International Journal of Information, Engineering & Technology

Volume 11, Issue 3, PP 16-27, ISSN: 2360-9194, December, 2020
Double Blind Peer Reviewed International Research Journal
garcjournalssubmit@gmail.com
Journal Series: Global Academic Research Consortium (garc)

Deficit Irrigation as a Technique for Maximizing Irrigation Water Productivity in Water-Scarce Regions: A Review

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Abstract: *In water limited areas , irrigation is essential for economic viability of individual producers and for the region. Irrigation practice at present and in the near future will shift from laying emphases on production per unit area towards maximizing production per unit water applied or consumed that is water productivity.The effects of water stress on crop growth and grain yield depend on the timing and magnitude of water stress as well as crop type, since different crops have different levels of tolerance to water stress.Litrature revealed that, modelling is useful tool to study and develop deficit irrigation strategies that would allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios. Several papers were reviewed with common consensus that deficit irrigation reduces nutrient loss through leaching from the root zone, resulting in improved ground water quality and lower fertilizer needs on the field. However, by using deficit irrigation strategies, that is adoptation of water stress at certain developmental periods could benefit yield and quality in fruit tree and vine production, and also is a way of maximizing water use efficiency for higher yields per unit of irrigation water used in agriculture. Deficit irrigation defined as the application of less water than that required by plant, is an important tool of reducing irrigation water use and thereby maximizing irrigation water productivity. Since water scarcity is one of the key problems for crop production in arid and semi-arid regions, thus achieving great values of water use efficiency is more reasonable than maximum yield. Therefore, moderate to mild deficit irrigation, that is soil water between 60 to 70 percent is recommended by many researchers. Although a certain reduction in yield is observed.*

Key words: *Deficit irrigation, Water productivity, Water stress and Full irrigation.*

Introduction

In water limited areas, irrigation is essential for the economic viability of individual producers as well as for the region. Irrigation provides supplemental water for the crop, augmenting depleting stored soil water when precipitation is insufficient to meet crop water demands. Crop water requirements depend on several factors, including crop type, variety, and growth stage; soil water and nutrient availability; soil physical and chemical properties; micrometeorological conditions (i.e., evaporative demand); among others. Unfortunately, applying irrigation to meet full water requirements is not always an option due to the effects of drought, declining groundwater levels, reduced stream flow, water allocations, insufficient irrigation system design capacity, load management (Rudnick et al., 2017).

Deficit irrigation

Deficit irrigation is a strategy that is often used when water is limiting factor (Rogers, Lawson and Kelly, 2016). It is a technique whereby crops are deliberately allowed to sustain a certain degree of water stress during tolerant growth stages (often the vegetative stages and the late ripening period), while ample water is applied during drought sensitive stages. The practice of deficit irrigation requires a precise knowledge of the crop yield response to water (Fereres and Soriano, 2007). Total irrigation application is therefore not proportional to irrigation requirements throughout the crop cycle. While this inevitably results in plant drought stress and consequently in production loss, deficit irrigation (DI) maximizes irrigation water productivity, which is the main limiting factor (English, 1990). In other words, DI aims at stabilizing yields and obtaining maximum water productivity (WP) rather than maximum yields (Zhang and Oweis, 1999). RDI is generally defined as an irrigation practice whereby a crop is irrigated with an amount of water below the full requirement for optimal plant growth; this is to reduce the amount of water used for irrigating crops, improve the response of plants to the certain degree of water deficit in a positive manner, and reduce irrigation amounts or increase the crop water use efficiency. In another words, it the application of less water than that is required by the plant. Reduced yield as the result of deficit irrigation, especially under water limiting situations, may be compensated by increased production from the additional irrigated area with the water saved by deficit irrigation (Ali et al., 2007).

Benefits of deficit irrigation

Deficit Irrigation causes maximization of water productivity with good harvest quality, it creates less humid environment for the crop, decreasing the risk of certain diseases (e.g fungi) in comparison with full irrigation (Cicogna et al., 2005), reduces the loss of nutrients due to reduction in leaching of the root zone, which result in better quality of the ground water table (Unlu et al., 2006), influencing Product Quality_ the effects of deficit irrigation on end use quality of products are inconsistent, varying with crop species or the quality traits evaluated. Tomato crop grown under partial root-zone deficit irrigation increased solid content and improved taste and sensory quality (Zegbe- Dominguez et al. 2003); and maintaining or increasing plant yield.

Deficit irrigation applied at the early growth stage or partial root-zone deficit irrigation has been shown to maintain or even increase yields in many field crops. Mild water deficit applied in the early stage is shown to enhance the level of drought resistance later in the life cycle and consequently maintain (Liu et al. 2006a) or even increase plant yields (Cui et al. 2009b; Xue et al. 2006).

Classification of deficit irrigation

According to Ali et al., (2007), deficit irrigation is classified into the following levels:

severe water deficit—soil water less than 50 % of the field capacity;

moderate water deficit: soil water between 50 to 60 % of the field capacity; mild water deficit: soil water between 60 to 70 % of the field capacity; no deficit (full irrigation): soil water is generally greater than 70 % of the field capacity during the plant growth period, and over-irrigation: the amount of water irrigated is greater than what plants required for optimal growth.

Deficit irrigation and water productivity

When water supplies are limiting, the farmer's goal should be to maximize net income per unit water used rather than per land unit. Recently, emphasis has been placed on the concept of water productivity (WP), defined here either as the yield or net income per unit of water used in ET (Kijne et al., 2003). WP increases under DI, relative to its value under full irrigation, as shown experimentally for many crops (Zwart and Bastiaansen, 2004; Fan et al., 2005). There are several reasons for the increase in WP under DI. Figure 1 presents the generalized relationship between yield and irrigation water for an annual crop. Small irrigation amounts increase crop ET, more or less linearly.

Fig. 1. Generalized relationships between applied irrigation water, ET, and crop grain yield. IW indicates the point beyond which the productivity of irrigation water starts to decrease, and IM indicates the point beyond which yield does not increase any further with additional water application.

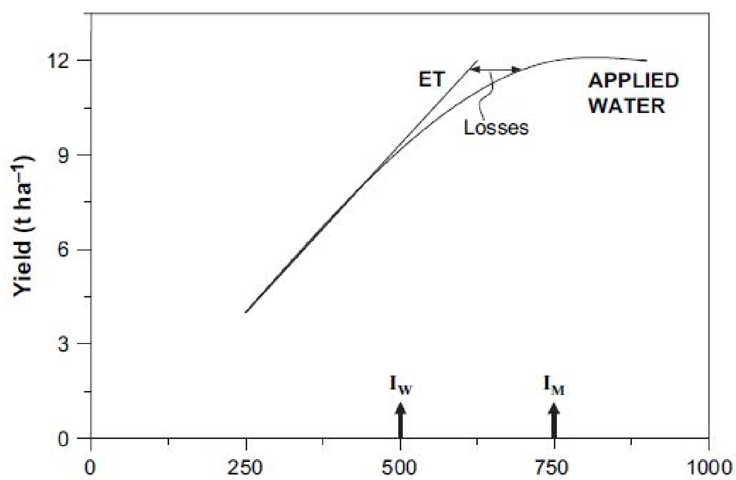

Figure 1: ET or Applied Irrigation Water (mm)

Source: Rudnick et al., (2017)

Deficit irrigation in annual crops

Harvestable yield of annual crops is normally a fraction of the biomass produced (Evans, 1993). Water deficits, by affecting growth, development, and carbon assimilation, reduce the yield of most annual crops (Hsiao and Bradford, 1983). The reduction in yield by water deficits is caused by a decrease in biomass production and/or by a decrease in the fraction of biomass that is harvested, termed the harvest index (HI). It should be noted that here reference is only made to above ground biomass production. This is because, in most studies, information on roots is scant, given the difficulties in quantifying root biomass under field conditions. Past research has shown that the response to water deficits very much depends on the pattern of stress imposed (Dorenboos and Kassam, 1979). In one pattern that has been frequently used, the water deficit increases progressively as the season advances due to a combination of the uniform application of a reduced amount and the depletion of the soil water reserve.

Deficit irrigation in fruit trees and vines

Deficit irrigation so far has had significantly more success in tree crops and vines than in field crops for a number of reasons (Fereres et al., 2003). First, economic return in tree crops is often associated with factors such as crop quality, not directly related to biomass production and water use. The yield-determining processes in many fruit trees are not sensitive to water deprivation at some developmental stages (Johnson and Handley, 2000). Because of their high water productivity (WP), tree crops and vines can afford high-frequency, micro-irrigation systems that are ideally suited for controlling water application and thus for stress management (Fereres and Goldhamer, 1990).

Moreover, experiments with regulated deficit irrigation (RDI) have been successful in many fruit and nut tree species such as almond (Goldhamer et al., 2000), pistachio (Goldhamer and Beede, 2004), citrus (Domingo et al., 1996; Gonza´lez-Altozano and Castel, 1999; Goldhamer and Salinas, 2000), apple (Ebel et al., 1995), apricot (Ruiz-Sa´nchez et al., 2000), wine grapes (Bravdo and Naor, 1996; McCarthy et al., 2002), and olive (Moriana et al., 2003), almost always with positive results. Thus, there is sufficient evidence at present that supplying the full ET requirements to tree crops and vines may not be the best irrigation strategy in many situations (Fereres and Evans, 2006).

Plant physiological responses to deficit irrigation

Stomata are pores on leaf surfaces through which plants exchange CO_2, water vapour, and other constituents with the surrounding environment. In general, stomatal conductance depends on stomatal density and size, and more stomata will provide more pores for transpiration. Under the given conditions, water stress caused by deficit irrigation may result in stomatal closure and thus reduce transpiration rate. Many researchers have reported that stomatal density responds to various environmental factors and water deficit leads to an increase in stomatal density and a decrease in stomatal size, indicating an adaptation to drought (Zhang *et al.*, 2006; Martinez *et al.*, 2007). A study on a perennial grass (*Leymus chinensis*) showed that moderate water deficits had positive effects on stomatal number but more severe deficits led to a reduction (Xu and Zhou, 2008). Furthermore, research on peanut suggested that soil drying reduced stomatal aperture and stomatal conductance but increased WUE, and the response was different among different peanut genotypes under moderate or mild water stress (Songsri *et al.*, 2013). The research progress in determining Wang et al. (2007) reviewed the genes regulating stomatal density and the possibility of increasing plant WUE. It appears that manipulating stomatal density may be a more amenable approach than manipulating stomatal behaviour in achieving a better plant WUE.

The effects of water stress on crop growth and grain yield will depend on the timing and magnitude of water stress as well as crop type, since different crops have different levels of tolerance to water stress (Irmak and Rudnick, 2014). For many field crops the most critical period of water stress is during the transition from vegetative to reproductive growth or from flowering to fruit setting (Doorenbos and Pruitt, 1977). For example, the critical period of water stress on corn is during the early reproduction period. Çakir (2004) reported that a 66 to 93% yield reduction could be expected as a result of prolonged water stress during the tasseling and ear formation growth stages.

Plant response to water stress and implication for irrigation water saving

Stomata of plant leaf close when the leaf potential declines below a threshold value. This is manifestation of the development of plant water deficit. Stomatal closure can cause marked but indirect effect on cell metabolism; changes in CO2 influx, water loss, leaf temperature and solute transport within the plant (Zhang *et al*., 1990). Evidences showed that, stomatal regulation process works through a chemical signal; the increased concentration of abscisic acid (ABA), in the xylem flow from roots to shoots controlling transpiration (Zhang *et al*. 1991). Reduction of evapotranspiration to decrease crop water requirement or reducing irrigation requirement has been a long-standing goal in arid and semi-arid regions. In some cases, the reduction of transpiration is accompanied with a reduction in photosynthesis; the water use efficiency of the plant is, therefore, unaffected (Zhang *et al*., 1990).

Modeling as a tool for assessing and developing deficit irrigation strategies

Examining the yield response to different water applications in field and/or controlled experiments is laborious and expensive. Nor can such experiments cover all possible combinations of differential drought stress or all environmental aspects affecting yield. Moreover, differential response to drought stress during different phenological stages can cause considerable scatter in the crop water productivity (CWP_c) function. Against this background, modeling can be a useful tool to study and develop promising DI strategies. it allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios (Liu et al., 2007). Furthermore, Sepaskhah and Akbari (2005) and Sepaskhah et al. (2006) developed a model with probability distributions for the amount of irrigation that should be applied for wheat and cotton in Iran.

It should be mentioned, however, that the quality and general applicability of derived DI strategies largely depends on the validity of the models describing crop growth and yield response to water, and these can only be derived from qualitative fieldwork. Dogan et al. (2007) mention their negative experiences with the modeling of soybean, which made it impossible to derive reliable DI strategies. When using models in different locations and for different crops, one should always be aware of the boundary conditions that were used when a particular model was developed and calibrated.

Deficit irrigation effects

The effects of water stress on crop growth and grain yield will depend on the timing and magnitude of water stress as well as crop type, since different crops have different levels of tolerance to water stress (Irmak and Rudnick, 2014). In deficit irrigation application, the crop is exposed to a certain level of water stress either during a particular growth period or throughout the whole growing season, without significant reductions in yields (FAO, 2000). The expectation is that the yield reduction by inducing controlled water stress will be insignificant compared with the benefits gained through diverting the saved water to irrigate additional cropped area (Kirda et al., 1999; Gijón et al., 2007). According to Birhanu and Tilahun, (2012) studies on deficit irrigation level have positively influenced marketable yield of tomato, with tomato yield decreasing as the water deficit level increased.

Effects of deficit irrigation, compared to full irrigation on water use efficiency and crop yields in some selected arid and semiarid areas are presented in the table below:

Author	Year	Region	Crop	Effects
Bekele and Tilahun	2007	Ethopia	Onion	6-13% increase in WUE
Yactayo et al.	2013	Lima, Peru	Potatoes	Saved water consumption by 32–54 % over full irrigation with early deficit application without yield penalty
Casa and Rouphael	2014	Portici, Italy	Tomato	WUE (in terms of marketable yield per unit of actual evapotranspiration) did not differ in crop yield.
Ma et al.	2014	Gangu, China	Wheat	Decreased grain yield by 43 % due to water stress imposed during reproductive growth stage
Li et al. (2010a)	2010	Yangling, China	Maize	Saved water by 11–32 %; increased canopy WUE by 10–42 %
Du et al.	2008	Minqin, Gansu	Cotton	Increased cotton yield by 5–21 % over full irrigation, due to improved harvest index

Advantages and constraints of deficit irrigation

The main advantage of deficit irrigation is that, it maximizes the productivity of water. Although a certain reduction in yield is observed, the quality of the yield (e.g. sugar content, grain size) tends to be equal or even superior to rain-fed or full irrigation (FI) cultivation (Hueso and Cuevas, 2008). In areas where water is the limiting factor for crop production, maximizing water productivity (WP) by deficit irrigation (DI) is often economically more profitable for the farmer than maximizing yield. Moreover, irrigated yields can be stabilized at a particular level, guaranteeing a stable income for the farmer and allowing economic planning. An additional advantage is that deficit irrigation creates a less humid environment around the crop than full irrigation (FI), decreasing the risk of fungal diseases (Cicogna et al., 2005).

Reducing irrigation applications over the crop cycle will also reduce nutrient loss through leaching from the root zone, resulting in improved ground water quality (Unlu¨ et al., 2006) and lower fertilizer needs on the field. Field observations indicate that crops under serious drought stress during the season might still produce reasonable yields when only a small amount of fertilizer is applied. Over-fertilization may cause crops to be more susceptible to dry spells and may lead to decreased harvest indexes (Garabet et al., 1998). On the other hand, FI can only result in high yields if sufficient N-fertilizer is applied (Pandey et al., 2000). This indicates that each DI strategy has its optimum fertilizer level (Cabello et al., 2009).

Another benefit of deficit irrigation (DI) is the possibility of controlling sowing dates by irrigation, which allows improved planning of agricultural practices (Oweis et al., 1998). If a common irrigation strategy is adopted in a region, peaks in irrigation water supply will occur during drought sensitive stages. This might result in under-irrigation of land at the tail end of the irrigation network, causing more severe yield reductions than anticipated. Using modeling, Oweis and Hachum (2001) demonstrated that thanks to the higher level of crop cycle control and the lower sensitivity to climate resulting from (deficit) irrigation, sowing dates can be staggered, thus reducing peak supply by 20%. In this way, basin-wide WP is increased.

Due to drought stress in particular growth stages, the length of the cropping cycle might change under rain-fed cultivation. Farre´ and Faci (2006) report a delay in flowering (7 and 17 days) and maturity (5 and 12 days) for sorghum and maize, respectively, under water deficit conditions. McMaster and Wilhelm (2003) find that drought decreases crop cycle length for wheat and barley. Geerts et al. (2008) demonstrate that differences in the crop cycle length of quinoa between DI and FI are negligible. Under rain-fed conditions, the crop cycle length of quinoa may increase substantially if severe drought stress occurs before flowering. By controlling the length of the crop cycle (deficit) irrigation allows improved planning of agricultural activities.

Along with these advantages, DI also entails a number of constraints. The use of DI requires that the following conditions are met:

crop response to drought stress should be studied carefully (Hsiao, 1973). Determining optimal timing of irrigation applications is particularly difficult for crops with CWP functions in which maximal WP is found within a small optimum range of ET;

irrigators should have unrestricted access to irrigation water during sensitive growth stages. This is not always the case in large block designs (Zhang, 2003) or during periods of water shortage;

a minimum quantity of irrigation water should always be available for application (Geerts et al., 2008). This is not always possible in extremely dry regions where irrigation water is scarce (Enfors and Gordon, 2008).

Finally, DI can only be successful if measures are taken to avoid salinization. By using DI strategies, over-irrigation only rarely occurs. Therefore, leaching of salts from the root zone is lower under DI than under FI (Geerts et al., 2008).

Deficit irrigation management

According to Rudnick et al. (2017), one strategy for managing deficit irrigation consists of trying to mitigate the impact of water stress on crop growth and grain yield by withholding water at growth stages that are less sensitive to water deficit as compared to others. This strategy is often practiced when there are pumping restrictions (e.g., water allocations), yet no constraints limiting the system's ability to meet peak ET demands. However, under situations when peak ET demands cannot be met, such as insufficient irrigation system capacity, water availability restrictions, and/or irrigation scheduling delays, adopting a percentage of full irrigation requirement strategy may be more appropriate. Other alternative irrigation strategies available to producers that are subjected to water limitations include:

i. planting crops that match the available water supply (i.e., less water demanding crops),

ii.planting the desired crop on a reduced area in combination with a less water demanding crop, and

iii. reduce the total irrigated area and substitute with fallow or a dry land crop (Martin et al., 1989; Klocke et al., 2006; Klocke et al., 2011).

Conclusion

Based on the literature reviewed on deficit irrigation, the following conclusions were drawn:

i. Deficit irrigation reduces nutrient loss through leaching from the root zone, resulting in improved ground water quality and lower fertilizer needs on the field.
ii. By using deficit irrigation strategies, that is adoptation of water stress at certain developmental periods could benefit yield and quality in fruit tree and vine production, and also is a way of maximizing water use efficiency for higher yields per unit of irrigation water used in agriculture
iii. Modelling can be a useful tool to study and develop deficit irrigation strategies that would allow a combined assessment of different factors affecting yield in order to derive optimal irrigation quantities for different scenarios.
iv. Mild water deficit applied in the early stage enhances the level of drought resistance later in the life cycle and consequently maintained or even increase plant yields.

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