INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
13–035/2014/16–1–104–110
http://www.fspublishers.org

Full Length Article

Delineation of Management Zones and Response of Spring Wheat (*Triticum aestivum*) to Irrigation and Nutrient Levels in Saudi Arabia

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Abstract

This study was conducted to assess the soil spatial variability and determine the optimum fertilizer rate and irrigation regime to optimize grain yield of wheat. The experiment was carried out in a clay loam soil with center pivot irrigation system. Management zones of the field were delineated based on laboratory analyzed and geo-referenced soil EC, surface elevation from ASTER DEM (AST3A1) and historic composite Normalized Difference Vegetation Index (NDVI) from Landsat ETM+satellite imagery. A split plot experiment design with three replications was adopted. Main plot treatments consisted of four irrigation levels at 100, 90, 80 and 70% evapotranspiration (ET_c) and three fertilizer levels with 300:150:200 (low); 400:250:300 (medium) and 500:300:300 (high) kg $N:P_2O_5:K_2O$ ha^{-1} formed sub-plot treatments. The highest grain yield of 6.09 t ha^{-1} with water use efficiency (WUE) of 7.65 kg ha^{-1} mm^{-1} was obtained at 100% ET_c and lowest rate of fertilizer. Irrigation at 70% ET_c with fertilizer level of 300:200:200 kg $N:P_2O_5:K_2O$ ha^{-1} produced yield of 6.06 t ha^{-1} at WUE of 10.67 kg ha^{-1} mm^{-1}. This treatment combination resulted in saving of 30% water used in irrigation without sacrificing the yield. © 2014 Friends Science Publishers

Key words: Spring wheat; Management zones; Irrigation levels; Nutrient levels; Saudi Arabia

Introduction

Wheat is one of the important crops of Saudi Arabia, cultivated on an area of 219,505 ha producing 1,349,389 metric tons of grain. An average yield of 4.5 t ha^{-1} with fertilizer productivity of 40 kg wheat per kg fertilizer nutrient was reported (FAO, 2000). Oweis *et al*. (2000) reported that WUE in wheat can be substantially improved by adopting deficit irrigation to satisfy up to 66% of irrigation requirement in West Asia and North Africa (WANA) regions. Zhang *et al*. (2005) observed that grain yield and WUE of spring wheat in arid environments can be greatly improved by regulated deficit irrigation with reduced amounts of water. The amount of irrigation water used for spring wheat in Saudi Arabia varied from 600 ha^{-1} mm^{-1} in central region (Alderfasi, 2000) to 1200 ha^{-1} mm^{-1} in Al-Hassa region (Al-Barrak, 2006).

The concept of Precision Agriculture is quite new to Saudi Arabia. Delineation of management zones was used as a basis for site specific application of crop inputs (Fridgen *et al*., 2004; Farid *et al.*, 2013). Many ways of developing Variable Rate Application (VRA) maps, using spectral reflectance of soils and crops (Read *et al.*, 2002; Daniel *et al.*, 2003), aerial photography and satellite imagery (Fleming *et al.*, 2000; Seelan *et al.*, 2003; Moran *et al.*, 2007; Sullivan *et al*., 2007) and multi-temporal images (Murthy *et al*., 2003) within a growing season of crops, were reported. Lobell *et al*. (2003) and Liu *et al*. (2006) used satellite imagery in the estimation of wheat yield. There are no reports of studies from Saudi Arabia on delineation of management zones and use of VRA of inputs in crop production. Therefore, this research was carried out with the following objectives: (1) to create management zones of the study field and (2) to study the response of spring wheat to irrigation and nutrient levels.

Materials and Methods

The experiment was conducted on a farmer's field located between Al-Kharj and Haradh cities of Saudi Arabia within

To cite this paper: Patil, V.C., K.A. Al-Gaadi, R. Madugundu, E.H.M. Tola, S.A. Marey, A.M. Al-Omran, R. Khosla, S.K. Upadhyaya, D.J. Mulla and A. Al-Dosari, 2014. Delineation of management zones and response of spring wheat (*Triticum aestivum*) to irrigation and nutrient levels in Saudi Arabia. *Int. J. Agric. Biol.*, 16: 104–110

the latitudes of 24º10' 22.77" and 24º12' 37.25" N and the longitudes of 47º56' 14.60" and 48º05' 08.56" E.

Delineation of Management Zones

A management zone is a sub-region of field which is relatively homogenous. In this study, parameters such as lab analyzed soil EC, elevation from ASTER DEM (AST3A1, orthorectified product of ASTER Image) and composite Normalized Difference Vegetation Index (NDVI) were used as inputs for determining management zones, Management Zone Analysis (MZA) software (Fridgen, 2004).

A total of eight cloud free Landsat enhanced thematic mapper (ETM+) asatellite images (November 7 and December 25, 2009; February 11, October 18, November 3 and December 12, 2010; October 21 and December 8, 2011) were downloaded from Earth Explorer USGS website and NDVI images were prepared as per Rouse *et al*. (1973) and Sahoo *et al*. (2007). Geo-referenced data of lab analyzed soil EC, elevation from ASTER DEM and Landsat ETM+derived NDVI were subjected to fuzzy c-means cluster analysis. The output file was imported into the mapping program of ARC GIS 2010. Maps were created for two-zone columns based on MZA graphical representation of FPI and NCE performance indices relative to cluster number as described by Fraisse *et al*. (2001), then gridded to a common 10 m cell as per Kitchen *et al.* (2003).

Experimental Details

An experiment was laid out in the study field to determine the optimum levels of irrigation and fertilizer (nitrogen, phosphorus and potassium) for optimizing grain yield of wheat. The split plot design with three replications was adopted for the experiment, where the area covered by two spans formed one replication. The soil texture was clay loam with a pH of 7.58. The soil contained 72.53 (± 8.41) mg kg^{-1} N, 5.35 (± 3.58) mg kg^{-1} P and 60.81 (± 28.27) mg kg^{-1} K. The ground water used for irrigation had EC, pH, Sodium Absorption Ratio (SAR) of 3.178 (dSm^{-1}), 7.21 and 1.29, respectively.

Treatment

Hard red spring wheat (*Triticum aestivum* L.) seed (*cv.* Yecora Rojo) at 250 kg ha^{-1} was sown on January 1, 2012. Four irrigation treatments allocated to main plots were I_1: Irrigation at 100% ET_c, I_2: Irrigation at 90% ET_c, I_3: Irrigation at 80% ET_c and I_4: Irrigation at 70% ET_c and three levels of fertilizer nitrogen, phosphorus (P_2O_5) and potassium (K_2O) to the sub plots. The three fertilizer levels were defined as F1 (Low): 300:200:200 kg ha^{-1}; F2 (Medium): 400:250:250 kg ha^{-1} and F3 (High): 500:300:300 kg ha^{-1}. All of the phosphorus (Di-ammonium phosphate) and potassium (potassium sulphate) was band placed as basal. The remaining amount of nitrogen was applied as foliar spray in eleven splits starting from two weeks until ten weeks after sowing. After each irrigation cycle, nitrogen was applied at 20, 30 and 40 kg ha^{-1} in F1, F2 and F3, respectively. Irrigation requirement was worked out based on daily mean ET values recorded on the farm for the period between 1995 and 2011 (Allen *et al.*, 1998). Irrigation treatments were imposed by adjusting the pivot speed to deliver the required amount of water in each treatment.

Ground Truth Data Collection

Periodic data on crop $NDVI_{(G)}$ and $LAI_{(G)}$ at different crop growth stages corresponding to the Thermal time/Growing Degree Days (GDD) were collected (WMO, 2012). Hereafter, these stages will be referred to as Growth Stage 1, GS 1-(735 GDD) (February 17, 2012); GS 2(1047 GDD) (March 4, 2012); GS 3-(1353 GDD) (March 20, 2012); (April, 5, 2012); GS 4-(GDD 2111) (April 21, 2012). The crop was combine harvested at GS 5(2622 GDD) (May 9, 2012). The grain yield was recorded by weighing the combine harvested wheat corresponding to each treatment.

Normalized Difference Vegetation Index (NDVI)

$NDVI_{(G)}$ was measured in the field one meter above the crop canopy, on the dates of satellite pass, using the Crop Circle (Model: ACS-470) of Holland Scientific, USA. To determine field data coordinates, an OmniSTAR GPS receiver (Model 9200-G2) was connected to the Crop Circle.

Leaf Area Index (LAI)

LAI measurements on the ground ($LAI_{(G)}$) were made on the dates of satellite pass using the Plant Canopy Analyzer (Model: PCA – 2200) of LI-COR Biosciences, USA. At each measurement location, one above canopy and five below canopy readings were recorded to compute a single LAI value. Respective geo-locations were collected using a handheld Trimble GPS receiver (Model-Geo XH 600).

Satellite Data and Image Processing

Four ASTER images (February 17, March 4 and 20, and April 21, 2012) on full mode (L1a, L1B and 3A) were acquired from Japan Space Systems (http://ims.aster.ersdac.jspacesystems.or.jp). The spatial variation in the crop response was assessed with respect to predicted (ASTER generated) vegetation indices, such as $NDVI_{(P)}$ and $LAI_{(P)}$ for wheat in the 2011-2012 growing season. $NDVI_{(P)}$ was calculated using ASTER sensor bands 3 and 2 (Heiskanen, 2006). The scatter plot between computed $NDVI_{(P)}$ and field measured $NDVI_{(G)}$ at GS 2 was drawn and regressed for correlation (Zhang *et al*., 2012). Field measured $LAI_{(G)}$ was regressed against ASTER derived $NDVI_{(P)}$. The resulted regression equations were used to transform the satellite derived $NDVI_{(P)}$ to $LAI_{(P)}$ and construct the $LAI_{(P)}$ maps at GS 2 and 4 (Heiskanen, 2006; Zheng and Moskal, 2009).

Land Surface Temperature (LST)

The split-window algorithm of Mao *et al.* (2005) was used to retrieve LST from bands 13 and 14. This algorithm was coded to fit into Erdas Imagine by Sun *et al.* (2010), which was programmed for this study as per ENVI software (Ver. 5.0). The emissivity was calculated from the $NDVI_{(P)}$ as described by Van De Griend and Owe (1993) and Zhang *et al.* (2006).

Yield Map

Wheat grain yield map was prepared from the wheat yield (WY) data calculated by multiplying above ground biomass (AGB) by harvest index (HI) as described by Xin *et al.* (2009). AGB was estimated based on the function of radiation use efficiency and Photosynthetically Active Radiation (PAR). PAR was estimated from the $NDVI_{(P)}$ with the function of FPAR. Cumulative NDVI (CNDVI) was derived by averaging predicted NDVI (i.e. $NDVI_{(P)}$) of three stages (GS 2, 3 and 4) as described by Tucker *et al.* (1985) to compute mean AGB for the whole season. Subsequently, grain yield was estimated based on variations in pre and post $NDVI_{(P)}$ of grain filling stage.

Results

The management zone map for the field developed from soil EC, elevation and NDVI is presented in Fig. 1A. The field was divided in to two management zones.

Response of Wheat to Irrigation and Fertilizer Levels

Effect of irrigation and fertilizer levels on wheat grain yield and Water Use Efficiency (WUE): Crop yield integrates the effects of various soil, climate and management factors that vary across space and time. Irrigation and fertilizer levels significantly influenced the wheat grain yield (Table 1). Irrigating the crop at 100% ET_c resulted in higher grain yield (5.68 t ha^{-1}) than the lower irrigation levels. Lower level of fertilizer application at 300:200:200 kg of N, P_2O_5 and K_2O ha^{-1} recorded higher grain yield of 5.67 t ha^{-1} than medium and the high fertilizer levels. Treatment combinations of lower fertilizer level and irrigation at 100, or 90 or 80% ET_c were superior to irrigation at 70% ET_c. However, irrigation at 70% ET_c with medium fertilizer level produced a yield of 6.06 t ha^{-1}, which was on par with irrigation levels of 100 or 90% ET_c with lower fertilizer level (6.09 and 6.08 t ha^{-1}). Thus, saving in water of up to 30% can be assumed possible. The amount of water applied varied from 568 to 796 ha^{-1} mm^{-1}, with WUE vales ranging from 6.88 to 10.67 kg ha^{-1} mm^{-1} (Table 2).

Table 1: Effect of irrigation and fertilizer levels on wheat grain yield (t ha^{-1})

Irrigation Levels	Fertilizer Levels(N:P_2O_5:K_2O kg ha^{-1})			
	300:200:200	400:250:250	500:300:300	Mean
Irrigation at 100%ET_c	6.09	5.36	5.58	5.68
Irrigation at 90%ET_c	6.08	5.22	4.95	5.41
Irrigation at 80%ET_c	5.92	5.41	4.92	5.41
Irrigation at 70%ET_c	4.58	6.06	5.96	5.54
Mean	5.67	5.51	5.35	5.51
				$LSD_{0.05}$
For comparison between irrigation level means:				0.09
For comparison between fertilizer levels means:				0.06
Comparison between two fertilizer level means at the same irrigation treatment:				0.13
Comparison between two irrigation level means at the same or different fertilizer treatments:				0.11

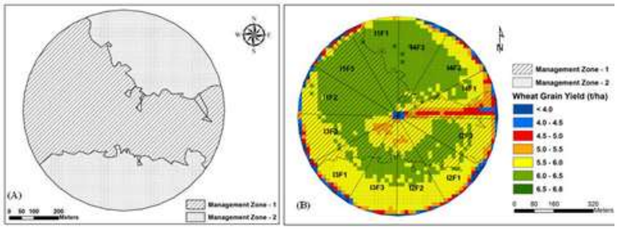

Fig. 1: (A) Management zone map; (B) Wheat grain yield map

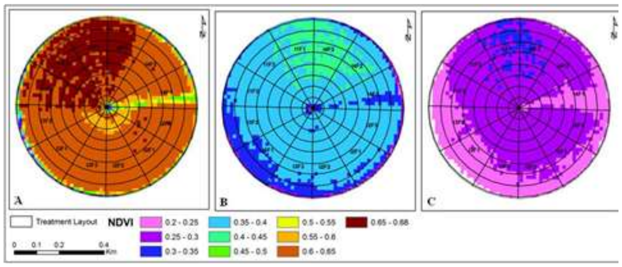

Fig. 2: Temporal changes in satellite derived NDVI ($NDVI_{(P)}$) of wheat at different crop growth stages: A) GS 2, B) GS 3 and C) GS 4

Grain Yield Map

The wheat grain yield map was computed from the cumulative NDVI derived from ASTER images of crop growth stages GS 2, 3 and 4. In the grain yield map (Fig. 1B), higher yields were found in the northern half of the field. The cNDVI derived grain yield was marginally higher in MZ-1 than in MZ-2 (Table 3). In both of the management zones, higher grain yield of 6.16 to 6.26 t ha^{-1} was observed at 100% ET_c, with the three fertilizer levels (Table 3). However, in MZ-2, similar grain yields (6.07 to 6.25 t ha^{-1}) were also observed with irrigation at 70% ET_c at medium and high levels of fertilizers.

Effect of irrigation and fertilizer levels on NDVI: Four sectors in the northern half of the field exhibited higher NDVI at GS 2. These sectors included all the three fertilizer levels with irrigation at 100% ET_c and higher fertilizer level with irrigation at 70% ET_c. However, with progression in the crop growth, higher NDVI area shifted

Table 2: Effect of irrigation and fertilizer levels ($N:P_2O_5:K_2O$ kg ha^{-1}) on grain yield and water use efficiency of spring wheat

Treatment	Water applied (mm)	Grain Yield (kg ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
I1F1	796	6090	7.65
I1F2	796	5360	6.73
I1F3	796	5580	7.01
I2F1	720	6080	8.44
I2F2	720	5220	7.25
I2F3	720	4950	6.88
I3F1	644	5920	9.19
I3F2	644	5410	8.40
I3F3	644	4920	7.64
I4F1	568	4580	8.06
I4F2	568	6060	10.67
I4F3	568	5960	10.49

I1F1 = Irrigation at 100% ETc. + 300:200:200; I1F2 = Irrigation at 100% ETc. + 400:250:250; I1F3 = Irrigation at 100% ETc. + 500:300:300; I2F1 = Irrigation at 90% ETc. + 300:200:200; I2F2= Irrigation at 90% ETc. + 400:250:250; I2F3 = Irrigation at 90% ETc. + 500:300:300; I3F1 = Irrigation at 80% ETc. + 300:200:200; I3F2 = Irrigation at 80% ETc. + 400:250:250; I3F3 = Irrigation at 80% ETc. + 500:300:300; I4F1 = Irrigation at 70% ETc. + 300:200:200; I4F2 = Irrigation at 70% ETc. + 400:250:250; I4F3 = Irrigation at 70% ETc. + 500:300:300

Table 3: Wheat grain yield (t ha^{-1}) data derived from cumulative NDVI

Treatment	Grain yield (t ha^{-1})		
	Management Zone–1	Management Zone – 2	Mean
I1F1	6.25	6.26	6.26
I1F2	6.16	**	6.16
I1F3	6.21	**	6.21
I2F1	5.94	5.91	5.92
I2F2	5.92	5.91	5.92
I2F3	5.97	5.80	5.88
I3F1	5.92	5.88	5.90
I3F2	6.06	**	6.06
I3F3	5.91	5.92	5.91
I4F1	5.83	5.87	5.85
I4F2	5.83	6.07	5.95
I4F3	6.14	6.25	6.20
Mean	**6.01**	**5.98**	**6.00**

** The treatments did not fall in Management Zone- 2
I1F1 = Irrigation at 100% ETc. + 300:200:200; I1F2 = Irrigation at 100% ETc. + 400:250:250; I1F3 = Irrigation at 100% ETc. + 500:300:300; I2F1 = Irrigation at 90% ETc. + 300:200:200; I2F2= Irrigation at 90% ETc. + 400:250:250; I2F3 = Irrigation at 90% ETc. + 500:300:300; I3F1 = Irrigation at 80% ETc. + 300:200:200; I3F2 = Irrigation at 80% ETc. + 400:250:250; I3F3 = Irrigation at 80% ETc. + 500:300:300; I4F1 = Irrigation at 70% ETc. + 300:200:200; I4F2 = Irrigation at 70% ETc. + 400:250:250; I4F3 = Irrigation at 70% ETc. + 500:300:300

slightly to the right at GS 3. At this stage, three sectors maintained higher NDVI. These sectors represented irrigation at 100% ET$_c$ with lower fertilizer level and irrigation at 70% ET$_c$ with medium and high fertilizer levels. The relation between NDVI$_{(G)}$ and NDVI$_{(P)}$ at GS 2 was highly significant (Fig. 3A). Similar relationship was observed between grain yield and NDVI$_{(G)}$ and NDVI$_{(P),}$ (Fig. 3B). However, the R^2 value was higher with NDVI$_{(G)}$ (0.62) than with NDVI$_{(P)}$ (0.56).

Effect of irrigation and fertilizer levels on LAI: There

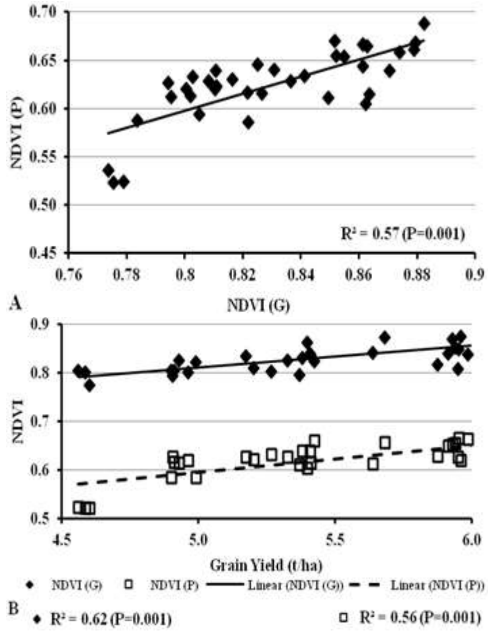

Fig. 3: Regression between **(A)** field measured (NDVI$_{(G)}$) and satellite image derived NDVI (NDVI$_{(P)}$) of GS 2; (B) Grain yield and field measured (NDVI$_{(G)}$) and satellite image derived NDVI (NDVI$_{(P)}$) of GS 2

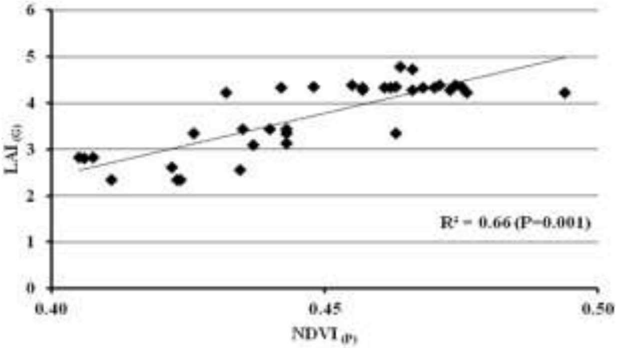

Fig. 4: Regression between field measured LAI (LAI$_G$) and satellite image derived NDVI (NDVI$_P$) of GS 2

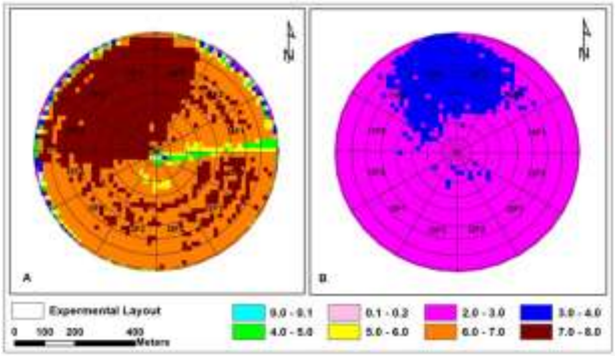

Fig. 5: Temporal changes in ASTER derived LAI $_{(P)}$ of wheat crop at different crop growth stages: A) GS 2, and B) GS 4

Table 4: Regression between wheat grain yield and measured vs satellite derived LAI and NDVI*

Sl. No	Parameter	Stage	Equation	R^2	Adj R^2	Error of estimation
1	$NDVI_{(G)}$ and $NDVI_{(P)}$	GS 2	$NDVI_{(P)} = 0.6456*NDVI_{(G)}+0.5701$	0.57	0.56	0.002
		GS 4	$NDVI_{(P)} = 0.9971*NDVI_{(G)}+0.03413$	0.26	0.23	0.018
2	$LAI_{(G)}$ and $NDVI_{(P)}$	GS 2	$LAI_{(G)} = 13.542*NDVI_{(P)}-2.8858$	0.54	0.52	0.666
		GS 4	$LAI_{(G)} = 17.647*NDVI_{(P)}-0.6337$	0.52	0.51	0.367
3	$LAI_{(G)}$ and $LAI_{(P)}$	GS 2	$LAI_{(P)} = 0.7567*LAI_{(G)}+1.7456$	0.68	0.67	0.548
		GS 4	$LAI_{(P)} = 0.8942*LAI_{(G)}-0.6348$	0.48	0.46	0.494
4	Grain Yield and $NDVI_{(G)}$	GS 2	$Yield = 13.821*NDVI_{(G)}-6.0231$	0.62	0.61	0.318
5	Grain Yield and $NDVI_{(P)}$	GS 2	$Yield = 10.135*NDVI_{(P)}-0.8157$	0.56	0.55	0.343
6	Grain Yield and $LAI_{(G)}$	GS 2	$Yield = 0.3446*LAI_{(G)}+3.4874$	0.53	0.52	0.352
7	Grain Yield and $LAI_{(P)}$	GS 2	$Yield = 0.4579*LAI_{(P)}+2.6884$	0.59	0.58	0.330

*Significant at P = 0.001

was a strong correlation between $LAI_{(G)}$ and $NDVI_{(P)}$ at GS 2 (Fig. 4). The R^2 values between $LAI_{(P)}$ and $LAI_{(G)}$ were highly significant at GS 2 (0.68) and GS4 (0.48) (Table 4). The temporal changes in $LAI_{(P)}$ at GS 2 and GS 4 can be seen in (Fig. 5). At GS 2, R^2 value observed between grain yield and $LAI_{(P)}$ (0.59) was higher than the R^2 value between grain yield and $LAI_{(G)}$ (0.53) (Fig. 6).

Effect of irrigation and fertilizer levels on Land Surface Temperature (ºC): Lower Land Surface Temperature (LST) areas in the northern parts of the field at GS 3 and 4 (Fig. 7) were associated with high yielding irrigation treatments i.e., at 100 and 70% ET_c.

Discussion

In this study, three years' Landsat ETM+ images were used in identifying management zones. Boydell and McBratney (2002) used multi-year Landsat TM imagery for identifying potential within-field management zones. Arno *et al.* (2011) used fuzzy *c*-means algorithm for better identification of site-specific management zones. The experimental field was delineated in to two convenient management zones. The number of zones was decided based on the least number of classes observed (two) in the Normalized Classification Entropy (NCE) index value.

Application of lower level of fertilizers (300: 200:200: kg ha^{-1} of $N:P_2O_5:K_2O$) was sufficient to meet the crop requirements and produced significantly higher measured grain yield (Table 1). Similar lack of response of spring wheat to higher N fertilizer levels was reported by Wang *et al.* (2012) who obtained 7.4% higher grain yield at 221 kg N ha^{-1} than at 300 kg N ha^{-1}. Further increase in the levels of fertilizers caused yield reduction. The yield reduction might be due to the excessive vegetative growth that could have resulted in moisture stress during grain filling stage. The observed differential response of wheat was due to the synergistic effect of irrigation and fertilizer levels. When the quantity of irrigation water was sufficient, lower level of fertilizer was enough to produce the maximum yield. However, when the quantity of irrigation water was reduced, lower fertilizer level did not suffice and medium and higher fertilizer levels, especially those of phosphorus and potassium, were necessary to maintain the higher yield levels.

The higher grain yield seen in northern part of the field, corroborates well with the higher grain yield harvested (Table 1) with irrigation at 100% ET_c with all the three fertilizer levels and irrigation at 70% ET_c with medium and high levels of fertilizers The variability in the grain yield was mainly due to the effect of treatments rather than due to the differences between the management zones. Majority of the variability (88.6%) in wheat grain yield was observed within treatments and was attributed mainly to variations in management (Lobell *et al.* , 2002). Studies have shown that seasonal accumulated NDVI values have been correlated well with the reported crop yields in semi-arid regions (Groten, 1993). Doraiswamy and Cook (1995) demonstrated that accumulated AVHRR derived NDVI values for spring wheat only during grain filling period improved the estimates of crop yields in North Dakota. Further, Doraiswamy *et al.* (1996) found that spring wheat yield simulated from Landsat TM data was similar to country average and farm level reported yields. Lee *et al.* (2010) also developed a yield map from ASTER satellite imagery for mapping within-field yield variability and as a surrogate to yield monitor data.

The highly significant R^2 values (Table 4) between $LAI_{(G)}$ and $NDVI_{(P)}$ at GS 2 (0.54) and GS 4 (0.52) were similar to the R^2 value of 0.52 reported earlier by Chen and Cihlar (1996). The pattern of spatial variability in $LAI_{(P)}$ at GS 4 (Fig. 5B) and grain yield (Fig. 1B) was noted to be similar. At GS 4, higher $LAI_{(P)}$ was seen to be more in the northern part of the field than in other areas. This resulted in higher grain yield, presumably due to the greater leaf area duration. Maas (1988) used LAI derived from satellite data to improve model estimates of crop yield. Monitoring of LAI during the crop growth cycle was helpful to assess crop response to levels of inputs (Dente *et al.*, 2008).

Lower LST areas of the field associated with high yielding irrigation treatments (at 100 and 70% ET_c), can be attributed to the moderating effect of lower temperatures during grain filling and maturity stages. High temperature in the terminal growth stage of wheat was reported to have serious negative effects on grain yields (Egli, 2004; Ugarte *et al.*, 2007).

Although highest rate of irrigation (at 100% ET_c) resulted in significantly higher grain yield than the lowest rate of irrigation (at 70% ET_c) (Table 1), higher WUE of

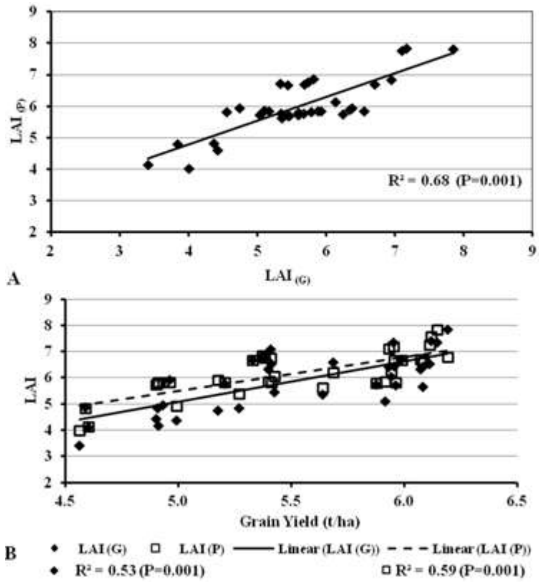

Fig. 6: Relationship between **(A)** Ground measured $\text{LAI}_{(G)}$ and ASTER derived $\text{LAI}_{(P)}$ (B) Grain yield Vs. $\text{LAI}_{(G)}$ and $\text{LAI}_{(P)}$ of GS 2

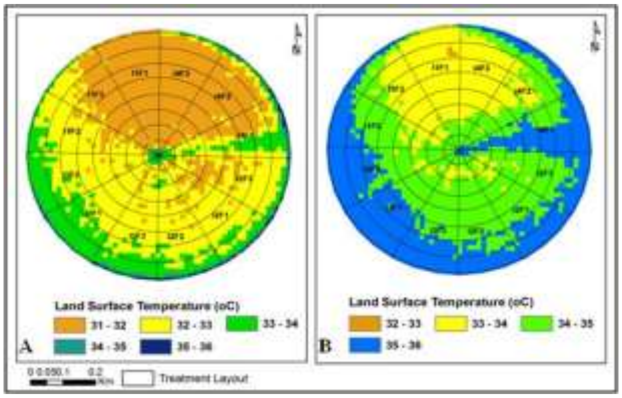

Fig. 7: Temporal changes in ASTER derived Land Surface Temperature (ºC) at different crop growth stages: A) GS 3 and B) GS 4

9.74 kg ha^{-1} mm^{-1} was observed with the lowest rate of irrigation than with the highest rate of irrigation (7.13 kg ha^{-1} mm^{-1}). Irrigation effectively increases crop yield although water-use efficiency (WUE) decreases as the irrigation rate increases (Al-Kaisi and Yin, 2003). Hussain and Al-Jaloud (1995) obtained wheat grain yield of 5.01 t ha^{-1}, with WUE of 2.67 to 12.24 kg grain ha^{-1} mm^{-1} in Saudi Arabia. Alderfasi (2000) did not observe significant effect of irrigation levels on grain yield of four wheat genotypes grown on sandy loam soil in the central region (Riyadh area) of Saudi Arabia. However, they observed very high WUE of 23 to 31.8 kg ha^{-1} mm^{-1} by irrigating the crop at 100 mm CPE (600 mm water). Al-Barrak (2006) obtained wheat grain yield of 6.5 tons ha^{-1} with WUE of 6.5 kg m^{-3} on a sandy loam soil in Al-Hassa region of Saudi Arabia. It was further reported that the increase in the amount of irrigation over and above 12000 m^3 ha^{-1} did not increase the yield. Mustafa *et al*. (1989) reported that 1146 mm ha^{-1} (11460 m^3 ha^{-1}) was needed to produce 6.5 tons ha^{-1} of wheat grain in Tabuk region of Saudi Arabia. The highest amount of irrigation water applied in this study (between Al-Kharj and Haradh regions) was 796 mm ha^{-1} with irrigation at 100% ET_c, as against 600 mm ha^{-1} in the central region, 1200 mm ha^{-1} in Al-Hassa region and 1146 mm ha^{-1} in Tabuk regions. The regional differences justify assessment of irrigation needs of crops in different regions within Saudi Arabia.

IN conclusion, two management zones were delineated in a 50 ha field based on soil EC, NDVI and elevation based on the least number of classes observed in the Normalized Classification Entropy (NCE) index value. Irrigation at 100% ET_c resulted in grain yield of 5.68 t ha^{-1}, which was significantly superior to the other three lower levels of irrigation. Application of 300:200:200 kg ha^{-1} of $\text{N:P}_2\text{O}_5\text{:K}_2\text{O}$, produced the highest yield of 5.67 t ha^{-1}. Increasing the levels of fertilizers decreased the grain yield. Irrigation at 70% ETc coupled with application of 400:250:250 kg ha^{-1} of $\text{N:P}_2\text{O}_5\text{:K}_2\text{O}$ resulted in water saving of 30% without affecting the yield. Yield map generated from the Cumulative NDVI helped in assessing the effect of different treatments on grain yield in the absence of yield monitor. GS 2 of wheat corresponding to 1047 GDD or 63 days after sowing showed good correlation with grain yield.

Acknowledgements

This research work was carried out in the project number 10 SPA 1193-02 supported by the NSTIP strategic technologies program in the Kingdom of Saudi Arabia. The assistance provided by the graduate students, namely, Eng. Mohammed Elsiddig Ali Abass, Eng. Ahmed Galal Kaiad and Eng. Ahmed Hassan Zeyada in the field was quite valuable. The unstinted cooperation and support extended by Mr. Jack King, Mr. Alan King, and Mr. Noel Hernandez in carrying out the research work are gratefully acknowledged.

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(Received 10 January 2013; Accepted 06 May 2013)