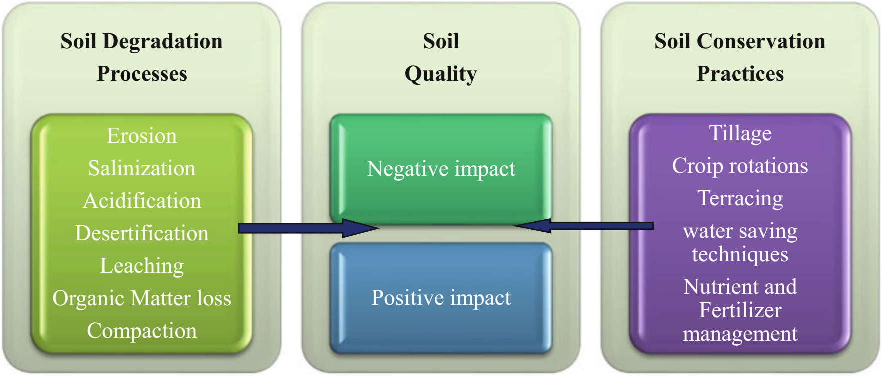

Fig. 11.3 Relationship of process of soil degradation and conservation practices with their quality

agricultural practices including both agronomic and engineering has been given below.

11.6.1 Agronomical Measures

Agronomic measures basically include different types of bench terraces, contour bunding, contour strips, strip cropping, cover crops, crop rotation, off-season and deep tillage, summer fallow, mulching, sowing in furrows, etc.

11.6.2 Mulching

In dryland agriculture, the primary limiting component is soil moisture. It evaporates from soil by evaporation and is lost by transpiration from canopy surfaces. Evaporation loses between 60% and 75% of the rainfall, and mulches check these losses. Mulch is any material that is placed to the surface of the soil to reduce evaporation. Apart from it, it is a water-saving practice for soil moisture conservation, controlling temperature, preventing erosion, and lowering evaporation from soil in dryland regions also (Vishwakarma et al. 2022; Kader et al. 2017; Qin et al. 2016; Yang et al. 2015). Surface mulching is an overarching water conservation tactic for rainfed systems (Chakraborty et al. 2008; Zribi et al. 2015). Plastic mulching conserves soil water better than straw mulch of wheat (Li et al. 2013). Different types of mulching like stubble mulch, straw mulch, dust mulch, plastic mulch, etc. have been used to check soil evaporation and conserve soil moisture (Fig. 11.4).

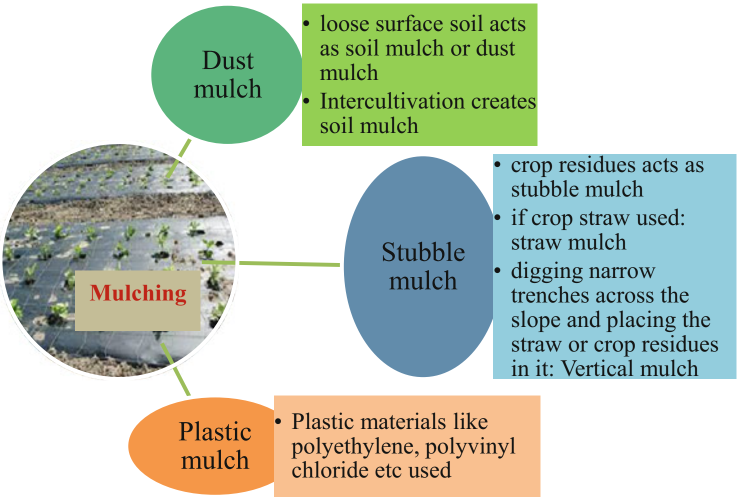

Fig. 11.4 Types of mulching

11.6.3 Tillage

Tillage is often beneficial to crop productivity in dryland farming. It has several advantages, including seedbed preparation, weed control, and incorporation of excess crop residues on soil surface, fertilizers and pesticides, etc., but it can also be harmful to maintaining soil sustainability for longer durations. Tillage has a minimal impact on long-term dynamics and survival of weed seed in soil when crops rotate with diverse life cycles, i.e. crop rotations and diversifications (Anderson et al. 2006). Off-season tillage increases moisture conservation and minimizes weed development especially in alfisols, whereas in soils with hard pan, deep tillage aids in boosting water intake (Sivanappan 1995). Due to its positive consequence on soil moisture storage, conservation tillage systems like reduced tillage or no tillage have been identified as one of the most promising strategies for increasing SOC stocks in dryland areas (Aguilera et al. 2013). When adopting no tillage, significant C sequestration rates have been documented in various dryland systems (Palm et al. 2013; Farina et al. 2011; Govaerts et al. 2009; Vågen et al. 2005). Reduced tillage has a positive impact on many characteristics of the soil, but unsustainable and unneeded tillage operations have the reverse effect, causing soil damage. As a result, there is a lot of attention and focus right now on the transition from high tillage to minimal/no tillage.

11.6.4 Intercropping/Mixed Cropping and Crop Rotation

Agronomic practices that boost crop yield, such as intercropping and crop rotation, must be popularized in dryland regions. Crop rotation provides a number of advantages like lowering the prevalence of insect pests, weeds, and crop diseases, as well as improving the physical like better water-holding capacity and aggregate stability, chemical, and biological qualities like improvement in organic matters of the soil, etc. Crop rotation combined with a no-till system can also help with soil aggregation and water saving in intensified agriculture cropping systems, particularly in dry and semiarid climate regions (Lal 2015). Similarly, in intercropping/mixed cropping, crop water requirements for different crops can be influenced by the variation in root structures and their length in the soil profile, especially in rainfed or dryland agriculture (Nielsen et al. 2011). These systems also help in minimization of crop failure risk and enhancing water productivity of cropping systems. Intercropping has also huge potential for improvement of crop yield and water productivity (Borghi et al. 2013; Qin et al. 2013), as well as the crop yield in next year in rotational mode (Sharma et al. 2017). A combination of intercropping and deficit irrigation (Chai et al. 2014) or crop straw mulching (Yin et al. 2017) can significantly improve WUE in semiarid/arid areas (Yang et al. 2011; Fan et al. 2013). Both (intercropping and mixed) cropping systems in a broad range of situations are expected to enhance resource usage efficiency (Willey 1979; Francis 1989).

11.6.5 Nutrient Management

Fertilizers not only promote crop development, but it also encourages root growth, which allows water to be absorbed from deeper soil layers, which is very important during droughts. Apart from it, quick expansion of the plant canopy as a result of fertilizer application provides more shade on soil, which reduces the amount of evaporated water. Various scholars have demonstrated the positive influence of nutrient management on water use efficiency (IAEA 2005; Rao and Ryan 2004; Van Duivenbooden et al. 1999; Monteith and Webb 1981). INM (integrated nutrient management) needs to be promoted with special prominence on biofertilizers used to maintain the soil fertility in dryland areas. Biofertilizers like blue green algae, *Rhizobium*, *Azospirillum*, *Azotobacter*, vesicular arbuscular mycorrhiza, and phosphate-solubilizing organisms could be used as part of dryland agriculture's INM. Fertilizer efficiency can be increased by using biological nitrification inhibitors as well as slow and controlled release fertilizers and also led to reduction of nitrogen losses in dryland soils (Nawaz and Farooq 2016).Correct fertilizer application in the soil at sowing time can boost the production and quality of dryland crops by reducing leaching and the aerial environment (Janzen et al. 1999).Trials of balanced nutrient management have proved that agronomic efficiency of used nitrogen can be enhanced by adding P and K nutrients, 6.7 kilograms of sorghum grain per kilogram of nitrogen, 10.3 kilograms of pearl millet per kilogram of nitrogen, and 19.5 kilograms of maize grain per kilogram of nitrogen, etc. Nitrogen usage efficiency went from a pitiful 6% to 20% in rainfed pearl millet, sorghum, and maize (Prasad 2009). The 50 percent N through organics or FYM and the remaining N through inorganic fertilizer as integrated nutrient management method can be widely advocated (Vittal et al. 2002).

11.6.6 Use of Antitranspirants

Antitranspirants inhibit photosynthesis, and their application is restricted to preventing crop death due to extreme moisture stress. The main benefits of antitranspirants are to reduce transplantation shock especially in nurseries and horticultural crops. There are generally four types: stomatal closure (phenylmercuric acetate), reflectant (5% Kaolin spray), film forming (Mobileaf, hexadeconol, etc.), and growth retardant (Cycocel).

11.6.7 Crop Choice and Improved Varieties

Many conventional dryland crops do not meet with water availability due to longer crop duration. Therefore, numerous trials have been done to meet crop water requirement with rainfall and duration of water availability. A vast variety of enhanced pulses, millets, and oil seeds were examined for yield variation trend in comparison to local farmers' used varieties (All India Coordinated Research Project for Dry land Agriculture 2000). Yield improvements of 15–50% were noted by high-yielding varieties and 15–25% by more suitable crops. Adoption of short duration crops and varieties are more recommended in dryland regions to enhance crop productivity. For example, rice cultivars ZHU-11–26 in Phulbani and brown gora in Ranchi, linseed cultivar HUL-62 in Varanasi, black gram cultivar KB-51, green gram cultivar CO-5 in Kovilpatti, and soybean cultivar JS-87–59 in Rewa are also extremely sustainable in context of Indian dryland scenario (Vittal et al. 2002). Sowing at the right time helps to maximize seasonal rainfall use, lowers the incidence of pests and diseases, and provides a buffer against drought. The ideotype should have a short growth cycle, extensive root growth, fundamental dryland adaptations, and drought resistance. Apart from this can be written in place of apart from it, diversification by high-value crops like aromatic, spices, dye-yielding, medicinal plants, sericulture, and alternative land uses included to maximize returns, such as agri-horticulture, silvipasture, agroforestry, hortipasture, and other viable strategies, should come under agronomic practices for minimizing risk and maximizing return on investment in dryland environment.

11.6.8 Engineering Measures

Engineering measures varied spatially with respect to slope, soil type, and rainfall variation in terms of intensity, quantity, and other factors. Contour trenches, staggered trenches, contour stone walls and bunding, compartmental bunding, creating temporary and permanent check dams, gully plugging, land levelling, and other techniques are used as engineering approaches depending on these parameters.

11.6.9 Water Harvesting

Water harvesting is one of the viable options for excess runoff collection in a tank and utilizing it to improve agricultural output in the collected or other locations in dryland agriculture. Farm ponds (lined/unlined), percolation ponds, and silt detention tanks are the three types of collector tanks which are mainly recommended in these regions. Protective irrigation is carried out with water collection in the farm pond. Whereas, roof water harvesting also recharges the groundwater and is used for protective or supplementary irrigation by dig wells. The rainwater harvesting system basically classified into in situ moisture conservation like micro-catchment system (within field) and runoff-based system (catchment/storage) like small and macro-catchment systems (Ngigi 2003; Kushwaha and Bhardwaj 2017). They reduce runoff, promote water infiltration into soils, recharge aquifers, and help to improve local water supplies.

11.6.10 In Situ Water Conservation

Several technology treatments like terraces and conservation bench to improve in situ rainwater conservation have been demonstrated to be efficient in dryland regions. Technical interventions' success is determined by local biophysical and socioeconomic factors and therefore necessitates local neighbourhood action. Planting pits or zai, demilunes (half-moon-shaped moons that have been raised), earthen dividers, stone lines go along the contours, ridge tillage following the contours, etc. are also the examples of in situ rainwater harvesting techniques (Winterbottom et al. 2013).

11.6.11 Terraces

Terraces are built by bringing soil from the upper to lower side of a strip to form a level bench/step which has been used to control soil erosion and runoff. Because of the diversity of the landscape, they are guided by neighbourhood and local conditions when they are designing and building. Among terraces, CBTs (conservation bench terraces) also known as Zingg terraces are one of the recommended practices, where rainfall varied from 300 to 600 mm for appropriate crop production, also control erosion in addition to reduce overall runoff, and reliably boost yields (Koohafkan and Stewart 2008; Kushwaha and Yousuf 2017). But, their design should be location-specific for the most effective operation. Conservation terraces are unlikely to be effective in places with minimal rainfall (less than 300 mm) due to high installation costs.

11.6.12 Contour Furrow

They are similar to CBTs in concept but need less soil movement and more popularized among small/marginal farmers and/or in locations with minimal rainfall. Contour furrows at a 1- to 2-metre interval are made, and cropping is frequently done in strips or in rows. Apart from it, the excavated trench is sometimes used for runoff water collection which overflows without being damaged in severe storms.

11.6.13 Contour Bunds

Contour bunds are constructed with ties in the basin on a level gradient. On the bottom side of the earth bund, a stone wall is built to prevent harm if the basin is overtopped. They are also one of the more efficient SWC (soil and water conservation) measures in dryland areas.

11.6.14 Tied Ridges

Mechanized farming systems that use tie-ridges or furrow-diking for SWC (soil and water conservation) are proven methods. Crops are grown on contour ridges, with crossties/dykes blocking the furrows to catch rainwater for irrigation. Apart from it, they can be cultivated on the contours with any tillage strategy, including RT (reduced tillage) and no tillage. TR (Tied ridging), on the other hand, has not been widely embraced by small farmers, owing to variable yields.

11.6.15 Land Levelling with Lasers and Mini Benches

Laser-assisted land levelling is also very effective to overcome runoff losses. For example, this approach resulted in 20% water savings, a 30% increase in crop yields, and a 50% labour savings with 90% irrigation uniformity in the Tadla region of Morocco (Koohafkan and Stewart 2008). Minimum soil cutting and soil fertility issues connected with large volume of surface soil transfer are greatly reduced by the use of thin mini benches. They are generally built on gentle slopes of up to 2%, which is an alternative to land levelling (Jones et al. 1985). Kahlown et al. (2006) reported that technologies focus on efficient use of resource conservation like zero tillage, laser levelling, and bed and furrow planting leads to water saving of 23–45% at the same time as increasing yield in Indus basin of Pakistan.

11.6.16 Windbreaks and Shelterbelts

Wind breakers are any constructions that hinder wind flow and slow it down, whereas shelterbelts are rows of trees placed to protect crops from the wind. They do not totally block the wind flow. Amount of wind travels through the shelterbelts, while the rest deflect and cross over them, depending on their porosity. As a result, the wind speed is reduced without disturbance. The amount of protection provided by shelterbelts is determined by the height of the middle tree row. Shelterbelts provide protection against desiccating winds up to 30 times and 5 to 10 times their height, respectively, on the leeward and windward side. Evaporation losses are reduced as a result of the reduced wind speed, resulting in more water available for plants. During dry years, the protective impact of shelterbelts is more visible. They also help to prevent erosion from wind.

11.7 Irrigation Methods

India is the agricultural power house at global level in which 63% is rainfed and 37% is irrigated out of approximately 195 million-hectare (M ha) area under cultivation. India has the second largest net irrigated area, after China, but the share of water allotted for irrigation has been decreased by 10–15% in the next two decades, and average yield in irrigated and canal command area is still pathetically low. Climate change has also aggravated these problems. Presently, most of the farmers are marginal and irrigate their lands manually through conventional irrigation. In spite of its wide use, the method is characterized by poor irrigation efficiency (35–40%) which might be due to more conveyance, distribution, and application losses as well as lack of availability of reliable gadgets for water accounting and auditing at on-farm. Apart from it, most of the canal command farmers don't get timely and adequate amount of water, and tail-end farmers suffer from water shortage especially during peak season. Promoting micro-irrigation (irrigation efficiency 75–95%) and adopting advanced technologies to fulfill the dream of "more crop per drop" mantra is today's need. Enhancing land and water productivity (WP) in dryland agriculture is important not only for enhancing agricultural production on existing land with limited water availability but also for saving water for future use. It has been the subject of long-term researches, and they are well documented (Elbeltagi et al. 2021; Rockstrom and Barron 2007; Molden 2007; Bouman 2007; Kijne et al. 2003a, b). Enhancing water productivity options depends upon various factors like reducing water losses, judicious use of water resources, adopting modern agronomic practices, etc. Regarding engineering aspects, several examples described the irrigation water management effect on water productivity (Kushwaha et al. 2021; Oktem et al. 2003; Yazar et al. 2002; Kang et al. 2000; Zhang et al. 1998). Some important irrigation methods suitable to dryland regions (Fig. 11.5) are described below:

11.7.1 Alternate Furrow Irrigation (AFI) Method

In it, water applies in alternate furrows and reported as more efficient (25–50% water saving) as compared to the regularly utilized every furrow irrigation approach (Eba 2018; Golzardi et al. 2017; Kang et al. 2000). Many researchers also reported that

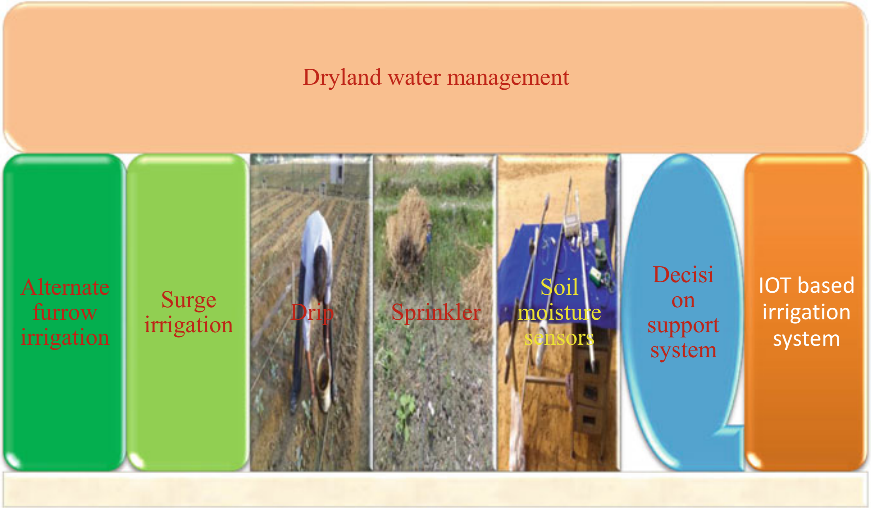

Fig. 11.5 Options of irrigation water management in drylands

such type of strategy has enormous potential to improve crop water productivity by reducing soil water loss through evaporation (Einsenhaver and Youth 1992; Davies and Zhang 1991; Stone et al. 1982).

11.7.2 Surge Irrigation

Surge irrigation refers to irrigation water applied intermittently at steady or variable rates in "on" and "off" series of pulses (Bahu et al. 2005). This method works well for Vertisols because they expand and contract when wet and dried (Stringham 1988). This approach is more suitable for uniform infiltration in Vertisols led to irrigation water saving, improving irrigation efficiency (20–30%), and higher crop water productivity in addition to achieving water application efficiency up to 85% (Valipour 2013; Horst et al. 2007; Mintesinot et al. 2007).

11.7.3 Pressurized Irrigation System

Pressurized systems like centre pivot system, drip, sprinkler, low-energy precision application (LEPA) system, etc. are one of the most popular for effective utilization of resources like water, soil nutrients, and energy. This system has capacity to reduce the irrigation cost (20%–50%), electricity consumption (about 31%), and fertilizer saving in the range of 7–42% (PMKYS). Among them, subsurface drip irrigation is one of the effective techniques to reduce soil evaporation in context of dryland agriculture. Similarly, bucket kits of gravity-run drip irrigation are one of the low-cost viable options in vegetable garden of dryland regions. They produce vegetable as par with commercial drip systems by efficient water utilization. Sensor-based irrigation system also helps in scheduling of irrigation and enhances water use efficiency in these regions. Aside from it, it is high time to increase the use of solar energy in agriculture. Solar micro-irrigation system can play a significant role in reducing energy consumption and carbon emissions. The variable rate irrigation system enhances water efficiency by managing nutrient and water uses at the site, but in Indian dryland condition due to lack of land consolidation, such types of technologies are not feasible.

11.7.4 Sensor-Based Irrigation System

Sensors basically help in irrigation scheduling and automation of irrigation system. Keeping these facts, various soil moisture sensors, i.e. neutron probe, tensiometers, watermarks, granular matrix, TDR (time domain reflectometry), and FDR (frequency domain reflectometry), and canopy sensors like dendrometer, infrared thermometer, infrared gas analyser, sap flow metre, etc., have been widely used in irrigation scheduling (Fig. 11.6). They help the irrigators to take the decision regarding irrigation scheduling, but site-specific calibration is required before taking moisture content in field (Kumari et al. 2019). Wireless sensor array also helps in real-time irrigation scheduling and saves a lot of water (Vellidis et al. 2008).

11.7.5 Decision Support System (DSS)

Policymakers/decision-makers use DSS to solve complex problems in an improved and fast system by providing many alternatives. It also acquires real-time weather data from weather station and monitoring of soil moisture by sensor network distributed across the field via wireless communication. Various applications such as water management in various crops, yield forecasting, irrigation scheduling, computer-aided mapping, etc. have been implemented by DSS. In this context, soil-water balance softwares like CROPWAT (Smith and Martin 1991), IrriSatSMS (John et al. 2009), IrriSat (Urso et al. 2013), PILOTE (Khaledian et al. 2009), etc. help in various crop irrigation scheduling, and the DRIPD developed by Rajput and

Fig. 11.6 Sensors for irrigation scheduling

Patel (2003) was used to determine the design criteria for a drip irrigation system. Thus, the irrigation scheme derived from DSS helps the precise application of water and supports "more crops per drop" paradigm.

11.7.6 IOT-Based Smart Irrigation System

This helps in automatic regulation of the irrigation system at predefined moisture content in fields from remote areas by using mobile phone which saves irrigation time and water along with farmers' drudgery reduction (Abhilash et al. 2020). They have applied uniform moisture distribution in the farm which ultimately enhances crop water productivity even in dryland agriculture also. It also provides web-based services for collection of field sensor data, weather information, soil water status, as well as precise irrigation. It has huge potential to site-specific irrigation control even in dryland regions.

11.8 Economics of Deficit Irrigation Strategies

The main advantage of deficit irrigation is that the water saved from optimal irrigation may be used to irrigate more area, enhancing net income (English et al. 2002). But the accurate quantification of this economic gain is critical for future cropping and irrigation strategies. Reduced planting area, reduced water use, adoption of drought-resistant cultivars, or change in crop planning may be optimal options for increasing economic return. However, by using a good economic optimization model for irrigation and other inputs, potential income from the same land and crop type can be improved. This model primarily establishes the relationship between crop growth, water, and other inputs.

11.8.1 Bio-Economic Model for Deficit Irrigation

English et al. (1990) provided a simplified economic model that provides insight into the field level application of deficit irrigation and the economic gain associated with it in the context of limited inputs. Because it incorporates both land and water limitation constraints, this economic model may be applied to all places with minimal variation based on regional agricultural and climactic characteristics. Figure 11.7 depicts the analytical framework used in the basic English model.

To obtain an optimum deficit irrigation strategy, the English model and all other economic optimization models use both crop water production functions and revenue functions. Crop production functions describe the correlation between plant yield and water applied, which is not always a deliberate under-irrigation strategy (Doorenbos and Kassam 1979). It is an analytical framework for determining an optimal profit-maximizing water application level that is less than full irrigation under specified conditions. Because gross income is closely linked to crop yield, the

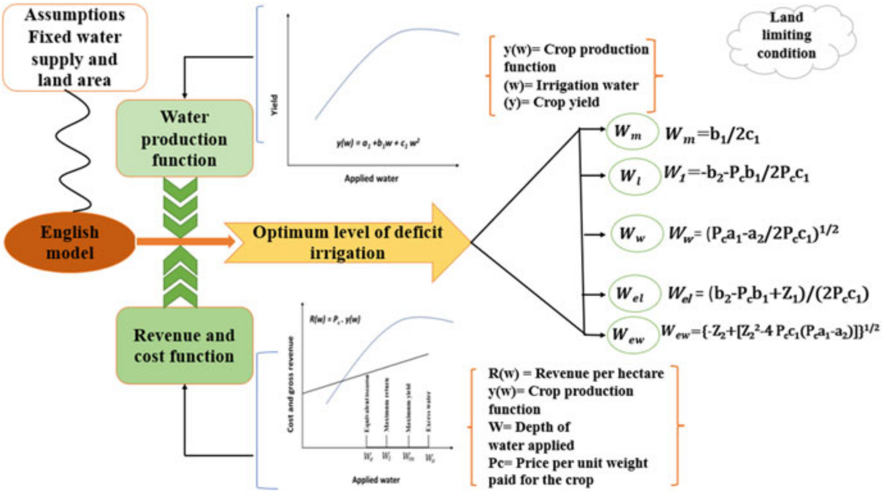

Fig. 11.7 Analytical framework of English model for economics of deficit irrigation

revenue function will exhibit the same trend as the crop production function. This revenue function covers both fixed and variable costs incurred in farm level processes, and it is mostly influenced by regional farm input variables.

11.8.2 Land Limiting Condition and Opportunity Cost of Water

A bio-economic model for deficit irrigation must account for regional land and water resource limitations. Because these elements influence the plant's marginal production, the model should anticipate the optimal level of irrigation while taking into account the limiting conditions of land and water. The term "land limiting condition" refers to a non-water scarcity situation with fixed land usage. The most effective deficit irrigation approach maximizes income per unit of land. However, the opportunity cost of water is the water saved in deficit irrigation practice in the field that can be used to irrigate more farmlands, increasing overall gross income. This essentially illustrates water-limiting conditions in which we have a scarcity of water resources yet need to irrigate as much area as possible for cultivation.

11.8.3 Empirical Models Used in Deficit Irrigation Economics

To be sustainable, a system must strike a balance between profit and the environment in which it operates. On the one hand, it should provide the maximum benefit while without endangering natural resources such as crops, land, and water. An economic analysis gives a clear overview of any irrigation practices used in a certain set of conditions. Many researchers investigated the economic benefit of deficit irrigation

Table 11.2 Various types of methods used for economics of deficit irrigation

S. no.	Types of empirical economic models		References
1.	Programming model	Normative model	Ali et al. (2017); Doppler et al. (2002)
		Linear programming model	Bartolini et al. (2007); Galko and Jayet (2011); Hazell and Norton (1986)
		Positive mathematical programming model	Heckelei and Wolff (2003); Howitt (1995); Merel et al. (2011)
2.	Econometrics model		Hendricks and Peterson (2012); Moore et al. (1994)
3.	Field experiments		Bouarfa et al. (2011); Cusicanqui et al. (2013); Maestre-Valero et al. (2016)
4.	Hedonic pricing		Campos et al. (2021); Joshi et al. (2017); Kakhki et al. (2010)
5.	Contingent valuation		Mezgebo et al. (2013); Storm et al. (2011); Weldesilassie et al. (2009)

by using various approaches and bio-economic models to assess its long-term viability in crop yield and farmer profitability. Table 11.2 shows the various approaches used for deficit irrigation economics.

11.9 Conclusion and Outlook

Being able to provide food and fibre for the world's population has become a conundrum amidst freshwater scarcity especially in arid and semiarid region. The dryland areas (i.e. 41% of the global terrestrial) are dominated for grazing and rainfed cropping because of water scarcity, and the crop water productivity generally remains low due to on-farm water losses through seepage and evaporation. In water-short areas, irrigation water supplies remain abundant, and efforts are to maximize crop productivity and may be done through on-demand irrigation service. This will help to meet the full crop demand with negligible deep percolation losses. Stressing crops enhances water usage efficiency, without hampering the yields. Under such conditions in the dryland farming system, sustainable crop production may be achieved by employing deficit irrigation (DI) techniques. Deficit irrigation with scheduling reduces irrigation water consumption and conserves available water resources.

This chapter presents detailed discussion on improving water productivity through deficit irrigation in conjunction with irrigation scheduling and management practices such as mulching, tillage, mixed cropping or crop ration, and nutrient management. Major water saving from the irrigation system is the future need, and that could be achieved by precise management and innovative design for water delivery and field irrigation. Previous study showed that deficit irrigation has potential for sustainable reducing in agricultural water use. Present chapter could provide information that contributes in improving crop water productivity in high water-competitive environment. In conclusion, the adoption of DI may be promising in areas where available soil moisture for crop is limited and adequate land is available.

References

Abhilash RA, Kumari A et al (2020) Water resource and use efficiency under changing climate. In: Resources use efficiency in agriculture. Springer, Singapore, pp 519–576

ACIAR (Australian Centre for International Agricultural Research) (2002) Improving water –use efficiency in dryland cropping. http:www.aciar.gov.au/web,nsf/att/ACIA-5K36CC/$file/2-3PDF (verified 16 Oct. 2003)

Aguilera E, Lassaletta L, Sanz-Cobena A et al (2013) The potential of organic fertilizers and water management to reduce N2O emissions in Mediterranean climate cropping systems. A review. Agric Ecosyst Environ 164:32–52

Ahmad A (1999) Yield response of groundnut grown under rainfed and irrigated conditions. In: Kirda, Moutonnet CP, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands

Ali MH, Hoque MR, Hassan AA et al (2017) Effects of deficit irrigation on yield, water productivity, and economic returns of wheat. Agric Water Manag 92(3):151–161

All India Coordinated Research Project for Dry land Agriculture (2000) Annual report of the AICRPDA. Central Res. Inst. for Dryland Agric, Hyderabad, India

Anac MS, Ali Ul M, Tuzel IH et al (1999) Optimum irrigation scheduling for cotton under deficit irrigation conditions. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands

Anderson RL, Bailey KL, Peairs FB (2006) Guidelines for integrating ecological principles of pest management with rotation design. In: Peterson GA et al (eds) Dryland agriculture. 2nd ed. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI, pp 195–226

Bahu RR, Rajput TBS, Bhattacharya AK et al (2005) Modelling of water front advance under surge furrow irrigation. J Agric Eng 42(3):68–73

Bartolini F, Bazzani GM, Gallerani V et al (2007) The impact of water and agriculture policy scenarios on irrigated farming systems in Italy: an analysis based on farm level multi-attribute linear programming models. Agric Syst 93:90–114

Bastug R (1987) A study on determining the water production function of cotton under Cukuorova conditions. Cukurova University, Adana, Turkey

Borghi E, Crusciol CA, Mateus GP et al (2013) Intercropping time of corn and palisadegrass or guineagrass affecting grain yield and forage production. Crop Sci 53:629–636

Bouarfa S, Brunel L, Granier J et al (2011) Évaluation en partenariat des stratégiesd'irrigation en cas de restriction des prélèvementsdans la nappe de Beauce (France). Cahiers Agricultures 20(1–2): 124–129

Bouman B (2007) A conceptual framework for the improvement of crop water productivity at different spatial scales. Agric Syst 93:43–60

Campos PM, Thompson JS, Molina JP (2021) Effect of irrigation water availability on the value of agricultural land in Guanacaste, Costa Rica: a hedonic pricing approach. e-Agronegocios 7(1): 38–55

Carmen R, Rodriguez P, Jose R et al (2018) Avocado (Perseaamericana Mill.) Trends in Water-Saving Strategies and Production Potential in a Mediterranean Climate, the Study Case of SE Spain: A Review. Water Scarcity and Sustainable Agriculture in Semiarid Environment. https://doi.org/10.1016/B978-0-12-813164-0.00014-4

Chai Q, Gan Y, Turner NC et al (2014) Water-saving innovations in Chinese agriculture. Adv Agron 126:149–201

Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y, Siddique KHM (2016) Regulated deficit irrigation for crop production under drought stress. A review. Agron Sustain Dev 36(1):3

Chakraborty D, Nagarajan S, Aggarwal P, Gupta VK, Tomar RK, Garg RN, Sahoo RN, Sarkar A, Chopra UK, Sarma KSS, Kalra N (2008) Effect of mulching on soil and plant water status, and the growth and yield of wheat (Triticum aestivum L.) in a semi-arid environment. Agric Water Manag 95:1323–1334

Chalmers DJ, Mitchell PD, VanHeek L (1981) Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. J Am Soc Hortic Sci 106:307–312

Craciun L, Craciun M (1999) Water and nitrogen use efficiency under limited water supply for maize to increase land productivity. In: Kirda et al (eds) Crop yield response to deficit irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands

Cui NB, Du TS, Kang SZ (2008) Regulated deficit irrigation improved fruit quality and water use efficiency of pear-jujube trees. Agric Water Manag 95:489–497

Cusicanqui J, Dillen K, Geerts S et al (2013) Economic assessment at farm level of the implementation of deficit irrigation for quinoa production in the Southern Bolivian Altiplano. Span J Agric Res 4:894–907

Davies WJ, Zhang J (1991) Root signals and the regulation of growth and development of plants in drying soil. Ann Rev Plant Physiol Plant Mol Biol 42:55–76

Doorenbos J, Kassam AH (1979) Yield response to water by irrigation and drainage paper no. 33. FAO, Rome

Doppler W, Salman AZ, Al-Karablieh EK et al (2002) The impact of water price strategies on the allocation of irrigation water: the case of the Jordan Valley. Agric Water Manag 55(3):71–182

Dry PR, Loveys BR (1999) Grapevine shoot growth and stomatal conductance are reduced when part of the root system is dried. Vitis 38:151–156

Dry PR, Loveys BR (2000) During H. Partial drying of the rootzone of grape. II. Changes in the pattern of root development. Vitis 39:9–12

Eba AT (2018) The impact of alternate furrow irrigation on water productivity and yield of potato at small scale irrigation, Ejere District, West Shoa. Ethiopia J Plant Sci Agric Res 2(2):16

Einsenhaver DE, Youth CD (1992) Managing furrow irrigation system. In: Proc. Central Plain Irrigation. USA grim, Nebraska, Feb. 5–6

El Amami H, Zairi A, Pereira LS, et al (2001) Deficit irrigation of cereals and horticultural crops: economic analysis. Agricultural Engineering International: the CIGR Journal of Scientific Research and Development. Manuscript LW 00 007b. Vol.I

Elbeltagi A, Aslam MR, Mokhtar A et al (2021) Spatial and temporal variability analysis of green and blue evapotranspiration of wheat in the Egyptian Nile Delta from 1997 to 2017. J Hydrol 594:125662. https://doi.org/10.1016/j.jhydrol.2020.125662

Elias F, Soriano MA (2007) Deficit irrigation for reducing agricultural water use. J Exp Bot 58:147–159

English MJ, Nuss MS (1982) Designing for deficit irrigation. J Am Soc Civil Eng 91–106

English M, Raja SN et al (1996) Perspectives on deficit irrigation. Agric Water Manag 32:1–14

English MJ (1990) Deficit irrigation: an analytical framework. J Irrig Drain Eng, ASCE 116(3): 399–412

English MJ, Musick JT, Murty VVN (1990) Deficit irrigation. Management of farm irrigation systems (Hoffman, G.J., Howell, T.A., and Solomon, K.H., Editors). ASAE Monograph no. 9. American Society of Agricultural Engineers publisher, 1020p

English MJ, Salomon KH, Hoffman GJ (2002) A paradigm shift in irrigation management. J Irrig Drain Eng 128(5):267–277

Fabeiro Cortes C, de Santa M, Olalla F, Lopez R et al (2003) Production and quality of the sugar beet (Beta vulgaris L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate. Agric Water Manag 62:215–227

Fan T, Stewart BA, Payne WA et al (2005) Supplemental irrigation and water: yield relationships for plasticulture crops in the loess plateau of China. Agron J 97:177–188

Fan Y, Wang C, Nan Z (2014) Comparative evaluation of crop water use efficiency, economic analysis and net household profit simulation in arid Northwest China. Agric Water Manag 146: 335–345

Fan Z, Chai Q, Huang G et al (2013) Yield and water consumption characteristics of wheat/maize intercropping with reduced tillage in an oasis region. Eur J Agron 45:52–58

Farina R, Seddaiu G, Orsini R et al (2011) Soil carbon dynamics and crop productivity as influenced by climate change in a rainfed cereal system under contrasting tillage using EPIC. Soil Tillage Res 112:36–46. https://doi.org/10.1016/j.still.2010.11.002

Food and Agricultural Organization (2012) Coping with water scarcity: An action framework for agriculture and food security, FAO water reports

Food and Agriculture. (1979) Yield response to water. Irrigation and Drainage Paper No. 33. Rome

Food and Agriculture Organization (2002) Deficit irrigation and practice

Francis CA (1989) Biological efficiencies in multiple cropping systems. Adv Agron 42:1–42

Galko E, Jayet PA (2011) Economic and environmental effects of decoupled agricultural support in the EU. Agric Econ 42(5):605–618

Geerts S, Raes D (2009) Deficit irrigation as an on-farm strategy to maximise crop water production in dry areas. Agric Water Manag 96(9):1275–1284

Girona J, Mata M, Del Campo J et al (2006) The use of midday leaf water potential for scheduling deficit irrigation in vineyards. Irrig Sci 24:115–127

Girona J, Mata M, Goldhamer DA et al (1993) Patterns of soil and tree water status and leaf functioning during regulated deficit irrigation scheduling in peach. J Am Soc Hortic Sci 118: 580–586

Golzardi F, Baghdadi A, Afshar RK (2017) Alternate furrow irrigation affects yield and water-use efficiency of maize under deficit irrigation. Crop Pasture Sci 68(8):726–734

Goodwin I, Boland AM (1998) Scheduling deficit irrigation of fruit trees for optimizing water use efficiency Department of Natural Resources. Tatura, Australia

Govaerts B, Verhulst N, Castellanos-Navarrete A et al (2009) Conservation agriculture and soil carbon sequestration: between myth and farmer reality. Crit Rev Plant Sci 28:97–122. https://doi.org/10.1080/07352680902776358

Guang-Cheng S, Zhang Z-Y, Liu N, Shuang-En Y (2008) Comparative effects of deficit irrigation (DI) and partial rootzone drying (PRD) on soil water distribution, water use, growth and yield in greenhouse grown hot pepper. Sci Hortic 119(1):11–16

Hazell PBR, Norton RD (1986) Mathematical programming for economic analysis in agriculture. Macmillan, New York

Heckelei T, Wolff H (2003) Estimation of constrained optimisation models for agricultural supply analysis based on generalised maximum entropy. Eur Rev Agric Econ 30(1):27–50

Hendricks NP, Peterson JM (2012) Fixed effects estimation of the intensive and extensive margins of irrigation water demand. J Agric Resour Econ:1–19

Horst MG, Shamutalov SS, Goncalves JM et al (2007) Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. Agric Water Manag 87:115–127

Howitt RE (1995) A calibration method for agricultural economic production models. J Agric Econ 46(2):147–159

Hsiao TC (1993) Growth and productivity of crops in relation to water status. Acta Hortic 335:137–148

IAEA (International Atomic Energy Agency) (2005) Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas. IAEATECDOC-1468. IAEA, Vienna, Austria

Janzen HH, Desjardins RL, Asselin JMR, et al (1999) The health of our air: towards sustainable agriculture in Canada. Research Branch, Agriculture and Agric-Food Canada, Ottawa, Publication No. 1981/E

John WH, Nicholas JC, Evan WC et al (2009) IrriSatSMS irrigation water management by satellite and SMS - a utilization framework. CSIRO Land and Water Science

Jones OR, Unger PW, Fryrear DW (1985) Agricultural technology and conservation in the southern High Plains. J Soil Water Cons 40:195–198

Joshi J, Ali M, Berrens RP (2017) Valuing farm access to irrigation in Nepal: a hedonic pricing model. Agric Water Manag 181:35–46

Kader MA, Senge M, Mojid MA et al (2017) Recent advances in mulching materials and methods for modifying soil environment. Soil Tillage Res 168:155–166

Kahlown MA, Azam M, Kemper WD (2006) Soil management strategies for rice-wheat rotations in Pakistan's Punjab. J Soil Water Conserv 61(1):40–44

Kakhki MD, Shahnoushi N, Khajehroshanaee N (2010) Valuation of water and its sensitive analysis in agricultural sector a hedonic pricing approach. Am J Agric Biol Sci 5(1):20–24

Kang S, Shi W, Zhang J (2000) An improved water-use efficiency for maize grown under regulated deficit irrigation. Field Crops Res 67:207–214

Kang SZ, Zhang L, Hu XT (2001) An improved water use efficiency for hot pepper grown under controlled alternate drip irrigation on partial roots. Sci Hortic 89:257–267

Khaledian MR, Mailhol JC, Ruelle P et al (2009) Adapting PILOTE model for water and yield management under direct seeding system: the case of corn and durum wheat in a Mediterranean context. Agric Water Manag 96:757–770

Kijne JW, Barker R, Molden D (2003a) Water productivity in agriculture:limits and opportunities for improvement. International Water Management Institute, Sri Lanka

Kijne JW, Barker R, Molden D et al (2003b) Water Productivity in Agriculture: Limits and Opportunities for Improvement. Comprehensive Assessment of Water Management in Agriculture Series 1. CAB International, Wallingford, UK in association with International Water Management Institute (IWMI), Colombo

Kirda C (2002) Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. In: Food and Agricultural Organization of the United Nations (FAO) (ed.), Deficit irrigation practices. Rome, Italy, p. 3–10

Kirda C, Kanber R (1999) Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation, Dordrecht. Kluwer Academic Publishers, The Netherlands

Kirda C, Kanber R, Tulucu K (1999a) Yield response of cotton, maize, soybean, sugarbeet, sunflower and wheat to deficit irrigation. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands

Kirda C, Moutonnet P, Hera C (1999b) Crop yield response to deficit irrigation. The Netherlands, Kluwer Academic Publishers, Dordrecht

Klocke NL, Payero JO, Schneekloth JP (2007) Long-term response of corn to limited irrigation and crop rotations. Trans ASABE 50:2117–2124. https://doi.org/10.13031/2013.24113

Koohafkan P, Stewart B (2008) Water and cereals in drylands. The Food and Agriculture Organization of the United Nations and Earthscan, London-Sterling, VA, UK. pp 113

Kriedemann PE, Goodwin I (2003) Regulated deficit irrigation and partial root zone drying. Land and Water Australia, Canberra

Kumar A, Sharma SK, Sharma CL et al (2018) Impact of water deficit (salt and drought) stress on physiological, biochemical and yield attributes on wheat (Triticumaestivum) varieties. Indian J Agric Sci 80(10):1624–1632

Kumari A, Patel N, Ahmed A (2019) Standardization of frequency domain reflectometry and watermark sensors for soil moisture measurement at field level. J AgriSearch 6(4):175–180

Kushwaha NL, Bhardwaj A (2017) Prioritization of micro watershed in shivalik foot hills. J Agric Eng 57:122–129

Kushwaha NL, Bhardwaj A, Verma VK (2016) Hydrologic response of Takarla-Ballowal watershed in Shivalik foot-hills based on morphometric analysis using remote sensing and GIS. J Indian Water Resour Soc 36:17–25

Kushwaha NL, Kanojia V (2018) Evaluation of central pivot irrigation system under different soil and climatic conditions. J Pharmacogn Phytochem 7:2551–2553

Kushwaha NL, Rajput J, Elbeltagi A et al (2021) Data intelligence model and meta-heuristic algorithms-based pan evaporation modelling in two different agro-climatic zones: a case study from Northern India. Atmos 12:1654. https://doi.org/10.3390/atmos12121654

Kushwaha NL, Yousuf A (2017) Soil erosion risk mapping of watersheds using RUSLE, remote sensing and GIS: a review. Res J Agric Sci 8:269–277

Lal R (2015) A system approach to conservation agriculture. J Soil Water Conserv 70(4):82–88

Li S-H, Huguet J-G, Schoch PG et al (1989) Response of peach tree growth and cropping to soil water deficit at various phenological stages of fruit development. J Hortic Sci 64:541–552

Li R, Hou X, Jia Z, Han Q, Ren X, Yang B (2013) Effects on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the Loess Plateau, China. Agric Water Manag 116:101–109

Maestre-Valero JF, Martin-Gorriz B, Alarcon JJ et al (2016) Economic feasibility of implementing regulated deficit irrigation with reclaimed water in a grapefruit orchard. Agric Water Manag 178:119–125

Matthews MA, Anderson MM, Schultz HR (1987) Phenological and growth responses to early and late season water deficits in cabernet franc. Vitis 26:147–160

Merel P, Simon LK, Yi F (2011) A fully calibrated generalized constant-elasticity-of-substitution programming model of agricultural supply. Am J Agric Econ 93(4):936–948

Mezgebo A, Tessema W, Asfaw Z (2013) Economic values of irrigation water in Wondo Genet District, Ethiopia: an application of contingent valuation method. J Econ Sustain Dev 4(2): 23–36

Miller DE, Hang AN (1980) Deficit, high-frequency irrigation of Sugarbeets with the line source technique. Soil Sci Soc Am J 44

Mintesinot B, Verplancke H, Ranst EV et al (2007) Enhancing the productivity of irrigated Vertisols: a comparative study between a traditional method and surge/ intermittent management. Soil Use Manag 23:36–39

Mitchell PD, Goodwin I (1996) Micro-irrigation of vines and fruit trees. Agmedia, Melbourne, Australia

Mitchell PD, Van den Ende B, Jerie PH et al (1989) Responses of `Barlett' pear to withholding irrigation, regulated deficit irrigation, and tree spacing. J Am Soc Hortic Sci 114:15–19

Molden D. (ed.) (2007) Water for food, water for life: comprehensive assessment of water management in agriculture. Earthscan, London, in association with International Water Management Institute (IWMI), Colombo

Monteith J, Webb C (1981) Soil, water and nitrogen in Mediterranean-type environments. Developments in Plant and Soil Sciences, Vol. 1. MartinusNijho_/Dr. W. Junk Publ., _e Hague, _e Netherlands

Moore MR, Gollehon NR, Carey MB (1994) Multicrop production decisions in western irrigated agriculture: the role of water price. Am J Agric Econ 76(4):859–874

Moutonnet P (2002) Yield response factor of field crops to deficit irrigation. International Atomic Energy Agency Joint FAO/IAEA Division Vienna Austria

Nawaz A, Farooq M (2016) Nutrient management in dryland agriculture systems. In Innovations in dryland agriculture 115–142. Springer, Cham

Ngigi SN (2003) What is the limit of up-scaling rainwater harvesting in a river basin? Phys Chem Earth, Parts A/B/C 28(20–27):943–956

Nielsen DC, Vigil MF, Benjamin JG (2011) Evaluating decision rules for dryland rotation crop selection. Field Crops Res 120:254–261

Oktem A, Simsek M, Oktem AG (2003) Deficit irrigation effects on sweet corn (Zea mays saccharata Sturt) with drip irrigation system in a semi-arid region: I. Water-yield relationship. Agric Water Manag 61(1):63–74

Oweis T, Pala M, Ryan J (1998) Stabilizing rainfed wheat yields with supplemental irrigation in a Mediterranean—type climate. Agron J 90:672–681

Ozbahce A, Tari AF (2010) Effects of different emitter space and water stress on yield and quality of processing tomato under semi-arid climate conditions. Agric Water Manag 97(9):1405–1410

Palm C, Blanco-Canqui H, De Clerck F et al (2013) Conservation agriculture and ecosystem services: an overview. Agric Ecosyst Environ 187:87–105. https://doi.org/10.1016/j.agee.2013.10.010

Panigrahi P, Sharma RK, Hasan M et al (2014) Deficit irrigation scheduling and yield prediction of Kinnow mandarin (Citrus reticulate Blanco) in a semiarid region. Agric Water Manage 140:48–60

Pene CBG, Edi GK (1999) Sugarcane yield response to deficit irrigation at two growth stages. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation, Dordrecht. Kluwer Academic Publishers, The Netherlands

Pereira LS (2001) Higher performances through combined improvements in irrigation methods and scheduling: a discussion. Agric Water Manag 40(2):153–169

Pereira LS, Cordery I, Iacovides I (2012) Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric Water Manag 108:39–51

Prasad R (2009) Enhancing nutrient use efficiency - Environmental benign strategies. Souvenir, 67–74. Indian Society of Soil Science, New Delhi

Prieto D, Angueira C (1999) Water stress effect on different growing stages for cotton and its influence on yield reduction. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation, Dordrecht. Kluwer Academic Publishers, The Netherlands

Qin AZ, Huang GB, Chai Q, Yu AZ et al (2013) Grain yield and soil respiratory response to intercropping systems on arid land. Field Crop Res 144:1–10

Qin S, Li S, Kang S, Du T, Tong L, Ding R (2016) Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition ? Agric Water Manag [Internet] 177:128–137

Rajput TBS, Patel N (2003) User's guide for – DRIPD- software for designing drip irrigation system. TB-ICN: 2003. WTC, IARI, New Delhi

Rao, SC, Ryan, J (2004) Challenges and strategies of dryland agriculture. Special Publication No. 32. Crop Soil Sci Soc Am, Madison, WI, USA

Rockstrom J, Barron J (2007) Water productivity in rainfed systems: overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrig Sci 25:299–311

Romero P, Rocio G, Del Francisco AM et al (2013) Regulated deficit irrigation based upon optimum water status improves phenolic composition in Monastrell grapes and wines. Agric Water Manag 121:85–101

Ruiz-Sanchez MC, Domingo R, Castle JR (2010) Review: deficit irrigation in fruit trees and vines in Spain. Span J Agric Res 8(S2):S5–S20

Savic S, Stikic R, VucelicRadovic B et al (2008) Comparative effects of regulated deficit irrigation (RDI) and partial root-zone drying (PRD) on growth and cell wall peroxidase activity in tomato fruits. Sci Hortic 117(1):15–20

Schoups G, Hopmans JW, Young CA et al (2005) Sustainability of irrigated agriculture in the San Joaquin Valley, California. Proc Natl Acad Sci, USA 102:15352–15356

Seckler D, Molden D, Barker R (1998) Water scarcity in the twenty-first century. IWMI water brief 1. International Water Management Institute, Colombo, Sri Lanka

Shanan L (1992a) Planning and management of irrigation systems in developing countries. Agric Water Manag 22(1&2)

Shanan L (1992b) Planning and management of irrigation systems in developing countries. Agric Water Manag 22(1&2):20–24

Sharma NK, Singh RJ, Mandal D et al (2017) Increasing farmer's income and reducing soil erosion using intercropping in rainfed maize-wheat rotation of Himalaya, India. Agric Ecosyst Environ 247:43–53

Singh J, Kaur J (2019) India's water crisis: challenges, solutions and barriers, working paper, rajiv gandhi institute for contemporary studies

Sivanappan RK (1995) Soil and water management in the dry lands of India. Land Use Policy 12(2):165–175

Smith, Martin (1991) CROPWAT: manual and guidelines. FAO of UN, Rome

Snyder RL (1992) When water is limited how many acres do you plant? Calif Agric 47:7–9

Stewart BA, Musick JT (1982) Conjunctive use of irrigation and rainfall in semi-arid regions. Adv Agron 1:1–23

Stewart JI, Cuenca RH, Pruitt WO (1977) Determination and utilization of water production functions for principal California crops. W-67 California contributing project report. University of California, Davis, United States of America

Stikic R, Popovic S, Sordic M et al (2003) Partial root drying (PRD): A new technique for growing plants that saves water and improves the quality of fruit. Proceedings of the European Workshop on Environmental Stress and Sustainable Agriculture, September 7–12, 2002, Varna, Bulgaria, 164–171

Stone JF, Reeves HE, Garton JE (1982) Irrigation water conservation by using wide- spaced furrows. Agric Water Manag 5:309–317

Storm H, Heckelei T, Heidecke C (2011) Estimating irrigation water demand in the Moroccan Drâa Valley using contingent valuation. J Environ Manag 92(10):2803–2809

Stringham GE (1988) Surge flow irrigation: final report of the western regional research project W-163. Utah Agricultural Experiment Station, Utah State University, Logan

Urso GD, Michele CD, Bolognesi SF (2013) IRRISAT: The Italian on-line satellite irrigation advisory service. EFITA-WCCA-CIGR Conference "Sustainable agriculture through ICT innovation", Turin, Italy

Vågen TG, Lal R, Singh BR (2005) Soil carbon sequestration in Sub-Saharan Africa: a review. Land Degrad Dev 16:53–71. https://doi.org/10.1002/ldr.644

Valipour M (2013) Increasing irrigation efficiency by management strategies: cutback and surge irrigation. J Agric Biol Sci 8(1):35–43

Van Duivenbooden N, Pala M, Studer C, et al (1999) E_cient soil water use:_e key to sustainable crop production in the dry areas of West Asia, and North and Sub-Saharan Africa. International Center for Agricultural Research in the Dry Areas, Aleppo, Syria, and International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India

Vellidis G, Tucker M, Perry C et al (2008) A real-time wireless smart sensor array for scheduling irrigation. Comput Electron Agric 61:44–50

Vishwakarma DK, Pandey K, Kaur A et al (2022) Methods to estimate evapotranspiration in humid and subtropical climate conditions. Agric Water Manag 261:107378. https://doi.org/10.1016/j.agwat.2021.107378

Vittal KPR, MaruthiSankar GR, Singh HP et al (2002) Sustainability of practices of dryland agriculture: methodology and assessment. All India Coordinated Research Project for Dryland Agriculture, Central Research Institute for Dryland Agriculture, Indian Council of Agricultural Research, Hyderabad-500, 59(100): 3–4

Waheed RA, Naqvi HH, Tahir GR et al (1999) Some studies on pre-planned controlled soil moisture irrigation scheduling of field crops. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop yield response to deficit irrigation. Kluwer Academic Publishers, Dordrecht, The Netherlands

Wakrim R, Wahbi S, Tahi H et al (2005) Comparative effects of partial root drying (PRD) and regulated deficit irrigation (RDI) on water relations and water use efficiency in common bean (Phaseolus vulgaris L.). Agriculture, Ecosystems and Environment, 106275–287

Wang J, Wang EL, Yang XG et al (2012) Increased yield potential of wheat-maize cropping system in the North China plain by climate change adaptation. Clim Chang 113:825–840

Weldesilassie AB, Fror O, Boelee E et al (2009) The economic value of improved wastewater irrigation: a contingent valuation study in Addis Ababa, Ethiopia. J Agric Resour Econ:428–449

Willey R (1979) Intercropping—its importance and research needs. Part 1. Competition and yield advantages. Field Crop Abstracts 32:1–10

Winterbottom R, Reij C, Garrity D, et al (2013) Improving land and water management. World Resources Institute Working Paper. Accessed on April, 2(2014), 1

Yang C, Huang G, Chai Q et al (2011) Water use and yield of wheat/maize intercropping under alternate irrigation in the oasis field of Northwest China. Field Crop Res 124(3):426–432

Yang N, Sun Z, Feng L, et al (2015) Plastic film mulching for water-efficient agricultural applications and degradable films materials development research. Mater Manuf Process.:37–41

Yavuz MY (1993) FarkliSulamaYontemlerininPamuktaVerimvesuKullaniminaEtkileri (Ph.D. Thesis). Adana, Turkey, Cukurova University, Faculty of Agriculture

Yazar A, Sezen SM, Gencel B (2002) Drip irrigation in the Southeast Anatolia Project (GAP) area in Turkey. Irrig Drain 51:293–300

Yin W, Chen G, Feng F et al (2017) Straw retention combined with plastic mulching improves compensation of intercropped maize in arid environment. Field Crop Res 204:42–51

Zhang JH, Sui XZ, Li B et al (1998) An improved water-use efficiency for winter wheat grown under reduced irrigation. Field Crop Res 59:91–98

Zhang Y, Suyker A, Paustian K (2018) Improved crop canopy and water balance dynamics for agroecosystem modeling using DayCent. Agron J 110:511–524

Zribi W, Aragues R, Medina E et al (2015) Efficiency of inorganic and organic mulching materials for soil evaporation control. Soil Till Res [Internet] 148:40–45

Zwart SJ, Bastiaansen WGM (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag J 69:115–133