Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2017) 41: 50-58
© TÜBİTAK
doi:10.3906/tar-1604-47

Effect of irrigation regimes on carbon isotope discrimination, yield and irrigation water productivity of wheat

Sema KALE[1,*], Bülent SÖNMEZ[2], Sevinç MADENOĞLU[2], Kadri AVAĞ[2], Ufuk TÜRKER[3], Gökhan ÇAYCI[4], Ali Cihat KÜTÜK[4]

[1]Department of Irrigation, Faculty of Agriculture, Süleyman Demirel University, Isparta, Turkey
[2]Soil, Fertilizer and Water Resources Central Research Institute, Ankara, Turkey
[3]Department of Agricultural Machinery, Faculty of Agriculture, Ankara University, Ankara, Turkey
[4]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Ankara University, Ankara, Turkey

Received: 10.04.2016 • **Accepted/Published Online:** 15.01.2017 • **Final Version:** 20.02.2017

Abstract: The present research study was carried out during the years 2009–2010 and 2010–2011 to identify the relationship between carbon isotope discrimination (Δ) of grain and leaf, yield of winter wheat, and irrigation water productivity (IWP) under different water conditions in a semiarid climate. The field experiments were conducted with four different irrigation treatments (I_1: rainfed: I_2: irrigate when calculated soil water depletion is 60 mm below field capacity (full irrigation); I_3: two irrigations maximum, one at tillering and another at grain filling; I_4: no irrigation after establishment until heading, after which irrigate when soil water depletion is 60 mm below field capacity). The leaf (ΔL) and the grain (ΔG) carbon isotope discriminations, biomass, and grain yield (GY) were measured in the experiments and the harvest index (HI) and IWP were calculated. At the end of the study, taking a 2-year average, GY and HI were found to be 3.35 t ha^{-1}, 4.53 t ha^{-1}, 4.13 t ha^{-1}, and 4.37 t ha^{-1} and 29%, 31%, 31%, and 32%, respectively, according to the treatments. The results showed a significant positive linear correlation between Δ and GY. These results highlight that grain Δ at the pre-anthesis stage could be beneficial for predicting yield under well-irrigated conditions. The highest IWP value was obtained from I_4 treatment. Δ-IWP and GY-IWP were negatively correlated. IWP can be indicated as an advantage in deciding about limited irrigation regimes for wheat production in arid areas. The results of the present study show that full irrigation treatment (I_2) could be recommended in areas with no water shortage conditions. Moreover, limited irrigation such as treatment I_4 at 4.8% level produced only optimum yield reduction and had the potential for saving approximately 50% of irrigation water.

Key words: Carbon isotope discrimination, irrigation water productivity, winter wheat

1. Introduction

One of the most important consequences of climate change, perhaps the most important, is its negative effect on water sources (Rosenzweig et al., 2004; Alcamo et al., 2007; Arnell et al., 2011; Iglesias and Garrote, 2015). Agriculture is the main consumer (75%–80%) of available water resources in many countries (Baris and Karadag, 2007). Generally, crop productivity where there is sufficient soil water is higher than in dry soil conditions (Misra et al., 2010). In semiarid regions such as Central Anatolia in Turkey water scarcity is a serious problem for sustainable crop production (Oweis and Ilbeyi, 2001). Efficient use of water by plants plays a crucial role especially in arid regions. Regulation of water productivity is particularly important in arid ecosystems where plants are sporadically exposed to water stress (Tanner and Sinclair, 1983). As reported by Molden et al. (2003), productivity of irrigation water can be evaluated at the plant, field, farm, system, and basin level. The irrigation water productivity at the field level is the ratio between evapotranspiration and total diverted irrigation water for crop production (Kijne et al., 2003).

In recent decades important progress has been made using isotopic techniques of water management in agriculture (Heng et al., 2005). Oxygen, hydrogen, carbon, and nitrogen abundance measurements in soil, water, and plant components can be useful in identifying the sources of water and nutrients used by plants (Bazza, 1993; IAEA, 2006). Several studies have shown that carbon isotope discrimination is highly correlated with plant water status (Xu et al., 2007; Misra et al., 2010; Wahbi and Shaaban, 2011).

Two parameters are currently used to characterize carbon isotope ratio in plants: carbon isotope composition (δ) and carbon isotope discrimination (Δ). Carbon isotope composition is calculated as $\delta^{13}C(\Delta) = ([R_{sample}/R_{reference} - 1] \times$

* Correspondence: semakale@sdu.edu.tr

1000), R being $^{13}C/^{12}C$ ratio and has negative values. Carbon isotope discrimination (Δ) is calculated as Δ (‰) = $[(\delta_a - \delta_p)/(1 + \delta_p)] \times 1000]$, where δ_p is the carbon isotope composition ($\delta^{13}C$) of the samples and δ_a, the $\delta^{13}C$ of the atmospheric CO_2, −8‰. Δ varies from −22‰ to −38‰ in C_3 plants and from −8‰ to −15‰ in C_4 plants (Yeh and Wang 2001).

The isotopic ratio of 13C to 12C in plant tissue is less than the isotopic ratio of 13C to 12C in the atmosphere, indicating that plants discriminate against 13C during photosynthesis (Merah et al., 2001). Therefore, carbon isotope discrimination provides an integrated measure of crop water use (Cregg and Zhang, 2000; Zhu et al., 2008). Methods used to determine carbon (13C/12C) isotopes are effective and safe methods to determine irrigation water productivity due to the relationship between water stresses (Farquhar and Richards, 1984; Ehdaie et al., 1991; Heng, 2012).

The objective of the present study was to evaluate the relationship between leaf and grain carbon isotope discrimination and yield of wheat and irrigation water productivity under different irrigation regimes.

2. Materials and methods

2.1. Materials

The experimental sites were located in the Ankara Murted Basin (39°57′N and 32°53′E) in the Central Anatolia region of Turkey (Figure 1). The experiment was conducted from October to July 2009–2010 and 2010–2011 at the Research Farm Station of the Soil, Fertilizer and Water Resources Central Research Institute.

The climate is characterized as semiarid in this region. Annual rainfall is about 350 mm and evaporation is 1300 mm. Daily weather data were recorded on an hourly basis from a meteorological station 50 m away from the experimental site. Daily maximum and minimum temperatures, precipitation, and ET_o references during the growing season are presented in Figure 2.

The soil of the experimental areas mostly ranges in texture from silty clay about 0.20 m thick lying on the surface with a layer of clay texture roughly 1.5 m below the surface. Some soil properties of the experimental site are presented in Table 1.

2.2. Methods

The experimental design was a completely randomized block design. The experiment consisted of four irrigation regimes with four replications giving a total of 16 plots: I_1: rainfed; I_2: irrigate when calculated soil water depletion is 60 mm below field capacity (full irrigation); I_3: maximum two irrigations, one at tillering and another at grain filling; I_4: no irrigation after establishment until heading, after which irrigation when soil water depletion is 60 mm below field capacity.

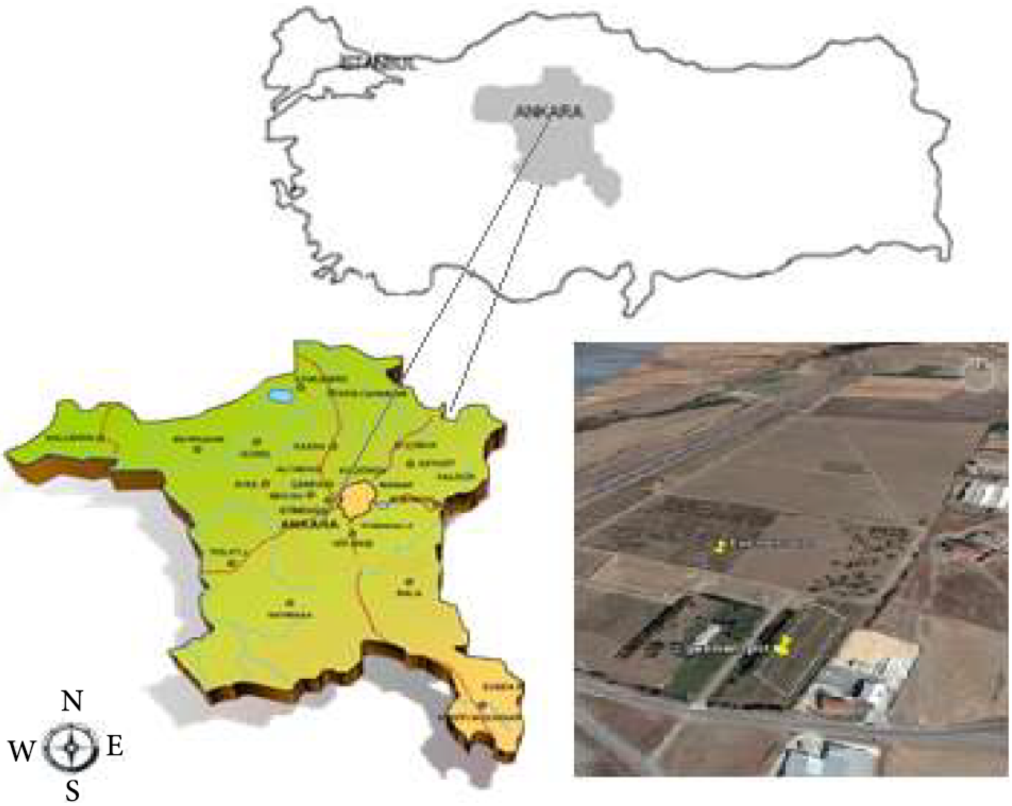

Figure 1. Field experimental site.

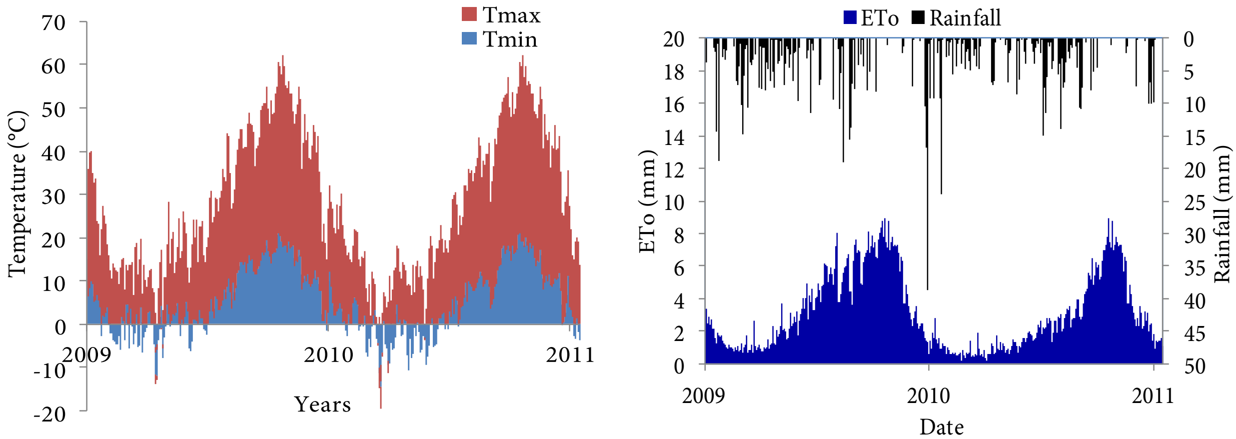

Figure 2. Daily max.–min. temperature, precipitation. and ET_o between 2009 and 2011.

Table 1. Some physical and chemical analysis results of experimental soils.

Depth	0–20 cm	20–40 cm	40–60 cm	60–80 cm	80–100 cm
pH	7.89	7.97	8.07	8.08	7.88
EC	1.019	0.72	0.685	0.655	0.65
CEC	35.62	36.14	33.2	32.56	31.88
ESP	1.45	1.29	1.31	1.37	1.45
OM	1.6	1.17	1.05	0.98	0.65
$CaCO_3$	14.11	13.74	14.11	14.48	15.6
N	0.14	0.12	0.07	0.06	0.04
K_2O	0.86	1.57	1.56	1.52	156.20
P_2O_5	0.068	0.010	0.009	0.006	0.52
FC	36.13	38.67	38.22	37.49	35.95
WP	20.67	20.99	20.06	20.07	18.79
γ_s	1.24	1.27	1.21	1.20	1.19
Texture	SiC	C	C	C	C

EC dSm^{-1}: Electrical conductivity, CEC: Cation Exchangeable Capacity (me 100 g^{-1}), ESP: Exchangeable Sodium Percentage (%), OM: Organic Matter (%), $CaCO_3$: Lime (%), N: Total nitrogen (%), K_2O: Potassium (t ha^{-1}), P_2O_5: Phosphorus (t ha^{-1}), FC: Field Capacity (vol.%), WP: Wilting Point (vol.%), γ_s: Bulk density (g cm^3), SiC: Silty Clay (%), C: Clay (%)

Plot dimensions were 3.5 m × 5 m = 17.5 m^2 for seeding and 1.2 m × 4 m = 4.8 m^2 for harvesting. Prior to wheat planting, all trial plots were precision leveled to zero-grade and plots were surrounded by soil bands and irrigated with surface irrigation. Commercial N fertilizers were applied (ammonium sulfate; 220 kg ha^{-1} before sowing (DOY; 263) + 350 kg ha^{-1} on 15 March (DOY; 71) + 175 kg ha^{-1} DAP) according to the soil fertility analysis results. Microelements were analyzed. Plant available microelements were as follows: Fe 5.66 mg kg^{-1}, Cu 2.34 mg kg^{-1}, Zn 0.76 mg kg^{-1}, and Mn 9.87 mg kg^{-1} at 0–30-cm soil depths. According to Lindsay and Norwell (1969), Fe, Cu, and Zn was sufficient but Mn level was slightly lower than the critical level (10 mg kg^{-1}). The *Bayraktar 2000* wheat variety was used as the trial crop. Wheat was planted around 20 October and harvested between 15 and 20 July. Postharvest grain and biomass yields were obtained from each plot and weighed. Harvest index (HI) values of the plots were calculated using the average yield and biomass values in respect of the treatments (HI = [Grain yield/ Biomass] × 100).

Soil volumetric moisture contents were monitored by neutron probe (CPN-503DR Hydroprobe) at 20-cm intervals from a depth of 0–100 cm twice a week. The amount of soil water at 0–90 m depth was used to initiate irrigation. Soil water content for the irrigation period is presented in Figure 3. Evapotranspiration of wheat was calculated based on Eq. (1) (Allen et al., 1998):

$$ET = I + P \pm \Delta S - R - D, \tag{1}$$

where I is irrigation water (mm), P precipitation (mm), ΔS change in soil water content (mm), R surface flow (mm), and D deep seepage (mm, irrigation water applied until field capacity so deep percolation considered negligible).

The irrigation water productivity (IWP) at field level was calculated as the ratio between evapotranspiration (ET) and total diverted irrigation water for crop production given by Kijne et al. (2003).

Samples were taken for carbon isotope discrimination on grain at maturity and on leaves at the pre-anthesis stage. For isotopic measurements 10–20 south-facing sun leaves of five marked plants per treatment were collected once at the stage of pre-anthesis. Only fully mature leaves from the latest growth period were used. Leaves were oven dried at 70 °C for 48 h and finely ground for carbon isotope analysis (Hood et al., 2003; Freres and Heng, 2014). Carbon isotope was analyzed (Δ) in leaf samples and postharvest grain. Carbon isotope ratios ($^{13}C/^{12}C$) of the samples ($^{13}C/^{12}C_{sample}$) and the standard ($^{13}C/^{12}C_{standard}$) were determined using mass spectrometric techniques at the International Atomic Energy Agency (IAEA) Laboratories, Seibersdorf, Vienna, Austria. $^{13}C/^{12}C$ value was transformed into $\delta^{13}C$ (‰ per mil) with the help of Eq. (2).

$$\delta^{13}C(‰) = \frac{(^{13}C/^{12}C)_{sample} - (^{13}C/^{12}C)_{standard}}{(^{13}C/^{12}C)_{standard}} \times 1000 \tag{2}$$

The standard used to evaluate the carbon is known as PDB (Pee Dee Belemnite). PDB standard is the CO_2 isotope ratio obtained from the Belemnite limestone present in the Pee Dee formation in South Carolina (Akhter et al., 2008). $\delta^{13}C$ values were transformed into the carbon isotope discrimination/difference (Δ) using Eq. (3) developed by Farquhar et al. (1982):

$$\Delta\ (‰) = (\delta^{13}C_a - \delta^{13}C_p)/(1 - \delta^{13}C_p/1000), \tag{3}$$

where a and p indicate the isotopic ratios of air and plant, respectively. In the formula, 8‰ was used for air while transforming the $\delta^{13}C$ value into Δ (Keeling et al., 1979).

A statistical evaluation of the results was performed by correlating grain yield, leaf and grain carbon isotopic discrimination, and irrigation water productivity. The data were analyzed using SPSS 18.0.

3. Results and discussion

3.1. Biomass, grain yields, and harvest index

The highest grain yield and biomass values were recorded in full irrigation (I_2) and the lowest in the rainfed (I_1) treatment. Average grain yield values of I_1 were 26%, 20%, and 21% less than the irrigated (I_2, I_3, I_4) treatments, respectively (Table 2).

According to the statistical analysis, year interaction was not significant for all evaluations. Significant differences ($P < 0.05$) in grain yield were found among water treatments. The highest harvest index was obtained from I_4 treatment. The relationship between grain, biomass, and HI was significant and positive as shown in Figure 4.

According to the results, C_3 plants such as wheat have more apparent effects under limited irrigation conditions compared to the conditions of adequate irrigation (Kimball et al., 1983; Morison, 1985).

3.2. Carbon isotope ratio of leaf and grains

Within each year, the highest leaf (ΔL) and grain (ΔG) carbon isotope values were found in the full irrigation treatment (Table 3). According to the statistical analysis, there was no significant difference in ΔL and ΔG between all irrigated treatments but significant differences were found between rainfed and irrigated treatments.

Limited water caused a considerable decrease in □ content of leaf and grain compared to irrigated conditions. The mean Δ value of grain under rainfed conditions (I_1)

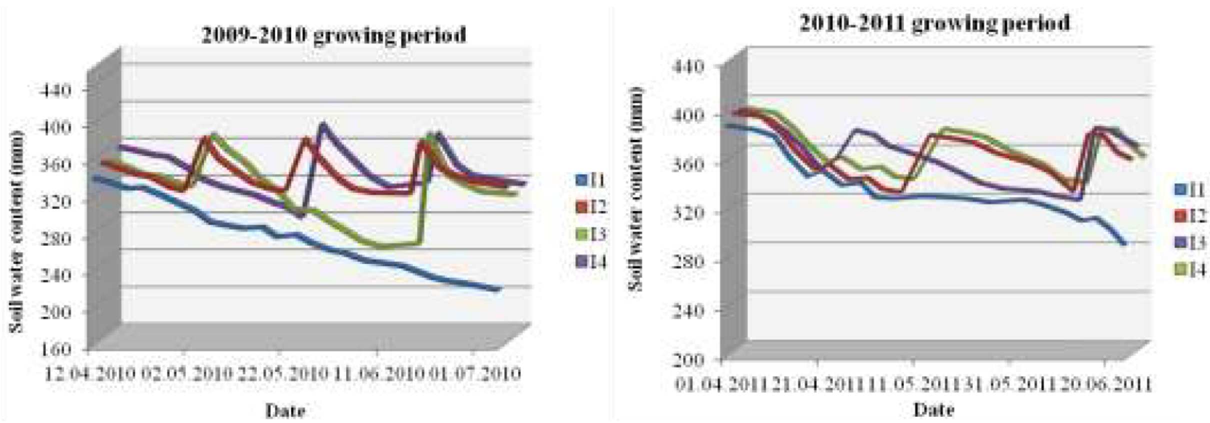

Figure 3. Soil water content (0–90 cm) for winter wheat irrigation period (2009–2011).

Table 2. Average yield, biomass and harvest index values

Years	Treatments	Grain yields (t ha^{-1})	Biomass (t ha^{-1})	HI
2009–2010	I_1	3.54c*	11.61c	30.5
	I_2	4.58a	14.90a	30.7
	I_3	4.15b	13.25b	30.9
	I_4	4.36ab	13.28b	31.3
2010–2011	I_1	3.16c	11.54c	27.3
	I_2	4.49a	14.52a	30.9
	I_3	4.12b	13.68b	30.1
	I_4	4.38ab	13.90b	31.5

*Duncan classes, HI; harvest index

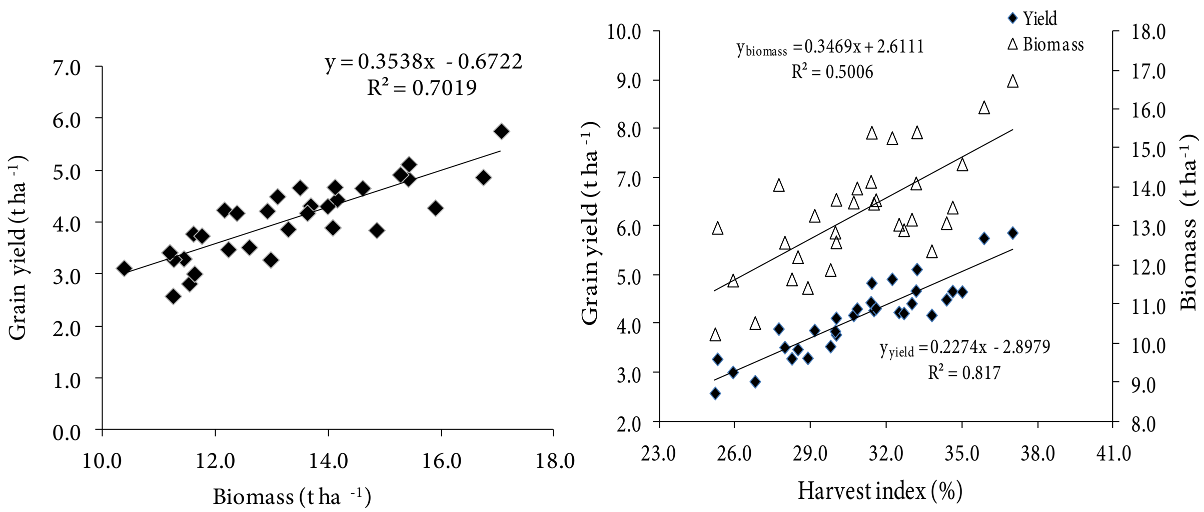

Figure 4. Relationship between grain yield, biomass, and harvest index.

Table 3. Average carbon isotope ratio of the leaf and grain samples.

Years	Treatments	Δ ^{13}C - Leaf (‰)	Δ ^{13}C - Grain (‰)
2009–2010	I_1	19.15b*	16.94b
	I_2	19.91 a	18.99 a
	I_3	19.89 a	17.47 a
	I_4	19.82a	18.76 a
2010–2011	I_1	19.10 b	16.54 b
	I_2	19.97 a	18.74 a
	I_3	19.86 a	17.76 a
	I_4	19.91 a	18.44 a

*Duncan classes.

decreased by 10.7%, 3.03%, and 9.7% compared to the I_2, I_3, and I_4 irrigation treatments, respectively. Yasir et al. (2013) also reported a decrease in □ under limited irrigation of 6.12% compared to sufficient irrigation. According to Yasir et al. (2013), Monneveux et al. (2005), Xu et al. (2007), and Zhu et al. (2008) the lower □ value for limited water conditions is indicative of lower average stomatal conductance in the treatment. A positive and significant relationship was found between ΔL and ΔG and also between the grain yields as shown in Figure 5.

Similarly, a positive relationship was found between yield and Δ^{13}C under most climatic conditions (Sayrek et al., 1995; Monneveux et al., 2005; Xu et al., 2007). In the studies conducted generally under arid and semiarid conditions, a significant and positive relationship was determined between yield and grain Δ^{13}C and leaf Δ^{13}C under the conditions of stress. The positive and significant correlation between Δ and grain yield tends to suggest that wheat with high Δ values is cultivated under water deficit conditions. This was also confirmed by field experiments carried out previously (Condon et al., 1987; Ehdaie et al., 1991; Bazza, 1993; Morgan et al., 1993; Araus et al., 1998, 2003; Merah et al., 2001; Misra et al., 2006; Monneveux et al., 2006; Wahbi and Shaaban, 2011; Yasir et al., 2013).

3.3. Irrigation water productivity

Seasonal ET and applied irrigation water calculated using the irrigation water productivity (IWP) is given in Table 4. As for the IWP for both years, the best outcome was provided by plot I_4. It was followed by I_3. The irrigation water had the lowest productivity in I_2 (2.07). Salvador et al. (2011) reported lower IWP values for alfalfa, barley, maize, sunflower, and wheat (1.8, 2.5, 1.6, 0.68, and 1.6, respectively) for semiarid conditions. Likewise, Andrés and Cuchí (2014) reported IWP values for barley (1.01), maize (1.19), and alfalfa (1.04) lower than those observed in our study. The relationships between IWP and grain yield and biomass within the irrigated treatments are shown in Figure 6. A significant negative relationship was noted between IWP and grain yield and biomass. Additionally, IWP and leaf and grain carbon isotope discrimination was negatively correlated (Figure 6). Under different water conditions, □^{13}C is a simple, direct, and effective method of determining irrigation water productivity. A significant negative relationship was found between irrigation water productivity and grain □^{13}C values with correlation coefficient of −0.53 (R^2). Johnson and Tieszen (1994) reported a significant negative correlation (r = −0.63 to −0.73) between irrigation water productivity and Δ for alfalfa genotypes and Raeini-Sarjaz et al. (1998) also found a negative correlation (r = −0.88 to r = −0.92) between IWP and Δ in bean.

A weak relationship was found for leaf carbon ratio and IWP (R^2 = 0.48). Kirda et al. (1992) reported that the ^{13}C isotope discrimination value (□) of plants at an early

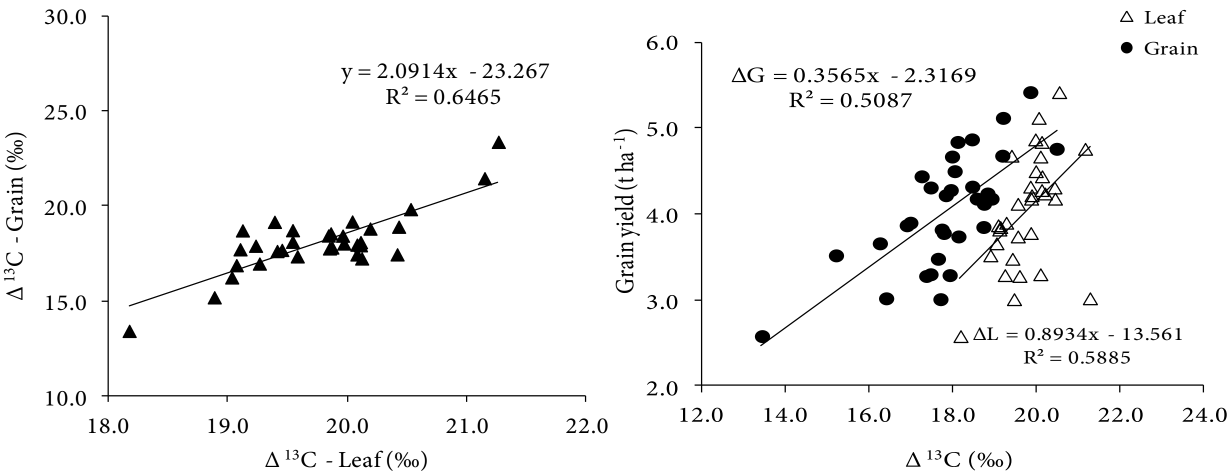

Figure 5. The relationship between leaf and grain Δ^{13}C and wheat yield and ΔL and ΔG.

Table 4. Irrigation water productivity values and Duncan classification.

Years	Treatments	ET (mm)	Irrigation (mm)	IWP
2009–2010	I_2	609	279	2.18 b
	I_3	425	123	3.46 a
	I_4	486	135	3.60 a
2010–2011	I_2	554	268	2.07 b
	I_3	410	118	3.47 a
	I_4	473	131	3.61 a

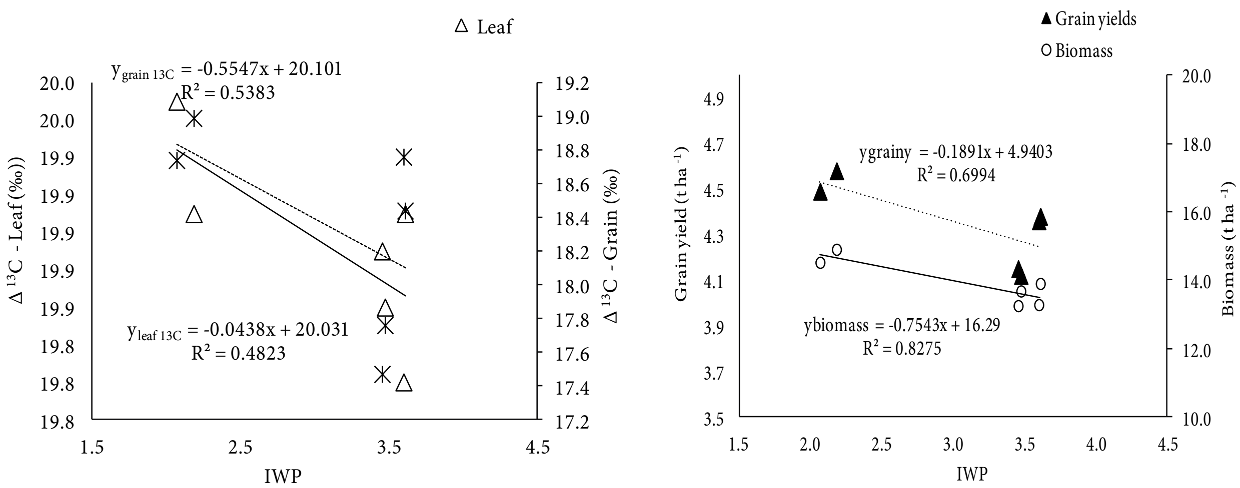

Figure 6. Relationship between IWP and yield and biomass and IWP and leaf–grain Δ^{13}C under three different irrigation treatments.

stage of growth can be used to predict water use of field-grown wheat.

In conclusion, full irrigation treatment (I_2) can be recommended in areas with no water shortage conditions. Moreover, limited irrigation such as I_3 and I_4 at 9.6% and 4.8% levels produced only optimum yield reduction and had the potential for saving approximately 50% of irrigation water. Water stress reduced Δ^{13}C in both leaf and grain and a significant positive linear correlation was found between grain yield and biomass. However, Δ^{13}C (leaf and grain) and yield (grain and biomass) were negatively correlated with IWP, which shows that the IWP was improved, indicating a definitive advantage in selecting IWP deficit irrigation for wheat production in arid areas.

Acknowledgments

We gratefully acknowledge the technical and financial support of the International Atomic Energy Agency through the research contract number TUR/14463 and Scientific and Technological Research Council of Turkey, project number TÜBİTAK 1001/108O654. Special appreciation is given to the Soil Fertilizer and Water Resources Central Research Institute for providing the labor and land for this experiment.

References

Akhter J, Sabir SA, Lateef MZ, Ashraf Y, Haq MA (2008). Relationships between carbon isotope discrimination and grain yield water-use efficiency and growth parameters in wheat (*Triticum aestivum*) under different water regimes. Pakistan J Bot 40: 1441-1454.

Alcamo J, Floerke M, Maerker M (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrology Sci 52: 247-275.

Allen RG, Pereira LS, Raes D, Smith M (1998). Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56.

Andrés R, Cuchí JA (2014). Analysis of sprinkler irrigation management in the LASESA district, Monegros (Spain). Agr Water Manag 131: 95-107.

Araus JL, Amaro T, Casadesus J, Absati A, Nachit MM (1998). Relationship between ash content, carbon isotope discrimination and yield in durum wheat. Aust J Plant Physiol 25: 835-842.

Araus JL, Bort J, Steduto P, Villegas D, Royo C (2003). Breeding cereals for Mediterranean conditions: ecophysiological clues for biotechnology applications. Ann Appl Biol 142: 129-141.

Arnell NW, Vuuren DP, Isaac M (2011). The implications of climate policy for the impacts of climate change on global water resources. Global Env Change 21: 592-603.

Baris ME, Karadag AA (2007). Water resources management issues in Turkey and recommendations. Journal of Applied Sciences 7: 3900-3908.

Bazza M (1993) Carbon-13 discrimination as a criterion for identifying water use efficiency cultivars under water deficit conditions. In: Isotope Studies on Plant Productivity. IAEA-TECDOC-889: 123-130.

Condon AG, Richards RA, Farquhar GD (1987). Carbon isotope discrimination is positively correlated with grain yield and dry matter production in field-grown wheat. Crop Sci 27: 996-1001.

Cregg B, Zhang J (2000). Carbon isotope discrimination as a tool to screen for improved drought tolerance Proceedings of the 11th Metropolitan Tree Improvement Alliance Conference. pp. 23-24.

Ehdaie B, Hall AE, Farquhar GD, Nguyen HT, Waines JG (1991). Water-use efficiency and carbon isotope discrimination in wheat. Crop Sci 31: 1282-1288.

Farquhar GD, O'Leary MH, Berry JA (1982). On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Aust J Plant Physiol 9: 121-137.

Farquhar GD, Richards RA (1984). Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. Aust J Plant Physiol 11: 539-552.

Fereres E, Heng LK (2014). Enhancing the contribution of isotopic techniques to the expansion of precision irrigation. Proceedings International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation. FAO, pp. 259-263.

Heng L (2012). Greater agronomic water use efficiency in wheat and rice using carbon isotope discrimination. IAEA-TECDOC-1671: 1-4.

Heng LK, Cai G, Ramana MV, Sachdev MS, Rusan MM, Sijali I V (2005). The effect of soil fertility and crop management on carbon-isotope discrimination and their relationships with yield and water-use efficiency of crops in semi-arid and arid environments. In: Nutrient and water management practices for increasing crop production in rainfed arid/semi-arid areas. IAEA-TEDOC-1468: 15-41.

Hood RC, Khan M, Haque A, Khadir M, Bonetto JP, Mayr L, Heiling M (2003). Development of preparation methods for $^{13/12}C$ analysis of soil and plant samples using optical breath test analyzers. Commun Soil Sci Plan 34: 2219-2227.

IAEA (2006). Irrigation management technologies on water use efficiency and crop water. IAEA soils newsletter 29: 1.

Iglesias A, Garrote L (2015). Adaptation strategies for agricultural water management under climate change in Europe. Agr Water Man 155: 113-124.

Johnson RC, Tieszen LL (1994). Variation for water-use efficiency in alfalfa germplasm. Crop Sci 34: 452-458.

Keeling CD, Mock WG, Tans PP (1979). Recent trends in the $^{13}C/^{12}C$ ratio of atmospheric carbon dioxide. Nature 277: 121-123.

Kijne J, Barker R, Molden D (editors) (2003). Water Productivity in Agriculture: Limits and Opportunities for Improvement. Wallingford, UK: CABI.

Kimball BA, Mauney JR, Guinn G, Nakayama FS, Pinter PJ, Clawson KL, Reginato RJ, Idso SB (1983). Effects of increasing atmospheric CO_2 on the yield and water use of crops. Env Resources 21: 125-129.

Kirda C, Arag M, Kumarasinghe KS, Montenegro A, Zapata F (1992). Carbon isotope discrimination at vegetative stage as an indicator of yield and water use efficiency of spring wheat (*Triticum turgidum* L var *durum*). Plant Soil 147: 217-223.

Lindsay WL, Norwell WA (1969). Development of DTPA Soil test for zinc, iron, manganese and copper. Soil Sci Soc Amer Proc 33: 49-54.

Merah O, Deléens E, Souyris I, Nachit M, Monneveux P (2001). Stability of carbon isotope discrimination and grain yield in durum wheat. Crop Sci 41: 677-681.

Misra SC, Randive R, Rao VS, Sheshshayee MS, Serraj RI, Monneveux P (2006). Relationship between carbon isotope discrimination ash content and grain yield in wheat in the Peninsular Zone of India. J Agron Crop Sci 192: 352-362.

Misra SC, Shinde S, Geerts S, Rao VS, Monneveux PS (2010). Can carbon isotope discrimination and ash content predict grain yield and water use efficiency in wheat? Agr Water Man 97: 57-65.

Molden DH, Sakthivadivel MS, Makin I (2003). A water productivity framework for understanding and action. In: Kijne J, Barker R, Molden D, editors. Water Productivity in Agriculture: Limits and Opportunities for Improvement. Wallingford, UK. pp. 1-18.

Monneveux P, Reynolds MP, Trethowan R, González-Santoyo H, Peña RJ, Zapata F (2005). Relationship between grain yield and carbon isotope discrimination in bread wheat under four water regimes. Eur J Agr 22: 231-242.

Monneveux P, Rekika D, Acevedo E, Merah O (2006). Effect of drought on leaf gas exchange carbon isotope discrimination transpiration efficiency and productivity in field grown durum wheat genotypes. Plant Sci 4: 867-872.

Morgan JA, LeCain DR, McCaig TN, Quick JS (1993). Gas exchange carbon isotope discrimination and productivity in winter wheat. Crop Sci 33: 178-186.

Morison J (1985). Sensitivity of stomata and water use efficiency to high CO_2. Plant Cell Env 8: 467-474.

Raeini-Sarjaz M, Barthakur NN, Arnold NP, Jones PJH (1997). Water stress water use efficiency carbon isotope discrimination and leaf gas exchange relationships of bush bean. J Agron Crop Sci 180: 173-179.

Rosenzweig C, Strzepek DC, Major A, Iglesias DN, Yates A, Hillel D (2004). Water resources for agriculture in a changing climate: international case studies. Global Env Change 14: 345-360.

Oweis T, Ilbeyi A (2001). Supplemental irrigation potential for wheat in the Central Anatolian plateau. International central for agricultural research and dry areas ICARDA report. 103: 78-87.

Salvador R, Martinez-Cob A, Cavero J, Playán E (2011). Seasonal on-farm irrigation performance in the Ebro Basin (Spain): crops and irrigation systems. Agr Water Manag 98: 577-587.

Sayrek KD, Acevedo E, Austin RB (1995). Carbon isotope discrimination and grain yield for three bread wheat germ plasma groups grown at different levels of water stress. Field Crops Res 41: 45-54.

Tanner CB, Sinclair TR (1983). Efficient water use in crop production; research or re-search. In: Taylor HM, Jordan WR, Sinclair TR, editors. Limitations to Efficient Water Use in Crop Production. Madison, WI, USA: American Society of Agronomy. pp. 1-27.

Wahbi A, Shaaban ASA (2011). Relationship between carbon isotope discrimination yield and water use efficiency of durum wheat in northern Syria. Agr Water Man 98: 1856-1866.

Xu X, Yuan H, Li S, Trethowan R, Monneveux P (2007). Relationship between carbon isotope discrimination and grain yield in spring wheat cultivated under different water regimes. J Int Plant Bio 49: 1497-1507.

Yasir TA, Min D, Chen X, Condon AG, Hu YG (2013). The association of carbon isotope discrimination with gas exchange parameters and yield traits in Chinese bread wheat cultivars under two water regimes. Agr Water Man 119: 111-120.

Yeh HW, Wang WM (2001). Factors affecting the isotopic composition of organic matter. (1) Carbon isotopic composition of terrestrial plant materials. Proc Natl Sci Counc ROC (B) 25: 137-147.

Zhu L, Liang ZS, Xu X, Li SH (2008). Relationship between carbon isotope discrimination and mineral content in wheat grown under three different water regimes. J Agron Crop Sci 194: 421-428.