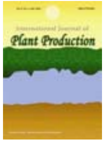

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Evapotranspiration and yield of okra as affected by partial root-zone furrow irrigation

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Abstract

Partial root-zone drying or partial root-zone irrigation is a newly proposed water saving technique which may improve water use efficiency and nutrient uptake by a crop without affecting its yield. A study was conducted to investigate the response of furrow-irrigated okra to partial root zone drying in relation to crop-evapotranspiration (ETc), vegetative growth, yield, and nutrient use efficiency in a sandy loam soil. The experiment was conducted during December-March with three furrow irrigation strategies: alternate partial root-zone irrigation (APRI), fixed partial root-zone irrigation (FPRI), and full root-zone irrigation (FRI). Two levels of irrigation: 25% available soil moisture depletion (ASMD) and 50% ASMD were imposed under each furrow treatment. The plant vegetative growth was significantly ($P<0.05$) higher in FRI, whereas the pod yield was more in APRI. Lower depletion soil water treatment produced higher vegetative growth and yield. However, APRI at 50% ASMD resulted in highest irrigation water use efficiency (IWUE) for pod yield, and FPRI at 25% ASMD resulted in highest IWUE for total biomass. The maximum ETc was observed under FRI, followed by APRI. The crop co-efficient (Kc) values of 0.38, 0.74, 0.98 and 0.49 may be used in initial growth stage, mid growth stage, final growth stage, and maturity stage of okra, respectively, to estimate the volume of irrigation water under APRI. Partial factor productivity for the nutrients (N, P and K) followed the similar trend as pod yield. Root biomass of the crop was more in FPRI, where as total root length was more in APRI. The higher root length with finer roots, in conjunction with better nutrients availability in soil produced the higher nutrients content in leaves and pods of alternate partially irrigated plants. Overall, these results reveal that the application of optimum quantity of water through APRI at 50% ASMD could impose desirable water stress on okra plants, improving their fruit yield and quality, without producing higher vegetative growth.

Keywords: Okra; Partial root-zone irrigation; Crop coefficient; Root morphology; Irrigation water use efficiency.

Introduction

Water availability is the major constraint to crop production in different parts of the world. Due to water demand for rapid industrialization and high population growth, the share of water in agriculture is going to be reduced in the coming decades. The further scarcity of irrigation water for crop production, therefore, should be checked for sustaining the food supply through efficient water conservation and management practices even in high rainfall areas (Panda et al., 2004). Moreover, the harvest per every drop of irrigation water should be enhanced while considering the best water use efficiency associated with any crop.

Okra (*Abelmoschus esculentus* L. Moench.) is one of the important vegetables grown throughout the tropics and warmer parts of the world, where water availability is the major constraint to crop production (Tiwari et al., 1998). The crop is commonly grown with irrigation in dry season. India is the topmost country, producing 4.18 million tones of okra annually which is around 70% of global okra production (FAO, 2008). Okra has a great scope in world trade.

Eastern India (Assam, West Bengal, Jharkhand, Orissa, Chhattisgarh and Eastern Uttar Pradesh) is the major hub of okra production in the country (NHB, 2010). Sowing of okra seeds with the residual soil moisture of lands in post-rainy season (November-December) is a common agricultural practice in this region. Short supply of soil moisture and nutrients in any stage of the crop growth cycle reduces productivity. Moreover, limited fresh water availability and ground-water pollution with salinity and nitrate in this region restricts the irrigation water supply to post-rainy season crops. Thus, it is utmost essential to use the ground-water judiciously, adopting efficient irrigation strategy to sustain the crop productivity, as well as to irrigate more lands with existing water resources.

Furrow is the widely adopted method of irrigation in okra. After 20 to 25 days of germination of seeds, ridge formation, and supply of irrigation water through furrows between each row is a common irrigation method practiced worldwide in okra cultivation. The non-scientific irrigation scheduling under furrow method creates a substantial loss of water and nutrients in fields, resulting in low yield, and sub-optimum water use efficiency and nutrients use efficiency of crops (Michael, 1973). Moreover, this problem becomes more acute in sandy and sandy loam soils, where deep percolation of water is very high (Behera and Panda, 2009).

Partial root-zone irrigation (PRI) under furrow irrigation is a deficit irrigation strategy in which only part of the root system is exposed to watering, while the rest part is left in drying soil. PRI has been found as a potential water saving technique over full root-zone irrigation, without affecting the yield and yield attributes of various crops in water scarce environments (Prabhakar and Srinivas, 1995; Ramlan and Nwokeocha, 2000; Singh and Murthy, 2001; Kang et al., 2001; Kirda et al., 2004; Liu et al., 2006; Patanèa et al., 2011). Water and nutrients losses through deep percolation may be a cause for low water and nutrient use efficiency under FRI. Achieving higher water use efficiency in any crop can be possible by enhancing yield and/or reducing the water losses through deep percolation and evaporation from the field. Under PRI, the reduction of percolation and evaporation of water is expected from partially wetted soil surface. Moreover, low leaf-transpiration takes place through controlled closure of stomata under alternate partial root zone irrigation (Ahmadi et al., 2010; Sepaskhah and Ahmadi, 2010). Higher nutrient use efficiency can be achieved through reducing the losses through deep percolation and proper nutrient distribution in root-zone.

Quantification of crop-evapotranspiration (ET_c) in different growth stages of a crop is a pre-requisite for efficient irrigation scheduling. ET_c of a crop grown in any region depends upon the management practices including irrigation. The soil moisture content and its spatial distribution in root-zone significantly affect the ET_c. The ET_c can be determined either empirically by adopting various standard methods (Doorenbos and Pruitt, 1977; Allen et al., 1998) with the help of crop-coefficient (K_c) values, or can be measured using lysimeter and/or field water balance. As the values of ET_c and K_c of a crop depend on growth stages, management practices, and environmental factors of a region, their measurement is more accurate than their estimation through empirical models. Where, the lysimeter is not available, determination of ET_c and K_c values using field water balance method is suggested, as both the methods are based on water balance studies in root zone of plants (Prihar and Sandhu, 1987; Bandyopadhyay and Mallick, 2003). The information on K_c values of okra is not mentioned either in FAO-24 (Doorenbos and Pruitt, 1977) and/or FAO-56 (Allen et al., 1998), which are considered as the important documents for guiding irrigation water management in crops grown in different agro-climatic regions. Thus, it is difficult to estimate ET_c values for okra in any region. Moreover, the estimated K_c value from measured ET_c values for okra under partial irrigation, even under full irrigation is very limited worldwide.

Water and nutrient management practices have greater impact on root morphology (Skinner et al., 1998). Root morphology governs the efficient utilization of water and nutrients for crop production. Earlier studies proved that partial root-zone irrigation had a significant effect on the root morphology and nitrogen uptake in field crops (Skinner et al., 1998; Wang et al., 2005). However, information on root morphology and plant nutrition in response to partial root-zone irrigation in vegetable crops including okra is scanty. The objectives of this study, therefore, were to a) determine ET_c and K_c values of okra under both full root-zone irrigation and partial root-zone irrigation b) investigate the effects of partial root-zone irrigation on root morphology, yield and nutrient use efficiency in okra in a sandy loam soil under sub-humid tropical climate of eastern India.

Materials and Methods

Experimental site

The experiment was carried out at the Central Research Station of Orissa University of Agriculture and Technology, Bhubaneswar, Orissa, India (20^0 15' N latitude, 85^0 52' E longitude and 25.9 m above mean sea level) during December-March for two seasons in 1996-1997 and 1997-1998. The mean annual rainfall of the region is 1300 mm, out of which 90% falls in between July and October. The data observed at meteorological station located at about 1 km away from experimental site indicates that the maximum air temperature, minimum air temperature, maximum RH, minimum RH, and daily class-A pan evaporation rate during the experimental period varied in the range 24.8-29.7 ^oC, 14.9-23.2 ^oC, 90-95%, 17-22% and 1.0-5.2 mm, respectively. No rainfall was recorded during the experimental period. The experimental soil has sandy loam texture (74.8% sand, 10.4% silt and 14.8% clay), with bulk density 1.68 g cm^{-3} and pH 7.3. The gravimetric soil water content at field capacity (-0.033 MPa) and permanent wilt point (-1.50 MPa) is 12.8% and 3.6%, respectively. The chemical properties of the soil were pH 6.8, EC 0.64 dS m^{-1}, cation exchange capacity 7.2 cmol, organic carbon 6.8 g kg^{-1}, available-nitrogen, phosphorous and potassium as 72, 10 and 47 mg kg^{-1} soil, respectively. Ground-water level remained at a depth of about 60 m below ground surface during the study. Both the soil and irrigation water were free from salinity and alkalinity.

Experimental design

The okra cultivar grown under the experiment was 'Vijaya', an Indo-American hybrid. A standard seed rate of 10 kg ha^{-1} was used for the experiment. The seeds were sown at a row spacing of 0.50 m, and plant spacing of 0.25 m in each plot. Each replicated plot accommodated total 150 plants in 6 rows.

The experimental layout was a randomized complete block, split-plot design. The six treatments were comprised of factorial combinations of three irrigation methods: alternate partial root-zone irrigation (APRI), fixed partial root-zone irrigation (FPRI) and full root-zone irrigation (FRI), and two different irrigation scheduling: 25% available soil moisture depletion (I_1), 25% ASMD and 50% ASMD (I_2). APRI means that one of the two neighboring furrows was alternately irrigated during consecutive watering. FPRI means that irrigation was fixed to one of the two neighbouring furrows. FRI was the conventional way where all furrows were irrigated during each watering. Under both PRI and FRI methods, the closed-end furrows were used. The irrigation methods were assigned to the main plot, while the irrigation schedules were in the subplots. Each treatment was replicated 4 times.

The experimental field plot of size 38.5×21 m was divided into four equal parts (8.5×21 m) to impose 4 replications, and each part further divided into three equal plots of size 8.5×6 m for main-plot treatment. Each main plot was again sub-divided in to two sub-plots (3.5×6 m) for applying two different irrigation scheduling. Buffer strips of 1.5 m wide were provided between each main plots and sub-plots to minimize the chances of water movement from one treatment to another. Moreover, each replicated treatment plot was surrounded by dikes of height 0.3 m to obstruct the surface runoff and a polythene sheet of 50 micron (0.05 mm) thickness was inserted to a depth of 0.6 m from soil surface at interior side of dikes to restrict the lateral seepage.

Irrigation scheduling and crop management practices

For establishment of seedlings during initial stages, 10 mm of water was applied uniformly by hand watering in all the treatments. Shallow furrows of size 0.40 m top width, 0.10 m bottom width and 0.25 m depth with 0.3% slope along the furrow length were opened between each row at 20 DAS.

Before imposing the irrigation treatments, the soil moisture in all plots were brought to field capacity by applying 13.0 mm irrigation water uniformly to each treatment.

The gravimetric soil moisture contents on percentage basis were determined for 0-0.45 m layer at 0.15 m vertical interval once in 2-days near the central furrows in each plot. One furrow for both FRI, and two furrows (one wetted and one dry) for both APRI and FPRI were taken for soil moisture measurement. The volumetric moisture contents were determined by multiplying gravimetric soil moisture values with bulk density of respective soil layers. The percent of available soil moisture depletion (ASMD) was estimated by the equation (Martin et al., 1990):

$$\text{available soil moisture depletion (\%)}=100\times\sum \frac{FC_i-\theta_i}{FC_i-PWP_i} \qquad (1)$$

Where n is the number of soil layers used in soil moisture sampling, FC_i is the volumetric soil moisture at field capacity for i^{th} layer, θ_i is the volumetric soil moisture in the i^{th} layer and PWP_i is the volumetric soil moisture at permanent wilting point for i^{th} layer. The soil moisture depletion at 0-0.15 m depth was taken at initial growth stage (IGS) of the crop (from germination to 25 DAS), whereas 0-0.30 m and 0-0.45 m depths were taken for mid growth stage (MGS: from 26 DAS to 55 DAS) and final growth stage (FGS: from 56 DAS to 90 DAS) and maturity stage (MAS: from 91 DAS to 110 DAS), respectively. The IGS was considered from date of germination to 10% ground cover by the plants, MGS was from end of IGS to 70% ground cover, FGS was from end of MGS to full ground cover, and MAS was from end of FGS to final harvest, as suggested by Doorrenbos and Pruitt (1977). The differential depth considered for soil moisture observation to schedule irrigation was based on the actual effective root zone observed during various crop growth stages in the experimental field condition. Irrigation was applied as soon as the soil attends the required soil moisture depletion under different treatments. Water quantity applied each time in different irrigation treatments was computed using the following equation:

$$V_i=D\times A\times (FC_i-\theta_i) \qquad (2)$$

Where V_i is the volume of irrigation water (m^3), D is the depth of effective root zone (m), A is the area to be irrigated (m^2), FC_i is the field capacity of i^{th} layer (volume basis), θ_i is the pre-defined soil moisture content of i^{th} layer before irrigation (volume basis). The values of FC and θ are in fraction. Further, A was calculated based on the equation (Michael, 1973):

$$A=N\times W\times L \tag{3}$$

Where N is the number of wetted furrows, W is the width of each furrow (m) and L is the row length (m). The number of wetted furrow in case of APRI and FPRI was half of that in FRI method. The depth of irrigation under APRI and FPRI was estimated by dividing the volume of irrigation (m^3) by surface area of the plot (m^2). The quantities of irrigation water supplied to different irrigation treatments were regulated through water meters and gate valves. The flexible pipes made up of poly vinyl chloride (PVC) were used to convey the irrigation water from pump outlet to experimental plots.

Each experimental plot received the standard fertilizer doses of 50 kg N, 50 kg P_2O_5 and 50 kg K_2O ha^{-1} prior to seed sowing, and 50 kg N ha^{-1} in two equal splits at 40 and 70 days after sowing (DAS). Plant protection measures against diseases and pests were done following the recommendations given for the crop in this region.

Measurements and analysis

Crop evapotranspiration (ET_c) was estimated from water balance equation (Ahmed and Mishra, 1987) as:

$$ET_c=E_R + I + C_p - D_p - R_f \pm \Delta S \tag{4}$$

Where, E_R is effective rainfall, I is depth of irrigation water (mm), C_p is contribution through capillary rise from ground-water (mm), D_p is deep percolation loss (mm), R_f is surface water runoff (mm), and ΔS is change in soil moisture storage in root zone between two consecutive samplings (mm). Four tensiometers were placed at 0.15 m, 0.30 m, 0.45 m and 0.60 m soil depths near to central plants in one replicated plot per treatment to determine the water potential gradient. As precise amount of water was applied in each irrigation to bring the soil moisture in effective root zone to field capacity, D_p was observed negligible. C_p was ignored as the ground-water depth was below 60 m throughout the crop growing season. As D_p was negligible and E_R, C_p and R_f were nil, the eq. (4) reduces to the following form to calculate Etc:

$$ET_c=I \pm \Delta S \tag{5}$$

Crop coefficient (K_c) was computed as the ratio of ET_c to reference evapotranspiration (ET_0=pan coefficient×class-A pan evaporation), as suggested by Doorenbos and Pruitt (1977). Pan coefficient was taken as 0.8 for the crop growing seasons.

Six plants in central rows of each sub-plot were tagged for growth, yield, and root observations. The vegetative growth (plant height, stem diameter, number of branches, number of leaves), and yield parameters (pod number, pod length, weight per pod, pod yield) of the tagged plants in each plot were recorded. The total pod yield per hectare in different treatments was estimated considering the mean yield per unit area obtained from 0.75 m^2 area of replicated plots.

The weight of total dry biomass (TDB), which includes the dry weights of shoot and root, was recorded at final harvest. The shoot (leaf, stem, branch and pod) portion of all the tagged plants was recorded after drying in an oven at 65 ^oC to a constant weight. However, the dry weight of pod was determined after each (9 times) harvesting.

For root biomass quantification, a trench was dug up to 0.6 m depth at a distance of 0.25 m surrounding the plants, and the plants along with the soil were lifted carefully. Later the roots were separated from soil and other residues by gentle washing under a flow of swirling water in a washing unit. After thorough washing, fibrous roots were separated from tap root. The length of the tap root was measured and put in an oven for dry weight quantification. Fibrous root length was estimated by modifying the method suggested by Habib (1988). The roots were separated based on the diameter determined by 'Vernier' calliper with 0.001 m division. Long roots having different thickness were cut in different pieces, and divided accordingly to their thickness.

In order to measure the root length, roots were divided into four categories: L_1 (> 2 mm diameter), L_2 (1-2 mm diameter), L_3 (1-0.5 mm diameter), and L_4 (< 0.5 mm diameter). The length of 30 randomly selected roots (A) was measured using a ruler in each category. This root sample was subsequently dried in an oven to a constant weight and finally, the dried weight (B) was taken. The rest of the roots in this category were also dried and weighed (C) for calculating the total weight of the root. Total root weight (W) was determined as:

$$W=B+C \quad (6)$$

A factor (F) was derived by dividing the length of 30 roots by its dry weight:

$$F=A/B \quad (7)$$

The factor 'F' was multiplied with total dry weight of the root (W) to find the length of the root (L_1) in this category:

$$L_1 = FW \tag{8}$$

The same procedure was repeated for the roots in different categories. Finally the length obtained for different categories were added up to get the total length (L) of the roots:

$$L = L_1 + L_2 + L_3 + L_4 \tag{9}$$

The total dry weight (*W*) of roots was also estimated by adding up the root dry weight in each category:

$$W = W_1 + W_2 + W_3 + W_4 \tag{10}$$

Volume of each root sample was calculated considering a cylindrical form of the roots, and the total root volume was determined by adding the root volume of all root samples. Morphology of root was studied by estimating specific root length (SRL, root length per unit root weight) and root fineness (RF, root length per unit root volume), as suggested by Ryser and Lambers (1995). The plants having higher SRL and RF values are assumed to have higher water and nutrients acquisition ability in a particular environment.

Soil samples were collected from 0-0.2 m, 0.2-0.4 m and 0.4-0.6 m soil layers, at the sites located at a distance of 0.10 m, 0.20 m and 0.30 m from the plant stem both along and across the crop row. The sampling was done at beginning (November) and end (June) of the experiment in both the years. Three plots from each treatment were taken for soil sampling. Each soil sample was analysed for available nutrients (N, P and K), by following standard procedures (Tandon, 1995). The depth wise mean values of available nutrients were calculated.

The leaves and pods of the experimental plants were collected, and dried at 65 ^{o}C for 48 hours in an oven. Leaf (from 3th-4th branch from bottom of plant) sampling was done at 10 days after flowering and pod analysis was done for all harvested pods. The dried samples were powdered homogeneously and analysed for total N, P and K, by following standard procedures (Tandon, 1995).

Irrigation water use efficiency for pod yield ($IWUE_{pod\ yield}$) was worked out as the ratio of total weight of pod yield to total irrigation water applied, whereas irrigation water use efficiency for total biomass ($IWUE_{biomass}$) was the ratio of total weight of biomass of plants to total irrigation water applied.

The partial factor productivity (PFP), one of the indices commonly used to describe nutrient use efficiency of a crop, was defined as the ratio of pod yield to the nutrient applied (Olk et al., 1999).

Statistical analysis

Data generated for all the parameters were subjected to analysis of variance (ANOVA) and least significant difference at 5% probability level ($LSD_{0.05}$) was obtained according to the methods described by Gomez and Gomez (1984).

Results and Discussion

Irrigation requirement

The imposed treatments influenced the number of irrigation, and quantity of water applied under various treatments (Table 1). The number of irrigation decreased with increasing soil water depletion from 25% ASMD to 50% ASMD, irrespective of furrow treatment. However, more number of irrigation was applied under APRI (8-20) than FPRI (7-17) and FRI (5-15), due to higher moisture depletion rate from wetted soil volume under the former method in comparison to latter ones. The higher moisture depletion under APRI and FPRI over FRI was due to increased water extraction rate by plants from partially wetted soil volume. The similar trend of water extraction by maize plants from wetted soil volume was observed by Kang et al. (2000).

Table 1. Irrigation water applied to okra under various furrow irrigation strategies*.

Treatments		Irrigation		
		Number	Depth (mm)	Volume (m^3 ha^{-1})
APRI	I_1	20	211.5	2115.6
	I_2	8	181.5	1815.2
FPRI	I_1	17	184.6	1846.7
	I_2	7	163.8	1638.3
FRI	I_1	15	246.7	2467.6
	I_2	5	220.9	2209.5

* Mean of 1996-1997 and 1997-1998.

APRI: Alternate partial root-zone irrigation, FPRI: Fixed partial root-zone irrigation, FRI: Full root-zone irrigation, I_1: Irrigation at 25% available soil depletion (ASMD), I_2: Irrigation at 50% ASMD.

The quantities of irrigation water applied under APRI and FPRI were 1815.2-2115.6 and 1638.3-1846.7 m^3 ha^{-1}, as compared with 2209.5-2467.6 m^3 ha^{-1} under FRI (Table 1). However, in spite of half number irrigated furrows under both APRI and FPRI that of under FRI treatments, the water required under the former treatments was more than 50% of that required under latter treatment. This happened due to more frequent irrigation under APRI and FPRI treatments. Earlier studies also indicated that the water applied under APRI reduced by 40% in capsicum (Hegde, 1989), 39-42% in cauliflower (Prabhakar and Srinivas, 1995) and 33% in brinjal (Singh and Murthy, 2001) over FRI system. The volume of water applied decreased with increasing soil water depletion from 25% ASMD to 50% ASMD, irrespective of furrow treatment.

Crop evapotranspiration (ET_c) and crop-coefficient (K_c)

The magnitude of ET_c in different growth stages of okra under FRI (0.52-4.77 mm day^{-1}) was higher than that under APRI (0.46-4.29 mm day^{-1}) and FPRI (0.46-3.89 mm day^{-1}), in corresponding irrigation regimes (Table 2). The higher ET_c in FRI was caused by higher transpiration of crop under increased water supply, coupled with more evaporation from fully wetted soil surface under FRI treatment over other treatments. Moreover, changing irrigation sides under APRI might cause abscisic acid (ABA) formation in roots and its consequent translocation from root to shoot reduced stomatal conductance and transpiration rate of leaves (Ahmadi et al., 2010). The highest ET_c value was observed in FGS of plants, followed by MGS, whereas the minimum value was in IGS. The higher atmospheric evaporative demand (4.2-4.8 mm day^{-1}), and the maximum plant growth during FGS caused the higher ET_c in this stage. The ET_c was higher under irrigation at 25% ASMD than at 50% ASMD, indicating the higher ET of the crop under higher soil moisture content maintained under frequent irrigation. However, the reduction of irrigation water depth over ET_c (ΔS) was higher in FPRI (47.55-49.90 mm) and APRI (38.85-39.25 mm) treatments than that in FRI (32.00-37.70 mm), in corresponding irrigation regimes (Table 2). The higher ΔS value in FPRI and APRI was due to the higher use of soil moisture storage under soil water deficit condition in these treatments. The total ET_c value followed the same trend of volume of irrigation water applied under different irrigation treatments.

Table 2. Crop-evapotranspiration (ET_c) and crop coefficient (K_c) of okra as affected by furrow irrigation strategies*.

Treatments		ET_c (mm)					ΔS	K_c			
		IGS	MGS	FGS	MAS	Total	(mm)	IGS	MGS	FGS	MAT
APRI	I_1	12.50 (0.50)	45.30 (1.51)	150.15 (4.29)	42.40 (2.12)	250.35	38.85	0.42	0.76	1.17	0.55
	I_2	11.50 (0.46)	44.10 (1.47)	127.05 (3.63)	38.10 (1.90)	220.75	39.25	0.38	0.74	0.98	0.49
FPRI	I_1	12.00 (0.48)	44.40 (1.48)	136.15 (3.89)	39.60 (1.98)	232.15	47.55	0.40	0.74	1.06	0.52
	I_2	11.50 (0.46)	43.20 (1.44)	123.20 (3.52)	35.80 (1.79)	213.70	49.90	0.38	0.72	0.95	0.47
FRI	I_1	14.25 (0.57)	51.30 (1.71)	166.95 (4.77)	46.20 (2.31)	278.70	32.00	0.48	0.86	1.29	0.60
	I_2	13.00 (0.52)	47.10 (1.57)	154.70 (4.42)	43.80 (2.19)	258.60	37.70	0.43	0.79	1.20	0.57

* Mean of 1996-1997 and 1997-1998.

IGP: Initial growth stage, MGP: Mid growth stage, FGP: Final growth stage, MAS: Maturity stage.

Values in parenthesis ( ) is daily ET_c value (mm day^{-1}), ΔD: difference between ET_c and depth of irrigation water applied.

The values of K_c followed the similar trend of ET_c, under different irrigation treatments during different growth stages (Table 2). The minimum and maximum K_c values in FRI treatment was 0.43-0.48 and 1.20-1.29, respectively, whereas these values were 0.38-0.42 and 0.98-1.17 in APRI, and 0.38-0.40 and 0.95-1.06 in FPRI. The higher K_c value was obtained at FGS of plants in FRI with 25% ASMD, due to higher ET_c in this treatment.

Root morphology

The root weight, root length, specific root length (SRL), and root fineness (RF) of the plants in different treatments are presented (Table 3). The weight and length of tap roots was insignificantly (P>0.05) affected by irrigation. However, FRI produced the plants with significantly higher root weight (2.977-3.199 g) compared with FPRI (2.670-2.921 g), and APRI (2.724-3.058 g). The frequent irrigation (at 25% ASMD) produced more root weight, irrespective of furrow irrigation treatment. The plants in APRI treatment produced higher root length (16.6-18.9 m). The root length under different irrigation treatments increased with increase in ASMD from 25%

to 50%, indicating the effect of soil water deficit on increasing root length of the plants. The higher root length at 50% ASMD was probably caused by osmotic adjustment and prolonging root cell expansion under mild water stress in this treatment (Jupp and Newman, 1987). It was also observed that when root elongation is decreased by soil water stress at 50% ASMD, root weight increased, probably due to suberization of roots under this treatment (Kramer and Boyer, 1995). Suberization is the deposition of suberin (a waxy substance found highly hydrophobic) on the wall of plant cells. The higher SRL was observed in APRI (6.09-6.18 m g^{-1}) than FRI (4.77-5.03 m g^{-1}) and FPRI (3.83-4.04 m g^{-1}). Root finesses, which is an indicator of finer roots in a root sample was observed higher in APRI treatment (2.75-3.01 mm mm^{-3}), followed by FRI (2.46-2.60 mm mm^{-3}). This reflects that plants under APRI could produce thinner roots, which are essential for better water and nutrients accusation by them.

Table 3. Effect of furrow irrigation strategies on root morphology of okra*.

Treatments		Tap root		Fibrous root			
		Length (m)	Weight (g)	Weight (g)	Length (m)	SRL (m g^{-1})	RF (mm mm^{-3})
+APRI	I_1	0.42	5.671	2.724	16.6	6.09	2.75(6030.91)#
	I_2	0.44	6.584	3.058	18.9	6.18	3.01(6274.01)
#FPRI	I_1	0.38	5.320	2.670	10.8	4.04	1.81 (5956.78)
	I_2	0.40	6.601	2.921	11.2	3.83	1.87 (5998.53)
*FRI	I_1	0.41	5.654	2.977	14.2	4.77	2.46 (5783.76)
	I_2	0.43	5.891	3.199	16.1	5.03	2.60 (6198.39)
$LSD_{0.05}$	F	ns	ns	0.04	0.31	0.08	0.03 (103.45)
	I	ns	ns	0.02	0.33	0.05	0.07 (98.71)
	F×I	ns	ns	0.15	0.41	0.34	0.09 (107.50)

* Mean of 1996-1997 and 1997-1998.

SRL: Specific root length, RF: Root fineness, ns: not significant.

\# Data presented in parenthesis ( ) is mean fibrous root volume (mm^3);

F: Furrow treatment; I: irrigation level, F×I: Interaction of furrow treatment and irrigation level.

Changes in available nutrients in soil

The magnitudes of changes in available nutrients (N, P and K) at 0-0.20 m, 0.20-0.40 m and 0.40-0.60 m soil showed an increasing trend under various treatments (Table 4). This is due to application of fertilizers during crop growing season. However, the increase is more under FPRI compared to other treatments. This indicated the low uptake of nutrients by plants under FPRI. Moreover, the better availability of plant nutrients in 0.40 m upper soil under APRI was probably facilitated by optimum soil-water, coupled with lower nutrients leaching from this soil layer under this treatment. The increase in available-N, P and K at both 0-0.2 m and 0.2-0.4 m soil was higher at higher level of water application. The higher nutrients availability in effective root-zone of the plants under APRI indicated a greater efficacy of fertilizer application, and suggests some further studies to optimize the fertilizer doses for okra cultivation under this irrigation method. The incremental available-N, P and K in 0.4-0.6 soil layer showed a higher improvement under FRI over partially-irrigated plots. The higher increase in available N, P and K at 0.4-0.6 m soil under FRI was probably caused by higher rate of deposition of nutrients that leached out from top 0.4 m soil over the combination of plant uptake and losses (leaching, denitrification) of such nutrients from this soil layer (Tafteh and Sepaskhah, 2012). This reflects some scope of curtailment of N, P and K-based fertilizer doses applied under APRI over that recommended for full root-irrigated okra plants.

Table 4. Changes in available N, P and K concentration in different soil layers under various irrigation treatments in okra*.

Soil depth (m)	Treatments						#$LSD_{0.05}$
	25% ASMD			50% ASMD			
	APRI	FPRI	FRI	APRI	FPRI	FRI	
N ($mg\ kg^{-1}$ soil)							
0-0.2	+9.0	+15.0	+7.0	+7.5	+12.5	+5.4	1.2, 0.6, 1.4
0.2-0.4	+8.0	+7.5	+8.7	+6.2	+5.7	+5.9	0.8, 0.4, 0.9
0.4-0.6	+4.7	+0.6	+9.4	+3.2	+0.1	+6.4	0.6, 0.2, 0.7
P ($mg\ kg^{-1}$ soil)							
0-0.2	+0.9	+1.0	+0.8	+1.0	+1.2	0.4	0.2, 0.2, 0.4
0.2-0.4	+0.6	+0.4	+0.8	+0.4	+0.3	0.2	0.1, 0.04, 0.3
0.4-0.6	+0.1	+0.1	+0.2	+0.2	-0.2	0.1	0.08, 0.1, 0.2
K ($mg\ kg^{-1}$ soil)							
0-0.2	+8.9	+9.5	+5.5	+6.0	+4.7	3.7	1.0, 0.4, 1.2
0.2-0.4	+6.4	+4.3	+6.7	+3.4	+1.9	3.9	0.6, 0.2, 1.0
0.4-0.6	+3.9	+0.4	+5.1	+1.7	+0.2	2.4	0.4, 0.1, 0.7

* Mean of 1996-1997 and 1997-1998.

Data presented in first, second and third positions are for furrow treatment (F), irrigation (I), and interaction of furrow treatment and irrigation (F×I), respectively.

Nutrient composition of leaf and pod

Nutrient (N, P and K) concentration showed a differential response to irrigation treatments (Table 5). APRI produced the higher concentrations of N, P and K in both leaf and pod compared to that with fully-irrigated plants. The higher leaf nutrients was caused by higher plant uptake with increased availability of such nutrients in soil coupled with efficient rooting (long and fine) of alternately partial-irrigated plants. In spite of higher nutrients availability in soil under FPRI, the nutrients acquisition by the plants under FPRI was lower than FRI. This was due to lower uptake of such nutrients from drying side of the root zone under FPRI, suggesting some modulation of the fertilizer application method under FPRI for better nutrients uptake. The concentrations of leaf N, P and K decreased with increase in soil water deficit from 25% ASMD to 50% ASMD. The nutrient concentration and total nutrients contents of pods showed the similar response as leafs. Overall, the higher nutrients uptake by plants under APRI produced higher use efficiency of such nutrients in the plants (Ahmadi et al., 2011).

Table 5. Leaf and pod nutrients (N, P and K) concentration in okra under different irrigation treatments*.

Plant component	Nutrients (%)	Treatments						#$LSD_{0.05}$
		25% ASMD			50% ASMD			
		APRI	FPRI	FRI	APRI	FPRI	FRI	
Leaf	N	3.86	2.33	3.72	3.46	1.93	3.20	0.4, 0.09, 1.0
	P	0.29	0.27	0.35	0.18	0.09	0.23	0.1, 0.08, 0.7
	K	1.91	0.98	1.83	1.44	0.62	1.35	0.4, 0.2, 0.5
Pod	N	3.47	2.31	3.38	3.08	1.64	2.97	0.5, 0.2, 0.8
	P	0.48	0.41	0.53	0.37	0.31	0.51	0.2, 0.06, 0.7
	K	2.38	1.68	2.13	1.92	0.95	1.80	0.4, 0.1, 0.6

* Mean of 1996-1997 and 1997-1998.

Data presented in first, second and third positions are for furrow treatment (F), irrigation (I), and interaction of furrow treatment and irrigation (F×I), respectively.

Vegetative growth

A differential response of plant height, stem diameter, number of leaves and branches per plant to irrigation was observed (Table 6). The FRI produced significantly higher plant height (0.603-0.710 m), stem diameter

(20.5-22.0 mm) and number of branches per plant (3.4-3.9) than that produced under APRI (0.523-0.678 m plant height, 15.6-17.8 mm stem diameter, 3.1-3.4 number of branch) and FPRI (0.501-0.643 m plant height, 14.8-15.2 mm stem diameter, 2.6-3.0 number of branches). The superior vegetative growth of plants observed in FRI was probably caused by increased metabolic activity of plants under higher available soil moisture in root zone under this treatment over other treatments. However, the magnitudes of plant growth parameters decreased with increase in ASMD from 25% to 50% under each furrow irrigation treatment. These results corroborate the findings of Hegde (1989) in capsicum, and Sepaskhah and Kamgar Haghighi (1997) in sugar beet. However, no significant response of number of leaves per plant to irrigation treatments was observed.

Table 6. Effect of furrow irrigation strategies on vegetative growth of okra*.

Treatments		Plant height (m)	Stem diameter (mm)	Branch (number $plant^{-1}$)	Leaf (number $plant^{-1}$)
APRI	I_1	0.678	17.8	3.4	20.7
	I_2	0.523	15.6	3.1	19.6
FPRI	I_1	0.643	15.2	3.0	18.1
	I_2	0.501	14.8	2.6	15.7
FRI	I_1	0.710	22.0	3.9	32.2
	I_2	0.603	20.5	3.4	23.6
$LSD_{0.05}$	F	0.07	1.80	0.08	ns
	I	0.03	0.70	0.02	ns
	F×I	0.12	1.84	0.09	ns

* Mean of 1996-1997 and 1997-1998.

Total dry matter partitioning

The more quantity of total dried biomass (TDB) under FRI (81.35-89.50 g $plant^{-1}$) indicates that the plants in this treatment synthesized more photosynthates than other treatments (Table 7). Dry matter partitioning between vegetative and reproductive parts of a crop causes variations in yield. In FRI, the vegetative growth components (stem, branch, leaf) contributed the higher portion (60.07-64.10%) of the TDB in comparison to that in FPRI (34.85-42.18%) and APRI (25.56-41.29%) in okra. However, the yield component (pod) in APRI produced the highest per cent (48.84-52.86%) of TDB, followed by FPRI (47.68-51.09%). The highest dry weight of root was observed in FRI treatment (8.63-10.09 g plant^{-1}), followed by APRI (8.39-9.64 g plant^{-1}). The root contributed 10.13-14.04% towards TDB in FPRI, compared with 9.86-12.91% in APRI and 8.67-11.17% in FRI. The contribution of TDB to vegetative parts decreased with increase in soil water depletion from 25% ASMD to 50% ASMD, whereas the reverse trend was observed with reproductive part (yield). The increased translocation of dry matter towards reproductive parts might have caused an increase in dry weight of reproductive parts at higher soil water depletion where the plants were more dehydrated than other treatments (Westgate and Boyer, 1985).

Table 7. Total dry biomass (g plant^{-1}) of okra plants as affected by furrow irrigation*.

Treatments		Vegetative components+	Yield component	Root	Total
APRI	I_1	35.13	41.56	8.39	85.08
	I_2	25.56	39.46	9.64	74.66
FPRI	I_1	33.26	37.60	7.99	78.85
	I_2	23.63	34.64	9.52	67.79
FRI	I_1	57.35	23.48	8.63	89.46
	I_2	49.45	22.81	10.09	82.35
$LSD_{0.05}$	F	1.45	4.71	0.18	3.45
	I	0.92	1.22	0.07	2.44
	F×I	1.77	6.32	0.22	4.87

* Mean of 1996-1997 and 1997-1998.
+ Vegetative growth components include stem, branches and leafs.

Yield parameters

The number of pods per plant, and pod quality such as length and weight per pod were significantly influenced by irrigation treatments (Table 8). The number of pods per plant in FRI (17.20-17.91) was significantly higher than APRI (14.91-15.32) and FPRI (12.81-12.97), in corresponding irrigation regimes. However, APRI and FPRI produced the pods with higher length (2.7-25.7% more) and higher weight (6.5-27.4% more) than that produced in FRI treatment. The increased number of pods with FRI could be a reason for smaller fruits in this treatment. Earlier studies comparing APRI with FRI also demonstrated that APRI produced better fruit quality in cauliflower (Prabhakar and Srinivas, 1995), capsicum (Hegde, 1989), hot pepper (Kang et al., 2001) and tomato (Kirda et al., 2004) than that under FRI.

The total pod yield was decreased with increase in ASMD from 25% to 50%, under all irrigation methods (Table 8). The treatment APRI produced 4.1-6.0% higher pod yield over FRI, in corresponding irrigation regimes, even with 14.3-17.9% deficit irrigation water supply under former treatment. The higher yield under APRI was probably caused by: (1) better availability of nutrients with optimum soil moisture content, fewer weeds, and the higher nutrients up-take by more fine roots under this treatment and (2) higher percentage of phtosynthates investment by the plants towards reproductive growth (fruiting) than the vegetative growth in this treatment over that under FRI. The beneficial effect of APRI on yield improvement of different vegetables was also reported by earlier investigators (Hegde, 1989; Prabhakar and Srinivas, 1995; Sepaskhah and Kamgar Haghighi, 1997; Kang et al., 2001; Kirda et al., 2004). However, FPRI was inferior to FRI in relation to pod yield. This is probably due to the reason that the continuous exposure of roots to dry soil may cause the anatomical changes in roots e.g. higher suberization of epidermis, and collapse of cortex of roots, along with loss of succulent secondary roots (North and Nobel, 1991; Kang et al., 2000). With these changes, the plant might not be able to extract the required amount of nutrients from soil, which resulted in less productivity.

Irrigation water use efficiency and partial factor productivity

A significantly higher IWUE in term of pod yield ($IWUE_{pod\ yield}$) was observed in APRI (8.41-9.18 kg m^{-3}) than that in FPRI (6.98-7.85 kg m^{-3}) and FRI (6.79-7.25 kg m^{-3}), in corresponding irrigation regimes (Table 8). The highest $IWUE_{pod\ yield}$ occurred in APRI was attributed to higher yield using comparatively less irrigation water under this treatment over other treatments. The improvement in IWUE in response to APRI over FRI was earlier reported in capsicum (Hegde, 1989), cauliflower (Prabhakar and Srinivas, 1995), and brinjal (Singh and Murthy, 2001). The $IWUE_{pod\ yield}$ increased with increase in ASMD from 25% to 50% in all irrigation methods. However, IWUE for TDB ($IWUE_{biomass}$) was superior in FPRI treatment than APRI and FRI. The maximum $IWUE_{biomass}$ in FPRI was due to higher dry matter portioning towards vegetative growth, with least amount of irrigation water consumption under this treatment. The partial factor productivity followed the similar trend of pod yield under different irrigation treatments (Table 8).

Table 8. Yield parameters, irrigation water use efficiency (IWUE), and partial factor productivity (kg pod yield per kg nutrient applied) of okra under various furrow irrigation strategies*.

Treatments		Yield parameters				IWUE		+PFP		
		Pod number plant^{-1}	Pod length (mm)	Weight pod^{-1} (g)	Pod yield (kg ha^{-1})	$IWUE_{pod\ yield}$ (kg m^{-3})	$IWUE_{biomass}$ (kg m^{-3})	N	P	K
APRI	I_1	14.91	84.09	16.70	17785.60	8.41	2.87	177.85	355.70	355.70
	I_2	15.32	91.82	15.23	16665.07	9.18	2.93	166.65	333.30	333.30
FPRI	I_1	12.81	69.79	14.08	12883.27	6.98	3.05	128.83	257.66	257.66
	I_2	12.97	78.50	13.88	12858.90	7.85	2.95	128.58	257.16	257.16
FRI	I_1	17.91	67.98	13.11	16771.53	6.79	2.59	167.71	335.42	335.42
	I_2	17.20	73.02	13.03	16008.38	7.25	2.66	160.08	320.16	320.16
$LSD_{0.05}$	F	0.32	5.25	0.85	650.59	0.52	0.24	9.87	6.96	7.55
	I	0.11	2.14	0.33	76.52	0.34	0.08	6.59	4.24	5.16
	F×I	0.46	5.96	1.23	723.71	0.76	0.31	12.37	8.59	9.88

*Mean of 1996-1997 and 1997-1998.

+PFP: Partial factor productivity.

Conclusions

Alternate partial root-zone irrigation is found as a productive and potential water saving technique in okra cultivation. The yield enhancement of 4% with better quality pods, using 18% less irrigation water in alternate partial root-zone irrigation at 50% available soil moisture depletion resulted in 27% improvement in irrigation water use efficiency in this treatment over full root-zone irrigation. The higher nutrient content of leaves and pods are associated with better nutrients availability in soil coupled with higher root length and finer roots of plants under alternate partial root-zone irrigation. On the basis of these results, it could be inferred that the adoption of APRI at 50% ASMD would be a better option for okra cultivation with less water in sandy loam soil of eastern India, and elsewhere having similar agro-climatic conditions of the study site. This will help to reduce the shortage of irrigation water, resulting in higher crop production. The further studies related to optimizing the quantities of NPK-based fertilizers applied under alternate partial root-zone irrigation system for okra cultivation is suggested.

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