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# Interactive effects of nitrogen fertilization and irrigation on grain yield, canopy temperature, and nitrogen use efficiency in overhead sprinkler-irrigated durum wheat

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ABSTRACT

Nitrogen and irrigation management are crucial in the production of high protein irrigated durum wheat (*Triticum durum* Desf.) in arid regions. However, as the availability of irrigation water decreases and potential costs and regulation of nitrogen (N) increase, there is a need to better understand how irrigation levels interacts with N fertilizer rates. A two-year field experiment was conducted in Maricopa, Arizona USA on a Casa Grande sandy loam to assess effects of N fertilizer and irrigation rates on grain yield, grain N, canopy temperatures yellow berry, and N use efficiency. Five rates of N fertilizer as urea ammonium nitrate (0, 84, 168, 252, and 336 kg N ha$^{-1}$) were applied in three equal splits at Zadoks stages 30, 32, and 39. Ten un-randomized, sequential rates of irrigation ranging from 0.35 to 1.14 fraction of a non-deficit base irrigation treatment (maintained >45% soil water depletion) were applied by sequentially varying the nozzles in a gradient in an overhead sprinkler system. Irrigation plus rain ranged from 230 to 660 mm in the first season, and 180 to 600 mm in the second season. Grain yield was maximum in 2013 at the 252 kg N ha$^{-1}$ fertilizer rate and at the 10th water level (1.14 irrigation), and between 168 kg and 252 kg N ha$^{-1}$ at the 8th water level (1.0 irrigation) in 2014. The maximum grain yield of 7500 kg ha$^{-1}$ in 2013 was reduced to 5000 kg ha$^{-1}$ in 2014 due to a warmer, shorter growing season. Economic optimum N rate was at water level 8 both years (196 and 138 kg N ha$^{-1}$ in 2013, and 2014, respectively). Recovery efficiency of added N was high in this system (i.e., >70%) at N fertilizer and water levels that maximized biomass and grain yields. Grain N was maximum at a lower water level (level 3 or 0.50–0.54 irrigation), was positively affected by N fertilizer rate, and was negatively related to yellow berry incidence. Canopy temperature minus air temperature values decreased linearly with increasing irrigation level. Nitrogen fertilizer applications reduced canopy temperature when water levels >0.54 and 0.69 irrigation fraction in 2013, and 2014, respectively. The study results suggested that canopy temperature and weather data that reflects the grain-filling period could be used to improve irrigation and N management, respectively. In short, irrigated durum wheat growers on this soil would achieve the economically optimum grain yield, with the least risk of yield or protein reduction, by applying 200 kg N ha$^{-1}$ at the base irrigation level which maintains root zone soil moisture depletion below 45%.

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## 1. Introduction

Durum wheat is an important winter crop in the desert regions of the southwestern United States. Due to a higher price paid for durum wheat, a large fraction of wheat producing areas of Arizona and California converted to durum wheat in the 1970s (Robinson et al., 1979). Currently, Arizona covers the third largest acreage of durum wheat grown in the United States, after North Dakota and Montana (USDA-NAAS, 2015). Durum wheat is a major crop in the EU, North Africa, and the Middle East (Garabet et al., 1998; Garrido-Lestache et al., 2005; Boukef et al., 2013). Similar to other crops, durum wheat production in an arid environment is limited by N and water availability. All field crop production in Arizona is irrigated (Schillinger et al., 2006). Due to growing populations and changes in climate patterns, water availability around the world is increasingly limited. Therefore, increasing crop yield and productivity with reduced water inputs is crucial.

Nitrogen management in durum wheat also faces constraints. Concerns include possible regulatory controls on N inputs or pressures from buyers to reduce carbon footprints associated with

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grain production. However, high N inputs are favored by producers because they receive a reduced price if durum grain protein is <14.3% protein (23 g N $kg^{-1}$) (Blandino et al., 2015; Liang et al., 2014). Several studies have reported that late N applications near heading can boost durum grain protein (Ottman et al., 2000; Garrido-Lestache et al., 2005; Blandino et al., 2015). In addition to N fertilizer management, irrigation amounts and timing strongly influence grain N (Ottman et al., 2000). Low supplemental irrigation was associated with high durum protein grain, and full supplemental irrigation resulted in reduced grain protein (Oweis et al., 1999).

Another important grain quality measure in durum wheat is hard vitreous amber count (HVAC). Durum grain protein is positively related to HVAC and negatively associated with yellow berry, a starchy condition (Robinson et al., 1979; Anderson, 1985; Boukef et al., 2013; Blandino et al., 2015). Ottman et al. (2000) reported that decreasing levels of irrigation during grain-fill in Arizona increased HVAC. Thus, tools to improve irrigation scheduling can assist in the production of durum wheat with high HVAC and protein content. Ehlerer et al. (1978) suggested that durum wheat canopy temperature can be used to guide irrigation scheduling. Much of the seminal research on the use of infrared thermometry to monitor crop water stress and guide irrigation management was conducted with durum wheat in Arizona (Jackson et al., 1977; Idso et al., 1978; Idso, 1982). Over-application of N and irrigation in excess of crop requirements lead to greater lodging, grain loss, and N loss to the environment (Riley et al., 2001; Yu-Hua et al., 2007). In Tunisia, N fertilizer applications improved water use-efficiency of irrigations in durum wheat (Latiri-Souki et al., 1998).

The interacting effects of water and nitrogen balances in durum wheat cropping systems can be described with crop growth simulation models (Thorp et al., 2009). After thorough evaluation against measured cropping system data, the models can be extended to study long-term impacts of field management, assess climate change impacts on cropping systems, and provide guidance for in-season management decisions. However, limited field-measured data is often a critical weakness for crop simulation model evaluation. In particular, field studies that thorough assess durum wheat responses over a wide range of water and nitrogen management conditions are lacking.

It is clear therefore, that irrigation water and N fertilizer require judicious management for high quality durum wheat production in arid and semiarid regions. However, studies are lacking that investigate interactive effects of N and irrigation levels for irrigated durum wheat in dry regions. Recently however, moving overhead sprinkler irrigation has become more common (NASA, 2008). This enables much finer control over irrigation schedules than was previously feasible (Evans and Sadler, 2008), and provides the opportunity to evaluate whether or not infrared thermometry has a corresponding role in improved water and N management. The objectives of this study were (1) to determine the effects of N fertilizer rate on grain yield, above-ground biomass, canopy temperature, total N uptake, N use efficiency, grain N content, kernel weight, and percent yellow berry at varying overhead sprinkler irrigation levels and (2) to estimate optimal N fertilizer rate and overhead sprinkler irrigation level for durum wheat grain yield and grain N.

## 2. Materials and methods

### 2.1. Experimental Layout and overhead sprinkler irrigation system

This field study was conducted in two growing seasons, 2012–2013 and 2013–2014, on a 1.3-ha, laser-leveled field at the Maricopa Agricultural Center (33.0675°N, 111.9715°W, 358 m above sea level) of the University of Arizona in Maricopa, Arizona. The site receives an average annual rainfall of 200 mm, and is classified as a hot desert climate (Köppen climate classification). The soil is a Casa Grande sandy loam (fine-loamy, mixed, superactive, hyperthermic, Typic Natrargid, USDA-NRCS, 2013).

The study was conducted under one span (55 m long) of a two-span end-feed linear-move an overhead irrigation system (Valmont Industries, Inc., Valmont, Nebraska). Sprinkler height was 1 m above the ground, and sprinkler spacing was 1.52 m. A 69-kPa pressure regulator was affixed to each sprinkler head to maintain near constant pressure to sprinklers regardless of overall system pressure fluctuations. Water was provided to the irrigation system through a 0.15 m diameter drag hose. The drag hose was connected to a nearby pumping station that could provide a flow of up to 1171 L $min^{-1}$ when operating the entire system.

### 2.2. Irrigation levels and scheduling

Irrigations were scheduled based on estimated daily evapotranspiration ($ET_c$) as calculated by the FAO-56 dual crop coefficient procedures (Allen et al., 1998):

$$ET_c = (K_{cb} K_s + K_e) ET_o \quad (1)$$

where the basal crop coefficient ($K_{cb}$) represents the transpiration portion of $ET_c$, $K_e$ is the wet soil evaporation coefficient, $K_s$ is the water stress coefficient, where $K_s < 1$ when the available soil water is insufficient for full $ET_c$, $K_s = 1$ when there is no soil water limitation on $ET_c$, and $ET_o$ is grass-reference evapotranspiration, in mm. Measured daily meteorological data, including solar radiation, rainfall, maximum and minimum air temperatures, wind speed, and humidity were used to compute daily values for $ET_o$ by the FAO-56 Penman-Monteith equation (Allen et al., 1998). Weather data were provided by a University of Arizona, AZMET weather station (http://cals.arizona.edu/azmet/), located approximately 200 m from the field. Monthly mean AZMET temperature data, monthly cumulative growing degree days (GDD), rain, and $ET_o$ for the 2012–13 and 2013–14 growing seasons are given in Table 1. Weekly mean air temperature, and GDD are shown in Fig. 1.

The seasonal $K_{cb}$ curve used in Eq. (1) was an empirically-derived function based on the hard red spring wheat (*Triticum aestivum* L.) 'Yecora Rojo' crop coefficient data obtained in prior field studies at this site (Hunsaker et al., 2007). The wheat $K_{cb}$ data were derived as a function of cumulative GDD, calculated using maximum and base temperatures of 30 °C and 4.44 °C, respectively. The benefit for using thermal-time GDD rather than days after planting for $K_{cb}$ is that actual $K_{cb}$ can be better-matched when growing season temperatures vary by season. The parameters used to evaluate the soil evaporation coefficient ($K_e$) were the FAO-56 recommendations for a sandy loam soil. The water stress coefficient ($K_s$) was evaluated using a daily root zone soil water balance (SWB).

A spreadsheet, similar to the one developed in Hunsaker et al. (2005), and originally patterned after Annex 8 in FAO-56, was developed to calculate a daily SWB for estimating soil water depletion of the wheat root zone. Inputs to the SWB included measured daily irrigation and rainfall data, while outputs were the calculated daily $ET_c$ (FAO-56 procedures), and deep percolation, which was calculated as the residual from the SWB equation. Runoff was assumed to be negligible for this laser-leveled field. Twenty-year historical MAC AZMET weather data and weather-based $ET_o$ data were used in the SWB spreadsheet to project root zone available soil water into the future.

Prior to imposing differential gradient irrigation to 10 unrandomized sections in the field, all 10 sections were uniformly irrigated from planting until January 17–18 with 70 mm and 46 mm in the 2012–2013 and 2013–14 seasons, respectively. During this

**Table 1**
Maximum, minimum, and mean daily air temperature, growing degree days, rainfall, and Penman-Monteith reference evapotranspiration ($ET_o$) in 2012–2013 and 2013–2014 growing seasons, Maricopa, AZ, USA.

| Year | Month | $T_{max.}$ (°C) | $T_{min}$ (°C) | $T_{mean}$ (°C) | GDD (°C) | Rain (mm) | $ET_o$ (mm) |
|---|---|---|---|---|---|---|---|
| 2013 | January | 17.39 | 0.5 | 8.3 | 172.3 | 31 | 61.27 |
| | February | 19.2 | 2.7 | 10.8 | 190.9 | 5 | 78.36 |
| | March | 27.4 | 8.3 | 17.9 | 415.7 | 14 | 136.3 |
| | April | 30.6 | 11.5 | 21.6 | 492.6 | 2 | 203.5 |
| | May | 35.1 | 17.2 | 26.7 | 667.5 | 0 | 255.8 |
| 2014 | January | 21.9 | 1.9 | 11.9 | 241.9 | 0 | 67.8 |
| | February | 24.5 | 5.2 | 14.6 | 293.6 | 29 | 84.2 |
| | March | 26.6 | 8.5 | 17.6 | 406.9 | 0 | 140.3 |
| | April | 29.9 | 11.9 | 20.9 | 488.3 | 0 | 190.0 |
| | May | 34.6 | 16.1 | 25.4 | 635.5 | 0 | 242.8 |

**Table 2**
Water inputs (irrigation plus rain) and the fraction irrigation (plus rain) relative to water level 8 in 2012–2013 and 2013–2014, Maricopa, AZ, USA.

| | 2012–2013 | | | 2013–2014 | | |
|---|---|---|---|---|---|---|
| Water levels | Irrigation | Irrigation + rain | Irrigation fraction | Irrigation | Irrigation + rain | Irrigation fraction |
| | mm | | | mm | | |
| 1 | 162 | 232 | 0.4 | 135 | 183 | 0.35 |
| 2 | 200 | 270 | 0.46 | 171 | 220 | 0.42 |
| 3 | 244 | 313 | 0.54 | 213 | 262 | 0.50 |
| 4 | 293 | 362 | 0.62 | 261 | 310 | 0.59 |
| 5 | 347 | 417 | 0.71 | 314 | 363 | 0.69 |
| 6 | 405 | 474 | 0.81 | 370 | 418 | 0.80 |
| 7 | 472 | 542 | 0.93 | 435 | 483 | 0.92 |
| 8 | 514 | 584 | 1.00 | 475 | 524 | 1.00 |
| 9 | 549 | 619 | 1.06 | 509 | 558 | 1.06 |
| 10 | 590 | 659 | 1.13 | 549 | 598 | 1.14 |

period, sprinkler irrigations were applied to maintain soil water depletion at < 45% in all sections. After January 18 in 2013 and 2014, variable irrigation amounts were applied to the sections by varying the nozzle size in a gradient pattern across 50 m of the 55-m linear span. Each section was 4.6 m wide and was irrigated by three sprinkler nozzles of the same flow. The range of the 10 nozzle flow outputs varied from 2.4 L $min^{-1}$ to 13.8 L $min^{-1}$. The SWB spreadsheet was parameterized using irrigation rates for the 8th section nozzle (12.0 L $min^{-1}$), and irrigation schedules for this section were designed to maintain the maximum allowable root zone soil water depletion of that section at 45%. All other sections received a fraction of the 8th irrigation rate (i.e., higher or lower) based on the fractional change in nozzle size for each section. Typically, depending on growth stage, climate conditions, etc., irrigations were applied two to four times per week with daily irrigation amounts ranging from 4 to 24 mm for the 8th section. Table 2 details the 10 irrigation levels applied for the two growing seasons.

### 2.3. Pre-plant soil $NO_3$-N and planting

Before planting, soil samples were taken from 42 locations across the experimental plots at the depths of 0–15, 15–30, 30–60, 60–90, and 60–120 cm. The samples were air-dried and then extracted using a 1 M KCl solution at a 1:5 soil: solution ratio. The extracts were analyzed for $NO_3$ concentration using a spectrophotometer (Alpkem Co., Clackamas, OR). In the summers of 2012 and 2013, a forage sorghum (*Sorghum bicolor* L. Moench) cover crop was grown for 10 weeks and harvested, for the purpose of removing residual soil $NO_3$. Average soil $NO_3$ content from 0–1 m depth was about 30 kg N $ha^{-1}$ prior to planting in both growing seasons. Following medium-level P soil tests, in the fall of 2012, 39 kg $ha^{-1}$ of $P_2O_5$ (0-0-45) was broadcast and incorporated across the field. Due to the low initial soil $NO_3$, 33 kg N $ha^{-1}$ of N fertilizer (ammonium sulfate, 21-0-0) and 35 kg N $ha^{-1}$ of urea fertilizer were applied in all plots as starter fertilizer at the soil preparation in 2013 and 2014, respectively. Durum wheat cultivar ‘Orita’ was drill-planted at 150 kg seed $ha^{-1}$ in 18-cm rows on 3 December in 2012 and 10 December, 2013. ‘Orita’ has been a popular cultivar in Central Arizona, California and Mexico the last 15 years (Ottman, 2008), and yielded the highest among six cultivars in a recent study at this site (Liang et al., 2014).

### 2.4. Experimental design and N fertilizer strip plots

A total of 15 main experimental plots were laid out perpendicular to the irrigation system/irrigation levels in a randomized complete block design for five N treatments with three replications. The plot size was 50 m × 4 m (length × width) and ran north to south. The five N fertilizer rates of 0, 84, 168, 252, and 336 kg N $ha^{-1}$ of liquid urea ammonium nitrate ($NH_4NO_3$, 320 g N $kg^{-1}$) were applied using a high clearance vehicle equipped with a Raven SCS 440 controller, Raven flow meter, GPS, and butterfly valve (Raven Industries, Sioux Falls, SD, USA). Eight drop lines were fitted with spray nozzles every 30 cm. The N rates imposed were chosen to purposely exceed the University of Arizona’s N recommendation of 168 and 280 kg N $ha^{-1}$ for durum wheat for Trix clay loam and Casa Grande sandy loam soils, respectively (Doerge et al., 1991). The total amount of N fertilizer for each treatment was equally split for three applications and applied at Zadoks 30, 32, and 39 (Zadoks et al., 1974). Every fertilizer application was followed immediately by an irrigation.

### 2.5. Plant biomass, nitrogen uptake, and yield measurements

Above-ground plant biomass and total N uptake were measured by taking plant samples from five alternative subplots (i.e., 1, 3, 5, 7, 9) per N treatment at Zadoks 75, the stage of maximum biomass accumulation and N uptake (Malhi et al., 2006). Plant samples were taken from the eastern half of the 4 m-wide north-south N fertilizer plots. Two rows of plants were randomly selected and 0.5 m row were cut at the ground surface from each N subplot, and oven-dried at 70 °C.

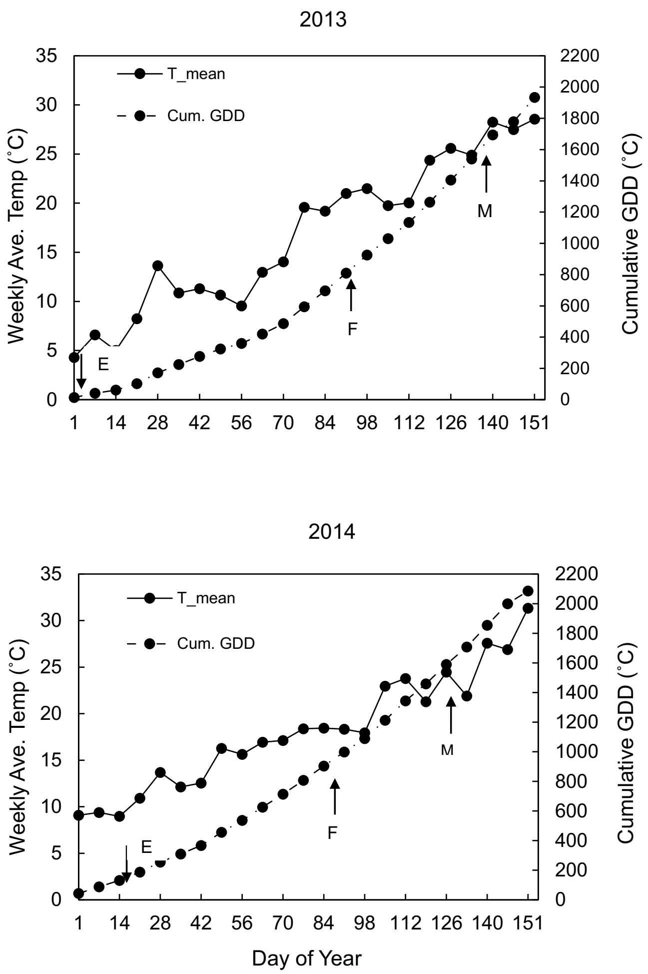


**Fig 1.** Weekly mean air temperature, cumulative growing degree days (GDD), and day of years of plant emergence (E), flowering (F, Zadoks 50) and maturity (M, Zadoks 60) in 2012–2013 and 2013–2014 growing seasons.

At grain maturity (Zadoks 92), the undisturbed areas on the western half of the 4-m-wide N plots were harvested for grain yield. These harvests occurred on 16–17 May in 2013. In 2014, irrigation level plots 1–3, 4–6, and 7–10 were harvested on 6, 14, and 20 May, respectively, since the low water plots matured first. Before the harvests, north-south and east-west alley ways were cut using a sickle bar mower leaving 150 (15 N plots by 10 irrigation gradient plots) rectangular areas of undisturbed wheat 6 to 8 rows wide (≈1.14–1.52 m) by approximately 3.6 m long. The dimensions of each harvest area was measured prior to machine harvesting. In 2013, plots were harvested using a Hege 180 plot combine (Wintersteiger AG, Ried im Innkreis, Austria) equipped with a 1.98-m cutter bar. In 2014, plots were harvested with a small Model 8 combine (Massey Ferguson, Duluth, Georgia) equipped with a 1.52-m cutter bar. In both years, grain from each plot was collected in bags and immediately weighed. Subsamples of grain samples were weighed and oven-dried at 65 °C for 3 days, to determine moisture content. Grain yield was reported on a dry weight basis. Oven dry-plant and grain samples were ground to 0.5 mm and analyzed for N analysis using a Leco-Truspec CN analyzer (Leco Corp., St. Joseph, MO). One thousand kernel weight (TKW) was determined with the aid of a seed counter. Percent yellow berry was determined visually on 40 seeds per plot (Blandino et al., 2015).

### 2.6. Calculations of nitrogen use efficiency

Several N use efficiency (NUE) measures were calculated from total N uptake and grain yield data. Recovery efficiency (RE) was calculated as (Dilz, 1988):

$$\mathrm{RE}\,(\%) = \frac{(\text{TNU in N fertilized plot} - \text{TNU in Zero-N plot})}{\text{N fertilizer rate in N-fertilized plot}} \times 100 \quad (2)$$

where TNU = total N accumulation in grain and straw at Zadoks 75. Physiological efficiency (PE) was calculated as (Isfan, 1990):

$$\mathrm{PE}\,(\text{kg grain/kg N in plant}) = \frac{\text{Grain yield in N fertilized plot} - \text{Grain yield in Zero-N plot}}{\text{TNU inN-fertilized plot} - \text{TNU in Zero-N plot}} \quad (3)$$

Agronomic efficiency (AE) was calculated as (Novoa and Loomis, 1981):

$$\mathrm{AE}\,(\text{kg grain/kg N applied}) = \frac{\text{Grain yield in N fertilized plot} - \text{Grain yield in Zero-N plot}}{\text{N fertilizer rate in fertilized plot}} \quad (4)$$

internal use N efficiency (IUE) was calculated as grain yield divided by total N uptake (Witt et al., 1999).

### 2.7. Canopy temperature

Using a proximal sensing four-wheel cart, Apogee IRR-P infrared thermometers (IRTs) were mounted level to the ground with sensors facing nadir and at a 30° positive angle in the direction of travel. (White and Conley, 2013). The dual view IRTs (both with 22° field-of-view) were deployed to reduce soil temperature effects upon plant observations (Kimes and Kirchner, 1983). Air temperature was monitored next to the IRTs with a copper-constantan thermocouple sensor. Temperature data were logged at 5 Hz with CR1000 data logger (Campbell Scientific, Logan, Utah, USA). Canopy thermodynamics were sensed about every 10 days from mid-January to early April of each year. To better represent transpiration, radiometric temperatures were analyzed as canopy/air temperature differences ($T_C - T_A$) (Idso et al., 1978; Jackson et al., 1977). Canopy temperature ($T_C$) data are more meaningful as an indicator of crop water status when analyzed as a temperature difference because this differential temperature reflects the surface energy balance, transpiration, and the resulting leaf temperatures due to stomatal regulation (Jackson et al., 1977; Idso et al., 1978).

### 2.8. Statistical analysis

The effects of year, N fertilizer rate, irrigation level, and their interaction on grain yield, grain N, TKW, percent yellow berry, total biomass, TNU, RE, PE, IUE, and canopy temperature were determined using the PROC MIXED procedure (SAS, 2013), with a repeated measures option for irrigation level. Piepho et al. (2004) recommended a mixed modelling approach with repeated measures to account for the correlations arising from serial ordering of a treatment like line-source irrigation that is not randomized. Replicate and replicate × N rate were considered random effects. Nitrogen rate, irrigation level, and N × irrigation were considered fixed effects. A second PROC MIXED procedure was performed, similar to above, but "by water level", with irrigation level removed as a fixed effect. The ESTIMATE option was used to estimate the single degree of freedom contrasts for linear and quadratic trends among N fertilizer rate means and irrigation level means for all dependent variables for both mixed model procedures. PROC REG was used to fit linear or quadratic models of grain yield, grain quality

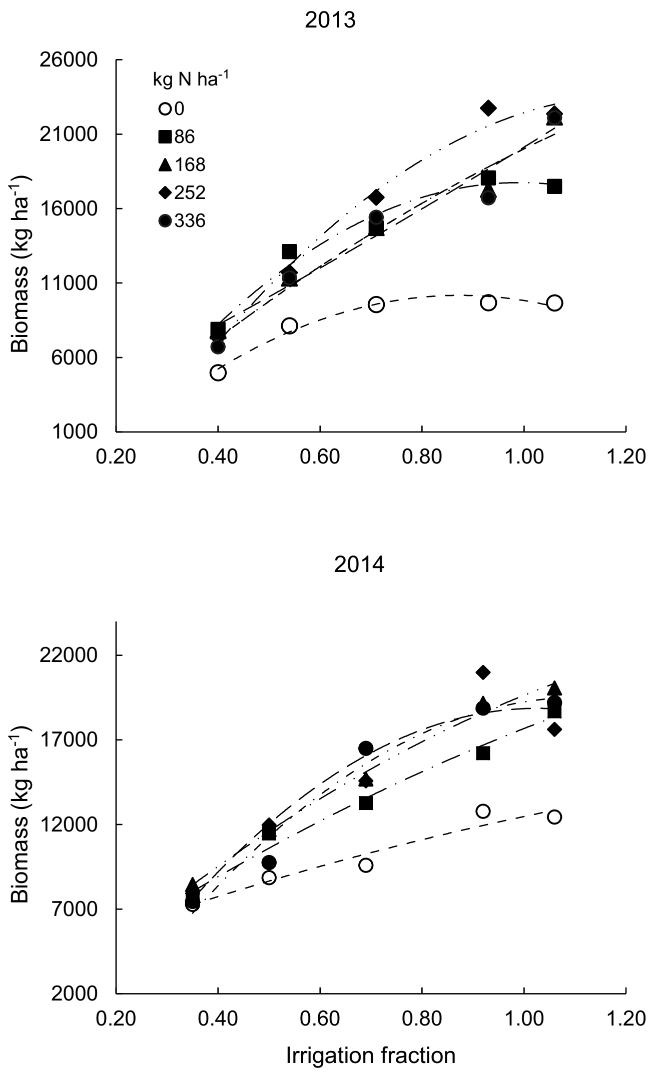


**Fig. 2.** Total aboveground biomass of durum wheat as affected by sprinkler irrigation level at varying N fertilizer rates, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

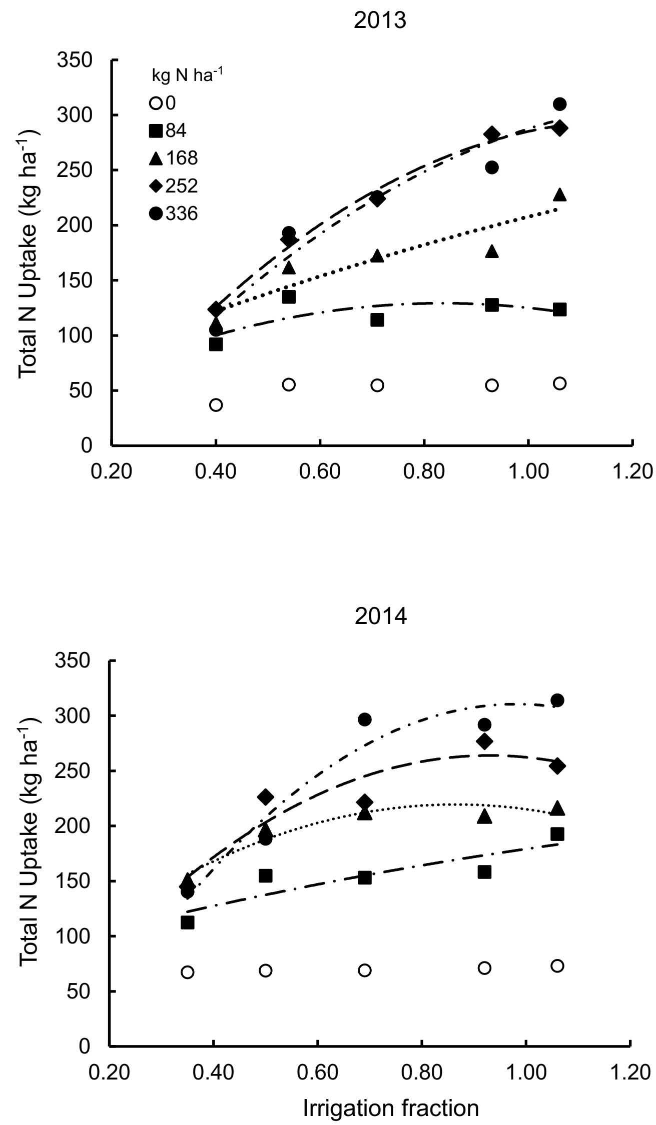


**Fig. 3.** Total N uptake of durum wheat as affected by sprinkler irrigation level at varying N fertilizer rates, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

measures, biomass, and NUE measures vs. N fertilizer rate, for each irrigation level, and vs. irrigation level for each N fertilizer rate. Economic optimum N fertilizer rate (EONR) was calculated using a durum wheat grain price of \$ 0.21 kg$^{-1}$ and \$ 0.99 kg N$^{-1}$ as urea ammonium nitrate-N fertilizer for a N fertilizer to grain price ratio of 10.2. These prices are averages between 2003 and 2013 (USDA-ERS, 2013). The EONR was calculated setting the first derivative of the quadratic grain yield vs. N rate models equal to the price ratio of 10.2, and solving for x (N rate) (Cerrato and Bremner, 1990).

## 3. Results

### 3.1. Plant biomass and total N uptake

Total above ground biomass increased linearly with an irrigation level up to level 7 (irrigation fraction 0.92–0.93) in both years, then plateaued (Tables 3 and 4, Fig. 2,). In 2013, biomass ranged from about 5000 to 8000 kg ha$^{-1}$ among N treatments at 0.40 irrigation fraction, while 0.9 and higher irrigation fraction produced 10,000 to 23,000 kg ha$^{-1}$ of biomass, depending on N treatments. Total biomass yields in 2014 were similar to those in 2013 (Table 3). Nitrogen fertilizer rate significantly affected biomass in both years, but only above water level 3 (0.54 irrigation) in 2013 and level 1 (0.35 irrigation) in 2014 (Tables 3 and 4). Biomass *F* tests were greater for water than for N rate (Table 3). Biomass interacted with water and N in 2013, but not in 2014. At the lowest irrigation levels, water limitations to biomass growth surpassed N deficiencies.

Total N uptake (TNU) of durum wheat response to irrigation levels was observed both years, but the effect was not as significant as the response to N rate (Table 3). A positive N rate effect on TNU was observed at all irrigation levels in both growing seasons (Fig. 3, Table 4). In 2013, TNU was similar between the 252 and 336 kg N ha$^{-1}$ fertilizer rates. Water × N interaction for TNU was significant both years. In 2014, the highest N rate had the highest TNU with increasing water availability (Fig. 3). The maximum TNU was similar in both years, at 310 and 314 kg ha$^{-1}$ in 2013, and 2014, respectively (Table 3). Total N uptake in zero-N plots was not affected by irrigation level in either year (Fig. 3).

### 3.2. Canopy temperature

Multi-angle canopy temperatures measured at nadir and 30° view angles did not show significant differences, they were within 1.5% of each other both seasons. Therefore, only nadir observations

**Table 3**
*F* tests of year, N fertilizer rate, water level, and N × water interaction on durum wheat total biomass, total N uptake, grain yield, one thousand grain weight, percent yellow berry, recovery efficiency of N (RE), physiological N use efficiency (PE), Internal N use efficiency (IUE), and agronomic N use efficiency (AE), from mixed procedure with repeated measures in 2012–2013, and 2013–2014, Maricopa, AZ, USA.

| *F* test | Total biomass | Canopy temperature | Total N uptake | Grain yield | 1000 grain weight | Grain N | Yellow berry | RE | PE | IUE | AE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | NS | 53** | NS | 42** | 44** | 37** | 23** | NS | 6.1* | 18** | 28** |
| N rate | 70** | NS | 70** | 50** | 10.0** | 215** | 152** | 9.3** | 9.6** | 24** | 82** |
| Year × N rate | NS | NS | NS | 8.3** | 5.9** | NS | 3.7* | NS | NS | NS | 8.3** |
| Water | 39** | 136** | 39** | 124** | 8.6** | 35** | 9.6** | 15** | 46** | 76** | 65** |
| Year* water | NS | 17** | NS | 7.0** | NS | 2.2* | NS | NS | NS | 3.5* | 4.6** |
| N × water | 4.9** | NS | 4.9** | 5.6** | 1.6* | 5.9** | 3.8** | NS | NS | NS | 3.4** |
| Year* N* water | NS | NS | NS | 1.6* | 1.6* | 1.5* | NS | NS | NS | NS | 2.1** |

NS is not significant at $P = 0.05$.
* Is significant at $P < 0.05$.
** Is significant at $P < 0.01$.

**Table 4**
*F* tests of N fertilizer rate by irrigation level on durum wheat total biomass, canopy temperature, total N uptake, grain yield, one thousand grain weight, percent yellow berry, recovery efficiency of N (RE), physiological N use efficiency (PE), Internal N use efficiency (IUE), and agronomic N use efficiency (AE) in 2012–2013, and 2013–2014, Maricopa, AZ, USA.

| Water levels | Total biomass | Canopy temperature | Total N uptake | Grain yield | 1000 grain weight | Grain N | Yellow berry | RE | PE | IUE | AE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013 | | | | | | | | | | | |
| 1 | NS | NS | 7.7** | 4.5* | NS | 147** | 47** | $NS_L$ | $NS_L$ | $NS_L$ | NS |
| 3 | NS | $NS_L$ | 14** | NS | 6.5* | 39** | 100** | $NS_L$ | $NS_L$ | 8.1** | 4.7* |
| 5 | 6.7* | $NS_L$ | 26** | 6.5* | 5.3* | 25** | 10** | NS | $NS_L$ | 5.8* | 15** |
| 7 | 6.1* | ** | 16** | 15** | NS* | 218** | 28** | NS | NS | $NS_L$ | 12** |
| 9 | 5.4* | ** | 16** | 79** | ** | 281** | 30** | NS | $NS_L$ | $NS_L$ | 18** |
| 2014 | | | | | | | | | | | |
| 1 | NS | NS | 10** | NS | NS | 8.9** | 7.1** | NS | NS | 9.0** | NS |
| 3 | 4.5* | NS | 8.2** | NS | 10.5** | 125** | 239** | 6.0* | NS | 18** | NS |
| 5 | $NS_L$ | $NS_L$ | 9.3** | 6.6* | 15** | 155** | 13** | NS | 6.4* | 6.0* | 20** |
| 7 | $NS_L$ | $NS_L$ | 13** | 9.6** | 8.0** | 10.5** | 32** | NS | NS | $NS_L$ | 32** |
| 9 | 9.2** | $NS_L$ | 12** | 8.7** | 16** | 159** | 164** | $NS_L$ | 7.0* | $NS_L$ | 13** |

NS is not significant at $P = 0.05$.
L is linear single degree of freedom contrast significant at $P > 05$.
* Is significant at $P < 0.05$.
** Is significant at $P < 0.01$.

are presented. Season-long average canopy temperatures were 4 °C warmer in 2014 compared to 2013 (Table 3).

Increasing irrigation level resulted in decreasing $T_C - T_A$ (Tables 3 and 4, Fig. 4). However that this temperature gradient effect diminished at irrigation fractions exceeding ~0.60. On the other hand, N rates at the higher irrigation fractions were increasingly related to canopy/air temperature gradients, most notably for 2013 results. Nitrogen fertilizer rate resulted in decreasing $T_C - T_A$ at water levels 3 to 10 (0.54–1.13 irrigation) in 2013, and at water levels 5–10 (0.69–1.14 irrigation) in 2014 (Fig. 4, Table 3). Positive $T_C - T_A$ values at the lower irrigation levels reflect water stress, and negative $T_C - T_A$ indicate well-watered conditions (Jackson et al., 1977; Idso et al., 1978). Canopy temperature showed no interaction between N and water (Table 3).

### 3.3. Grain yield and grain N content

Grain yields in both years responded strongly to irrigation (Table 3, Fig. 5) and N rate (Table 4, Fig. 6). *F* test values were much larger for irrigation than for N rate (Karam et al., 2009), and the water × N interaction was significant. In 2014, grain yields were much lower, and the response to N rate was quadratic. Year × N rate and year × irrigation level interactions were significant (Table 3). Grain yield response in season 2013 to the high irrigation levels was nearly linear, suggesting yields could have been higher with more irrigation. However, in 2014, grain yield responses to irrigation was quadratic for all N rates (Fig. 5). The highest grain yield of 7500 kg ha$^{-1}$ in 2013 was reduced to 5000 kg ha$^{-1}$ in 2014. The large grain yield reduction in the second season was likely due to hotter-than-average January and February (Table 1 and Fig. 1). It is well known that grain yield can be negatively affected by high air temperature (Macnack et al., 2014). Nitrogen fertilizer rate response of grain yield was only absent at water level 2 (0.46 irrigation) in 2013 and at water levels 1 and 2 (0.35–0.42 irrigation) in 2014.

In 2013, at water level 9 (1.06 irrigation), the highest grain yield of 7000 to 7100 kg ha$^{-1}$ was achieved at the 252 kg N ha$^{-1}$ N rates (Figs. 5 and 6). At the 336 kg N ha$^{-1}$ N rate at water level 9, grain yield decreased to 6000 kg ha$^{-1}$. In 2014, grain yields reached a maximum of 4700 kg ha$^{-1}$ in between 168 and 252 kg N ha$^{-1}$ at irrigation levels 7–9 (0.92–1.06 irrigation) (Fig. 6). The one exception to this trend was at water level 8 (1.0 irrigation), where 4700 kg ha$^{-1}$ was reached at 84 kg N ha$^{-1}$.

Economic optimum N rate could not be calculated at the lowest water levels, but increased to a maximum of 196 and 138 kg N ha$^{-1}$ in 2013 and 2014, respectively (Table 6). Maximum EONR was at water level 8, the base irrigation level (1.0), in both years (Table 6).

A positive N rate effect on grain N was observed in both years at every water level (Tables 3 and 4). Water × N rate and water × N rate × year interactions were significant for grain N (Table 3). Grain N content reached a maximum at water level 3 (0.50–0.54 irrigation) with 37 and 34 kg N kg$^{-1}$ in 2013 and 2014, respectively (Fig. 7). Grain N was higher in 2014 than in 2013 (Table 3, Fig. 7). Unlike the grain yield, grain N did not appear to be affected by the warmer temperature or shorter growing season. In comparing the grain yields and grain N between the two seasons, the inverse relationship reflects a well-known trend (Terman et al., 1969; Entz and Fowler, 1989).

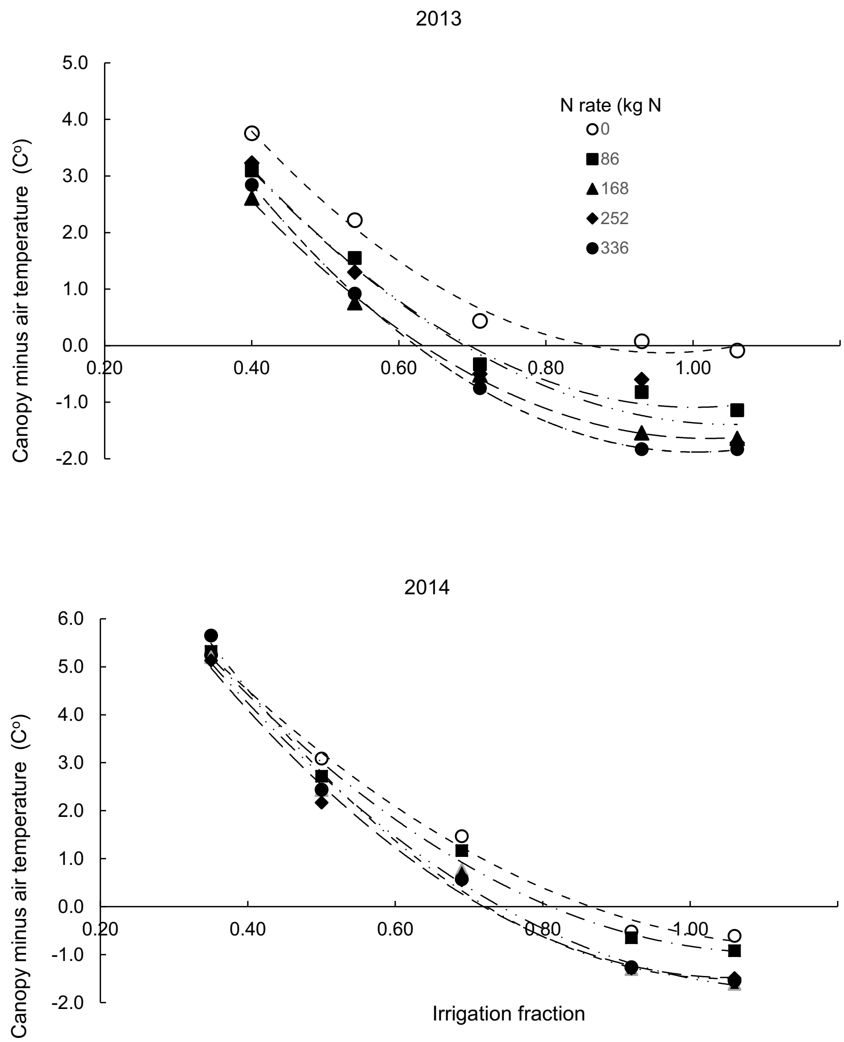


**Fig. 4.** Season-long average canopy temperature minus air temperature of durum wheat as affected by sprinkler irrigation level at varying N fertilizer rates, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

### 3.4. 1000-Grain weight

Seed weight responded positively to irrigation level in both seasons (Tables 3 and 4), though not nearly as strongly as grain yield and biomass. The mean TKW was 55 g (range 49–69 g) in the first season and 51 g (range 42–61 g) in the second season. Nitrogen rate effects were more widespread across irrigation levels in 2014 than in 2013 (Table 4). In all cases, N effects were negative. Lower TKW in 2014 compared to 2013 was consistent with the lower grain yields observed in year two. Seed weight in both years of our study was greater than nearly all of the reported durum wheat TKW (Oweis et al., 1999; Blandino et al., 2015). Oweis et al. (1999) reported that TKW increased with irrigation, but was not affected by N fertilizer rate.

### 3.5. Yellow berry

Irrigation level affected percent yellow berry both years (Table 3). Yellow berry showed a very strong effect of N rate at all irrigation levels (Tables 3 and 4). F values for yellow berry were larger for N rate than for irrigation level, especially in 2014, and the water × N interaction was significant both years. Zero-N plots had the highest yellow berry rates of 87 and 86% of seed in 2013 and 2014, respectively, with no effect of water level (data not shown). This compares to the 16–18% yellow berry Boukef et al. (2013) reported for zero-N durum wheat in Tunisia. Yellow berry incidence was higher, and at a greater range of irrigation levels in 2014 compared to 2013 (Table 3). In 2013, yellow berry incidence averaged 54 and 7% at N rates 84 and 168 kg N ha$^{-1}$, respectively, with irrigation levels 6–10, (0.88–1.13 irrigation). In 2014, yellow berry incidence averaged 71 and 37% at N rates 84 and 168 kg N ha$^{-1}$, respectively, at irrigation levels 4–10, (0.59–1.14 irrigation). Yellow berry was negligible at N rates of 252 kg N ha$^{-1}$ or greater. At all irrigation levels percent yellow berry showed a strong negative correlation to grain N content (Fig. 8). When the grain N content was less than 20 g kg$^{-1}$, yellow berry percentage was higher than market recommended rate (<25%). However, yellow berry decreased to a negligible level at grain N above 25 g kg$^{-1}$, the critical grain protein level (Fig. 9). Robinson et al. (1979) reported that an N fertilizer rate of 270 kg ha$^{-1}$ produced the highest durum wheat yield and less than 25% yellow berry in southern California.

### 3.6. N use efficiency

Nitrogen RE generally increased with an irrigation level in both seasons (Tables 4 and 5). Nitrogen rate had a significant negative linear trend with RE in two of five water levels in both years. The magnitude of RE was similar between the two years (Table 3). Recovery efficiency in 2013 was a very high 92% of added N at water level 9 (1.06 irrigation) and 252 kg N ha$^{-1}$ (Table 5), a combination

**Table 5**
Recovery efficiency of N (RE, %), physiological N use efficiency (PE, kg grain kg $N^{-1}$), and agronomic N use efficiency (AE, kg grain kg $N^{-1}$) of durum wheat as affected by N and irrigation level, in 2012–2013, and 2013–2014, Maricopa, AZ, USA.

| Water level | | N fertilizer rate (kg N $ha^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 84 | 168 | 252 | 336 | 84 | 168 | 252 | 336 |
| | | 2012–2013 | | | | 2013–2014 | | | |
| 1 | RE | 65.4 | 44.3 | 34.4 | 20.3 | 43.0 | 44.5 | 32.5 | 21.8 |
| | Linear | * | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | PE | 7.2 | 10.0 | −0.6 | −1.0 | −3.8 | −1.8 | −1.9 | −2.7 |
| | Linear | * | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | AE | 3.6 | 3.6 | −0.3 | −0.01 | −0.2 | −0.8 | −0.4 | −0.6 |
| | Linear | * | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | IUE | 8.2 | 9.9 | 2.8 | 3.4 | 8.4 | 5.5 | 5.3 | 5.0 |
| | Linear | * | | | | ** | | | |
| | Quadratic | NS | | | | * | | | |
| 3 | RE | 94.5 | 63.2 | 52.2 | 40.9 | 86.0 | 65.8 | 59.5 | 29.0 |
| | Linear | * | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |
| | PE | 13.3 | 12.7 | −0.5 | −0.6 | 4.1 | 3.6 | −2.3 | −0.9 |
| | Linear | * | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | AE | 12.0 | 8.6 | −0.3 | −0.3 | 4.2 | 2.2 | −1.2 | −0.4 |
| | Linear | * | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | IUE | 17.7 | 16.7 | 6.7 | 6.5 | 13.0 | 10.5 | 5.6 | 8.6 |
| | Linear | ** | | | | ** | | | |
| | Quadratic | NS | | | | ** | | | |
| 5 | RE | 70.6 | 70.1 | 67.2 | 50.8 | 82.8 | 86.0 | 60.8 | 63.1 |
| | Linear | NS | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | PE | 34.0 | 26.5 | 13.3 | 12.1 | 25.9 | 9.8 | 9.2 | 4.1 |
| | Linear | * | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |
| | AE | 23.7 | 17.6 | 8.9 | 6.0 | 21.5 | 8.4 | 3.8 | 2.8 |
| | Linear | ** | | | | * | | | |
| | Quadratic | NS | | | | ** | | | |
| | IUE | 33.0 | 28.0 | 17.9 | 17.1 | 28.4 | 16.5 | 15.2 | 10.2 |
| | Linear | ** | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |
| 7 | RE | 87.0 | 72.5 | 90.4 | 58.8 | 77.2 | 78.2 | 74.6 | 70.2 |
| | Linear | NS | | | | NS | | | |
| | Quadratic | NS | | | | NS | | | |
| | PE | 31.7 | 38.3 | 17.6 | 22.7 | 59.7 | 27.2 | 17.0 | 10.1 |
| | Linear | NS | | | | * | | | |
| | Quadratic | NS | | | | NS | | | |
| | AE | 22.2 | 26.5 | 16.0 | 12.3 | 30.7 | 19.3 | 11.1 | 7.0 |
| | Linear | ** | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |
| | IUE | 32.8 | 37.7 | 21.6 | 25.7 | 32.1 | 24.4 | 17.7 | 12.7 |
| | Linear | * | | | | * | | | |
| | Quadratic | NS | | | | NS | | | |
| 9 | RE | 79.9 | 102.1 | 91.9 | 75.4 | 130.7 | 76.1 | 67.0 | 64.9 |
| | Linear | NS | | | | * | | | |
| | Quadratic | NS | | | | NS | | | |
| | PE | 30.6 | 29.4 | 25.1 | 15.8 | 22.8 | 19.3 | 13.4 | 4.4 |
| | Linear | * | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |
| | AE | 24.3 | 29.0 | 20.0 | 11.8 | 27.9 | 14.5 | 8.9 | 2.4 |
| | Linear | ** | | | | ** | | | |
| | Quadratic | ** | | | | NS | | | |
| | IUE | 33.6 | 31.2 | 26.9 | 19.7 | 25.6 | 23.7 | 18.6 | 11.1 |
| | Linear | ** | | | | ** | | | |
| | Quadratic | NS | | | | NS | | | |

NS is not significant at $P = 0.05$.

that resulted in nearly the highest grain yield of 7100 kg $ha^{-1}$. No N uptake data was sampled from water level 10 (1.13 irrigation), which had the greatest grain yield of 7500 kg $ha^{-1}$ in 2013. In 2014, REs of 67–78% were observed for N rates of 168 to 252 kg N $ha^{-1}$ and water levels 7 and 9 (0.99 and 1.06 irrigation) (Table 5). The highest grain yields of 4700 kg $ha^{-1}$ were achieved in these treatments.

Physiological use efficiency and IUE were greatly reduced in the second season (Tables 3 and 5). Since RE, biomass, and TNU were similar between the two seasons, reduced PE and IUE helps explain

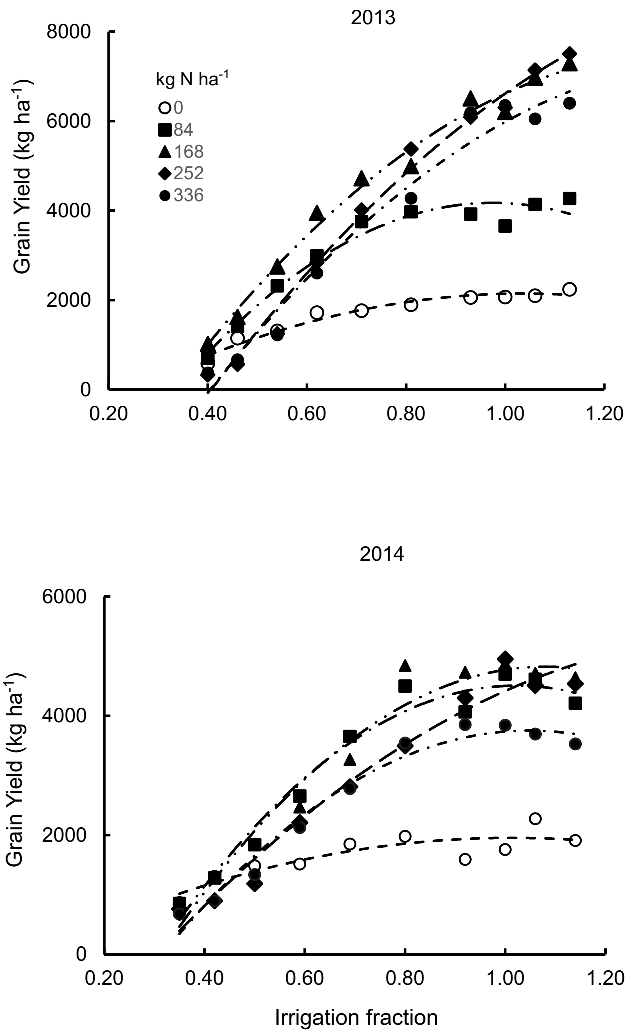


**Fig. 5.** Grain yield of durum wheat as affected by sprinkler irrigation level at varying N fertilizer rates, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

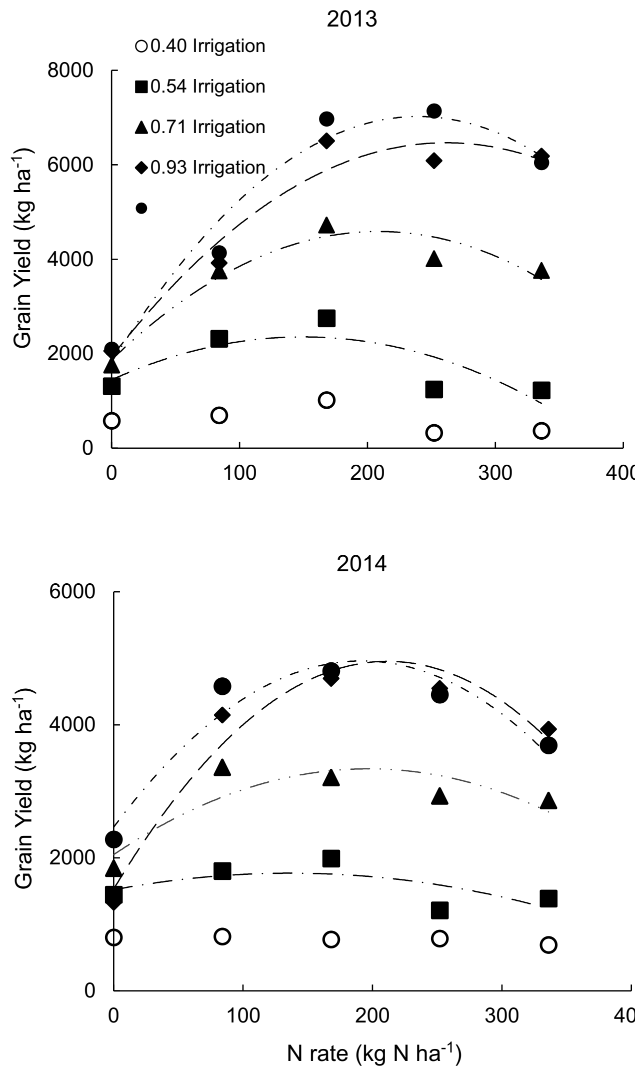


**Fig. 6.** Grain yield of durum wheat as affected by N fertilizer rate at varying sprinkler irrigation levels, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

reduced grain yield in year two. PE and IUE increased with irrigation level. At the low irrigation and high N rates, PE and AE were negative (Table 5). Nitrogen fertilizer effected RE, PE, IUE, and AE in a negative manner, but not at all water levels (Tables 3–5). Negative linear contrasts were significant for AE at 4 of 5 water levels in 2013 and in 3 of 5 water levels in 2014. Internal use efficiency had significant negative linear trends with N rate in all twenty water level year combinations sampled. Agronomic efficiency is the product of RE and PE, and was therefore, also reduced in 2014, compared to 2013 (Tables 3 and 5).

## 4. Discussion

This N × water durum wheat study demonstrated some well-known relationships involving grain yield, grain N, TKW, yellow berry, N rate, irrigation level, and high temperatures. Irrigated row cropping in arid regions is unique in achieving very high production levels compared to rainfed environments. Irrigation management with overhead sprinklers is assumed to be more efficient than flood irrigation. However, in this study RE of N was similar to a recent N rate study at the Maricopa site that included the 'Orita' cultivar (Liang et al., 2014). In that study, however, urea fertilizer was split-applied four times from Zadoks 21 to 59, which would have helped boost RE. Grain yields in both years of that 2-year study exceeded in 7000 kg ha$^{-1}$ at the higher N rates. Temperatures during both growing seasons in the Liang et al. (2014) study were similar to our 2013 season, which was close to the long-term average.

Rainfall was 70 and 49 mm in the first and second seasons, respectively. Grain yield responded up to the highest irrigation level in 2013, and N rate was maximum at 252 kg N ha$^{-1}$. The agronomic optimum N rate is similar to the 280 kg N ha$^{-1}$ recommendation of Doerge et al. (1991) for this soil, but lower than the report of Liang et al. (2014). In the lower-yielding second season, the response to irrigation was quadratic. The optimal irrigation response was at level 6, in 2013 which was 0.80 irrigation. In both seasons, N fertilizer improved grain yield response to irrigation (Latiri-Souki et al., 1998). Interestingly, maximum EONR was at the base (1.0) irrigation level both years.

The high RE of added N in this study reflects the high irrigation efficiency of the overhead sprinkler and the efficiency of three split applications of Liang et al. (2014) had similarly high RE at this site with flood irrigations, but with 5 splits of N fertilizer. López-Bellido et al. (2008) reported notably lower RE for rainfed durum wheat in Spain. Where NUE efficiency measures have significant N rate effects, the effects were negative (Cossani et al., 2012).

The CWSI is calculated from the negative relationship between $T_C - T_A$ and vapor pressure deficit (VPD) (Idso, 1982). The data in our study, however, did not show the VPD dependence previ-

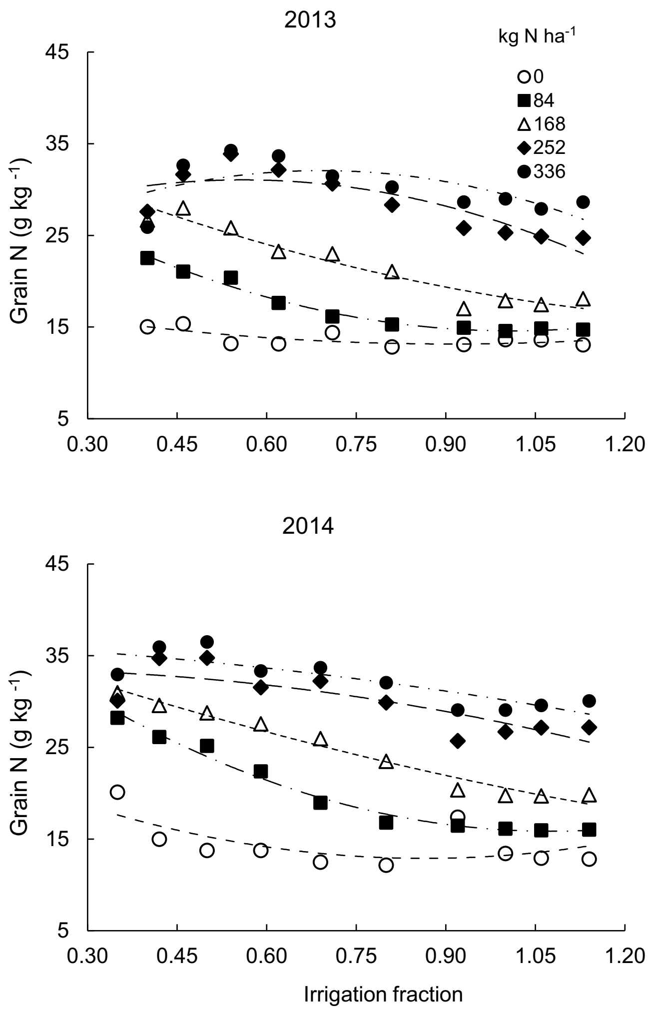


**Fig. 7.** Grain N content of durum wheat as affected by N fertilizer rate at varying sprinkler irrigation levels, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

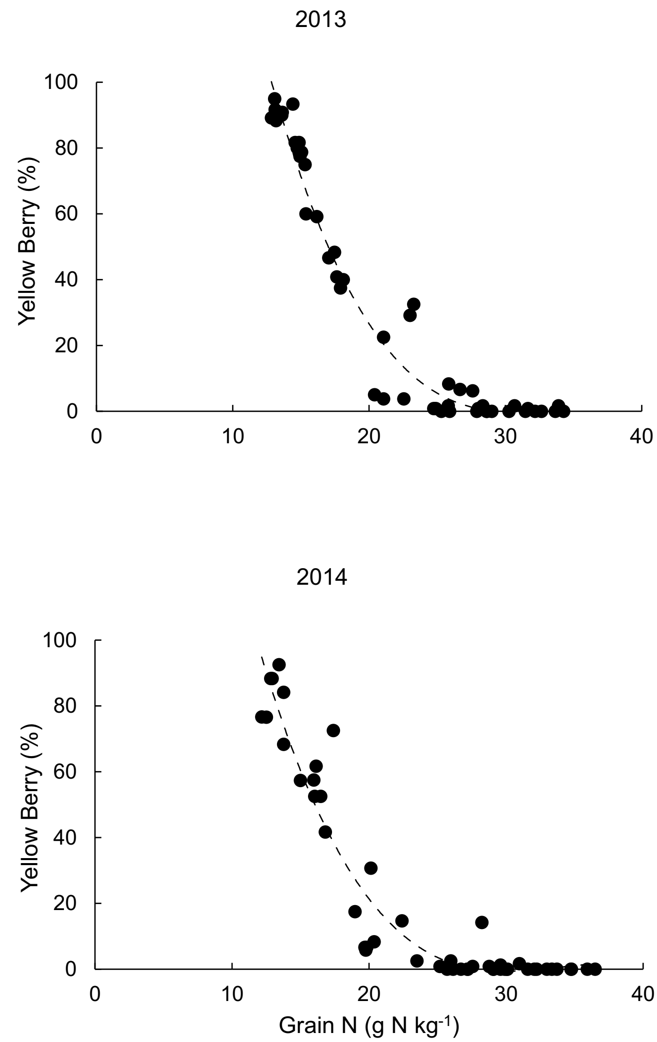


**Fig. 8.** Yellow berry percentage of durum wheat as affected by N fertilizer rate at varying sprinkler irrigation levels, 2012–2013, and 2013–2014, Maricopa, AZ, USA.

ously reported by Idso (1982), so we only present $T_C - T_A$. The 10 irrigation levels showed a large spread in $T_C - T_A$ (Fig. 4), but we did not measure VPD at the subplot level. As expected, $T_C - T_A$ increased as irrigation level decreased. Our findings that N fertilizer additions resulted in cooler canopy temperatures, have been previously reported (Fois et al., 2009; Seligman et al., 1983; Penuelas et al., 1996). However, those studies were limited to well-watered scenarios. A unique finding in our study is that N fertilizer cooled canopy temperatures in water-limiting conditions as well, at irrigation fractions as low as 0.54 in 2013 and 0.69 in 2014 (Fig. 3). Temperature depression effects by N could be important for many irrigation scenarios and should be considered when analyzing wheat canopy temperature.

The 4 °C greater average canopy temperature in 2014, reflects the warmer second season, and partially explains the lower grain yields in that season. The FAO-56/SWB irrigation approach used

**Table 6**
Economic optimum N rate (EONR) of durum wheat as affected by irrigation level, in 2012–2013, and 2013–2014, Maricopa, AZ, USA.

| Water levels | 2012–2013 | | 2013–2014 | |
|---|---|---|---|---|
| | $R^2$ of quadratic function | EONR[a] | $R^2$ of quadratic function | EONR |
| | | kg N ha$^{-1}$ | | kg N ha$^{-1}$ |
| 1 | 0.51 | –[b] | 0.90 | – |
| 2 | 0.60 | – | 0.82 | – |
| 3 | 0.63 | 23 | 0.49 | – |
| 4 | 0.82 | 87 | 0.68 | – |
| 5 | 0.93 | 127 | 0.60 | 49 |
| 6 | 0.99 | 147 | 0.71 | 105 |
| 7 | 0.95 | 184 | 0.95 | 134 |
| 8 | 0.96 | 196 | 0.94 | 138 |
| 9 | 0.96 | 183 | 0.92 | 116 |
| 10 | 0.95 | 187 | 0.98 | 126 |

[a] Calculated by setting the first derivative of the grain yield = N rate + N rate$^2$ + intercept = to the price of N fertilizer/price grain ration (10.2) and solving for x.
[b] Positive EONR could not be calculated. Either function was not quadratic, or X coefficient was <10.2 (N fertilizer/price grain ratio).

for irrigation scheduling did not utilize canopy temperature. The greater $T_C - T_A$ values in 2014 vs. 2013 suggest that irrigation management for durum wheat can be improved using canopy temperature data. For example, periodic canopy temperature measurements could be used in conjunction with or within the FAO-56 SWB procedures to increase precision in irrigation scheduling. Garrot et al. (1994) reported that in Arizona, the CWSI can be used as an indicator of actual soil water depletion percentage in irrigated durum wheat. Thus, an index such as the CWSI could potentially be used to both check the accuracy and update the calculated root zone soil water depletion within the FAO-56 model. However, Colaizzi et al. (2003) also presented a methodology to detect cotton crop water stress using the water deficit index, an expansion of CWSI. This canopy temperature-based application led to a more precise approach in assessing the water stress coefficient ($K_s$), as used in the FAO-56 daily $ET_c$ equation (Eq. (1)).

In the second season, where a warm January and February were experienced, N fertilizer rates could have been reduced, as EONR decreased from 196 to 138 kg N ha$^{-1}$. Given that 2014 was a warmer-than-average year, a general recommendation for EONR of 200 kg N ha$^{-1}$ is reasonable.

Crop growth models such as DSSAT may assist management decisions in case major in-season management adjustments are needed (Thorp et al., 2009). Specifically, if in a warm season, a model could predict a shortened grain-filling period, and therefore reduce the mid to late season N fertilizer applications, which would be very beneficial to producers.

The important grain quality measures of grain N and yellow berry in this study were only problematic when the crop was at zero or low N fertilizer rates. Those low N rates would not be used by Arizona durum growers, as they resulted in low grain yields. Kernel weight is not a typical grain quality measure, but in this study TKW was a valuable yield component that helped us understand how a warm second season led to low grain yields.

## 5. Conclusions

The durum wheat cultivar 'Orita' responded strongly to irrigation level and N fertilizer rate, though a warmer second season resulted in lower than expected yields. Grain yield was maximum at the 252 kg N ha$^{-1}$ fertilizer rate and at the 10th water level (1.14 irrigation) in 2013 and between 168 and 252 kg N ha$^{-1}$ at the 8th water level (1.0 irrigation) in 2014. Economic optimum N rate was at water level 8 in both years. Canopy temperature was related to grain yields and irrigation level. Higher irrigation and N fertilizer rates resulted in cooler crop canopies. Grain N responded to irrigation and N, but the optimal irrigation level was at 0.50–0.54 irrigation. Yellow berry was absent at N rates of >252 kg N ha$^{-1}$ for all irrigation levels. Lower TKW, IUE, PE, and AE in the second season reflected lower grain yields compared to the first season. Recovery efficiency of N was high in both seasons, i.e., >70% for the highest yielding N and water combinations. This study suggests that irrigation management can be improved by the use of canopy temperature data, and that N fertilizer management could be adjusted with weather data that reflects the grain-filling period.

The optimal irrigation level for durum wheat grain yield was >than 1.0 base irrigation level in the high-yielding, favorable climate year of 2012–2013. In the warmer, low-yielding environment of the second season, the 1.0 irrigation level was the optimum. The agronomic optimum N fertilizer level was near the recommended 252 kg N ha$^{-1}$ rate in the first season, but was reduced to 220 kg N ha$^{-1}$ in the lower-yielding second season. The EONR decreased from 196 to 140 kg N ha$^{-1}$ in year two. Durum wheat growers would maximize profit and minimize risk of protein reduction by applying 200 kg N ha$^{-1}$ and maintaining root-zone soil moisture depletion below 45% at the 1.0 base irrigation level.

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