water

MDPI

Article

Effects of Partial Root-Zone Irrigation on the Water Use Efficiency and Root Water and Nitrate Uptake of Corn

Rahman Barideh, Sina Besharat *, Mohamad Morteza and Vahid Rezaverdinejad

Water Engineering Department, Urmia University, Urmia 165, Iran; rahman.barideh@gmail.com (R.B.); mamad.morteza@gmail.com (M.M.); v.verdinejad@urmia.ac.ir (V.R.)

* Correspondence: s.besharat@urmia.ac.ir; Tel.: +98-914-443-2427

Received: 24 November 2017; Accepted: 15 March 2018; Published: 23 April 2018

check for updates

Abstract: Due to water shortages and the increasing need for food in recent years, the optimization of water consumption parameters, fertilizers, and food production are essential and a priority. The aim of this study is to investigate the effect of partial root-zone irrigation (PRI) methods on corn plant characteristics. The study also tried to measure the water use efficiency (WUE) of corn in pot cultivation and provide the best method of management in the fields of irrigation and fertigation. For this purpose, three irrigation methods, including alternate partial root-zone irrigation (APRI), fixed partial root-zone irrigation (FPRI), and conventional irrigation (CI) were studied in pots, and completely randomized blocks with eight replications were carried out. Each pot was evenly separated with plastic sheets into two sub-parts of equal volume, between which no water exchange occurred. The water content of the field capacity was calculated by the weighting method. The water requirement was provided daily, equal to 95% of the field capacity water content. Parameters including shoot and root dry weight, nitrate (N) uptake, the remaining nitrate in the soil, leaf area index, and WUE during the growing season were measured and compared. According to the results, the amount of saved water using the FPRI and APRI methods compared to the CI method were 28% and 32%, respectively. The highest and lowest WUE were observed as equal to 4.88 and 3.82 g/L using the APRI and CI methods, respectively, among which the CI method had the highest yield according to the amount of utilized water. Given the statistical examinations, there was no significant difference in the nitrate level of plants between CI and APRI, and the lowest uptake was observed in FPRI. Finally, considering indicators of yield production and WUE simultaneously, the APRI method was selected as the best method of management.

Keywords: leaf area index; N use efficiency; Time domain reflectometry (TDR); root density; water content distribution

1. Introduction

One of the indicators used to evaluate irrigation management is water use efficiency (WUE). In the current situation, due to the water shortage around the world, yield production is not the sole consideration, and WUE has gained importance in recent years. About two decades after the first deficit irrigation (DI), a new method known as partial root-zone irrigation (PRI) has been developed. PRI is a new method of irrigation which improves WUE without a significant decrease in the yield production [1–4]. In this method, the root zone is divided into two equal parts, so that in each period of irrigation only one of those two regions is irrigated and the other side remains dry. In other words, only 50% of the root zone receives the required water and the other half of the root zone remains stressed. This method is used in furrow irrigation as alternate furrow irrigation (AFI) and fixed furrow irrigation (FFI) methods. In AFI, one of two neighboring furrows is alternately irrigated during each irrigation event. In FFI, one of the two neighboring furrows is permanently skipped for watering [2,5].

Soil evaporation causes 20% water loss and if this method is used, then due to the reduced wet surface, evaporation losses decline by 50% [6]. Stone et al. [7] and Zhang et al. [8] reported that in AFI and FFI, evaporation decreased by 50% compared to conventional irrigation.

Many scholars believe that DI stimulates plant roots to interact more and uptake more water to the plant in drought conditions, thus under PRI, one part of the root is under high stress and cannot provide water for the plant. The root transmits some signals to the other parts of plant that leads to a reduction in transpiration and an increase in the roots' water uptake in areas where water content is more accessible [2,6,9].

The PRI method results indicate increased abscisic acid and thus increases WUE [10]. In most varieties of corn (*Zea mays* L.), PRI has shown great potential in saving water and increasing WUE [3,10].

Devkota et al. [11] in their research into soil salinity management on raised beds with different furrow irrigation modes in salt-affected land by three irrigation methods—including conventional furrow irrigation (CFI), alternate furrow irrigation (AFI), and fixed furrow irrigation (FFI)—stated that the AFI and FFI methods used 31% and 32% less water than the conventional furrow irrigation method, respectively. Additionally, the yield of product under the FFI method was 96%, equal to 984 kg more than under the CFI method and 64% more than under the AFI method [11]. Siyal et al. [5] studied the effects of the AFI and CFI methods on the water productivity of okra. The amount of water consumption under the AFI and CFI methods was 248 and 497 mm, respectively, and they reported that the AFI method only reduced yield production by 7.3% compared to the FFI method [5]. The PRI irrigation method with increased radial infiltration reduces deep percolation [12], resulting in increasing efficiency.

Several studies have shown that the PRI method caused soil nitrate uptake to increase and residual nitrate in the soil to decrease compared to the FFI method [6,13,14]. Kirda et al. [3] reported that the PRI method led to better efficiency of nitrogen fertilizer on corn yield in fields with lower soil nitrogen compared to full irrigation and normal deficit irrigation [3]. Wang et al. [15] proposed that at least two factors might have contributed to the improved crop N uptake under PRI treatment; namely an enlarged root system for nitrate (N) uptake and an increased N availability in the soil [16].

According to studies conducted in the field of PRI, satisfactory results have been achieved, but the effect of PRI management on the nitrate uptake, nitrate residues in the soil, and leaching potential have not been considered. The results of previous studies, based on soil nitrate and water uptake, were analyzed separately. The results of the analyses confirmed the PRI based on WUE, water efficiency, and nitrate leaching. The aim of this study was to investigate the effect of PRI on nitrate uptake and WUE in pot cultivation and provide the best method of management in the field of irrigation and fertigation. In the suggested management approaches, in addition to maintaining crop production per unit area and the proper WUE, the amount of nitrate leaching under the root zone should be minimized. Also, the best growing conditions for plants should be provided in order to optimize water consumption and other parameters.

2. Materials and Methods

2.1. Study Area

The present research was carried out in the research area of the Faculty of Agriculture, Urmia University, West Azerbaijan, Iran, in an outdoor and open area, equipped with a synoptic automatic weather station. The area has the geographical coordinates of 45 degrees east, 37 degrees north, and an altitude of 1332 m above sea level. Due to cold and wet winters and hot and relatively wet summers, this area is considered to have a Mediterranean climate. The average precipitation in the area is 323 mm/year. Experiments were conducted in a natural area. The average relative humidity and temperature of days and nights were 60% and 30%, and 27 and 18 °C, respectively.

2.2. Soil Properties

The measurements were applied to spatial pots. The pots were made from polyvinyl chloride (PVC) material (Figure 1), and the soil in the pots was added layer by layer without compaction. Field soil was used in the pots. The bulk density of the soil was controlled at different levels of the experiments, and the texture of the soil was measured using a hydrometer method. In this method, first 300 g of soil need to be dried and then 50 cc of 5% calgon and 300 cc water should be added and mixed. The solution should be 1 L at the end. Finally, the hydrometer (density reader) was read at standard intervals to determine the clay, silt, and sand percentages. Soil bulk density, field capacity and saturation water content were calculated by direct measurement, and the residual water content in the soil was calculated using the Rosetta model. In order to determine the amount of nutrients in the soil, soil analysis was conducted and the amount of CO_3^{2-}, NO_3^-, K and P were determined to be 0.98%, 0.1%, 0.00142% and 0.0457%, respectively (Table 1).

Table 1. Properties of the soil in the pots.

%			Soil Texture	ρ_b. (g/cm^3)	f (%)	θ_{fc}. (cm^3/cm^3)	θ_r (cm^3/cm^3)	%			
Sand	**Silt**	**Clay**						**P**	**K**	**Co_3^{-2}**	**No_3^-**
21	31	48	clay	1.3	49	0.385	0.099	0.0457	0.00142	0.98	0.1

2.3. Preparation of Media

Corn plants were planted on 21 June 2015 in 24 pots with specific dimensions (28 cm in diameter at the top edge, 24 cm in diameter at the bottom, 26 cm in depth). The experiment was carried out as a randomized complete design with three irrigation treatments and eight replications. During the experiments, 0.123 g KH_2PO_4 kg^{-1} of soil was added. Each pot was evenly separated with plastic sheets into two sub-parts of equal volume, between which no water exchange occurred. Each sub-part of the pot was filled with 8.7 kg dry soil, and a 3 cm thick layer of gravel was placed in the bottom for natural drainage. In order to avoid surface evaporation and crusting of the soil surface during irrigation practices, in every sub-part, a PVC pipe with a length of 15.5 cm was used. The PVC pipes were vertically put deep into the soil to lead the irrigation water to the bottom layer of soil and to avoid surface evaporation. This helped to irrigate each part carefully (Figure 1).

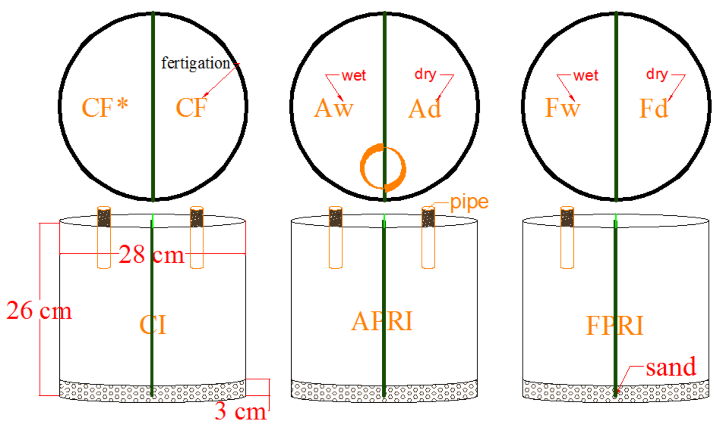

Figure 1. The picture of examined pots with an impenetrable middle layer, Conventional irrigation (CI), Alternate partial root-zone irrigation (APRI), Fixed partial root zone irrigation (FPRI).

Both sub-parts of the pots were irrigated before planting to 95% field capacity water content. In each pot three seeds were planted in the middle of the two sub-parts and after the germination of the seeds, the one with better distribution was kept in the pot and the other two seeds were removed.

This stage came after 14 days of planting in the pots. The cardinal temperature for the base and upper sections were 10 and 30 °C, respectively. The number of growing degree days was calculated as 207.9 °C.

2.4. Irrigation Methods

Conventional irrigation (CI): In this method, both parts of the roots were irrigated and this is shown by the CI symbol. In this method, the fertilizer was applied only to the root part, which is indicated by the CF symbol and other parts of the roots where fertilizer was not applied are indicated by the CF* symbol (Figure 1).

Alternate partial root-zone irrigation (APRI): In this method, one part of the pot was irrigated, while the other part was irrigated during the other irrigation cycle. In this treatment, a sub-part of the pot was irrigated in the first phase, which is indicated by the Aw symbol, while the dry part of root is indicated by the Ad symbol. It should be noted that under this method, an irrigation period of 10 days was applied. For example, the Aw part was irrigated for 10 days and the Ad remained dry while Ad irrigation was applied for 10 days and the Aw part remained dry (Figure 1).

Fixed partial root zone irrigation (FPRI): Under this method, during the growing season only one sub-part was irrigated and the other sub-part remained dry. The irrigated part is indicated by the Fw symbol while the dry part is indicated by the Fd symbol (Figure 1).

2.5. Measuring Nitrate and Water Content

A total of 36 days after the germination of the corn seed, 0.2 g N in the form of urea fertilizer, along with 500 mL water per kg of soil were added to the soil of each sub-part of the pot. On day 42, irrigation methods were applied. In all treatments, fertilization was the same. The study duration and measurement of indicators were related to the period of 40 days. The trial time from planting to harvest time was 82 days. During this time, water content was kept between 65% and 95% of field capacity. Irrigation was applied when the soil water content was determined to be in the lower limits. Irrigation was applied for all treatments at a specified time and soil water content was measured by TDR. A WET (Water content, Electric conductivity, Temperature) sensor (delta T) was used, and the sensor was installed at a depth of 15 cm into the soil. Irrigation water was calculated and applied for each treatment due to differences in moisture content up to 95% of field capacity. Finally, the amount of consumed water was recorded for each procedure daily and on the basis of volume.

Under all the management methods, three pots were randomly selected after periods of 42, 52, 62, 72, and 82 days and the corn was completely tested. The root and shoot of each plant sample were separated and the dry weight, wet weight, and nitrate content of each of the plant components were measured. Additionally, the leaf area index and residual nitrate in the soil were calculated. Plant tissues were dried at a constant temperature of 70 °C. Lastly, the dry weight of different parts of the samples was recorded [13] and the nitrogen concentration of the dried samples was measured for treatment. The amount of nitrate in the soil and plant was measured using the Kjeldahl method [17], and then the leaf area index was calculated by scanning the leaf area and also using the FLAECHE software (Version 1.0.2, Canon, Tokyo, Japan). The leaves were gathered from different treatments and were scanned by a Canon scanner, and the images were analyzed by the software [18].

2.6. Statistical Analysis

Treatment means were compared for significant differences ($P_{0.05}$ level) using Duncan's multiple range test. SPSS software (V22.0, IBM: Armonk, NY, USA) was used for this purpose.

3. Results and Discussion

3.1. Water Consumption

The total amount of water consumption in various time intervals for all methods is shown in Table 2. The amount of water used under the APRI and FPRI methods until day 52 was similar, due to the similar irrigation method. However, after 52 days, due to the displacement of wet and dry parts in the APRI method, this process was different. In general, through the management of the APRI and FPRI methods, the water consumption amount reduced by 28% and 32% compared to the CI method. In the present research, due to the use of subsurface irrigation, evaporation from the soil surface was not intended for any of the methods. Hu et al. [13] also stated that the FPRI and APRI methods led to 33% and 29.5% decreases in water consumption, respectively, compared to the CI method [13]. The decrease in water consumption under the FPRI and APRI methods, which was approximately 30%, was due to the half irrigation of the planting area, and the fact that the root absorbed water only from some parts of the soil. In fact, FPRI and APRI are kinds of deficit irrigation methods.

Table 2. Amounts of total irrigated water (L pot^{-1}) during different periods for three irrigation methods.

Irrigation Method	0–47	0–52	0–57	0–62	0–82
CI	8.56 (100) [a]	10.17 (100)	12.20 (100)	13.34 (100)	15.97 (100)
FPRI	7.73 (90)	8.42 (83)	9.17 (75)	9.51 (71)	10.87 (68)
APRI	7.73 (90)	8.42 (83)	9.56 (78)	10.14 (76)	11.42 (72)

[a] Values are means (% of CI).

In Figure 2, the water content is shown for the different methods over 40 days. The reduction procedure of water content for the Fd part under the FPRI method was due to the lack of irrigation. However, due to daily irrigation, the Fw part had the best water content state. Under the APRI method, according to Figure 2, one can see that the Aw and Ad parts were irrigated over 10-day periods and that the water content reduction was lower than Fd, revealing better conditions for root growth. Under the APRI method, alternative watering was carried out, and the appropriate ventilation on both sides of the pot created better conditions for the root to grow. Under the FPRI method, due to more intense stress, abscisic acid was released, which hinders growth [9,19].

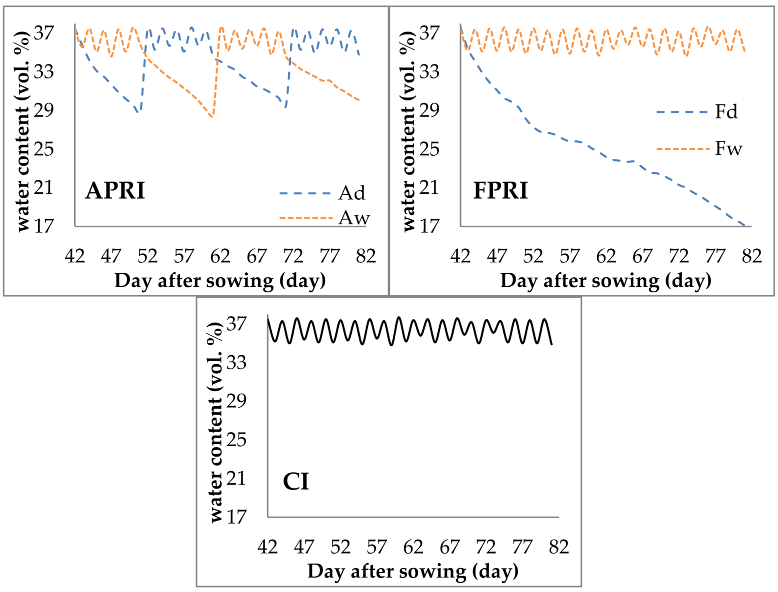

Figure 2. The soil water content data for each method during the test.

3.2. Shoot Dry Weight

In Table 3, it can be observed that before applying the irrigation methods (day 42), the amount of shoot dry weight in all three methods are close together, but after start of the experiment, the shoot dry weight of CI was higher than the other two treatments. The APRI and FPRI treatments had similar performance until day 42, but on day 52, irrigation of the Ad part in the APRI method led the plant roots to be in a better situation in terms of the available water content. Although a large amount of nitrate in the area was also provided for the plants, the other part of this root, which had not been irrigated in this period also had proper water content compared to the middle of this period, indicating the superiority of APRI to FPRI.

Table 3. The shoot dry weight in irrigation treatments (g).

Day	CI	FPRI	APRI
42	17.3 (100) [a]	17.32 (100)	17.26 (100)
52	26.25 (100)	24.3 (92)	24.1 (92)
62	33.13 (100)	27.2 (82)	30.7 (93)
72	39.95 (100)	30.6 (77)	36.1 (93)
82	46.4 (100)	31.7 (68)	41.9 (90)
Hu et al. [13]	43.37 (100)	31.49 (72)	34.79 (80)

[a] Values are means (% of CI).

As Table 3 shows, the growth conditions in CI were better than other treatments and the FPRI method was the most stressful treatment and in almost all periods had the lowest performance. The important thing is that the APRI treatment had only a 10% performance reduction compared to the CI treatment, but the FPRI treatment had 32% decreased performance compared to CI irrigation. The reason for this sharp reduction in performance could be related to the combined lack of water content and nitrate in the Fd. This part relates to the shoot dry weight, which is similar to the results of previous research, such as Wang et al. [9]. Considering the lack of water content and nitrogen uptake, it needs to be said that despite a decrease in shoot dry weight in the APRI and FPRI methods, the amount of WUE improved [4,9,16]. Siyal et al. [5] reported that AFI only reduced 7% of the product compared to the CI method [5]. The results obtained by Hu et al. [13] at the end of the experimental period are shown in Table 3, and they also show that the performance of dry shoot under the APRI and FPRI methods increased by 20% and 28%.

3.3. Root Dry Weight

According to Table 4, before applying irrigation techniques to all the sub-parts, the plants had almost equal root dry weight. Over time, no significant difference was observed in CI between the two sub-parts of the pots. In the FPRI method, the root dry weight in Fw was more than Fd due to their receiving water throughout the process and having proper conditions in terms of nitrate solubility. However, root growth continued in Fd and only its growth rate was reduced. The root dry weight in Fw had better performance compared to other sub-parts such as CF, CF*, Aw, and Ad, but due to the poor performance of other parts of the root in Fd, this treatment had a higher total low root dry weight than the other two treatments. As could be observed under the APRI method, in changing the irrigation from Aw to Ad, the root growth also periodically changed so that in each rotation the root growth was higher in each irrigation part. Finally, after 40 days of testing in the two sub-parts, APRI had almost equal performance.

Table 4. The root dry weight under the irrigation treatments (g).

Day	CI		FPRI		APRI	
	CF	**CF***	**Fd**	**Fw**	**Ab**	**Aa**
42	4.5	4.15	4.35	4.3	4.37	4.28
52	6.1	5.7	5.05	6.15	5.15	6.05
62	6.9	6.5	5.00	7.00	6.00	6.10
72	7.1	6.8	5.22	7.23	6.15	6.90
82	7.35	7.3	5.28	7.57	6.95	7.00
Total root dry weight	14.65(100)		12.85(88)		13.95(95)	

3.4. Variations of N Absorption from Different Root Zones

As can be concluded from Figure 3, the sub-treatment of Fw had the best performance in terms of nitrate uptake. The reasons for this were more root growth compared to other methods (Table 4), proper water content conditions in this part to aid absorption (Figure 2), and soil nitrate solution, resulting in increased nitrate uptake. Considering that the water content and the amount of nitrate in CF were similar to Fw, lower uptake and growth amounts were observed. This proves the accuracy of the conclusions of various studies, reporting that since one part of the root remained dry, more ABA acid was produced, leading to a reduction in transpiration and an increase in the absorption of nutrients [2,10,20,21].

As a result of the sharp drop in water content (Figure 2) Fd had the lowest uptake of nitrate (Figure 3). Overall, the performance of the FPRI treatment was worse than the other treatments, but the difference was not significant. The amount of nitrate in the roots under both the CI and APRI methods was almost equal, and a non-significant difference was observed.

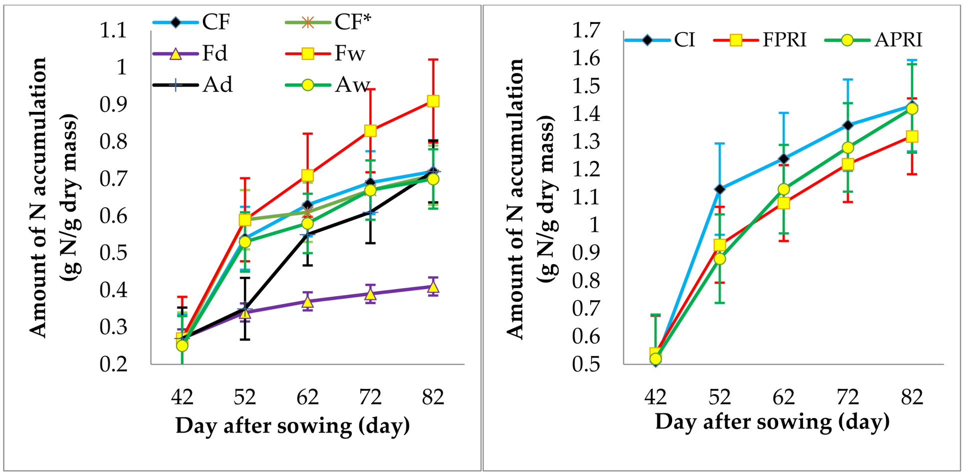

Figure 3. The amount of nitrate (N) accumulation in plant roots, the sub-treatments (**Left**) and treatments (**Right**).

3.5. Leaf Area Index

Leaf Area Index (LAI) is an expression of vegetative status in a plant that is a function of the amount of water content and nutrients. According to Figure 4, due to the conditions of growth being the same until day 42, the LAI index was equal for all three methods. The LAI index had the highest rate in the CI method and the lowest index was observed in the FPRI method, which illustrates the tensions applied to the plant compared to the CI and APRI methods. Based on the results, the APRI method is suggested for deficit irrigation. The most important result is that the amount of root water uptake from both sides in alternative methods puts the plant in a better situation. For the first 10 days of treatment, no difference was observed between APRI and FPRI, but after this the LAI in FPRI decreased significantly. This shows that the applied stress on LAI had a greater effect under this treatment.

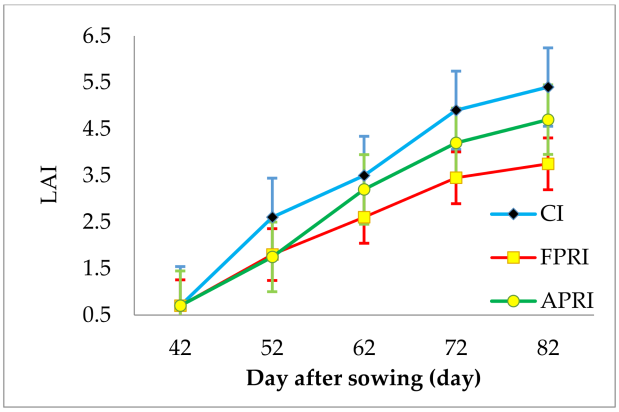

Figure 4. The leaf area index measured over 40 days (m^2/m^2).

3.6. Residual Soil Nitrate

As shown in Figure 5, at the beginning of irrigation treatments (day 42), the residual soil nitrate in each part of the root was equal. On day 52, the amount of residual nitrate in the soil was equal in all sub-treatments due to similar irrigation management. On day 62, two sub-treatments of Ad and Aw had equal amounts of soil nitrate uptake due to the amount of consumed water and identical growth conditions, hence the amount of nitrate in the soil remained equal. The amount of nitrate in the soil resulted in the least amount of soil nitrate in Fw and CF due to continuous water consumption and the highest absorption rate.

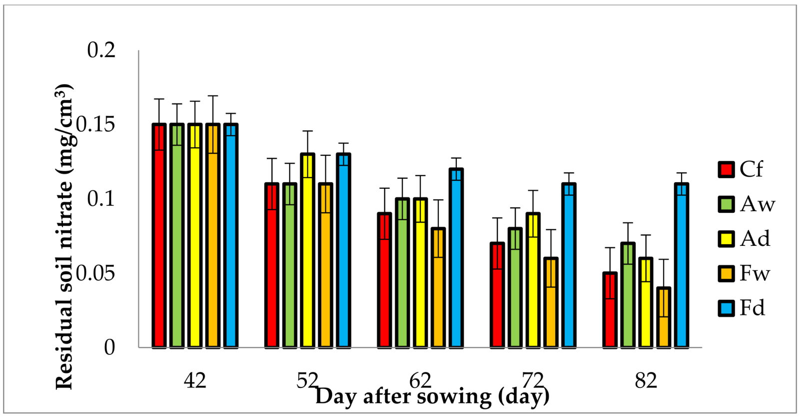

Figure 5. Compared residual nitrate in the soil under different types of irrigation management.

3.7. Water and N Use Efficiency

WUE is the best parameter for describing irrigation management in agriculture, representing a consensus regarding yield production and leading to the selection of preferred options in agriculture management. According to Table 5, APRI is the preferred option for this test in terms of WUE. FPRI has proper WUE, but in this method, the yield production is decreased significantly. In order to prevent the contamination of groundwater, nitrate leaching and to reduce the fertilization cost, a method should be selected that has the most efficient nitrate uptake (nitrate use efficiency: ratio of shoot dry weight to the amount of nitrate uptake by the plant). In this experiment, since there was no deep percolation of water and nitrate leaching, the CI method had the greatest nitrate use efficiency. Based on the results in Table 5, APRI also had relatively good performance, but the FPRI treatment, due to the lack of water content in half of the pot failed to take advantage of the sources of nitrates in the soil. A similar study was conducted by Hu et al. [13], those results are shown in Table 5. The increasing WUE procedure was similar in both studies, and the highest rate was obtained in APRI. Differences in nitrogen use efficiency and the root-to-shoot ratio in both studies could be due to the fertilization rate or environmental conditions such as temperature or net radiation. In the case of the root-to-shoot ratio in the FPRI method, it is obvious that as a consequence of the lack of water content, the shoot performance was poor. As a result, the root-to-shoot ratio obtained in the aforementioned treatment was greater than the two other treatments (Table 5). A similar study was conducted by Posadas et al. [19] and Wang et al. [22], in which the shoot weight rate under the PRI method decreased significantly, while in the root it did not decrease greatly. As a result, the ratio of root-to-shoot under PRI compared to the CI method shows larger amounts.

Table 5. Comparison of several parameters under different types of irrigation management.

Parameters	CI	FPRI	APRI	Hu et al. [13]		
				CI	FPRI	APRI
Water use efficiency (g dry mass/L water)	3.82 (61)	4.1 (44.56)	4.88 (55.72)	3.49	3.88	4.09
N use efficiency (%)	33.14	24.38	29.93	52.14	56.31	54.56
ratio of root to shoot (-)	0.32	0.41	0.33	0.25	0.29	0.29

3.8. Statistical Analysis

According to Table 6, the highest and lowest water consumption was observed in the CI and FPRI treatments. There were significant differences between shoot and root dry weight under the three methods and the maximum and minimum performances were exhibited under CI and FPRI, respectively. The highest WUE was related to the APRI method. Finally, the highest and lowest nitrate use efficiency was observed under the CI method and FPRI.

According to the data listed in Table 7, it can be seen that under different irrigation methods, there were significant differences in the measured parameters. To be clear, the PRI methods led to improved yield production and saved more water. In addition to improving crop WUE, recent studies on potatoes and tomatoes have demonstrated that PRI can improve plant N nutrition. In our study, N nutrients in plant tissues under the FPRI treatments were lower than under the CI treatment, and the amount of plant N nutrition under the APRI treatment and the CI treatment showed the same values [16,23]. According to the studies, PRI is one of the deficit irrigation methods which causes a minor decrease in yield. However, because of less irrigation water use (30%) the water use efficiency shows a significant increase compared to full irrigation. Abbasi et al. [24] stated that when the amount of irrigation water is less than 80% of the water requirement, nitrate leaching will not occur. In this study, the maximum change in the water requirement was 30% [16]. Mitchell et al. [23] reported that the AFI method increased nitrate uptake and decreased nitrate leaching .The effect of irrigation in this study was significant at 1% for all parameters except the ratio of root to shoot. Considering N in plants, the largest amount was observed under CI and APRI, and both of them showed a significant difference. However, the parameter of N in soil, which had the largest amount under FPRI showed a significant difference compared to the other two methods. The largest and the smallest amount of LAI was observed under the CI method and FPRI, respectively. The difference among all of the three treatments was significant. Also, our results showed that when compared to conventional whole root-zone irrigation, the two partial root-zone irrigations saved water in the plants by 28.4–31.9% during different treatment periods, confirming that PRI can reduce water consumption and enhance water use efficiency without much reduction in yield. These results are similar to the results of Kang et al. [21], Wang et al. [9]; Siyal et al. [5].

Table 6. Statistical comparison of the mean values of relevant characteristics of the product in each treatment.

Treatment	Water Consumption	Shoot Dry Weight	Root Dry Weight	N of Plant	N of Soil	LAI	Water Use Efficiency	N Use Efficiency	Ratio of Root to Shoot
CI	15.97 [a]	46.4 [a]	14.65 [a]	1.41 [a]	0.05 [b]	5.48 [a]	3.82 [c]	39.13 [a]	0.32 [a]
FPRI	10.87 [c]	31.7 [c]	12.85 [c]	1.32 [b]	0.11 [a]	3.82 [c]	4.1 [b]	28.56 [c]	12.95 [a]
APRI	11.42 [b]	41.9 [b]	13.85 [b]	1.41 [a]	0.06 [b]	4.73 [b]	4.88 [a]	35.72 [b]	0.33 [a]

[a,b,c]:Values followed by the same letter within columns are not significantly different according to the Duncan's multiple range test ($p < 0.05$).

Table 7. Analysis of variance related to the important characteristics measured in tests.

Source	df	Ms								
		Water Consumption	Shoot Dry Weight	Root Dry Weight	N of Plant	N of Soil	LAI	Water Use Efficiency	N Use Efficiency	Ratio of Root to Shoot
r	7	0.048 ns	0.01 ns	0.25 *	0.001 *	0.0002 ns	0.003 ns	0.001 ns	0.0012 ns	156.1 ns
irrigation	2	23.5 **	170 **	2.44 **	0.008 **	0.002 **	2.07 **	0.9 **	87 **	159.3 ns
E	4	0.01	0.02	0.01	0.0001	0.0001	0.02	0.009	0.001	157.2
CV		0.88	0.38	1	0.72	13.57	3.61	2.3	0.1	276.7

ns: indicates not significantly different and asterisks indicate significant different respectively, *: $p < 0.05$, **: $p < 0.01$.

4. Conclusions

In order to optimize the amount of water and fertilizer consumption and to study WUE in pot cultivation, the three different management methods of CI, FPRI and APRI were compared. Increased water uptake from each layer under PRI caused less water transfer to the lower layers and, therefore, reduced nitrate leaching potential. This irrigation method can be considered as a compromise between the DI and CI methods; this type of irrigation attempts to improve the amount of water and fertilizer consumption, as well as yield production. According to the results of the study, the APRI method can be considered the best method of irrigation management. In this management method, the product was at a desirable level in terms of WUE, N use efficiency, N leaching, yield production, and other measured parameters. As mentioned previously, the dry/wet cycles of soils under PRD can create soil organic N, thereby increasing the amount of mineral N available to the plants [16,22].

Based on the results of the research, new models can be applied to plant irrigation, and the plants can be monitored on different occasions during irrigation. The results can be analyzed to consider the best design. Having done this, soil and water management can be carried out without yield reduction. This can help achieve more efficient use of water and fertilizer in farming and help protect the environment. The use of PRI in irrigation causes a reduction in water use, enhancing both the quality and quantity of the yield by creating appropriate conditions of wetness and ventilation in the roots.

In summary, this study found that PRD irrigation enhanced root growth and stimulated soil organic N mineralization, and both might have contributed to the increased leaf N accumulation in maize plants. Accordingly, the irrigation technique might be promising for improving crop N nutrition in low-input organic farming systems where delayed mineralization of N from the organic fertilizers often limits crop yield. Thus, application of PRD irrigation in organically grown crops might increase soil mineral N availability, hence facilitating crop N uptake so that improved WUE and nitrogen use efficiency may be achieved simultaneously. This could result in an increased mineralization rate of soil organic N, provided that the appropriate conditions for PRD are created. The cycle of drying and wetting of soil under PRI could cause the "Birch effect", simulating the mineralization of soil organic N and thereby increasing the mineral N available to the plant [8,9,25,26].

This study indicated that partial root-zone irrigation reduced a possible N luxury uptake and increased N use efficiency. This was because reduced N supply and absorption from the dry zones of PRI might result in N stress in this zone, and thus induce plant adaptation to the nutrient stress [27,28]. However, the detailed mechanism involved requires further investigation.

In this experiment, completely controlled irrigation in separate parts of the root was carried out. Conducting measurements in bigger pots, in farm conditions, and comparing the results with the results of this experiment is suggested for future studies.

Acknowledgments: The authors are grateful for the support of Urmia University. We offer our sincere thanks to the farm irrigation managers of the University for their help in observing the experimental data. We are thankful for the work of many people in data collection and processing.

Author Contributions: Rahman Barideh conducted the data analysis, Sina Besharat was responsible for the idea of the study and writing of the manuscript, Mohamad Morteza provided information of the study area and Vahid Rezaverdinejad provided important advice on the concept of the methodology.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kaman, H.; Kirda, C.; Cetin, M.; Topcu, S. Salt accumulation in the root zones of tomato and cotton irrigated with partial root-drying technique. *Irrig. Drain.* **2006**, *55*, 533–544. [CrossRef]
2. Kang, S.; Liang, Z.; Pan, Y.; Shi, P.; Zhang, J. Alternate furrow irrigation for maize production in an arid area. *Agric. Water Manag.* **2000**, *45*, 267–274. [CrossRef]
3. Kirda, C.; Topcu, S.; Kaman, H.; Ulger, A.C.; Yazici, A.; Cetin, M.; Derici, M.R. Grain yield response and N-fertilizer recovery of maize under deficit irrigation. *Field Crop. Res.* **2005**, *93*, 132–141. [CrossRef]
4. Sepaskhah, A.R.; Hosseini, S.N. Effects of alternate furrow irrigation and nitrogen application rates on winter wheat (*Triticum aestivum* L.) yield, water-and nitrogen-use efficiencies. *Plant Prod. Sci.* **2008**, *11*, 250–259. [CrossRef]
5. Siyal, A.A.; Mashori, A.S.; Bristow, K.L.; Van Genuchten, M.T. Alternate furrow irrigation can radically improve water productivity of okra. *Agric. Water Manag.* **2016**, *173*, 55–60. [CrossRef]
6. Gheysari, M.; Mirlatifi, S.M.; Homaee, M.; Asadi, M.E.; Hoogenboom, G. Nitrate leaching in a silage maize field under different irrigation and nitrogen fertilizer rates. *Agric. Water Manag.* **2009**, *96*, 946–954. [CrossRef]
7. Stone, J.F.; Reeves, H.E.; Garton, J.E. Irrigation water conservation by using wide-spaced furrows. *Agric. Water Manag.* **1982**, *5*, 309–317. [CrossRef]
8. Zhang, B.; Li, F.M.; Huang, G.; Cheng, Z.Y.; Zhang, Y. Yield performance of spring wheat improved by regulated deficit irrigation in an arid area. *Agric. Water Manag.* **2006**, *79*, 28–42. [CrossRef]
9. Wang, Z.; Liu, F.; Kang, S.; Jensen, C.R. Alternate partial root-zone drying irrigation improves nitrogen nutrition in maize (*Zea mays* L.) leaves. *Env. Exp. Bot.* **2012**, *75*, 36–40. [CrossRef]
10. Liu, F.; Jensen, C.R.; Shahnazari, A.; Andersen, M.N.; Jacobsen, S.E. ABA regulated stomatal control and photosynthetic water use efficiency of potato (*Solanum tuberosum* L.) during progressive soil drying. *Plant Sci.* **2005**, *168*, 831–836. [CrossRef]
11. Devkota, M.; Gupta, R.K.; Martius, C.; Lamers, J.P.A.; Devkota, K.P.; Sayre, K.D.; Vlek, P.L.G. Soil salinity management on raised beds with different furrow irrigation modes in salt-affected lands. *Agric. Water Manag.* **2015**, *152*, 243–250. [CrossRef]
12. Ebrahimian, H.; Liaghat, A.; Parsinejad, M.; Playan, E.; Abbasi, F.; Navabian, M.; Lattore, B. Optimum design of alternate and conventional furrow fertigation to minimize nitrate loss. *J. Irrig. Drain. Eng.* **2013**, *139*, 911–921. [CrossRef]
13. Hu, T.; Kang, S.; Li, F.; Zhang, J. Effects of partial root-zone irrigation on the nitrogen absorption and utilization of maize. *Agric. Water Manag.* **2009**, *96*, 208–214. [CrossRef]
14. Shahnazari, A.; Liu, F.; Andersen, M.N.; Jacobsen, S.E.; Jensen, C.R. Effects of partial root-zone drying on yield, tuber size and water use efficiency in potato under field conditions. *Field Crop. Res.* **2007**, *100*, 117–124. [CrossRef]
15. Wang, H.; Liu, F.; Andersen, M.N.; Jensen, C.R. Comparative effects of partial root-zone drying and deficit irrigation on nitrogen uptake in potatoes (*Solanum tuberosum* L.). *Irrig. Sci.* **2009**, *27*, 443–448. [CrossRef]

16. Wang, Y.; Liu, F.; De Neergaard, A.D.; Jensen, L.S.; Luxhøi, J.; Jensen, C.R. Alternate partial root-zone irrigation induced dry/wet cycles of soils stimulate N mineralization and improve N nutrition in tomatoes. *Plant Soil* **2010**, *337*, 167–177. [CrossRef]
17. Kjeldahl, J. Neue Methode zur Bestimmung des Stickstoffs in organischen Körpern. *Z. Anal. Chem.* **1883**, *22*, 366–382. (In German) [CrossRef]
18. Kaur, G.; Din, S.; Brar, A.S.; Singh, D. Scanner image analysis to estimate leaf area. *Int. J. Comput. Appl.* **2014**, *107*, 5–10. [CrossRef]
19. Posadas, A. *Partial Root-Zone Drying: An Alternative Irrigation Management to Improve the Water Use Efficiency of Potato Crops*; International Potato Center: Lima, Peru, 2008.
20. Davies, W.J.; Zhang, J. Root signals and the regulation of growth and development of plants in drying soil. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1991**, *42*, 55–76. [CrossRef]
21. Kang, S.; Liang, Z.; Hu, W.; Zhang, J. Water use efficiency of controlled root-division alternate irrigation on maize plants. *Agric. Water Manag.* **1998**, *38*, 69–76. [CrossRef]
22. Wang, Y.; Liu, F.; Andersen, M.N.; Jensen, C.R. Improved plant nitrogen nutrition contributes to higher water use efficiency in tomatoes under alternate partial root-zone irrigation. *Funct. Plant Biol.* **2010**, *37*, 175–182. [CrossRef]
23. Mitchell, A.R.; Shock, C.C.; Perry, G.M. Alternating furrow irrigation to minimize nitrate leaching to grand water. In Proceedings of the Clean Water–Clean Environment–21st Century, Kansas City, MO, USA, 5–8 March 1995.
24. Abbasi, Y.; Liaghat, A.; Abbasi, F. Evaluation of nitrate deep leaching under maize furrow fertigation. *Water Soil* **2012**, *26*, 842–853.
25. Zegbe, J.A.; Serna-Pérez, A. Partial root-zone drying maintains fruit quality of 'Golden Delicious' apple at harvest and postharvest. *Sci. Hortic.* **2011**, *127*, 455–459. [CrossRef]
26. Xiang, S.R.; Doyle, A.; Holden, P.A.; Schimel, J.P. Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils. *Soil Biol. Biochem.* **2008**, *40*, 2281–2289. [CrossRef]
27. Robinson, D. The responses of plants to non-uniform supplies of nutrients. *New Phytol.* **1994**, *127*, 635–674. [CrossRef]
28. Liu, F.; Shahnazari, A.; Andersen, M.N.; Jacobsen, S.E.; Jensen, C.R. Physiological responses of potato (*Solanum tubersum* L.) to partial root-zone drying: ABA signaling, leaf gas exchange, and water use efficiency. *J. Exp. Bot.* **2006**, *57*, 3727–3735. [CrossRef] [PubMed]