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A Review on Partial Root-Zone Drying Irrigation

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Abstract

Available fresh water resources are subjected to an ever-increasing pressure due to extensive agricultural water demand for irrigated lands. A long-term perspective in shortage of fresh water resources, especially in arid and semi-arid area, highlights an urgent solution for innovative irrigation strategy and agricultural water management. This paper is a review on the wide applications of the partial root-zone drying irrigation (PRD) on diverse plant species. The PRD irrigation is a novel improvement of deficit irrigation in which half of the root zone is irrigated alternatively in scheduled irrigation events. In the last decade, scientists across the world, especially from arid to semi-arid countries, have extensively evaluated this irrigation as a water-saving irrigation strategy on agronomic and horticultural plants. This review paper focuses on the physiological and morphological aspects of PRD on plants and its ultimate impact on yield and water productivity. Overall, under limited water resources where water is precious, PRD is a viable irrigation option to increase water productivity while marinating the yield, rather than only increasing the economic yield without concerning the value of water in limited water environments.

Keywords: Partial root-zone drying irrigation; Full irrigation; Water productivity; Field crops; Vegetables; Trees.

Introduction

Irrigated agriculture is the main user of the available water resources. About 70% of the total water withdrawals and 60-80% of total consumptive water use are consumed in irrigation (Huffaker and Hamilton, 2007). There is a conflict in global increase in food demand and decrease in water resources that should be resolved. Food security can be achieved by irrigated agriculture since irrigation on average double the crop yield compared to that usually is produced in rain-fed conditions. The irrigated area should be increased by more than 20% and the irrigated crop yield should be increased by 40% by 2025 to secure the food for 8 billion people (Lascano and Sojka, 2007). Therefore, water resources should be used with a higher efficiency or productivity. To achieve this goal improvement in agricultural water management is a promising way.

Many investigations have been conducted to gain experiences in irrigation of crops to maximize performances, efficiency and profitability. However, investigations in water-saving irrigation still are continued (Sleper et al., 2007). Full irrigation (FI) is used by farmers in non-limited or even water-limited areas. In this method, crops receive full evapotranspiration requirements to result the maximum yield. Nowadays, full irrigation is considered a luxury use of water that can be reduced with minor or no effect on profitable yield (Kang and Zhang, 2004). Water-saving irrigations are used to improve the water productivity (WP) in recent years. Deficit irrigation (DI) and partial root-zone drying irrigation (PRD) are the water-saving irrigation methods that cut down irrigation amounts of full irrigation to crops. The amounts of irrigation reduction is crop-dependent and generally accompanied by no or minor yield loss that increases the water productivity (Ahmadi et al., 2010b).

Partial root-zone drying irrigation

Partial root-zone drying (PRD) is a modified form of deficit irrigation (DI) (English et al., 1990), which involves irrigating only one part of the root zone in each irrigation event, leaving another part to dry to certain soil water content before rewetting by shifting irrigation to the dry side; therefore, PRD is a novel irrigation strategy since half of the roots is placed in drying soil and the other half is growing in irrigated soil (Ahmadi et al., 2010a). Schematic diagram of FI, DI and PRD are shown in Figure 1 (after Davies and Hartung, 2004).

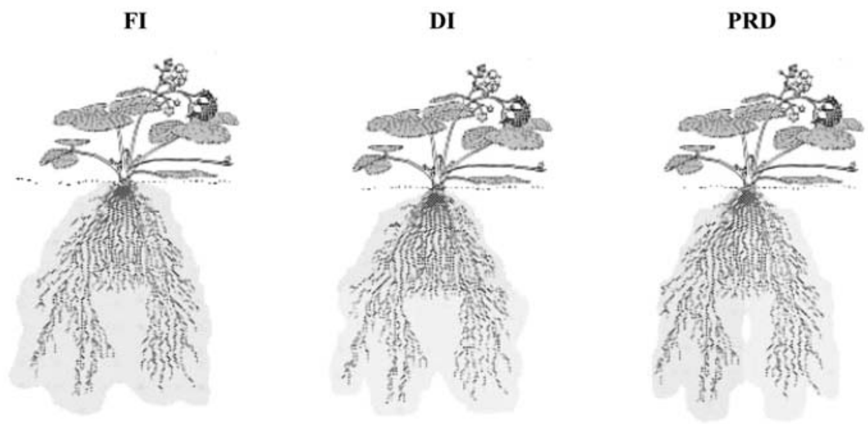

Figure 1. Schematic of the irrigation pattern in FI, DI, and PRD (After Davies and Hartung, 2004).

Originally, the concept of PRD was first applied by Grimes et al. (1968) in the USA on field cotton in alternate furrow irrigation and then followed by Sepaskhah et al. (1976), Sepaskhah and Amin-Sichani (1976), and Samadi and Sepaskhah (1984) on beans through surface and subsurface drip irrigations in Iran. Later on, some extensive studies on PRD were conducted in Australia and the PRD term was used and developed for grapevines (Loveys et al., 2000; Kriedmann and Goodwin, 2003).

Wetting and drying each side of roots are dependent on crops, growing stage, evaporative demands, soil texture and soil water balance (Saeed et al., 2008). Yet there is little understanding on mechanism of PRD effects on crop growth, therefore, no definite solid procedure exist on determining the optimum timing of irrigation for each side. Kriedmann and Goodwin (2003) indicated that when soil water extraction from dry side is negligible, wetting should be changed from irrigated side to non-irrigated side. Furthermore, Liu et al. (2008) stated that switching should be based on threshold soil water content in which the maximum xylem abscisic acid (ABA) concentration is produced. ABA is a plant hormone that is produced in the roots in drying soils and is transported by water flow in xylem to the shoot for regulating the shoot physiology (Kang and Zhang, 2004). Therefore, in PRD roots sense the soil drying and induce ABA that reduce leaf expansion and stomatal conductance and simultaneously the roots in wet soil absorb sufficient water to maintain a high water status in shoot (Zegbe et al., 2006; Liu et al., 2006a; Ahmadi et al., 2010a).

Practical results showed that crops under PRD yielded better than under DI when the same amount of water is applied. This resulted in higher water productivity (WP) and even better fruit quality (Sepaskhah and Kamgar-Haghighi, 1997; Kang et al., 1998; Kriedmann and Goodwin, 2003; Kirda et al., 2004; Kang and Zhang, 2004; Liu et al., 2006a; Leib et al., 2006; Shahnazari et al., 2007). However, Wakrim et al. (2005) reported no significant difference between water use efficiencies (WUE) in PRD and DI, but they resulted in a substantial increase in WUE compared to full irrigation (FI).

Practically, PRD can be used in different ways depending on the cultivated crops and/or soil conditions, environmental conditions and method of irrigation. Alternate furrow irrigation was successfully used as a water-saving irrigation (Grimes et al., 1968). Later on, PRD was adopted for different crops by using alternate furrow irrigation resulting in higher WP (Musick and Dusek, 1982; Samadi and Sepaskhah, 1984; Sepaskhah and Kamgar-Haghighi, 1997; Kang et al., 2000a; Sepaskhah and Khajehabdollahi, 2005; Kirda et al., 2005; Kaman et al., 2006; Sepaskhah and Parand, 2006; Sepaskhah and Ghasemi, 2008; Sepaskhah and Hosseini, 2008). PRD has been used by surface and subsurface drip irrigation methods for crops such as beans (Sepaskhah and Amin-Sichani, 1976), hot pepper (Kang et al., 2001), apple (Leib et al., 2006), potato (Liu et al., 2006a; Shahnazari et al., 2007; Shahnazari et al., 2008; Ahmadi et al., 2010b), tomato (Kirda et al., 2004; Kaman et al., 2006), cotton (Du et al., 2008a), and grape (de la Hera et al., 2007; Du et al., 2008b). Schneider and Howell (1999) have successfully used low energy precise application (LEPA) sprinkler method to apply PRD on maize, sorghum and winter wheat.

PRD in theory

Figure 2 depicts the effect of water stress on plants at physiological, biochemical and molecular levels and a crop that is imposed to PRD as a water-saving irrigation may show diverse responses to water stress in terms of these three responses levels according to the severity and timing of the water stress. However, in this review article much is focused on the effects of water stress at the physiological and morphological levels which play important roles in regulation of crop reproductive development, which directly relate to quantitative and qualitative properties of yield (Liu et al., 2005b).

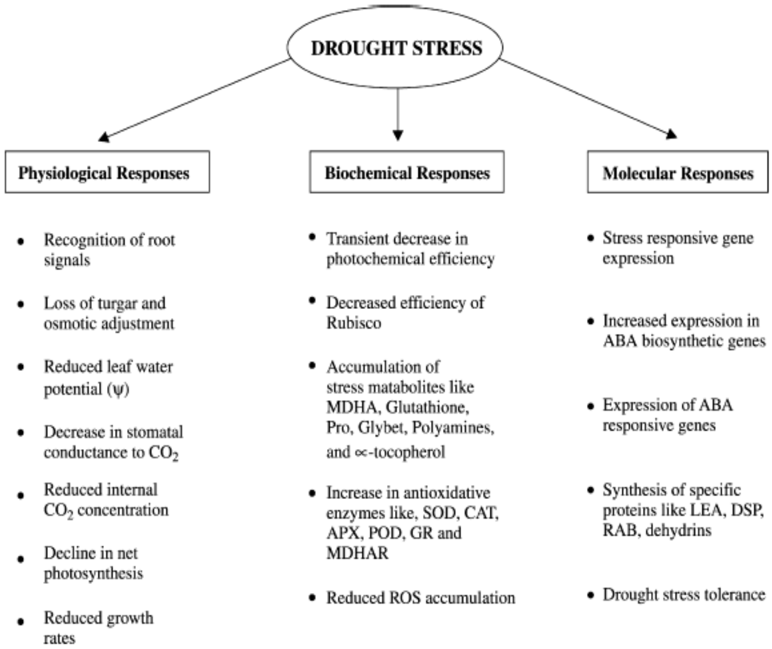

Figure 2. Physiological and molecular bases of drought stress tolerance (After Shao et al., 2008).

Chemical and hydraulic signaling in PRD

Roots in drying soil produce more ABA than under normal conditions (Davies and Zhang, 1991) and it is moved as an anti stress root chemical signal to shoot through transpiration stream and limits the stomatal conductance (Stoll et al., 2000; Kang and Zhang, 2004; Liu et al., 2005b; Liu et al., 2006a; Bauerle et al., 2006). It also resulted in leaf expansion rate in wheat (Ali et al., 1998), maize (Bahrun et al., 2002), soybean (Liu et al., 2005a), potato (Liu et al., 2006c), and tomato (Topcu et al., 2007). Decrease in leaf expansion declines the use of carbon and energy, and a higher proportion of the plant assimilates is distributed to the root system and support further root development (Taiz and Zeiger, 2006).

At mild water stress, ABA as a major chemical signal (CS) acts earlier than the change in plant water status (hydraulic signal, HS). However, under severe water stress, both CS and HS may be involved in regulating plant physiological processes (Ali et al., 1999; Liu et al., 2003; Liu et al., 2005b). In some plants CS and HS occur independent of each other, while in others they take place dependently (Tardieu and Davies, 1993; Comstock, 2002; Wakrim et al., 2005). A balance between CS and HS occur in PRD. In PRD, roots on the irrigated side absorb enough water to maintain high shoot water potential, and the roots on the non-irrigated side produce ABA for possible reduction in stomatal conductance. This mechanism optimize water use and increase WP (Kang et al., 2000b; Sobeith et al., 2004; Zegbe et al., 2004; Zegbe et al., 2006; Liu et al., 2006b; Saeed et al., 2008; Ahmadi et al., 2010b).

Other chemical signals were reported to act such as pH, inorganic ion concentration, and other plant hormones (Wilkinson, 1999; Stoll et al., 2000). Mild soil water stress reduces nutrient uptake and increases the xylem sap pH. This allows higher amounts of ABA in the leaf to be translocated to stomata through the transpiration stream (Davies et al., 2002; Dodd, 2003; Taiz and Zeiger, 2006). Higher pH in xylem sap considered as a drought signal for leaf elongation reduction through an ABA-dependent mechanism (Liu et al., 2003). It is also shown that xylem sap pH in barley (Bacon et al., 1998), maize (Bahrun et al., 2002), tomato (Halbrook et al., 2002; Mingo et al., 2003), and soybean (Liu et al., 2003) increased as soil dried and this increase was correlated to increased ABA concentration in the xylem sap.

Gas exchange in PRD

Water is lost as transpiration and CO_2 is absorbed for photosynthesis through stomata. Therefore, any variation in stomata opening affects stomatal conductance (g_s) and photosynthesis rate (A_n). The A_n is not as responsive to mild water stress as leaf expansion. This is because A_n is much less sensitive to a decrease in turgor pressure compared with leaf expansion (Taiz and Zeiger, 2006). However, severe water stress usually influences both A_n and g_s.

Reduced stomatal conductance in early stages of water stress inhibits transpiration rate more than it reduces the intercellular CO_2 concentration that is the driving factor for photosynthesis. In other words, due to non-linear relationship between A_n and g_s (Figure 3), and a lower sensitivity of A_n than g_s to water stress, WP increases at mild water stress (Davies et al., 2002; Liu et al., 2005c; Liu et al., 2006a). At severe water stress, the leaf water potential in mesophyll cells decreases and stomata will close to a greater extent that inhibits the A_n This is known as hydraulic signaling (Taiz and Zeiger, 2006).

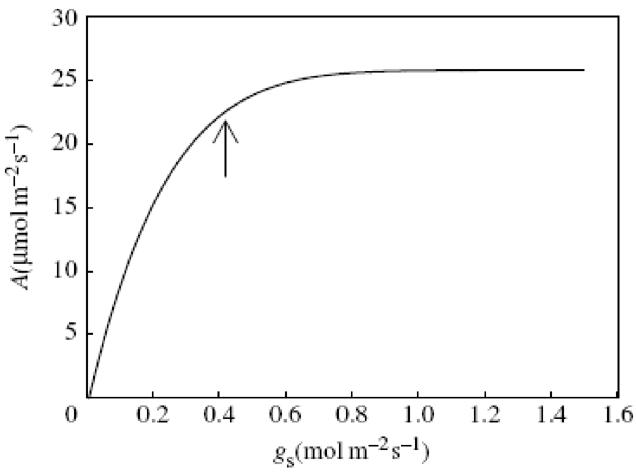

Figure 3. Typical relationship between photosynthesis rate (A_n) and stomatal conductance (g_s). The arrow shows the point where A_n decreases sharply due to severe drought stress (After Morison et al., 2008).

The advantage of PRD over DI is that water uptake from the wet side of the root system maintain a favorable plant water status, while the roots in the dry side promote the increase in ABA production that decrease the g_s (Tang et al., 2005; Costa et al., 2007; Shahnazari et al., 2007; Du et al., 2008b; Saeed et al., 2008) and increase water use efficiency (Davies et al., 2002). Several studies in different environmental conditions have shown that while g_s might be reduced in PRD (the degree of reduction depends on the crop drought sensitivity and/or drought severity), but A_n is not significantly affected compared to full irrigation (Costa et al., 2007; Ahmadi, 2009; Ahmadi et al., 2010a). Studies on cotton (Tang et al., 2005; Du et al., 2006; Du et al., 2008a), hot pepper (Kang et al., 2001), maize (Kang et al., 2000a; Kang et al., 2000b; Du et al., 2010), grape (de la Hera et al., 2007; Du et al., 2008b), potato (Liu et al., 2006a; Liu et al., 2008; Ahmadi et al., 2010a), tomato (Zegbe et al., 2004; Campos et al., 2009) and apple (Zegbe and Behboudian, 2008) have shown that A_n is PRD is not reduced compared to fully irrigated plants. However, there are studies on potato (Liu et al., 2006b) and maize (Kirda et al., 2005), which have reported A_n was significantly reduced under PRD. Such discrepancies might have originated from the special physical setup of the experiment, such that the PRD did not happen in the soil (Liu et al., 2006a; Costa et al., 2007; de la Hera et al., 2007; Ahmadi et al., 2010b). Furthermore, cultivar and weather conditions also significantly impact the outcome of the PRD experiments (Zegbe and Behboudian, 2008).

Gas exchange modeling in PRD

Many mathematical models are developed (either physical- or empirical-based) to represent the relationship between gas exchange and environmental parameters (A_n, g_s, xylem ABA concentration, relative humidity, and CO_2 concentration) under different water stress conditions (e.g., Ball et al., 1987; Tardieu, 1993; Gutschick and Simonneau, 2002; Liu et al, 2009). Tenhunen et al. (1990) and Tenhunen et al. (1994) suggested that the Ball et al. (1987) model should be modified by a correction factor to account for water stress and xylem [ABA] that has a down-regulating effect on g_s. These correction factors have been incorporated as an exponential decaying function or double exponential models (Gutschick and Simonneau, 2002; Tardieu, 1993). However, Dodd et al., (2008) reported that there was a lack of quantitative information on such relationship for PRD. To address the issue raised by Dodd et al. (2008) and to overcome this gap in gas exchange modeling, Ahmadi et al. (2009) developed a more mechanistic gas exchange model that could successfully simulate gas exchange under diverse irrigation strategies including PRD and soil textures.

Root development and water uptake

Root development and distribution are affected by spatial and temporal soil water distribution (Wang et al., 2006). Further, they affect water and nutrient uptake from the soil to maintain the physiological activities of the above-ground part of the crop. Mild water stress in soil leads to preferential root growth into the moist soil zone and water uptake through root system expansion and increasing root length density (RLD, cm root per cm^3 soil) (Benjamin and Nielsen, 2006; Songsri et al., 2008).

Earlier studies indicated that PRD enhanced the extension and inhibition of primary and secondary roots (Kang et al., 2000b), increased root growth (Dry et al., 2000) and root mass (Kang et al., 2000a; Mingo et al., 2004), improve ABA-induced root hydraulic conductivity (Glinka, 1980; Taiz and Zeiger, 2006; Thompson et al., 2007), and increased the nutrient uptake (Wang et al., 2009).

Plant water uptake rate is enhanced after re-watering in water stress condition compared to full irrigation. This is obtained due to improvement of hydraulic conductivity of root systems that is subjected to water stress (Kang and Zhang, 2004). This compensation in root hydraulic conductivity might be explained by new secondary roots and changes in the old roots when exposed to rewetting (Kang and Zhang, 2004). Furthermore, root hydraulic conductivity of apple, grape, peach and pear trees increased under restricted irrigation (Poni et al., 1992). It is proven by other studies that nutrient uptake is higher in PRD than FI for different field crops (Kirda et al., 2005; Li et al., 2007; Shahnazari et al., 2008; Wang et al., 2009). This is because the newly formed roots in PRD showed higher nutrient recovery from soil due to more available soil water (Kang and Zhang, 2004).

The soil water in the irrigated side of PRD is depleted more effectively than corresponding side in FI (Kang et al., 2000b; Kang et al., 2003; Rodrigues et al., 2008). This indicated that the root system can partially compensate for the increasing limited water availability on the non-irrigated side of PRD due to an increase in root hydraulic conductivity. A larger hydraulic gradient in the soil-root interface was observed under PRD than under FI (Liu et al., 2006a). This explained the greater rate of water extraction from soil in PRD. Deficit irrigation (DI) has extra disadvantages over PRD, that is prolonged expansion of roots to dry soil (DI) may cause anatomical changes in the roots such as suberization of the epidermis, collapse of the cortex and loss of succulent secondary roots (North and Nobel, 1991).

PRD in practice

1. Increasing water productivity

In the literature the term "water use efficiency" (WUE) is interchangeably used for crop yield per unit evapotranspiration. In this article, "water productivity" (WP) is defined as crop yield per unit applied irrigation water that is looking into the efficiency of applied irrigation water (Zhang, 2003). Partial stomatal closure and reduced leaf area occurred due to increased [ABA]. These are the main physiological responses to decrease transpiration in plants under PRD and enhance WP (Davies et al., 2002). Relationship between A_n and g_s is shown in Figure 3. The slope of this relationship is intrinsic water use efficiency. It is clear that at mild water stress a large reduction in g_s is coupled with a negligible effect on A_n. This means that decrease in g_s resulted in a large reduction in transpiration, while photosynthesis rate is not greatly affected. Therefore, a higher WP (or WUE) is obtained (Morison et al., 2008) and it is crucial to study the A_n and g_s when WP or WUE is of interest.

WP has been increased considerably by using PRD on different crops (e.g., Sepaskhah and Kamgar-Haghighi, 1997; Davies et al., 2002; Zegbe et al., 2004; Sepaskhah and Khajehabdollahi, 2005; Shani-Dashtgol et al., 2006; Fereres and Sariano, 2007; Costa et al., 2007; Shahnazari et al., 2007; Geerts and Raes, 2009; Ahmadi et al., 2010b). Recently, in a meta-analysis Sadras (2009) confirmed that use of PRD enhanced WP by 82% compared to

FI with no significant reduction in yields. However, Liu et al. (2006b) indicated that PRD was less effective than DI in enhancing WUE, and Wakrim et al. (2005) and Kirda et al., (2005) confirmed that PRD resulted in lower WUE than DI in beans and maize, respectively. Nevertheless, more positive effect on fruit quality was occurred in PRD than in DI (Kang and Zhang, 2004; Kirda et al., 2004; Zegbe et al., 2004; Leib et al., 2006; Shahnazari et al., 2007). de la Hera et al. (2007) and Ahmadi et al. (2010b) indicated that to analyze the effectiveness of PRD compared to DI, it is necessary to investigate i) hormonal changes resulted by long-term PRD on reproductive development, ii) whether the chemical signaling in PRD is different from DI, iii) the differences in the pattern of soil water uptake, root growth, and how the water redistribution from roots can influence chemical signaling in dry roots, and iv) the duration and best timing for application of PRD according to crop, soil, and site specifications.

2. Experimental studies on PRD

A significant water saving coupled with the economic yield has been documented by Ahmadi (2009) and Dodd (2009) in a review of greenhouse and field studies on the application of PRD on different species of trees and annual crops. Different experimental results in PRD have shown that irrigation water may be reduced by approximately 30-50% in PRD with no significant yield reduction. In some cases even better fruit quality was obtained in PRD (e.g., Kang and Zhang, 2004; Kirda et al., 2004; Leib et al., 2006; Shahnazari et al., 2007; Du et al., 2008a; Du et al., 2008b; Guang-Cheng et al., 2008). The most investigations on PRD have initiated in the last decade and, however, practical development of the technique still continues for agronomical and horticultural crops (Morison et al., 2008; Guang-Cheng et al., 2008; Ahmadi, 2009). The list of literature on experimental studies on PRD is exhaustive; however, the following subsections include, but not limited to, a relatively complete and broad list of diverse crop species on which the PRD has been applied in the last decade.

2.1. Field crops

2.1.1. Sugar beet and Sugarcane

Alternate or every-other furrow irrigation is considered as PRD irrigation. Every-other furrow irrigation resulted in an average of 18% reduction in sugar beet root yield with an average of 34% reduction in applied water at customized 10-day irrigation intervals (Sepaskhah and Kheradnam, 1977). de la Hera et al. (2007) indicated that duration and the timing for the application of PRD should be determined according to the crop, soil and site specifications. In this case (sugar beet as a vegetative crop), shorter irrigation intervals may play a key role in effectiveness of PRD. Therefore, Sepaskhah and Kamgar-Haghighi (1997) studied the effects of every-other furrow and every-furrow irrigation on yield and WP of sugar beet at different irrigation intervals of 6, 10, and 14 days. They indicated that every-other furrow irrigation at 10-day irrigation intervals used a smaller amount of irrigation water, however, some root yield reduction occurred. On the other hand, every-other furrow irrigation at 6-day intervals reduced irrigation water by 23% with similar yield to that of every-furrow irrigation at 10-day intervals.

Similar results were also obtained for sugar cane where variable alternate furrow irrigation (PRD) was used to determine the effects of PRD on sugar cane in a warm semi-arid region in Iran (Shani-Dashtgol et al., 2006). Results revealed that applied irrigation water was reduced by 26% in variable alternate furrow irrigation compared to ordinary furrow irrigation (FI) with even 10% higher cane production. Therefore, WP was increased 34% in PRD compared with that in FI. Similar water reduction was also reported by Sepaskhah and Kamgar-Haghighi (1997) for sugar beet. However, Pandias et al. (1992) reported 43-46% water reduction in PRD (alternate furrow irrigation) for sugarcane in India that is higher than that reported by Shani-Dashtgol et al. (2006).

2.1.2. Sorghum

Every-other furrow irrigation (PRD) in semi-arid region of Iran resulted in an average of 28% reduction in sorghum grain yield (reproductive crop) with a similar reduction in applied water at customized 15-day irrigation intervals (Sepaskhah and Ghasemi, 2008). They studied the effects of every-other furrow, and every-furrow irrigations on grain yield and WP of grain sorghum at different irrigation intervals of 10, 15, and 20 days. It was indicated that every-other furrow irrigation at 10-day intervals of every-other furrow reduced the applied water by 11% with no yield reduction compared with every-furrow irrigation at 15-day intervals.

2.1.3. Maize

Every-other furrow irrigation (PRD) in a semi-arid region resulted in an average of 28% reduction in maize grain yield (reproductive crop and highly sensitive to water stress) with an average of 31% reduction in applied water at customized 7-day irrigation intervals (Sepaskhah and Khajehabdollahi, 2005). They studied the effects of every-other furrow and every-furrow irrigations on maize grain yield and WP at different irrigation intervals of 4, 7, and 10 days. It was indicated that every-other furrow irrigation at 4-day intervals of every-other furrow reduced the applied water by 6% with no grain yield reduction compared with every-furrow irrigation at 7-day intervals.

It is clear that in a semi-arid region, PRD was not very effective in reproductive crops with high sensitivity to water stress. Therefore, a different strategy should be used to apply PRD for these crops. Sepaskhah and Parand (2006) studied the effects of alternate-furrow irrigation with supplemental every-furrow irrigation at different growth stages on grain yield of maize in a semi-arid region. The results indicated that under alternate-furrow irrigation with once or twice every-furrow irrigation at the tasseling or silking stages grain yields were statistically equal (about 11% reduction) to those obtained in every-furrow irrigation although the amounts of water used was 30% lower.

Kang et al. (2000a) and Kang et al. (2000b) also applied PRD in irrigated maize in an arid region in China. Irrigation was applied to furrow in three ways: alternate furrow irrigation (AFI), fixed furrow irrigation (FFI), and conventional furrow irrigation (CFI). Each irrigation method was further divided into three treatments with different irrigation amounts (45, 30, 22.5 mm). Furthermore, AFI maintained high grain yields coupled with a 50% reduction in the amount of irrigation water, while FFI and CFI both revealed a substantial reduction in yield with reduced irrigation water.

2.1.4. Winter wheat

PRD irrigation is also effective in increasing WP in winter wheat (reproductive crop) grown under rain-fed conditions with supplemental spring irrigation (Sepaskhah and Hosseini, 2008). They investigated the effects of AFI (variable and fixed) and ordinary furrow irrigation (OFI) under optimum nitrogen application rates on winter wheat grain yield in a semi-arid region with annual rainfall of 409 mm. Results showed that under variable AFI (PRD) grain yields were statistically equal (about 15% reduction) to those obtained in OFI although the amount of applied water was 41% smaller.

2.1.5. Beans

For dry beans, Samadi and Sepaskhah (1984) studied PRD under furrow irrigation in a semi-arid area. They found 38% grain yield reduction under alternate furrow irrigation with 22% less water application. Therefore, they conducted an experiment to study the effects of alternate furrow irrigation with supplemental every-furrow irrigation at different growth stages on grain yields of dry beans in a semi-arid region. Results revealed that under alternate furrow irrigation with every-furrow irrigation at podding stage grain yields were statistically equal (about 9% reduction) to those obtained in every-furrow irrigation although the amount of water used was 29% smaller.

Wakrim et al. (2005) studied the effects of PRD, DI and FI on growth, water relation of pot-grown beans. The leaf water potential for both PRD and DI decreased significantly compared with FI, but without any significant difference between PRD and DI. Furthermore, shoot and pod biomass was significantly decreased in both PRD and DI as compared with FI. These findings are in accordance to those reported by Samadi and Sepaskhah (1984). In another investigation on beans, the effects of conventional subsurface drip irrigation (CSDI) and alternate subsurface drip irrigation (ASDI) was studied on water use, yield and water use efficiency of green beans (Genocoglan et al., 2006). At each irrigation event, half of the volume of water applied to CSDI was applied to ASDI representing PRD irrigation. Green bean yields were not significantly different between CSDI and ASDI, however, 50% irrigation water saving occurred for ASDI compared with CSDI.

2.1.6. Cotton

A field experiment has been carried out by Du et al. (2006) to investigate the effects of PRD on the yield and physiological response of cotton. Irrigation treatments were used as: conventional furrow irrigation (CFI), fixed partial root zone furrow irrigation (FFI) and alternate partial root zone furrow irrigation (AFI). These irrigation methods were used in combination of three irrigation levels as 22.5, 30, and 45 mm for each irrigation event. AFI always resulted in highest seed cotton yield under the three irrigation levels, with reduced water loss and higher WUE. Du et al. (2008a) compared PRD with FI for cotton by drip irrigation with three irrigation levels of 15, 22.5, and 30 mm and similar results to those of Du et al. (2006) were obtained. They showed that similar seed cotton yields were obtained in PRD and FI with 31-33% less applied irrigation water in PRD compared with FI. However, similar results from an experiment using the alternate furrow irrigation (PRD) and ordinary furrow irrigation (FI) were also reported by Tang et al. (2005). They reported that PRD reduced irrigation by 30% while cotton seed yield was reduced by 8% that was not statistically different from that of in FI.

2.2. Vegetable crops

2.2.1. Potato

The effects of PRD on physiological responses of potato in greenhouse and field conditions were studied by Liu et al. (2006a). In greenhouse the treatments were FI, and PRD, while in field irrigation, treatments were drip-irrigated to near field capacity (FI) or using 70% of FI on alternate sides. In a field experiment, PRD resulted in higher intrinsic WUE than in FI. The PRD treatment reduced water use by 30% and therefore increased WUE by 60%, and no significant reduction in tuber yield. In another study, Liu et al. (2006b) investigated the effects of FI, PRD (50% of ET_p), and DI (50% of ET_p) irrigations on yield and WUE of potato at tuber initiation stages. Results indicated that both DI and PRD significantly reduced tuber yield compared with FI that is in contrast with their previous study (Liu et al., 2006a). Furthermore, PRD and DI used 37% less water than FI, however, WUE was similar for PRD and FI and significantly decreased in DI. Therefore, with the same amounts of irrigation water, PRD showed no advantage compared with DI for WUE. This result may be attributed to the high water stress created due to low water application in PRD (50% ET_p). Similar results have been also reported by Wakrim et al. (2005) and Gencoglan et al. (2006) indicating that further investigations on DI and PRD are needed to determine the unknown factors influencing the soil water and plant relationships (Costa et al., 2007).

Therefore, an experiment was conducted by Shahnazari et al. (2007) under field conditions for two yeas to investigate the effects of FI and PRD with 70% water of FI on yield tuber size and WP of potato. Results indicated that no significant difference in leaf area index occurred between PRD and FI, however, top dry mass and tuber yields were slightly lower in PRD than in FI. The marketable tuber yield (size of 40-50 mm) was 20% higher in PRD than in FI. Finally, PRD saved 30% of irrigation water and resulted in 61% increase in irrigation WP coupled with maintaining tuber yield and better marketable tuber size. Similar results on potato are also reported by Jovanovic et al. (2010) that reported PRD saved irrigation water by 33% and 42% in two consecutive years compared to FI, while maintaining similar yield with FI. This resulted in 38% and 61% increase in WP for the two growing seasons, respectively. In agreement to the previous studies on potatoes, Ahmadi et al. (2010b) found that PRD interacts significantly with soil textures such that while PRD increased WP by 11% in a coarse sand and 36% in a sandy loam soil relative to FI, the WP in a loamy sand was decreased by 15%. This shows that there is a significant interaction between the PRD and soil textures in increasing the WP, and again reflects this point that a successful PRD experiment is dependent on crop, soil, and site specifications.

2.2.2. Tomato

Kirda et al. (2004) applied PRD on greenhouse processing tomatoes and depicted that PRD reduced up to 50% of irrigation water with a marginal yield reduction. They indicated that in PRD leaf area index and vegetative growth was reduced, therefore, photosynthetic assimilates transferred to fruit growth. Zegbe et al. (2004) conducted a similar study on processing tomato using full irrigation (FI) and 50% of FI irrigation water applied as PRD. They showed that the fruit yields were the same for the treatments, but WUE for PRD plants were 70% higher than that obtained for FI plots.

Zegbe et al. (2006) compared the PRD with FI at different phonological stages: during the vegetative stage until the first truss (flowers) was observed ($PRD_{VS–FT}$), from the appearance of the first truss (flowers) to fruit set ($PRD_{FT–FS}$), and from fruit set to harvest ($PRD_{FS–H}$). Compared with FI, water was saved by 6, 20, and 25% for $PRD_{VS–FT}$, $PRD_{FT–FS}$, and $PRD_{FS–H}$, respectively, while the WPs were not significantly different. However, total fresh weight of fruit was significantly reduced in $PRD_{FT–FS}$ and $PRD_{FS–H}$ compared with FI and $PRD_{VS–FT}$. On the other hands, as a processing tomato, fruit quality improvement in $PRD_{FS–H}$, could compensate for the reduction in total fresh and dry weight of fruit where water is expensive for tomato production in view of 25% of water saved for this treatment compared to FI. These results again highlight that for a reproductive crop such as tomato, special attention should be paid to the correct timing of PRD to obtain the desired results.

2.2.3. Hot pepper

Kang et al. (2001) applied PRD in a drip irrigation system for hot pepper planted in pots as: alternate drip irrigation (ADI), fixed drip irrigation (FDI), and even drip irrigation (EDI). They showed that ADI resulted in no reduction in yield with a reduction in applied irrigation water up to 40% compared with EDI. In another greenhouse study, Guang-Cheng et al. (2008) showed that PRD significantly reduced yield by 24%, while WP increased by 52% compared with the FI; however, the fruit quality was improved. Nevertheless, PRD increased the yield by 17% compared with DI.

2.3. Trees

2.3.1. Grape

Most PRD studies on woody crops were done on grapes that seem to respond well to this kind of deficit irrigation strategy (Fernandez et al., 2006). The studies on grapes are exhaustive and there are many reports on the successful application of PRD on grapes in terms of increasing WP and fruit quality (a review by Kang and Zhang, 2004; Sadras, 2009). However, in a comprehensive study, the effects of PRD applied in three different growth stages of vine grapes were investigated on leaf water relations, vegetative development, and fruit yield during a 3-year field experiment under a semi-arid area in Spain (de la Hera et al., 2007). Conventional (CI) and PRD drip irrigations were used with irrigation water of 30% of crop evapotranspiration. Results showed that transpiration rates and assimilation rates were not significantly affected by PRD. There was no significant treatment effect on vegetative growth, yield or fruit quality in first and second year. Vegetative growth and fruit yield increased in the last year in PRD compared to CI and resulted in a 43% higher yields and 40% higher WUE. It is indicated that early onset of PRD is desirable to intensify PRD response under semi-arid conditions.

2.3.2. Pear

PRD was compared with the fixed partial root zone irrigation (FPRD) and whole root zone irrigation (WRI) in a pear orchard in Australia using a flood irrigation system (Kang et al., 2002). The results indicated that yield was not reduced while the applied irrigation water was decreased by 52% and 23% and water use efficiency was increased by 28% and 12% in FPRD and PRD, respectively, compared with WRI.

2.3.3. Apple

A study was conducted by micro-sprinkler to investigate the effects of DI and PRD on apple yield, fruit size and quality for a 3-year period in a semi-arid region in the USA (Leib et al., 2006). In control irrigation (CI) soil water content was kept above 80% of field capacity, it was maintained 50% of CI for the first two years and 60% of CI in the last year for DI and PRD irrigations. Results depicted no significant difference in yield and fruit size among treatments for the first and last year of study, however, in the second year only DI showed a significantly lower yield than CI. In another study, Zegbe and Behboudian (2008) reported that PRD did not adversely affect yield and fruit quality of apples and improved WP by 120%, saving 0.14 mega litres of water per hectare.

2.3.4. Olive

The first evaluation of PRD on olive trees was done by Wahbi et al. (2005). They showed that PRD could maintain the yield and fruit quality, while reducing half of the irrigation water. They showed that the slight PRD-induced yield reduction (15-20%) compared to the full irrigation was achieved with 50% reduction in the total amount of water applied, which resulted in a water use efficiency increase by 60-70% under PRD compared to the FI. However, in another study on olives, Fernandez et al. (2006) compared PRD with DI based on the crop physiological parameters. They observed no improvement on the measured physiological parameters in mature olive trees under PRD as compared to DI. Despite the fact that they did not evaluate the influence of PRD on either growth or on yield, their results suggested that similar benefits are to be achieved in olive orchards with DI and PRD. Taking into account that an irrigation system suitable for the PRD approach is more expensive and difficult to manage, they saw no agronomical advantages on PRD as compared to DI.

Conclusions

Partial root-zone drying irrigation (PRD) is the novel deficit irrigation strategy that is generally adapted in the last decade to a vast kind of agronomic and horticultural crops to increase the water productivity (WP). This paper generally reviewed the most recent studies on PRD. Results from diverse crop species showed that in comparison to the traditional deficit irrigation strategy (DI) that the crop is subjected to some degree of water stress, PRD is a successfully alternative irrigation compared to FI that can save irrigation water up to approximately 50% without significant yield loss, while may improve the yield quality.

However, the amount of saved irrigation water and improved WP strongly depends on crop, soil, and site specifications. Moreover, cumulative results revealed that PRD could not be effective in reproductive crops that are sensitive to water stress. In such cases the recommended strategy is that irrigation event should be more frequent and supplementary full irrigation should be applied in sensitive phonological periods of crop growth. Since PRD is newly applied to some tree species, it is recommended to do more studies on different kind of trees in different environmental conditions. Therefore, PRD is recommended for irrigation of farms and gardens in arid and semi-arid areas which are suffering from lack of fresh water resources for agricultural production. PRD practices can be viable and advantageous option compared with full irrigation to prevent crop yield reduction when and if there is water shortage or to improve crop quality. It is noteworthy that studies on PRD are still continuing and in future new results will be available from other crop species, probably from horticultural and tree crops with a high irrigation water requirement.

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