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Plant water relations, crop yield and quality in coffee (*Coffea arabica* L.) as influenced by partial root zone drying and deficit irrigation

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Abstract

Recurrent drought is among the major factors constraining coffee production in Ethiopia. On the other hand, in most cases, there is shortage of water resources for irrigation during prolonged dry spells. Therefore, this study was conducted with the objective of developing an effective irrigation management strategy, which could minimize the adverse effect of drought on coffee production, save water and improve water use efficiency of this crop. Two deficit irrigation techniques: partial root zone drying (PRD) and normal deficit irrigation (NDI) were studied along with a well-watered (WW) treatment on six years old coffee (*Coffea arabica* L.) stand of cultivar F-59 in randomized complete block design with four replications. The experiment was conducted for 18 months at Jimma Agricultural Research Center of the Ethiopian Institute of Agricultural Research. Among the irrigation practices tested in the present study, full irrigation (WW) resulted in considerably higher soil moisture content, leaf relative water content (RWC), stomatal conductance (gs) and crop yield, compared to PRD and NDI. Yield components had also higher values under WW than in PRD and NDI treatments. However, the difference between WW and PRD was not significant for crop yield and for most of the yield components, and yet PRD and NDI significantly improved the quality of coffee beans. In addition, PRD saved 50% of the irrigation water required for WW and resulted in significantly higher irrigation water use efficiency (IWUE) than WW and NDI. Hence, it was concluded that PRD seems an effective irrigation strategy that could save water, increase IWUE and improve crop quality without a significant reduction in crop yield in areas where water is scarce for irrigation and the dry spells are prolonged.

Keywords: *Coffea arabica*; partial root zone drying (PRD); normal deficit irrigation (NDI); well watering (WW); crop yield; crop quality; irrigation water use efficiency (IWUE).

Introduction

Coffee (*Coffea arabica* L.) plays a significant role in the national economy of Ethiopia, contributing over 60% of the foreign exchange earnings and 30% of the government's direct revenue. Furthermore, the livelihood of 25% of the population depends on the coffee industry. However, the average national yield of the crop is very low primarily because of lack of improved varieties for different areas, diseases and pests and seasonal water deficits (Tesfaye and Ismail, 2008). Changes in local weather and global climate brought about reduced amount and erratic distribution of the seasonal precipitation, which in turn, resulted in frequent drought incidences in Ethiopia, as well as in most potential agricultural regions of the world. This situation makes crop production impossible or at least difficult without irrigation in these areas. On the other hand, the supply of water is limited and; thus, it could not satisfy the continuously increasing demand of water for irrigation in most cases (Kirda et al., 2004; Wakrim et al., 2005). Therefore, there is an urgent need to identify and adopt effective irrigation management strategies in most parts of the world. In this line, saving of water and increasing water use efficiency became high priority issue, which diverted the attention of researchers towards developing effective irrigation techniques for crop production.

It is well known that supplemental irrigation improves growth and productivity of crop plants, particularly in drier areas (Garside et al., 1992a; 1992b), though application of sub-optimal levels can lead to low irrigation efficiency and poor crop performances (Wakrim et al., 2005). One of the methods to achieve increased water use efficiency in crops is applying of deficit irrigation. In areas of recurrent water scarcity and prolonged drought spells, conventional deficit irrigation is a common practice, traditionally recommended to minimize drastic yield reductions due to severe water stresses. However, it is not effective in terms of water conservation in most cases (Kirda et al., 2004). On the other hand, specific and more sensitive crop growth stages and the volume of water supplied to plants during each application

Table 1. Effect of irrigation regime on raw and cup quality of coffee beans (WW = well-watering, PRD = partial root zone drying and NDI = normal deficit irrigation).

Treatment	Raw quality (40%)			Liquor value (60%)		
	Shape and make	Color	Odor	Acidity	Body	Flavor
WW	7.56 c	9.37 a	8.50 a	12.50 a	13.75 a	11.87 a
PRD	11.00 a	9.75 a	8.50 a	14.69 a	15.00 a	13.12 a
NDI	9.50 b	11.50 a	8.50 a	14.37 a	14.37 a	13.75 a

Values followed by same letters within a column are not significantly different at P ≤ 0.05.

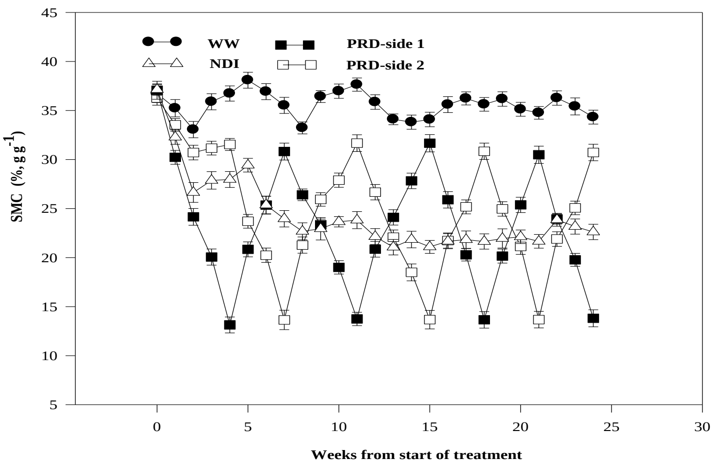

Fig 1. Soil moisture content as affected by deficit irrigation in a coffee stand (cv. F-59) (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). Bars represent standard errors of means of four observations for each treatment and measurement occasion.

should be considered while adopting deficit irrigation as a water saving strategy for crop production in drier areas (Zegbe et al., 2004; Dorji et al., 2005). Therefore, an effective use of deficit irrigation may be required to maximize returns from the practice by optimizing growth, yield and water use efficiency of crop plants.

So far, different deficit irrigation techniques have been developed and widely used in drought-prone areas. It has been reported that regulated deficit irrigation (RDI), which involves withholding or reducing water supply for specific periods during the growth cycle of crops, is a widely used and believed to be an effective management strategy for more efficient use of irrigation water and to improve crop yield and quality (Wakrim et al., 2005). Besides RDI, results of earlier studies with split-root system (Gowing et al., 1990; Davies and Zhang, 1991; Davies et al., 2000) have led to the development of a new deficit irrigation practice known as partial root zone drying (PRD), where the root system of a plant is divided into two parts, each exposed alternately to soil drying and re-watering cycles. This practice has been developed quite recently and has been tested for some crops and found to be more effective than other deficit irrigation practices and easy to use with substantial increase in irrigation water use efficiency (IWUE) and crop quality and about 50% decrease in the volume of water required for full irrigation, usually without significant reduction in crop yield (Dry and Loveys, 1998; Davies et al., 2000; Loveys et al., 2000; Kang et al., 2002; dos Santos et al., 2003; Kirda et al., 2004; Wakrim et al., 2005). In PRD, part of the root system is watered with the complement being left to dry to a pre-determined soil moisture level. Hence, adoption of PRD simply involves exposure of half of the root system to alternate wetting and drying cycles during the growing season.

Although PRD appeared to be an effective and water saving technique in different crops, its effect as a deficit irrigation system has not been tested on coffee orchards. The objectives of this study were to compare normal deficit irrigation (NDI) and partial root zone drying (PRD) and to determine their relative effect on plant water relations, crop yield, quality and water use efficiency of Arabica coffee under field condition.

Results

Soil moisture content

Soil moisture content (SMC) of the WW treatment was maintained within the range of 33% and 38% and it was considerably higher than that of the NDI treatment, which ranged between 22% and 27% during the study period. Depending on soil drying and re-watering cycles, the SMC in PRD treatment varied over the range of less than 14% and 31%, but mean of the two sides was higher than the SMC in NDI plot for most of the measurement occasions. On the other hand, SMC of the re-watered side of the PRD treatment, which was receiving the same volume of water as one of the two compartments of the WW plant during each application, was always lower than the SMC of either side or mean of the two compartments of the WW treatment (Fig. 1).

Leaf relative water content

Relative water content (RWC) of coffee leaves was consistently higher (92%–96%) for WW plants and it had lower values (84%–89%) for NDI treatment throughout the measurement period. Leaf RWC of PRD plants varied over the range of 88% and 93%, and was always lower than the

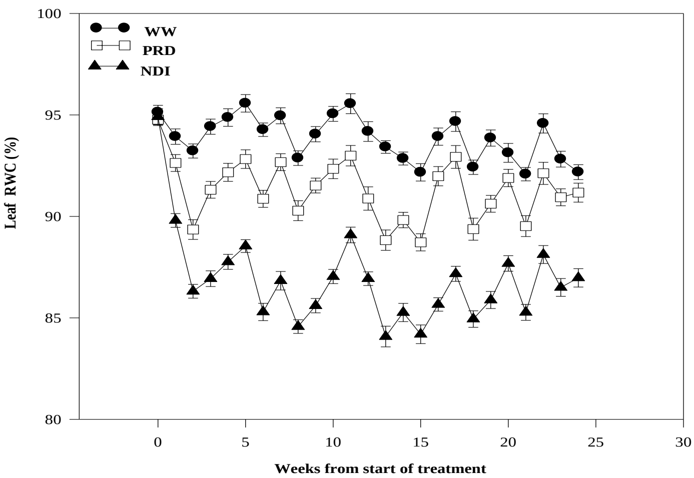

Fig 2. Leaf relative water content (RWC) of coffee plants (cv. F-59) as affected by deficit irrigation (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). Bars represent standard errors of means of four observations for each treatment and measurement occasion.

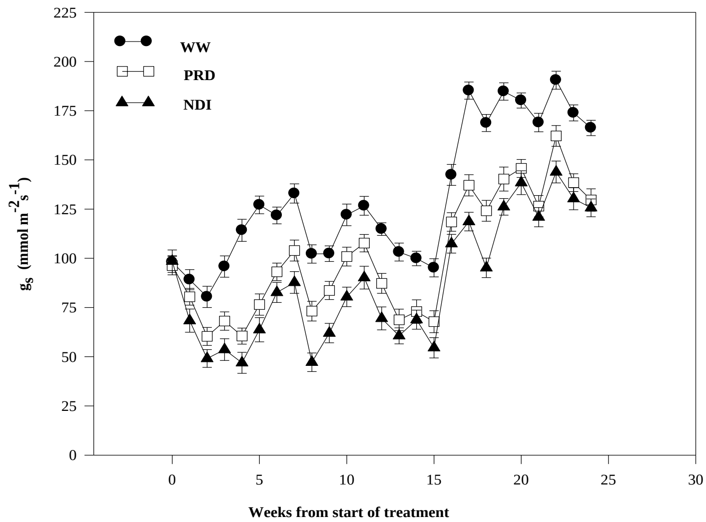

Fig 3. Stomatal conductance (g_s) of coffee plants (cv. F-59) as affected by deficit irrigation (WW = well watering, NDI = normal deficit irrigation and PRD = partial root zone drying). Bars represent standard errors of means of four observations for each treatment and measurement occasion.

RWC of WW but higher than that of the NDI treatment. However, it was closer to WW than to NDI treatment on most of the measurement occasions (Fig. 2).

Stomatal conductance

Deficit irrigation resulted in substantial reduction of stomatal conductance (g_s). Coffee plants in the WW treatment had always higher g_s, which was by an average of 28% and 39% more than that of PRD and NDI plots, respectively. The g_s in the PRD treatment was; however, closer to the value measured for NDI on most of the measurement occasions during the study period. On the other hand, all the treatments exhibited considerably lower g_s in the dry season than in the wet rainy season (Fig. 3).

Fresh cherry yield

Number of fruits per branch and per tree, fresh cherry weight per tree (Fig. 4) and total coffee yield (Fig. 5) were significantly ($P \leq 0.05$) affected by NDI. However, the difference between NDI and PRD, as well as among WW and PRD treatments, was not statistically significant. It was observed that WW plants had 31.08% and 14.13% yield advantage over NDI and PRD treatments, respectively (Fig. 4; Fig. 5).

Water use efficiency for crop yield

Irrigation water use efficiency (IWUE) for crop (fresh cherry) yield was significantly ($P \leq 0.05$) higher for the PRD treatment compared with NDI and WW plots. The difference between NDI and WW was also significant, where the former increased IWUE by 26.63% over the later treatment. On the other hand, the PRD practice resulted in 41.08% and 19.68% more IWUE than the WW and NDI treatments, respectively (Fig. 5).

Crop quality

As an international standard, coffee quality is evaluated by the appearance of raw beans (raw quality) and taste of the brew after roasting and grinding the beans (liquor or cup quality), accounting for 40% and 60% of the total coffee quality. The raw quality involves visual inspection and rating of the green bean samples for uniformity in size, conformity with known standards for shape and make, color and odor (free from smell of other substances and maintenance or preservation of natural standard bean odor). In line with this, among the attributes used to evaluate raw quality of coffee beans, the score value of only shape and make was significantly ($P \leq 0.001$) affected by irrigation treatments, where the highest mean value resulted from PRD and the lowest from WW treatment. The difference between PRD and NDI or between NDI and WW plots was also significant for bean shape and make. Although treatment variations were not statistically significant ($P > 0.05$), color value was higher for NDI. Similarly, acidity, body and flavor (sensory or organoleptic evaluation and scoring of the brew, following the standard procedure) in the cup taste had higher mean score values for the PRD and NDI treatments compared to WW plot, but treatment differences were not significant (Table 1). However, the overall raw and liquor quality, as well as summation of the two, significantly ($P \leq 0.05$) increased by PRD and NDI treatments compared with coffee beans from WW plants (Fig. 6).

Discussion

Soil moisture content (SMC), leaf relative water content (RWC) and stomatal conductance (g_s) were consistently higher for WW treatment than in NDI and PRD plots throughout the study period. Reductions in these parameters under deficit irrigation (DI) and PRD treatments compared with full irrigation have also been reported for different crops, such as pear (Kang et al., 2002), tomatoes (Hassan et al., 2003; Zegbe-Dominguez et al., 2003; Kirda et al., 2004; Mingo et al., 2004; Zegbe et al., 2004) and pepper (Dorji et al., 2005).

Although the SMC in the non-irrigated side of PRD treatment was continuously decreasing to less than 14%,

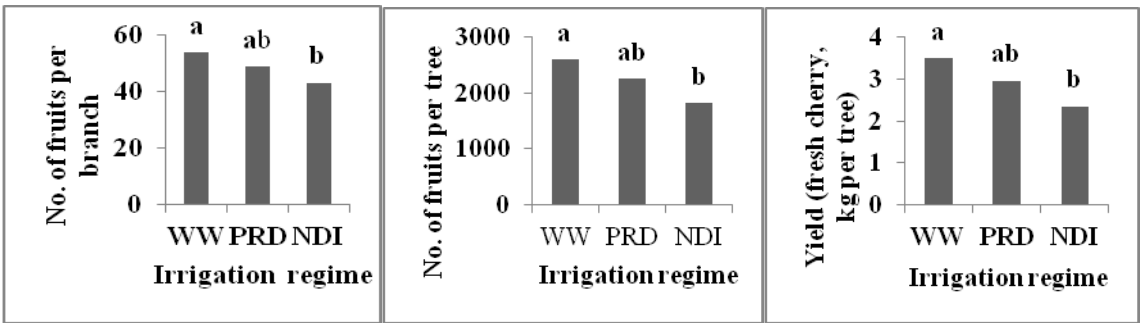

Fig 4. Yield and yield components (number of fruits per branch, number of fruits per tree and fresh cherry yield per tree) of Arabica coffee (cv. F-59) as affected by deficit irrigation (WW = well-watered; PRD = partial root zone drying and NDI = normal deficit irrigation). Columns capped with the same letter (s) are not significantly different at $P \leq 0.05$ with LSD test

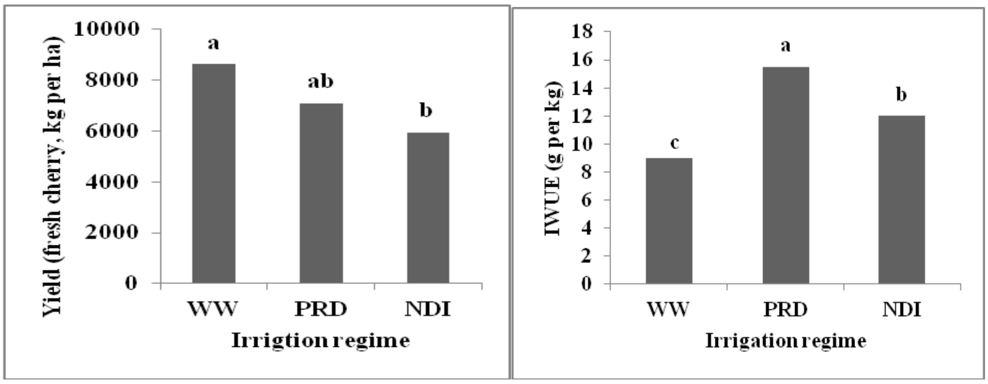

Fig 5. Fresh cherry yield (kg ha^{-1}) and irrigation water use efficiency (IWUE) of Arabica coffee plants (cv. F-59) as affected by deficit irrigation: well-watered (WW); partial root zone drying (PRD) and normal deficit irrigation (NDI). Columns capped with the same letter (s) are not significantly different at $P \leq 0.05$ with LSD test.

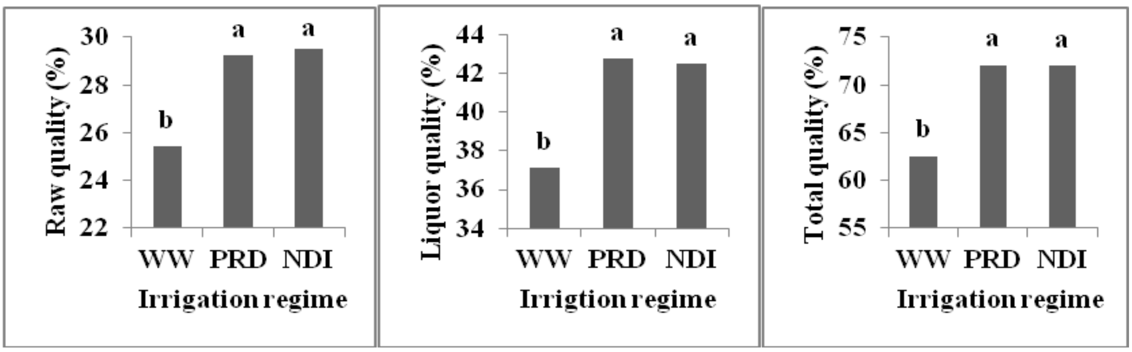

Fig 6. Overall raw, liquor and total quality of coffee beans as affected by different irrigation treatments: well-watered (WW), partial root zone drying (PRD) and normal deficit irrigation (NDI). Columns capped with the same letter (s) are not significantly different at $P \leq 0.05$ with LSD test.

which was lower than the values for NDI, mean of the two (wet and dry) sides was higher than that of NDI plot for most of the measurement occasions. Similarly, the extent of reduction in leaf RWC and g_s was consistently higher in NDI than in the PRD treatment.

These results were in agreement with the findings on field-grown grapevines (de Souza et al., 2003; dos Santos et al., 2003), hot pepper (Dorji et al., 2005) and common bean (Wakrim et al., 2005), indicating substantial reductions in leaf water potential (LWP) and g_s for both PRD and deficit irrigation (DI) treatments compared to WW plants. On the other hand, SMC of the re-watered (wet) side of the PRD treatment was always lower than that of either side of the WW treatment, which was receiving the same volume of water as did the wet compartment of PRD. Consistent with this observation, the findings of Kang et al. (2002) and Mingo et al. (2004) also confirmed that SMC of the wet side of PRD plants is depleted more rapidly than the same side of control plants in pear orchard and glasshouse-grown tomatoes, respectively. This indicates that the root system is taking up more water to compensate the increasingly limited water availability and; thus, reduced uptake from the dry side.

A significant decrease in LWP following the extent of decline in soil moisture availability has also been reported for water-stressed plants of sweet pepper (Hawa, 2003). On the other hand, leaf RWC values were fluctuating with measurement dates for all the treatments, and the PRD plants had values closer to those of WW than to NDI treatments on most of the measurement occasions. A similar trend has also been observed in tomatoes, where LWP was only slightly affected by the PRD treatment, despite significantly lower moisture content of the growing medium compared to the control (Hassan et al., 2003; Zegbe-Dominguez et al., 2003; Zegbe et al., 2004).

Fluctuations in leaf RWC of coffee plants in each treatment might be associated with changes in some environmental factors affecting plant water status over the study period. These environmental factors might also have contributed to maintenance of leaf RWC in PRD at a level sometimes closer to that of WW plants. In line with this, Zegbe-Dominguez et al. (2003) have suggested that lack of significant differences between PRD and control plots for LWP, despite significant reductions in SMC of the former treatment, could be associated with the low evaporative demand and radiation levels during the measurement period.

Besides, some metabolic changes and chemical signaling might have been involved in the maintenance of leaf RWC in PRD plants. As it has been observed in several crop species with split-root system or PRD practice, soil drying stimulated stomatal closure but did not significantly decrease LWP (Gowing et al., 1990; Davies and Zhang, 1991), RWC (Trejo and Davies, 1991) or leaf turgor (Liu et al., 2003). In line with this, it has been reported that stomatal closure induced by increased concentration of root-sourced abscisic acid (ABA) in the leaves (Davies and Zhang, 1991; Davies et al., 2000; Stoll et al., 2000), changes in pH of xylem sap (Gollan et al., 1992; Thompson et al., 1997; Bacon et al., 1998) or by hydraulic signals (Tardieu and Davies, 1993; Auge and Moore, 2002; de Souza et al., 2003; dos Santos et al., 2003) in response to soil drying or PRD can decrease water loss through transpiration and thus maintain the plant water balance. Furthermore, it has been reported that the rate of water uptake in PRD maize (Kang et al., 2000) and pear plants (Kang et al., 2002) considerably increased when roots in the dry soil were re-wetted. These findings might explain maintenance of leaf RWC of coffee plants in the PRD treatment in the present study.

Like leaf RWC, stomatal conductance (g_s) was also fluctuating over the study period for all the treatments, and g_s of WW plants was higher than those of PRD and NDI for all the measurement occasions. However, unlike leaf RWC, g_s of the PRD treatment had closer values to NDI than to WW plot on most of the measurement occasions. As discussed earlier, the decline of g_s without a significant change in leaf water status of PRD plants was quite in agreement with some previous findings with split-root experiments on maize (Kang et al., 1998), apple (Gowing et al., 1990), common bean (Trejo and Davies, 1991), grapevine (Stoll et al., 2000; de Souza et al., 2003), soybean (Liu et al., 2003) and tomatoes (Davies et al., 2000; Hassan et al., 2003; Mingo et al., 2004). Several workers have reported that roots in a drying soil produce a chemical signal, most likely ABA, which is transported through the xylem stream to the shoot to induce stomatal closure (Davies and Zhang, 1991; Davies et al., 2000; Stoll et al., 2000). Similarly, changes in xylem sap pH with soil water deficit can induce stomatal closure (Gollan et al., 1992; Thompson et al., 1997; Bacon et al., 1998). As observed in the present study, stomatal closure can also take place as a result of hydraulic signaling (reductions in soil and plant water status) (Tardieu and Davies, 1993; Auge and Moore, 2002; de Souza et al., 2003; dos Santos et al., 2003; Wakrim et al., 2005).

On the other hand, g_s had generally lower values regardless of the level of SMC or leaf RWC during the dry spell compared to the respective values recorded in the wet season. This could be associated with the higher air temperature and lower relative humidity during the dry season (data not available). In line with this, it has been suggested that in the absence of drought variations, g_s could primarily be correlated with leaf and air temperature, radiation level and evaporative demand of the atmosphere or leaf-to-air vapor pressure deficit (VPD) (Zegbe-Dominguez et al., 2003). It was observed that number of fruits per branch and per tree, fresh cherry weight per tree, and total crop yield per ha was significantly higher in WW plants, but differences among WW and PRD or between PRD and NDI were not significant. The reduction in yield per tree and per ha in PRD and NDI treatments might be associated with reduced number of fruits per branch and per tree due to lower levels of both SMC and leaf RWC or plant water status.

The adverse effect of moisture deficit stress on number of fruits per branch and potential crop yield has also been reported for pear (Mitchell et al., 1984), avocado (Adato and Levinson, 1988) and sweet pepper (Delfine et al., 2000; Hawa, 2003). Results of the present study were also quite in agreement with the findings of Dry and Loveys (1998), Loveys et al. (2000) and dos Santos et al. (2003) on grapevines; Kang et al. (2000) on maize; Kang et al. (2001) and Dorji et al. (2005) on hot pepper; Kang et al. (2002) on pear and Hassan et al. (2003); Kirda et al. (2004); Mingo et al. (2004) and Zegbe et al. (2004) on tomatoes, indicating that differences between PRD and full irrigation were not significant for crop yield, although PRD resulted in slight reductions. Furthermore, it has been reported that fruit dry mass yield of tomatoes was not affected by the PRD practice (Zegbe-Dominguez et al., 2003). On the other hand, it has been observed that normal or conventional deficit irrigation resulted in significantly lower crop yield, which was much less than that of PRD treatment in tomatoes (Kirda et al., 2004) and hot pepper plants (Dorji et al., 2005). In general, reductions in total crop yield of deficit irrigation in the present study could be attributed to decreases in number of fruits per branch and per tree as a result of probably reduced rate of total biomass production and its partitioning to shoot parts (leaf, branch, stem and fruit) in response to soil drying and water deficit stress in the plant system (Kang et al., 1998; 2001; Poorter and Nagel, 2000; Mingo et al., 2004).

Irrigation water use efficiency (IWUE) was significantly higher for PRD, followed by NDI, compared to WW treatment. The difference between NDI and WW treatments was also significant. Besides saving 50% of irrigation water, PRD resulted in 19.68% and 41.08% more IWUE than NDI and WW treatments, respectively. Such a substantial increase in IWUE and water saving without significant yield reduction with the PRD practice has also been reported for grapevines (Dry and Loveys, 1998; Loveys et al., 2000; de Souza et al., 2003; dos Santos et al., 2003), maize (Kang et al., 2000), pear (Kang et al., 2002), hot pepper (Kang et al., 2001; Dorji et al., 2005), tomato (Davies et al., 2000; Hassan et al., 2003; Zegbe-Dominguez et al., 2003; Kirda et al., 2004; Zegbe et al., 2004) and common bean (Wakrim et al., 2005). Although different methods have been used to calculate IWUE (Kang et al., 2001; Dorji et al., 2005), PRD exhibited 28% – 50% (Hassan et al., 2003), 56% (Kirda et al., 2004) or 70% (Zegbe et al., 2004) higher value compared to full irrigation in tomatoes.

The quality of coffee beans, as evaluated by raw characters and liquor tastes based on the standard procedure, was significantly improved by PRD and NDI treatments compared to coffee beans from WW plants. In agreement with these results, it has been reported that fruit quality of grapevines increased without a significant yield reduction for the PRD practice (Dry and Loveys, 1998; dos Santos et al., 2003), which has also enhanced fruit quality of tomatoes by way of increasing water soluble dry matter in fruits compared to those harvested from fully irrigated treatments (Kirda et al., 2004).

The findings of Zegbe-Dominguez et al. (2003) have indicated that tomato fruits in deficit irrigation and PRD plots were redder and had higher concentration of total soluble solids (TSSC) relative to those from WW control plants. Davies et al. (2000) and Zegbe et al. (2004) have also observed advancement in fruit maturity (redder color) and enhancement of quality (higher dry mass concentration and TSSC) in fruits from PRD treatment compared to those from fully irrigated tomato plants. Similarly, deficit irrigation has resulted in 21% higher TSSC and better color development in hot pepper fruits (Dorji et al., 2005). In general, increases in crop quality as a result of PRD practice might be associated with biochemical changes, such as altered hormone concentrations (Thompson et al., 1997; Stoll et al., 2000) and accumulation of proline, carbohydrates and other compatible solutes (Maestri et al., 1995; Sanchez et al., 1998; Hassan et al., 2003; Mingo et al., 2004), in response to soil drying. In line with this, Zegbe-Dominguez et al. (2003) have suggested that the increase in TSSC in the DI and PRD tomato fruits could be attributed to a lower fruit water content or higher rate of conversion of starch to sugars. Therefore, it is also possible that such water deficit stress-induced changes in biochemical constituents might have improved the quality of coffee beans from PRD and NDI plants compared to those harvested from WW treatments, although the concentration of these substances has not been measured in the course of the present study.

Materials and methods

Site description

The experiment was carried out at Jima Agricultural Research Center (JARC) of the Ethiopian Agricultural Research Organization (EARO), Ethiopia ($7^0$46' N, $36^0$0' E; elevation 1753m). The center receives an average annual rainfall of about 1530mm with monthly mean maximum and minimum temperatures of 25.9^0C and 11.3^0C, respectively, and an average relative humidity of 67.2%. The dominant soils on the hill sides and hill tops, and at the bottom of the hills in the research center have been classified as Eutric Nitosols and Chromic Cambisol, respectively (IAR, 1978).

Plant materials

A young (six-year-old) coffee stand of cultivar F-59 with a uniform management and growth performance of individual trees was selected in the research campus of JARC. Cultivar F-59 is a widely adaptable and high yielding type and commonly used as one of the best parental lines in Arabica coffee hybrid development program in the country. The stand was planted at 2.0m x 2.0m spacing between individual trees, and had been weeded at an interval of a month and fertilized with 150g of diammonium phosphate (DAP) and 100g of urea per tree every year.

Plot arrangement

A meter deep and 30cm wide ditch was dug in a rectangular form around the root system of each coffee tree. It was just one meter away from the base of the main stem of the trees. A plastic sheet was buried in the ditch to isolate the root system of each tree. Besides, the root system of each tree was further divided in to two equal parts by digging a similar ditch and burring plastic sheet in the ditch running along the diameter of the tree canopy from one end to the other end of the main ditch surrounding the whole root system of the tree. The soil surface of each half of the root system of a tree was separately covered by a similar plastic sheet that was buried in the ditch to prevent entrance of water from one part of the root system to the other, as well as from external sources. Eight trees were maintained in each irrigation treatment and the plots were arranged in randomized complete block design (RCBD) with four replications.

Irrigation treatment

Two deficit irrigation techniques: partial root zone drying (PRD) with alternate watering and drying of half of the root system and normal deficit irrigation (NDI) with even irrigation on whole roots (both sides of the root system) were studied along with a well-watered (WW) control treatment. Initially, irrigation was applied to a sufficient amount (nearly to field capacity, FC) to induce uniform flowering in each plot when the soil moisture content at 30 cm depth (comprising over 62% of the lateral or feeder roots) declined to less than 35% of the FC. Then, water was applied to both sides of the root system of the WW plot to FC level, while half of the irrigation water used in the WW plot was applied to both sides of the root system in the NDI and to one side of the root system in the PRD treatment during each irrigation application. In the PRD practice the wet side of the root system was allowed to dry and the dry side re-watered when the soil moisture content at 30cm depth declined below 35% of the FC. The amount of water applied to each treatment was determined based on the soil moisture level in the control plot before each irrigation application.

Measurement of water relations

Soil moisture content (SMC) was measured every week at a depth of 30cm from the surface using both volumetric (soil moisture probe TRIME-FM, Field Measurement Device P3, Germany) and gravimetric methods. Measurements were taken at 50cm distance from the main stem of each sampled tree. The SMC was measured for both sides of the root system of two randomly selected plants from each treatment before irrigation. Leaf relative water content (RWC) was also measured at weekly intervals using fully expanded leaves sampled from the third or fourth node from the apex of younger plageotropic branches. After measuring the fresh weight (FW) of leaves right after abscission, the petiole of each leaf was immersed in distilled water in a glass box, which was immediately sealed, and leaves were allowed to float in a dark at 4^0C for 24hr to determine their turgid weights (TW). Then, the leaves were oven-dried at 80^0C to a constant weight (DW). After measuring dry weights, RWC (%) was calculated based on the relationship: RWC = 100 (FW-DW/TW-DW). Like RWC, stomatal conductance (g_s) was also measured at weekly intervals at noon hours (between 11:00 and 13:00) on the same leaves right before abscising for RWC determination. Stomatal conductance was determined with a diffusive porometer (AP-4, Delta T Devices Ltd., Cambridge UK).

Crop yield and yield components

Crop yield was estimated based on fruit count per tree and actual fresh cherry weight harvested from each tree in a plot at the end of the cropping season. Besides number of fruits per tree, other yield components, such as number of fruits per branch were also counted using six primary branches (two from each canopy strata: bottom, middle and top position) of two randomly selected trees from each plot.

Irrigation water use efficiency

Irrigation water use efficiency (IWUE) was determined as total crop (fresh cherry) yield divided by gross irrigation water applied during the study period (Kang et al., 2001).

Coffee quality determination

Red, fully-ripe fruits were manually picked and processed in the wet (washed coffee) processing method. The wet parchment coffee was dried under shade to 10 – 12% moisture content and stored in a well ventilated coffee store with about 60% relative humidity at 20^0C. Then, it was hulled and three samples, each with 100g clean coffee, were taken from each plot and the beans were sorted by size using flat screen graders, visually inspected and evaluated for raw quality (shape and make, color and odor, accounting for 40% of the total coffee quality). A sample roaster (Probat welke, Von Gimborn Gmbhan Co. KG) was first heated to about 160^0C and green coffee beans were put in the roasting cylinder and roasted for 10 minutes until the final temperature reached 240 ^{0}C. Eight gram of the medium roast was ground using roasted coffee sample grinder and put into a clean standard porcelain cup with 160 ml capacity. Fresh boiled water was poured over the ground coffee up to about half of the cup was filled. The contents of the cup were stirred to ensure a complete infusion of the ground coffee and the cup was filled to full capacity with boiled water. Then, the cup was left for about three minutes, allowing the coffee to brew and the grounds to settle either at the bottom or float to the top. The floating grounds were skimmed off and the cup was left to cool down to a palatable temperature. A spoon full of the brew was tasted for sensory evaluation and determination of its liquor characteristics (acidity, body and overall flavor), accounting for 60% of the total coffee quality. The cup taste was carried out by a panel of three liquorers, well-trained in the field and who have a long experience in the art and have acquired a memory of flavors.

Statistical analysis

The data were subjected to analysis of variance (ANOVA) and tested for significance using Least Significant Differences (LSD) by PC-SAS software (SAS Institute, Cary, NC, 2001).

Conclusion

Results of the present study showed that soil drying or deficit irrigation during the reproductive phase decreased marketable crop yield by adversely affecting plant water relations (leaf RWC and g_s) and the growth of potential yield components. On the other hand, it was observed that the overall raw and liquor or cup quality of coffee substantially improved without significant yield losses by deficit irrigation particularly with the PRD practice. Results of the present work also show that PRD is an effective and a feasible irrigation strategy, which can save irrigation water by 50%, increase IWUE and maintain crop yield. Hence, PRD appears to be more advantageous than NDI for coffee production particularly in areas of recurrent water shortage and prolonged drought periods.

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