Review: partial root zone drying an approach to increase water use efficiency of horticultural crops and chlorophyll fluorescence

Simeneh Tamrat Alemu

Cogent Biology (2020), 6: 1767016
PLANT SCIENCES | RESEARCH ARTICLE

Review: partial root zone drying an approach to increase water use efficiency of horticultural crops and chlorophyll fluorescence

Simeneh Tamrat Alemu1*

Abstract: Nowadays, lack of irrigation water is critical factor that reduce horticultural crop production and productivity. This serious shortage of irrigation water requires improvement of our irrigation methods and irrigation management techniques. “One of the possible methods to maximize crop production with limited irrigation water was deficit irrigation one way of deficit irrigation was partial root zone drying”. Therefore, the objective of the review was to assess impact of partial root zone drying on soil water content, and physiology of plants mainly, water absorption, movement, its use efficiency by plants and to suggest role chlorophyll fluorescence on partial root zone drying irrigation management. Result of different studies showed that partial rootzone drying irrigation preserve soil moisture lessening and irrigation water absorption by compensating water absorbed from dry part of the root zone to the wetter part and dry part is irrigated or rewetted alternatively. When we use partial root-zone drying irrigation ABA mediated aquaporin activity increases, which in turn increase the movement of water upward in to stem and leaf. This occurs in both the wet to dried zones. Partial rootzone drying irrigation saves 518 m³ ha⁻¹ irrigation water in moisture deficit year and increase irrigation water use efficiency by 70%, and it reduce grain yield by only 10% compared to full irrigation. Chlorophyll fluorescence may help in early detection of plant water stress and ultimately to irrigation scheduling of partial rootzone drying irrigation. Generally, this review highlights some importance of partial rootzone drying irrigation and suggests methods to manage it mainly chlorophyll fluorescence.

ABOUT THE AUTHOR
Simeneh Tamrat Alemu: I have MSc degree in horticulture with specialization of stress physiology (UV-B and light quality). Currently, I am working as a lecturer at department of dry land crop and Horticultural science, college of dry land agriculture and natural resources, Mekelle University, Mekelle, Ethiopia. My research interest was stress physiology of plants and horticultural crops improvement.

PUBLIC INTEREST STATEMENT
Currently, due to climate change agricultural production and productivity is decreasing; the main factors affecting agricultural production and productivity are lack of rainfall and irrigation water. Many areas are currently changed in to drought, arid and semi-arid this area does not have a role in preserving our hydrological cycle. Therefore, severe water stress may emerge in the future. This review suggests water saving and effective irrigation methods to increase future agricultural production and productivity.
Subjects: Agriculture & Environmental Sciences; Botany; Soil Sciences; Conservation - Environment Studies; Ecology - Environment Studies

Keywords: Partial rootzone drying; soil water content; absorption; movement; chlorophyll fluorescence

1. Introduction

According to global climate model (IPCC, 2007) report many areas of the world would be changed in to arid and scarcity of water for irrigation occurs in the future. These deficits of irrigation water reduce production and productivity of horticultural crops unless we develop new irrigation methods that can save irrigation water and new irrigation management techniques (Sepaskhah & Ahmadi, 2010). Recently, one of the methods to maximize crop production and productivity with the limited irrigation water use was deficit irrigation (Sepaskhah et al., 2006). Deficit irrigation was a technique of irrigating the root zone with irrigation water which is lesser than potential evapotranspiration (English & Raja, 1996). There are different types of deficit irrigation, partial root—zone drying (PRD) irrigation methods are among them. By using PRD irrigation we can reduce the amount of irrigation water application and use by half amount (Kirda et al., 2004; Tang et al., 2005; Zegbe et al., 2004). The main difference of PRD drying irrigation from other deficit irrigation method is it can alternatively keep a wet as well as a drying portion of the root zone (Jovanovic & Stikic, 2018; White & Raine, 2009). However, Sadras (2009) found that on water use efficiency both PRD and other deficit irrigation methods do not differ significantly. On the other hand, Application of PRD and other deficit irrigation methods depend on understanding of the physiological response of plants to surplus water application and water stress (Morison et al., 2008). Such knowledge allows us to know responses of horticultural crops to change in soil water status and we can adapt horticultural crops to moderate water stress conditions by this effective irrigation method (Chaves & Oliveira, 2004; Davies et al., 2002). This adaptation was because of PRD allow half of the root zone to be irrigated and the other half side stay in dry and the wetted and dry sides are alternated in the successive irrigations (Dry et al., 2000; Jovanovic & Stikic, 2018), and by this alternated dry and wetted irrigation ABA based chemical signalling system will be initiated that can control water absorption, movement and its use by plants this means it increase water use efficiency by allowing plants to use the irrigation water in conservative and effective way (Davies et al., 2002). The principle behind was that irrigating part of the root zone keeps the leaves hydrated and the remaining part of the roots on dry parts of the soil allow synthesis and transport of chemical signals (particularly ABA) from roots to the shoot via the xylem (Jovanovic & Stikic, 2018; Loveys et al., 2000), and end up by partial stomatal closure and prevent excessive water loss and lead to better water balance (Chaves et al., 2002). Therefore, by understanding its importance many countries of the world are doing intensive research on partial root-zone drying irrigation techniques (Kang, 2004), and it was studied on many vegetable and fruit trees, including grapevine (Dry et al., 2000; Gu et al., 2000), pear (S. Kang et al., 2003), olive tree (Wahbi et al., 2005), cotton (Tang et al., 2005), tomato (Kirda et al., 2004) and potato (Liu et al., 2006), and it resulted improvement in water use efficiency and a stable yield (FAO, 2002; Davies et al., 2000). (Kirda et al., 2004; Davies et al., 2002), concluded that PRD can maintain shoot water balance and growth rate better than other deficit irrigations. On the other hand, one of the ways we can know photosynthetic performance of agricultural crops under abiotic stress conditions was chlorophyll fluorescence (Barbagallo et al., 2003; Gottiardini et al., 2014; Proctor, 2003). Therefore, leaf water status and photosynthesis mainly affected by water stress (Chaves et al., 2009), and different chlorophyll fluorescence parameters show that when water stress occur photosynthetic efficiency of photosystem II decrease and non-photochemical quenching increase (Lichtenthaler & Miehe, 1997). Therefore, chlorophyll fluorescence was an effective method to know water status and stress condition in plants by many ways (Schmuck et al., 1992; Cornic, 1994; Cerovic et al., 1996, Flexas et al., 1998). One way can be calculation of factors that relate with net CO2 assimilation, such as the quantum yield of PSII (Genty et al., 1989), and the other way was steady state chlorophyll fluorescence, it may help us to PRD irrigation scheduling and stress adaptation of
horticultural crops (Cerovic el al., 1996; Flexas et al., 2000, 1999). It tells us to understand how much time is needed to change from dry soil to wet soil as (interchanging dry to irrigated row) by giving us information on strength of stress on dry state. Therefore, the objectives of this review was to review the impact of partial root zone drying on soil water content, and physiology of plants mainly, water absorption, movement, its use efficiency by plants and to suggest chlorophyll fluorescence as an indicator of partial root zone drying irrigation management techniques.

2. PRD influence on ABA production and water absorption
In partial root zone drying irrigation, roots in the dry part changes its root metabolism to produce chemical signals mainly ABA and irrigation water absorption by plants from roots in the dry part diminished (Dodd et al., 2010), and through time sap flow from roots in drying soil may totally stop (Khalil & Grace, 1993; Stoll et al., 2000). The solution for this was alternating the wet and dry parts of the root-zone regularly, to keep some roots in drying state for same time that will keep producing signal and transport to the shoot as shown in (Figure 1), (Jovanovic & Stikic, 2018). It was proposed that soil drying caused root ABA accumulation by enhancing root ABA biosynthesis, then reduce water absorption and additional ABA transport to the shoots, but after maintaining a wet state by rewatering as alternate irrigation of PRD ABA concentration of leaf increase (Y. Wang et al., 2012), and it cause hydraulic redistribution of the water from the wet or (irrigated) roots to drying roots (Burgess et al., 1998; Caldwell & Richards, 1989). However, the root ABA accumulation will be diminished since water potential of the root (Ψ root) in partially dried parts of the roots become very limited (Puértolas et al., 2013). The increment or decrement of ABA pulse after a wet state or rewatering depends on the capacity of water absorption by the dried roots before rewatering, strength of the ABA pool absorbed within these roots and possible losses of ABA from the root system via metabolism and ABA efflux to the soil after rewatering. Therefore, alternation of the wet and dry parts of the root system may depend on the severity of soil drying. (Liu et al., 2007; Shahnazari et al., 2007) indicated that PRD strength depends on a spatial separation of dry and wet roots. These alternations of dry and wet roots give plants an advantage from an uneven distribution of soil water and through time allow plants to mechanisms of stress adaptation (Kang, 2004). As shown in (Figure 1), the principle of PRD is that well irrigated half of the root system maintains high shoot water content and dry part produce continuous stress signal (Dry et al., 2000; Rodrigues et al., 2008). Besides, water potential of the stem (Ψ stem) decrease progressively that may indicate an increase flow resistance in soil (Boursiac et al., 2005; Steudle, 2000), or from the soil to roots (Hutton et al., 2007), since the water supply by PRD was small. Therefore, this will result stress-induced decrease in water potential of the stem (Ψ stem) because

---

**Figure 1. PRD Irrigation and ABA relationships upon rewetting partially dried roots during the day and predawn.**

Source: (Dodd et al., 2006)
of its inability to maintain a higher hydraulic conductance in the xylem when stress occurs (Schultz, 2003; Vandeleur et al., 2009). Duration of alternating wet and dry sides has its own effect on water absorption and ABA concentrations, for example, after 3 days alternation of dry and wet side root had no effect on ABA concentration of leaf and water absorption further drying of the soil can release an ABA pounding following rewatering and increase water absorption (Dodd et al., 2006). When drying alternated by re-watering in PRD irrigation grapevines irrigation water use is much more effective and conservative (Collins et al., 2010). But, soil moisture application and distribution has its own effect on water absorption and ABA accumulation, when soil moisture applied and distributed in vertical gradient than homogenous unpredictably roots ABA accumulation will decrease and irrigation water absorption of plants become lower (Puértolas et al., 2013) and at the same time roots accumulate more ABA at the same soil water content when PRD is applied laterally rather than vertically. Therefore, these types of soil moisture distribution have an effect on effectiveness of PRD irrigation (Puértolas et al., 2015). Generally, when soil moisture is not uniformly distributed as by PRD irrigation method different gradients in soil water potential (Ψ soil) will develop and this will redistribute the water within the soil during the night, through the root system that acts as hydraulic bridges between wet and dry parts of the soil (Stoll et al., 2000), and the other is partial stomatal closure occurs due to increased ABA when plants are grown under water stress condition of PRD (Comstock, 2002). Then, root water absorption from the dry part of the soil may be compensated by absorption from the wetter parts of the root zone, in that way PRD can regulate soil moisture depletion by using the small amount of water by alternate drying and wetting cycle (Javaux et al., 2013). According to (Mahmoud et al., 2019) the soil moisture content was influenced by root development and water absorption. Therefore, the results of (Mahmoud et al., 2019) prove that the soil moisture content in PRD alternatively increase and decrease.

3. Influence of PRD on water movement inside plants and soil

PRD induce new roots as a result of alternate drying and rewetting cycle, this newer roots increase hydraulic conductance (Kang et al., 2000, 2002; Mingo et al., 2004; Kang et al., 2003; Kang, 2004), and at the same time aquaporin activity increase by activities of ABA that facilitate movement of water upward in to stem and leaf, also from wet to dried roots and higher daily leaf water use and photosynthesis will be attend (Lovisolo et al., 2010; Romero et al., 2012). The same findings was reported by (Lovisolo & Schubert, 2006; Martre et al., 2002), which stated that increase in hydraulic conductivity strength and water movement be facilitated by aquaporin activity. However, Martre et al. (2002) and Siefritz et al. (2002) showed that a significant part of the radial root water movement takes place through the cell-to-cell pathway. It is well known that highest stem water potential will be maintained when there is available water in the soil, higher soil or root hydraulic conductance and low transpiration rate (Choné, 2001). Contrasting finding on root conductance was reported by (Y. Wang et al., 2012; Yan et al., 2012) they found that morphological characteristics of stomata changes under partial root zone drying irrigation, such changes are smaller guard cells, lower stomata density and decrease in root conductance that lower transpiration and contribute to an increase water movement and its water use efficiency by fruit and vegetable crops. However, (Stikic et al., 2003) found that PRD has no effect on stomatal conductance, transpiration and photosynthesis. Reactions that cause sensitivity of the stomata to chemical signals such as ABA are modulated by differences in xylem pH but he did not get apoplastic pH values that in turn cause changes in stomatal conductance, transpiration and photosynthesis. Besides, root growth and development under PRD irrigation increase, that intern enhance plant hydraulic conductivity and water movement and its use efficiency (Ahmadi et al., 2011; Mingo et al., 2004; Pérez-Pérez et al., 2012). On the other hand, (Kang, 2004; Chaves et al., 2007, 2010; Santos et al., 2003; Stoll et al., 2000; Davies et al., 2002), found that PRD increase water use efficiency by regulating the growth of leaf area and size, and (Alsina et al., 2011) also reported that PRD increase water movement, hydraulic conductance and increase canopy water use efficiency because of its ability of facilitating movements of water in to the canopy (Jovanovic & Stikic, 2018). Besides, non-hydraulic signals and their interactions may also be involved in controlling water movement and leaf water use mainly cytokinins and xylem sap pH (Kudoyarova et al., 2007). (Wilkinson & Davies, 1997; Davies et al., 2002; Wilkinson, 2004) indicated that xylem sap pH can
control stomatal response to root chemical signals produced in drying soils. Actually, in acidic xylem sap, ABA is rapidly taken by the leaf and metabolised or partitioned into alkaline compartments in the symplast of the leaf cells, away from the sites of action of the hormone on the stomata. (Kang et al., 2003) found that when water content of the root zone in dry and wetter part is equal, root sap movement on the dry side of PRD irrigation treated plants is improved compared with fully irrigated plants because of high stress triggered by ABA, which were equally watered on both sides of the root system and at meantime, (Gu et al., 2004) indicated that plants response to the amount of irrigation are different on the way in which the irrigation is applied. Therefore, maintaining alternate wet/dry sides of roots in PRD has essential signalling effects on the shoots considering the transient nature of the root ABA accumulation in dehydrated roots. (Dodd et al., 2006; Dry et al., 2000; Loveys et al., 2004) find that PRD-treated tomato plants with equal application of water with full irrigation showed a transient increase in ABA in the xylem and as a result the stomata closed, this was due to enhancement of both hydraulic and chemical signals produced by partial root zone drying irrigation. Hypothetical guess for this condition was water movement from wet to dry root was by hydraulic reallocation (Caldwell et al., 1998), the other was dynamics of water movement by root systems have been studied using stable isotope tracing (Brooks et al., 2002; Smart et al., 2005) or sap flow measurements in roots (Burgess, 2006; Sakuratani et al., 1999), and they showed that water from the roots with access to soil moisture was laterally move across the vine trunk and into roots on the opposite on non-irrigated side and possible there is some hydraulic lift mechanism which allow the water to move vertically upward.

4. Influence PRD on water use efficiency of horticultural crops

Water use efficiency (WUE) can be defined in different ways depending on plant organization levels (Medrano et al., 2015). Agricultural crop water use efficiency was defined as dry weight of crops per litre of applied irrigation water (Savić et al., 2009), and he reported that PRD produced more fruit biomass per litre of water (1.70 g) compared to full irrigation (1.49 g). (As shown in Table 1 and 2) PRD significantly increase water use efficiency. (Mousavi et al., 2010) defined irrigation water use efficiency as a ratio of grain yield by the amount of irrigation water applied during the growing season and half application of irrigation water and applying this irrigation water alternatively on both sides of the root zone will produce the highest irrigation water use efficiency (Mousavi et al., 2010). According to (Battilani et al., 2014) the main advantage of partial root zone drying was irrigation water saving, and he reported that it is possible to save up to 13% of irrigation water by PRD and it allow a better use of the water stored in the root zone in dry years, it can use 7.9% of total available irrigation water stored in the root zone compared to full irrigation (as shown in Table 2) the water saving has been 518 m$^3$ ha$^{-1}$ during dry year and this effectiveness in saving water was indicated by many studies all over the world on vegetable and fruit crops, (Davies et al., 2000; Kang, 2004; Loveys et al., 2004). PRD improve irrigation water use efficiency by 70% and grain yield reduction only by less than 10% as compared to full irrigation (Zegbe et al., 2004). However, contrasting experiment done by (Kang et al., 2001) using hot pepper showed that PRD reduce water use only by 40% compared with fully irrigated plants. PRD maintain sugarcane productivity and water use efficiency (Siqueira et al., 2014), this fact shows that the technique can be an alternative to save water by using (41.8 m$^3$ ha$^{-1}$), than the full irrigation (50.4 m$^3$ ha$^{-1}$) in sugar cane production. Also, (Ben Nouna et al., 2016) indicated that the use of PRD with 60% of Etc from tuber initiation stage to tuberisation and harvest, improves the water use efficiency compared to full irrigation in potato, also

### Table 1. Impact of full irrigation (FI), partial root zone drying (PRD) and deficit irrigation (DI) on plant water use (PWU), fruit (DW), and water use efficiency (WUE) of tomato

| Treatments | PWU (L plant$^{-1}$) | Fruit DW (g plant$^{-1}$) | WUE (g L$^{-1}$) |
|------------|-----------------|----------------|-----------------|
| FI         | 29.5a           | 44.0a          | 1.4b            |
| PRD        | 21.1b           | 36.0b          | 1.7a            |
| DI         | 21.1b           | 36.0b          | 1.7a            |

Source: Savić et al. (2009)
can give the same tuber yield with that of the full irrigation. Similarly, (Dorji et al., 2005), find an increase in water use efficiency of hot pepper by 66.7% compared to full irrigation, and (Shahnazari et al., 2007) indicated that PRD irrigation can save 30% of irrigation water in potato and 61% increase in irrigation water use efficiency. (Mousavi et al., 2010) found that partial root zone drying irrigation increase water use efficiency of canola under greenhouse conditions. In other studies, it can save 20–30% of the irrigation water than used in fully irrigated plants and improve marketable yield by 15% in tomato (Jensen et al., 2010). This water saving capability of PRD was actually work, when water stress of dry part of the root occur, turgor pressure will be reduced and the root produce an ABA signal (Davies et al., 2002), or it produced in the leaves (Kim et al., 2010), and that can cause a reduction in the leaf area with a smaller leaf area, whole-canopy transpiration will be decrease that can effectively conserve the water supply in the soil for a longer period and improve water use efficiency (Wakrim et al., 2005). Similar findings were reported by (Huitzime´ngari et al., 2009) on tomato he attend 30 % field capacity on one side of the root zone and 90% on the other, subsequent decrease in leaf area by 15% which can minimize water loss by transpiration and increase water use efficiency. Beside, integrated application of PRD and drip irrigation method reduces water use by 50% and improve or enhance water use efficiency by 80–92% (Gotur et al., 2018).

5. Role of chlorophyll fluorescence in partial root-zone drying (PRD) irrigation management

Water accessibility, especially in arid and semi-arid regions was the most critical factor that reduces horticultural crop production and productivity (Flexas et al., 2002). As a result, there is a need to develop an accurate irrigation method to manage the limited irrigation water and to develop irrigation water management techniques that can indicate sustainable irrigation scheduling (). Chlorophyll fluorescence occurs in nature when red and far-red light is emitted from photosynthetic plants in response to photosynthetically active light. Then, light energy is harvested in the chloroplast and processed by two photosystems, which produce oxygen and energy by oxidation-reduction reactions during photosynthesis process (Ke, 2001). Therefore, the response of chlorophyll fluorescence to light quality and intensity could be a sensitive indicator of water deficit and it may have an important role in partial root zone irrigation management. Chlorophyll fluorescence parameters have been suggested as irrigation management techniques and measuring chlorophyll fluorescence parameters, including the steady-state chlorophyll fluorescence (Fs), quantum yield of photosystem PSII (Fv/Fm), photochemical quenching coefficient (qN) and non-photochemical quenching coefficient (NPQ), are widely used as water stress indicators (; Flexas et al., 2000, 2002; Marcassa et al., 2006; Meroni et al., 2009; Zarco-Tejada et al., 2003). Among all chlorophyll fluorescence parameters, steady-state chlorophyll fluorescence is especially important, because it can be measured by remote sensing and it does not affect plant performance (Flexas et al., 2000; Moya et al., 2006). This all makes the continuous remote recording of steady-state chlorophyll fluorescence (Fs) a capable tool for plant irrigation management. Thus, proper monitoring of steady-state chlorophyll fluorescence (Fs) would be a useful tool to decide when to irrigate PRD irrigated plants because it helps us to indicate moisture stress strength in dry state. chlorophyll fluorescence can be measured at short distances to several meters by using laser-based fluorometers (Flexas et al., 2000; Ounis et al., 2001), and from airborne using sun- induced chlorophyll fluorescence (Moya et al., 1998), and also by using the PAM-2000 and the Li-6400, we can measure fluorescence at smaller leaf area and by using FIPAM, or the new Laser-PAM, we can measure on large leaf area (Ounis et al., 2001). This method is especially helpful because it

| Treatments | Water use (L) | Reduction in H₂O use (%) | WUE (g dm⁻¹⁻¹) |
|------------|--------------|--------------------------|----------------|
| FI         | 50.4 a       | –                        | 3.6 ab         |
| PRD        | 41.8 b       | 17.6                     | 4.1 a          |
| NI         | 35.6 c       | 29.3                     | 2.9 b          |

Source: (Siqueira et al., 2014)
does not depend on measuring only small leaf but we can measure even by remote sensing (Flexas et al., 2002; Moya et al., 1998; Ounis et al., 2001). (Dobrowski et al., 2005) used the simple chlorophyll fluorescence index (DCI = D705/D722) to indicate chlorophyll fluorescence difference as a result of water stress, and (Perez-Priego et al., 2005) detect water stress by measuring chlorophyll fluorescence. (Burling et al., 2013) confirmed that blue-to-far-red fluorescence ratio is a good fluorescence index and increased as water stress increases. (Panigada et al., 2014) indicated that the use of chlorophyll fluorescence can help us to manage plant water stress. (Fedotov et al., 2016; Mistele et al., 2012; S. Wang et al., 2015) used the laser-induced fluorescence and detect plant water stress. On the other hand, (Gameiro et al., 2016) similarly, reported that the laser-induced fluorescence is a quick and non-destruction method to detect water deficit of Arabidopsis, and (Marcassa et al., 2006) said that by using fluorescence ratio (F685/F735, F452/F685 and F452/F735) we can detect the water stress. Therefore, Chlorophyll fluorescence can help us in early detection of plant water stress, and ultimately to irrigation scheduling of PRD irrigation and proper monitoring of Fs/Fo would be a useful tool for deciding when irrigation must be applied so that plants can be kept at a boundary between water stress and excess water consumption (Flexas et al., 2000; Moya et al., 1998; Ounis et al., 2001). In PRD irrigation one row or root zone is allowed to stay in dry state, and the other in wet state and after same time it has to be interchanged or alternated by seeing the stress imposed in dry state and to decide that chlorophyll fluorescence could be an important indicator of stress level and durations.

6. Conclusion

World population increase alarmingly and this increasing population demands an increment in arable land to boost production and productivity of agricultural goods. To do that they need additional land for agricultural activities they clear forest for agriculture, and this activities of human being alter hydrological cycle that result drought and shortage of agricultural water. This can create huge gap in food supply, population increment and agricultural activities that result negative impact on agriculture and food supply.

To preserve our hydrological cycle we have to rely on using irrigation water of different sources for our agricultural activities but it is not reliable as a result of limited water for irrigation use because of many areas in the world are already changed to arid or drought condition they does not have a role in preserving our hydrological cycle. Therefore, the only option we have, to supply agricultural goods to the increasing world population was preserving our hydrological cycle by a forestation and using our limited irrigation water resources wisely. One of the wise methods are partial root zone drying irrigation, it reduce irrigation water use by half amount and naturally allow plants to adapt moisture stress conditions by increasing activities of stress hormone mainly ABA and it allow an increase in water absorption, movement and its use efficacy of different crop plants. despite its importance partial root zone drying irrigation are not well practiced in different parts of the world especially in areas that are frequently affected by drought, and also there is no any methods developed to manage partial root zone drying irrigation especially ways to change from dry row to wet row or dry state to moist state. Generally, this review highlights some importance of partial root zone drying irrigation and methods to measure or manage partial root zone drying irrigation that is chlorophyll fluorescence, the review allow research on the area and develop management method of partial root zone drying irrigation.

Funding
This work was supported by the No fundings Received [No Grants].

Competing Interests
The author declares no competing interests.

Author details
Simeneh Tamrat Alemu1
E-mail: simattamrat@gmail.com
ORCID ID: http://orcid.org/0000-0001-7172-790X

1 Department of Dry Land Crop and Horticultural Science, College of Dry Land Agriculture and Natural Resources, Mekele University, Mekele, Ethiopia.

Cover Image
Sources: Author. (Yactayo et al., 2013)

Citation information
Cite this article as: Review: partial root zone drying an approach to increase water use efficiency of horticultural crops and chlorophyll fluorescence, Simeneh Tamrat Alemu, Cogent Biology (2020), 6: 1767016.

References
Ahmadi, S. H., Plauborg, F., Andersen, M. N., Sepaskhah, A. R., Jensen, C. R., & Hansen, S. (2011). Effects of irrigation strategies and soils on field grown potatoes: Root distribution. Agricultural Water Management, 98 (8), 1280–1290. https://doi.org/10.1016/j.agwat.2011.03.013
Alsina, M., Smart, D., Bauerle, T., de Herralde, F., Biel, C., Stockert, C., Negron, C., & Save, R. (2011). Seasonal changes of whole root system conductance by a drought-tolerant grape root system. Journal of
Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. The Annals of Applied Biology, 150 (2), 237–252. https://doi.org/10.1111/j.1744-7348.2006.00123.x

Chaves, M. V., Zanuncio, J. C., & Souza, C. O. (2002). Drought stress and high light effects on leaf photosynthesis. In B. NR & B. JR (Eds.), Photoinhibition of photosynthesis: From molecular mechanisms to the field (pp. 297–313). Bios Scientific Publishers.

Davies, W. J., Bacon, M. A., Thompson, D. S., Sobeigh, W., & Rodriguez, L. G. (2000). Regulation of leaf and fruit growth in plants drying soil: Exploitation of the plant's chemical signalling system and hydraulic architecture to increase the efficiency of water use in agriculture. Journal of Experimental Botany, 51(350), 1617–1626. https://doi.org/10.1093/jxb/erl085

Burgess, S. O. (2006). Redistribution of soil water by lateral roots mediated by stem tissues. Journal of Experimental Botany, 57(12), 3283–3291. https://doi.org/10.1093/jxb/erl085

Burgess, S. O., Adams, M. A., Turner, N. C., & Ong, C. K. (1998). The redistribution of soil water by tree root systems. Oecologia, 115(3), 306–311. https://doi.org/10.1007/s004420050521

Burling, K., Cerovic, Z. G., Comin, G., Ducruet, J.-M., Noga, G., & Hunsche, M. (2013). Fluorescence-based sensing of drought-induced stress in the vegetative phase of four contrasting wheat genotypes. Environmental and Experimental Botany, 89(51), 51–59. http://dx.doi.org/10.1016/j.envex.2013.01.003

Coldwell, M. M., Dawson, T. E., & Richards, J. H. (1998). Hydraulic lift: Consequences of water flux from the roots of plants. Oecologia, 113(2), 151–161. https://doi.org/10.1007/s004420050363

Coldwell, M. M., & Richards, J. H. (1989). Hydraulic lift: Water flux from upper roots improves effectiveness of water uptake by deep roots. Oecologia, 79(1), 1–5. https://doi.org/10.1007/BF00037823

Cerovic, Z. G., Goulas, Y., Gorbunov, M., Brantais, J. M., Camenen, L., & Moya, I. (1996). Fluorescent sensing of water stress in plants: Diurnal changes of the mean lifetime and yield of chlorophyll fluorescence, measured simultaneously and at distance with t-LIDAR and modified PAM fluorometer in maize, sugar beet and kalanchee. Remote Sensing of Environment, 58 (3), 311–321. https://doi.org/10.1016/0034-4257(96)00076-4

Chaves, M. M., Flexas, J., & Pinheiro, C. (2009). Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. Annals of Botany, 103(4), 551–560. https://doi.org/10.1093/aob/mcn125

Chaves, M. M., & Oliveira, M. M. (2004). Mechanisms underlying plant resilience to water deficits Prospects for water saving agriculture. Journal Experimental Botany, 55(407), 2365–2384. https://doi.org/10.1093/jxb/erh269

Chaves, M. M., Pereira, J. S., Maroco, J. P., Rodrigues, M. L., Ricardo, C. P. P., Osorio, M. L., Carvalho, I., Faria, T., & Pinheiro, C. (2002). How plants cope with water stress in the field: Photosynthesis and yield. Annals of Botany, 89(7), 1–10. https://doi.org/10.1093/aob/mcf105

Chaves, M. M., Santos, T. P., Souza, C. R., Ortuño, M. F., Rodrigues, M. L., Lopes, C. M., Maroco, J. P., & Pereira, J. S. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. The Annals of Applied Biology, 150 (2), 237–252. https://doi.org/10.1111/j.1744-7348.2006.00123.x

Chen, X. (2001). Stem water potential is a sensitive indicator of grapevine water status. Annals of Botany, 87 (4), 477–483. https://doi.org/10.1093/aob/mcmq030

Chen, M. J., Fuentes, S., & Borow, E. W. R. (2010). Partial rootzone drying on deficits irrigation increase stomatal sensitivity to vapour pressure deficit in anisohydric grapevines. Functional Plant Biology, 37(2), 128–138. https://doi.org/10.1071/FP09175

Comstock, J. P. (2003). Hydraulic and chemical signaling in the control of stomatal conductance and transpiration. Journal of Experimental Botany, 54(367), 195–200. https://doi.org/10.1093/jxb/erl085

Comin, G. (1994). Drought stress and high light effects on leaf photosynthesis. In B. NR & B. JR (Eds.), Photoinhibition of photosynthesis: From molecular mechanisms to the field (pp. 297–313). Bios Scientific Publishers.

Davies, W. J., Bacon, M. A., Thompson, D. S., Sobeigh, W., & Rodriguez, L. G. (2000). Regulation of leaf and fruit growth in plants drying soil: Exploitation of the plant’s chemical signalling system and hydraulic architecture to increase the efficiency of water use in agriculture. Journal of Experimental Botany, 51(350), 1617–1626. https://doi.org/10.1093/jxb/erl085

Davies, W. J., Wilkinson, S., & Loveys, B. R. (2002). Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. New Phytologist, 153(3), 449–460. https://doi.org/10.1046/j.1469-8137.2001.00341.x

Dobrowski, S. Z., Pushnik, J. C., Zorco-Tejada, P. J., & Ustin, S. L. (2005). Simple reflectance indices track heat and water stress-induced changes in steady-state chlorophyll fluorescence at the canopy scale. Remote Sensing of Environment, 97(3), 403–414. https://doi.org/10.1016/j.rse.2005.05.006

Dodd, I. C., Egee, G., Watts, C., & Whalley, W. R. (2010). Root water potential integrates discrete soil physical properties to influence ABA signaling during partial rootzone drying. Journal of Experimental Botany, 61 (13), 3543–3551. https://doi.org/10.1093/jxb/erq195

Dodd, I. C., Theobald, J. C., Bacon, M. A., & Davies, W. J. (2006). Alternation of wet and dry sides during partial rootzone drying irrigation alters root-to-shoot signalling of abscisic acid. Functional Plant Biology, 33 (12), 1081–1089. https://doi.org/10.1071/FP06203

Dorji, K., Behboudian, M. H., & Zegbe-domínguez, J. A. (2008). Water relations, growth, yield, and fruit quality of hot pepper under deficit irrigation and partial rootzone drying. Scintia Horticulturae, 104(2), 137–149. https://doi.org/10.1016/j.scienta.2004.08.015
Dry, P. R., Loveys, B. R., & Düring, H. (2000). Partial drying of the root zone of grape. I. Transient changes in shoot growth and gas exchange. Vitis, 39(1), 3–7.

English, M. J., & Raja, S. N. (1996). Perspectives on deficit irrigation. Journal of Agricultural Water Management, 32(1), 1–14. https://doi.org/10.1016/S0378-3774(96)01255-3

FAO. (2002). Deficit irrigation practices. Water Reports No. 22, Rome.

Fedotov, Y., Bullo, O., Belov, M., & Gorodnichiev, V. (2016). Experimental research of reliability of plant stress state detection by laser-induced fluorescence method. International Journal of Optics, (2016)1-6. https://doi.org/10.1155/2016/4543094

Flexas, J., Briantais, J. M., Cerovic, Z., Medrano, H., & Moya, I. (2000). Steady-state and maximum chlorophyll fluorescence responses to water stress in grapevine leaves: A new remote sensing system. Remote Sensing of Environment, 73(3), 283–297. https://doi.org/10.1016/S0378-4427(00)00104-8

Flexas, J., Escalona, J. M., Evain, S., Gullas, J., Moya, J., Osmond, C. B., & Medrano, H. (2002). Steady-state chlorophyll fluorescence (Fs) measurements as a tool to follow variations of net CO2 assimilation and stomatal conductance during water-stress in C3 plants. Physiologia Plantarum, 114(2), 231–240. https://doi.org/10.1046/j.1399-3042.2002.00429.x

Flexas, J., Escalona, J. M., & Medrano, H. (1999). Water stress induces different levels of photosynthesis and electron transport rate regulations in grapevines. Plant, Cell and Environment, 22(1), 39–48. https://doi.org/10.1046/j.1365-3040.1999.00371.x

Gameiro, C., Utkin, A. B., Cartaxana, P., da Silva, J. M., & Matos, A. R. (2016). The use of laser induced Chlorophyll Fluorescence (LIF) as a fast and non-destructive method to investigate water deficit Arabidopsis. Agricultural Water Management, 164, 1127–136. https://doi.org/10.1016/j.agwat.2015.09.008

Genty, B., Briantais, J. M., & Baker, N. R. (1989). The relationship between the quantum yield of photosynthetic electron transport and quenching of chlorophyll fluorescence. Biochimica Et Biophysica Acta (BBA) - General Subjects, 901(1), 87–92. https://doi.org/10.1016/0005-2728(89)90016-9

Gottardin, E., Cristofori, A., Cristofolini, F., Nali, C., Pellegrini, E., Bussotti, F., & Ferretti, M. (2014). Chlorophyll-related indicators are linked to visible ozone symptoms: Evidence from a field study on native Viburnum lantana L. plants in northern Italy. Ecological Indicators, (39), 65–74. https://doi.org/10.1016/j.ecolind.2013.11.021

Getur, M., Sharma, D. K., Joshi, C. J., & Rojani, R. (2018). Partial root-zone drying technique in fruit crops: A review paper. J.C.S, 6(2), 900–903.

Gu, S. L., David, Z., Simon, G., & Greg, J. (2000). Effect of partial rootzone drying on vine water relations, vegetative growth, mineral nutrition, yield, and fruit quality in field-grown mature sauvignon blanc grapevines. Research Notes, No00702.California Agricultural Technology Institute. California State University.

Gu, S. L., Du, G. Q., Zoldoske, D., Hakim, A., Cochran, R., Fugelsang, K., & Jorgensen, G. (2004). Effects of irrigation amount on water relations, vegetative growth, yield and fruit composition of Sauvignon blanc grapevines under partial rootzone drying and conventional irrigation in the San Joaquin Valley of California, USA. The Journal of Horticultural Science and Biotechnology, 79(1), 26–33. https://doi.org/10.1080/14620316.2004.11511732

Hartung, W., & Slovák, S. (1991). Physicochemical properties of plant growth regulators and plant tissues determine their distribution and redistribution: Stomatal regulation by abscisic acid in leaves. The New Phytologist, 119(3), 361–382. https://doi.org/10.1111/1469-8137.1991.tb00036.x

Huizhime’ngari, C., Trejo, C., Pen’aValdivia, C. B., RamírezAyala, C., & Sa’nchezGarcia, P. (2009). Effect of partial rootzone drying on growth, gas exchange, and yield of tomato (Solanum lycopersicum L.). Scientia Horticulturae, 120(4), 493–499. https://doi.org/10.1016/j.scienta.2008.12.014

Hutton, R. J., Landsberg, J. J., & Sutton, B. G. (2007). Timing irrigation to suit citrus phenology: A means of reducing water without compromising fruit yield and quality? Australian Journal of Experimental Agriculture, 47(1), 71–80. https://doi.org/10.1071/EA06113

IPCC. (2007). Climate change 2007: The physical basis summary for policy makers. Cambridge University Press.

Jovaux, M., Couvreur, V., Vanderborght, J., & Vereecken, H. (2013). Root water uptake: from three-dimensional biophysical processes to macroscopic modeling approaches. Journal of Vadose Zone, (12), 4.1-16. https://doi.org/10.2136/vzj2013.02.0042

Jensen, C. R., Battilani, A., Plauborg, F., Psarras, G., Chartzoulakis, K., Jnanowiak, F., Stikic, R., Jovanovic, Z., Li, G., Qi, X., Liu, F., Jacobsen, S. E., & Andersen, M. N. (2010). Deficit irrigation based on drought tolerance and root signalling in potatoes and tomatoes. Journal of water management,(983), 403–413. https://doi.org/10.1016/j.jwagro.2010.10.010

Jovanovic, Z., & Stikic, R. (2018). Partial root-zone drying technique: From water saving to the improvement of a fruit quality. Frontiers in Sustainable Food System Mini Review, (1),3-19 https://doi.org/10.3389/fsufs.2017.00003

Kang, S., Hu, X., Jerie, P., & Zhang, J. (2003). The effects of partial rootzone drying on root, trunk sap flow and water balance in an irrigated pear (Pyrus communis L.) orchard. Journal of Hydrology, 280(1–4), 192–206. https://doi.org/10.1016/S0022-1694(02)00226-9

Kang, S., Liang, Z., Pan, Y., Shi, P., & Zhang, J. (2000). Alternate furrow irrigation for maize production in an arid area. Agricultural Water Management, 43(3), 267–274. https://doi.org/10.1016/S0378-3774(00)00072-X

Kang, S., Zhang, L., & Li, G. (2001). An improved water use efficiency for hot pepper grown under controlled alternate drip irrigation on partial roots. Scientia Horticulturae, 89(4), 257–267. https://doi.org/10.1016/S0304-4238(01)000245-4

Kang, S. Z. (2004). Controlled alternate partial root-zone irrigation: Its physiological consequences and impact on water use efficiency. Journal of Experimental Botany, 55(407), 2437–2446. https://doi.org/10.1093/jxb/erh249

Ke, B. (2001). Photosynthesis: Photobiodynamics and photobiophysics. Kluwer Academic Publishing. https://doi.org/10.1093/9780195139003

Khalil, A. A. M., & Grace, J. (1993). Does xylem sap ABA control the stomatal behaviour of water-stressed sycamore (Acer pseudoplatanus L.) seedlings? Journal of Experimental Botany, 44(7), 1127–1134. https://doi.org/10.1093/jxb/44.7.1127

Kim, T. H., Boehmer, M., Hu, H., Nishimura, N., & Schroeder, J. J. (2010). Guard cell signal transduction network: Advances in understanding osbiscic acid, CO2, and Ca2+ signaling. Annual Review of Plant Biology, 61(1), 561–591. https://doi.org/10.1146/annurev-plant-042809-112226
White, S. C., & Raine, S. R. (2009). Physiological response of cotton to rot zone soil moisture gradient: Implications for partial root zone drying irrigation. *Journal of Cotton Science*, (13)1; 67–74.

Wilkinson, S. (2004). Water use efficiency and chemical signalling. In M. A. Bacon (Ed.), *Water use efficiency in plant biology* (pp. 75–112). Blackwell Publishing.

Wilkinson, S., & Davies, W. J. (1997). Xylem sap pH increase: A drought signal received at the a poplast face of the guard cell that involves the suppression of saturable abscisic acid uptake by the epidermal symplast. *Plant Physiology*, 113(2), 559–573. https://doi.org/10.1104/pp.113.2.559

Yan, F., Sun, Y., Song, F., & Liu, F. (2012). Differential responses of stomatal morphology to partial root-zone drying and deficit irrigation in potato leaves under varied nitrogen rates. *Scientia Horticulturae*, 145; 76–83. https://doi.org/10.1016/j.scienta.2012.07.026

Zarco-Tejada, P. J., Pushnik, J. C., Dobrowski, S., & Ustin, S. L. (2003). Steady-state chlorophyll a fluorescence detection from canopy derivative reflectance and double-peak red-edge effects. *Remote Sensing of Environment*, 84(2), 283–294. https://doi.org/10.1016/S0034-4257(02)00113-X

Zegbe, J. A., Behbouidan, M. H., Lang, A., & Clothier, B. E. (2004). Deficit irrigation and partial rootzone drying maintain fruit dry mass and enhance fruit quality in ‘Petopride’ processing tomato (Lycopersicon esculentum, Mill.). *Scientia Hort.*, 98(4), 505–510. https://doi.org/10.1016/S0304-4238(03)00036-0