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Water productivity mapping of agricultural fields in Saudi Arabia using landsat-8 imagery

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ABSTRACT

The main goal of this study was to develop water productivity map (WPM) from crop yield, and crop water use (actual evapotranspiration) maps. The study focused on WPM of alfalfa, corn and Rhodes grass crops cultivated on a commercial farm in Al-Kharj region of Saudi Arabia. The Surface Energy Balance Algorithm for Land (SEBAL) was applied on Landsat-8 image for October 9, 2013, to derive ET from thermal bands for developing Water Use Map (WUM). The accuracy of SEBAL derived evapotranspiration (ET) was assessed by comparing it with the actual ET recorded by the Eddy Covariance (EC) system installed on the farm. Crop Productivity Map (CPM) was developed for the farm from NDVI based crop yield models. WPM was generated by dividing the CPM with WUM. The deviation between SEBAL predicted ET and that recorded by Eddy Covariance flux tower was 22.22%. The mean predicted yield (kg/ha) of alfalfa, corn and Rhodes grass was 2934 (± 1738), 4650 (± 4557) and 3368 (± 1882), respectively. The predicted water productivity (kg/m^3) of corn was (0.99) higher than that of Rhodes grass (0.59) and alfalfa (0.55).

Keywords: Eddy covariance, evapotranspiration, SEBAL, Saudi Arabia, water productivity.

1. INTRODUCTION

Groundwater plays a vital role in sustaining agricultural production in many irrigated areas of the world. The rapidly growing competition for surface water resources among domestic use, industry, and agriculture, has resulted in substituting surface water by groundwater resources. Most of the 750 to 800 km^3/year of global groundwater withdrawals are used for irrigated crops (Shah et al. 2000). Application of the Surface Energy Balance Algorithm for Land (SEBAL) for the estimation of ground water extraction at the national level in Pakistan, Mexico and Saudi Arabia was reported by Bastiaanssen et al. (2007). In their study, SEBAL was applied on NOAA-AVHRR images for the period 1975 to 2004 to compute Kingdom wide groundwater abstraction, which was 21.75 km^3/year for the year 2003. In another study, Abderrahman (2005) reported a Kingdom wide abstraction of 21.5 km^3/year for 2004, using census data and crop water requirement models. Such studies are needed on a continuous basis to monitor the spatio-temporal ground water extraction patterns, which are lacking in recent years. Moreover, there are no reports on evapotranspiration (ET) data collection using Eddy Covariance (EC) system in Saudi Arabia. In this paper, SEBAL model (Bastiaanssen et al. 1998) and crop yield prediction models (Patil et al. 2014) were employed for developing water productivity map of a commercial farm in Saudi Arabia, using Landsat-8 imagery and ET data from EC system. The results of this study are useful in understanding the spatio-temporal variability in water use by crops, to decide on optimum cropping patterns for efficient use of ground water resources and to formulate policies for managing these resources.

2. MATERIALS AND METHODS

The study was carried out in Todhia Arable Farm (TAF), a farm of 47 fields (each of about 50 ha) under center pivot irrigation systems spread across an area of 6,967 ha. The farm lies within latitudes

24º10'22.77" and 24º12'37.25" N and within longitudes 47º56'14.60" and 48º05'08.56" E (Fig. 1). Alfalfa, corn and Rhodes grass cultivated as fodder crops were investigated for yield (t/ha), ET (m^3/ha/cropping period) and WP (kg/m^3). Cropping pattern of TAF for 2013, was provided in Table 1.

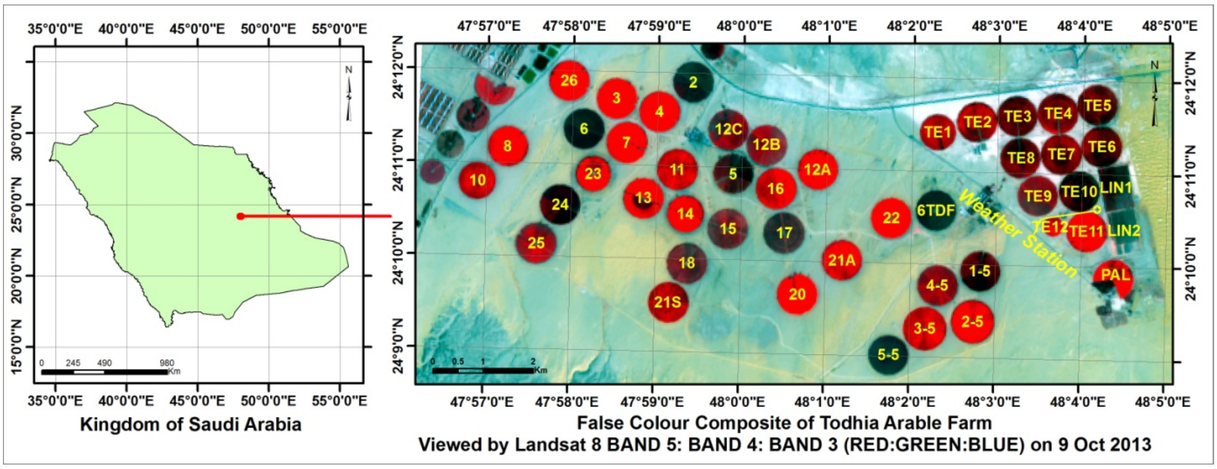

Figure 1. Location map of the study area along with field identities.

Table 1: The cropping pattern of Todhia Arable Farm for the year 2013

Crop	Total Number of Fields	Pivot (field) Number	Total Area (ha)
Alfalfa	18	2, 3, 4, 6, 7, 8, 13, 14, 16, 20, 22, 23, 24, 26, 12a, 21a, 6TDF, TE11	900
Corn	12	5, 1-5, LIN, TE1, TE10, TE2, TE3, TE4, TE5, TE6, TE7,TE8	640
Rhodes Grass	16	10, 11, 15, 17, 18, 25, 12B, 12C, 21s, 2-5, 3-5, 4-5, 5-5, PAL, TE12, TE9	592

Remote sensing based Energy Balance models were used to convert satellite sensed radiances into land surface based characteristics such as albedo, leaf area index (LAI), vegetation indices, surface emissivity, and surface temperature to estimate ET as a residual of the land surface EB equation as defined by (1):

$$LE = \mathrm{R_n} - G - H \qquad (1)$$

where, R_n is the net radiation resulting from the energy budget of short and long wave radiation, LE is the latent heat flux from ET, G is the soil heat flux into the ground, and H is the sensible heat flux (all terms in units of W/m^2) to the atmosphere. LE was converted to ET (mm/day) by dividing it by the latent heat of vaporization (lv; ~2.45 MJ/kg), the density of water (rw; ~1.0 Mg/m^3), and an appropriate time constant (e.g., 3600 s/h for hourly ET).

2.1 Processing of Landsat image

Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) images consist of nine spectral bands and two thermal bands (Table 2). Thermal bands 10 and 11 are useful in providing more accurate surface temperatures. Approximate scene size is 170 km north-south by 183 km east-west.

Landsat-8 image dated October 9, 2013 pertaining to Path-165 and Row-43 downloaded from the USGS site was used in this study to generate evapotranspiration, crop productivity and water productivity maps. The acquired image was radiometrically calibrated adopting “Top of Atmosphere (TOA)” through an equation based on values provided in the *.MTL file which was available with the imagery upon download (USGS, 2013; GIS-AG-Maps, 2013). Except TIR bands, scene centered Sun elevation angle (58.24078760°) and sun earth distance (1.0033825 (AU)) of the acquired image was used in computation of reflectance. Surface temperature (K) was obtained from thermal bands as described by Ghulam (2009). The Normalized Difference Vegetation Index (NDVI), which is widely used for the assessment of remotely sensed data, was derived from red (Band 4) and near-infrared (Band 5) channels (Rouse et al. 1973).

Table 2: Band details of Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) launched on February 11, 2013

Band	Description	Wavelength (μm)	Resolution (m)	RMB	RAB	RFMB	RFAB
1	Coastal aerosol	0.43 - 0.45	30	0.012816	-64.08188	0.00002	-0.1
2	Blue	0.45 - 0.51	30	0.013069	-65.34665	0.00002	-0.1
3	Green	0.53 - 0.59	30	0.011967	-59.83549	0.00002	-0.1
4	Red	0.64 - 0.67	30	0.010135	-50.67699	0.00002	-0.1
5	NIR	0.85 - 0.88	30	0.0061503	-30.75136	0.00002	-0.1
6	SWIR 1	1.57 - 1.65	30	0.0015496	-7.74781	0.00002	-0.1
7	SWIR 2	2.11 - 2.29	30	0.0005040	-2.52035	0.00002	-0.1
8	PAN	0.50 - 0.68	15	0.011417	-57.08443	0.00002	-0.1
9	Cirrus	1.36 - 1.38	30	0.025274	-12.63701	0.00002	-0.1
10	* TIRS 1	10.60 - 11.19	100	0.0003342	0.10000	0.00002	-0.1
11	*TIRS 2	11.50 - 12.51	100	0.0003342	0.10000	0.00002	-0.1

* TIRS bands are acquired at 100 meter resolution, but are resampled to 30 meter in delivered data product.
RMB = Band-specific multiplicative rescaling factor for Radiance; RAB = Band-specific additive rescaling factor for Radiance; RFMB = Band-specific multiplicative rescaling factor for Reflectance; RFAB = Band-specific additive rescaling factor for Reflectance.

2.2 Water productivity mapping (WPM)

Crop water productivity mapping (WPM) was achieved in three steps as per Platonov et al. (2008); Crop productivity mapping (CPM), Water use (evapotranspiration) mapping (WUM) and Water productivity mapping (WPM).

Table 3: Eddy covariance data used to compute ET (mm/hr) on the date of satellite pass

Sl.No	Parameter	Unit	Value
1	H	[W+1m-2]	-53.31
2	LE	[W+1m-2]	517.26
3	Air temperature	[K]	299.88
4	Air pressure	[Pa]	97541.43
5	Air density	[kg+1m-3]	1.12
6	Air heat capacity	[J+1kg-1K-1]	1017.53
7	Air molar volume	[m+3mol-1]	0.03
8	ET	[mm]	0.38
9	Water vapor density	[kg+1m-3]	0.015
10	E	[Pa]	2088.74
11	Es	[Pa]	3498.04
12	RH	[%]	59.71
13	VPD	[Pa]	1409.30
14	T_{dew}	[K]	291.36
15	Wind speed	[m+1s-1]	4.34

The crop yield prediction models developed for the farm by Patil et al. (2013) were used to develop CPM. Water use map (WUM) was prepared by using crop ET assuming that the amount of water used by crops was equal to seasonal ET_{actual}. The ET_{24} (per day) was obtained from Landsat-8 thermal data by applying Surface Energy Balance Algorithm for Land (SEBAL) model as described in Bastiaanssen et al. (2005). The weather components of SEBAL were taken from the Eddy Covariance (EC) system, which was located in the farm (Table 3). The Landsat derived ET (mm/day) was up-scaled by multiplying ET with the age of crops (number of days). In alfalfa and Rhodes grass crops, number of days after the previous harvest was considered to determine the age. While in corn, date of sowing was considered to determine the age. Water Productivity Map (WPM) was created by dividing the crop productivity map (CPM) with water use map (WUM).

3. RESULTS

Evapotranspiration (ET) of crops (mm/day) for the day of satellite pass (9 October, 2013) was provided in Table 4 and Figure 2. Landsat-8 image derived ET (mm/hr) was 0.28 (± 0.22) as compared to Eddy Covariance (EC) recorded ET of 0.18 (±0.17). Data on crop yield (kg/ha), ET (m^3/ha) and water productivity (kg/m^3) were provided in Table 5. The NDVI based crop yield maps were depicted in Figure 3. The average predicted yield (kg/ha) for alfalfa, corn and Rhodes grass was 2934 (± 1738), 4650 (± 4557) and 3368 (± 1882), respectively. Water productivity (kg/m^3) of 0.55, 0.59 and 0.95 was predicted for alfalfa, Rhodes grass and corn, respectively.

Table 4: Predicted ET (mm/day) using Landsat-8 image

Crop	Min	Max	Range	Mean	SD
Alfalfa	0.61	3.46	2.34	2.87	0.42
Corn	0.54	3.26	2.22	2.47	0.41
Rhodes Grass	0.61	3.46	2.16	2.55	0.35

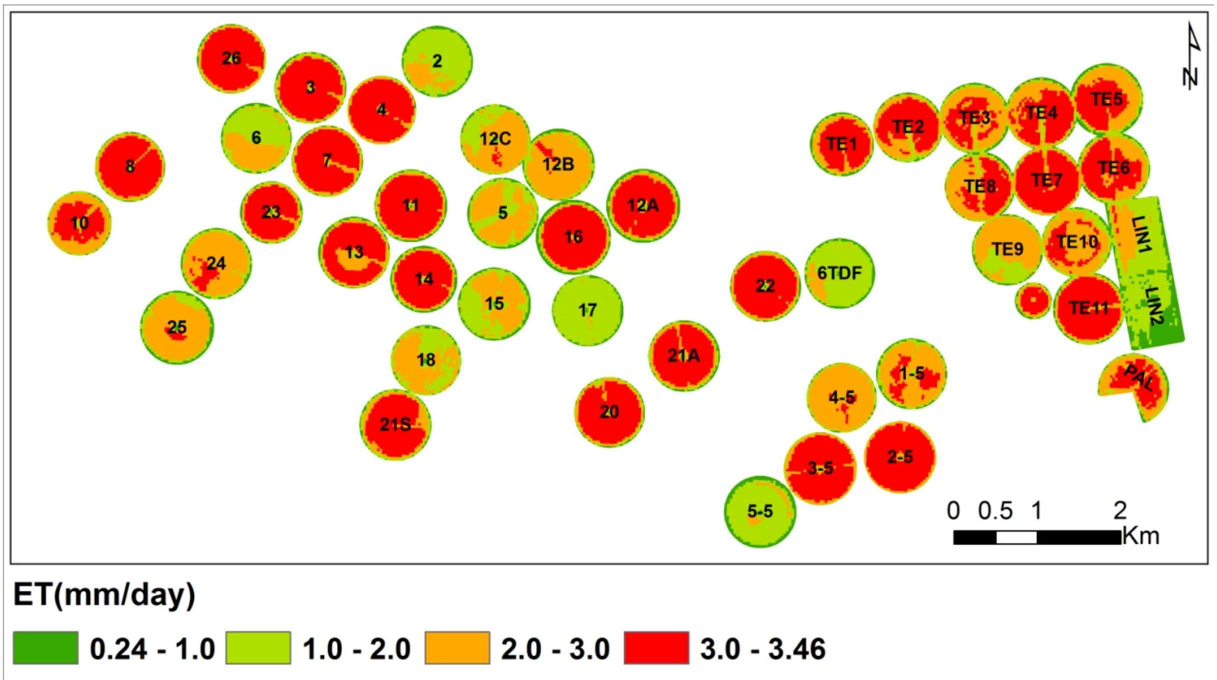

Figure 2: Crop water use map developed from Landsat-8 predicted ET

4. DISCUSSION

The deviation between mean ET derived from Landsat-8 image and that from EC system was 22%. The obtained results were in agreement with the previous report of Bastiaanssen et al. (2005), wherein most remote sensing techniques used for estimating evaporation (E) were reported to have accuracies of 70-85% compared with ground based measurements.

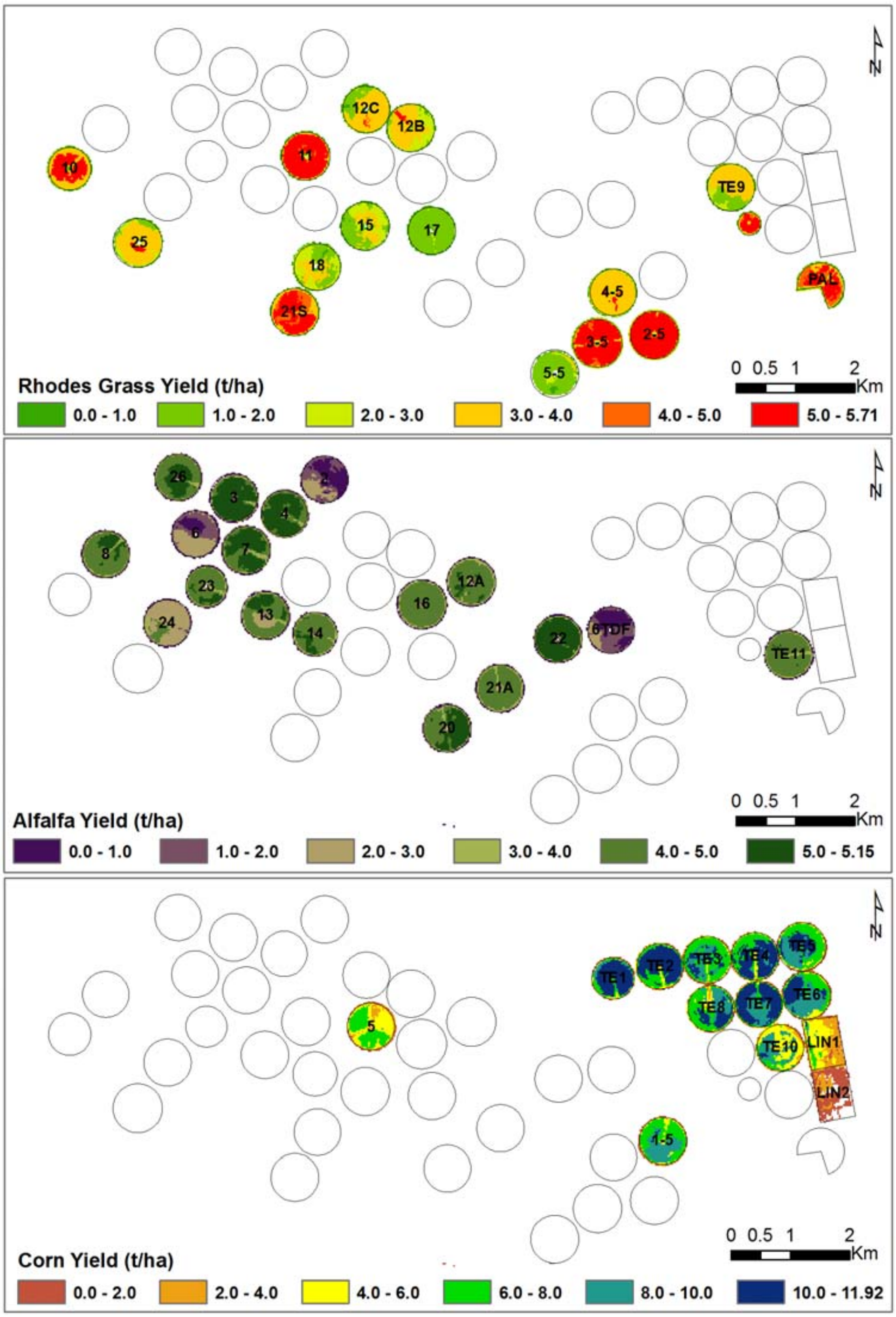

Figure 3. Crop productivity map of Rhodes grass, alfalfa and corn

In a previous study that summarized the accuracy of ET prediction using the Surface Energy Balance Algorithm for Land (SEBAL) model, although under different climatic conditions, the accuracy at field scale was 85% for one day (Kalma et al. 2008). However, in a study that used SEBAL model to estimate ET in Philippines, the deviation was reported to be much lower at 3% between Landsat-7 ETM+ ET and Penman-Monteith ET_c (Bastiaanssen and Bos 1999). The reasons for such differences in the accuracies could be attributed to the gradation of individual pixels' evaporative response which reflects upon the diversity of crops, growth stages, and gradients in soil moisture conditions across the fields (Hafeez et al. 2002; Mc-Cabe et al. 2005).

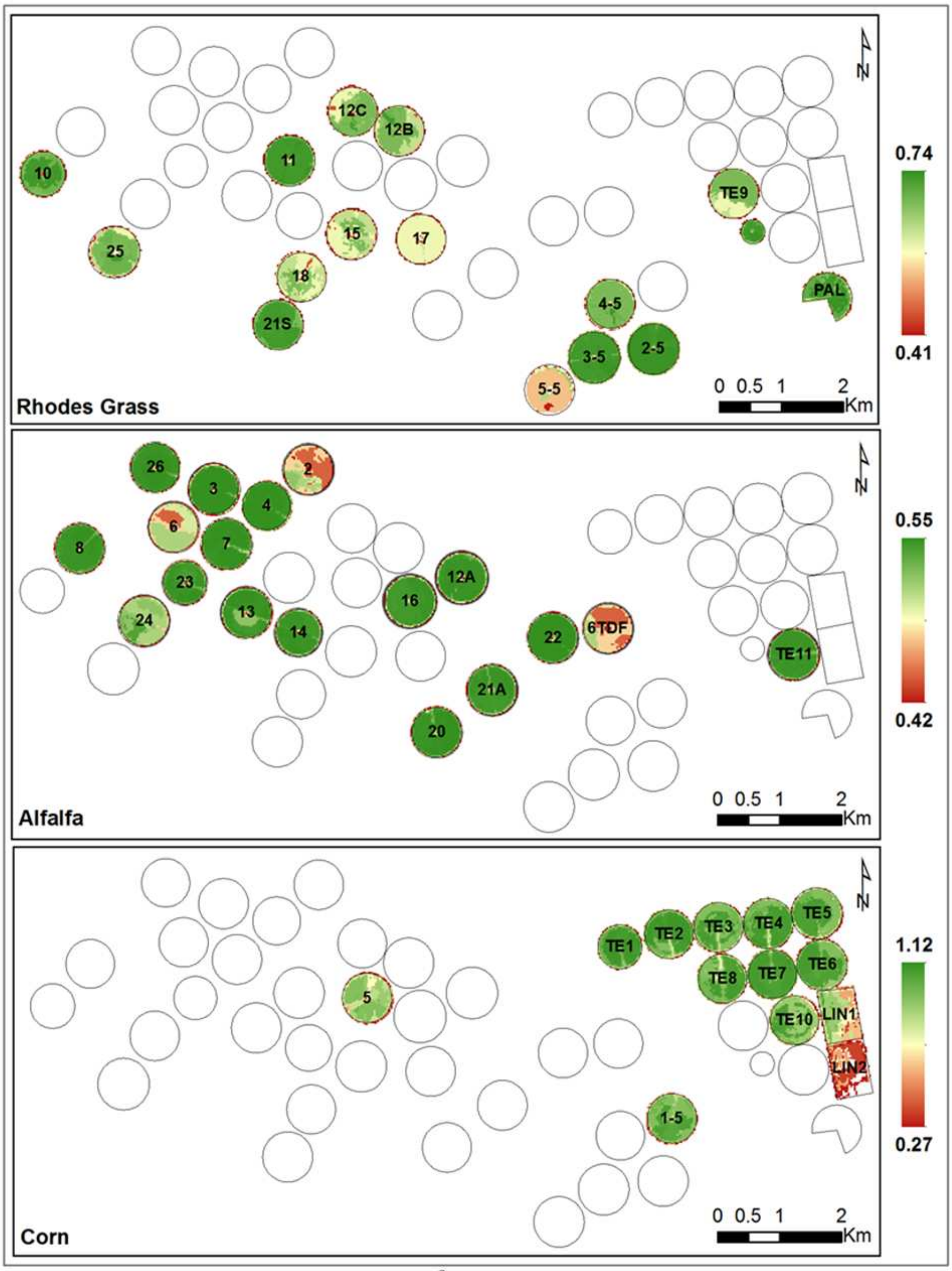

Figure 4. Water productivity (kg/m^3) map of Rhodes grass, alfalfa and corn

The predicted productivity/yield of crops showed visible and significant spatial variability both within and across the center pivot fields which could be seen in Fig. 3. The predicted yield of corn was much higher than in alfalfa and Rhodes grass. These yield differences among the crops could be due not only to differences in the nature of crops, but also to the age of crops at the time of satellite pass (Table 5).

The water productivity of alfalfa observed in this study (0.55 kg/m^3) was higher than the range of 0.38 – 0.43 kg/m^3 reported by Patil et al. (2014), but in close agreement with the values of up to 0.60 kg/m^3 reported recently by Ismail and Marshadi (2013). This small variation may be attributed to the influence of both spatial and seasonal climatic variations on ET, alfalfa productivity and water use efficiency.

For corn, the predicted WP of 0.95 kg/m^3 was in close agreement with the WP of 1.01 kg/m^3 reported by Moayeri et al. (2011). However, there were other reports with much higher WP of 0.58 - 1.74 kg/m^3 (Karimi and Gomrokchi 2011) and 1.91 to 4.4 kg/m^3 (Rafiee and Shakarami 2010). WP of 0.59 kg/m^3 for Rhodes grass observed in this study was closer to the earlier reported values of 0.53-0.85 kg/m^3 (Owens et al. 2008), but was lower than the values (1.18 – 2.13 kg/m^3) reported by ICARDA (2007).

Table 5: Predicted CP, ET and WP for the specified crop phenology (days after sowing/harvesting)

Crop	CP (kg/ha)		ET (m^3/ha/cropping period)		WP (kg/m^3)		Crop age on the date of Landsat-8 Pass	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Alfalfa	2934	1738	7025	378	0.55	0.09	22	8
Corn	4650	4557	4739	465	0.95	0.27	48	28
Rhodes Grass	3368	1882	5255	346	0.59	0.15	29	14

5. CONCLUSION

This study concludes that, SEBAL algorithm using the Landsat-8 imagery provided realistic estimates of ET, crop productivity and water productivity for alfalfa, Rhodes grass and corn crops cultivated under centre pivot irrigation system in Saudi Arabia. Water productivity of 0.55, 0.59 and 0.95 kg/m^3 was predicted for alfalfa, Rhodes grass and corn, respectively. The predicted ET value deviated by 22% from the Eddy Covariance ET data, is an issue that needs further empirical research.

6. ACKNOWLEDGEMENTS

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