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King Saud University

Water Productivity mapping and assessment of irrigation performance for irrigation water conservation: A study in Al-Kharj region of Saudi Arabia

The National Plan for Science & Technology (NPST)

Precision Agriculture Research Chair (PARC)

Water Productivity mapping and assessment of irrigation performance for irrigation water conservation: A study in Al-Kharj region of Saudi Arabia

Project Information

Project Code	11- SPA1503 - 02
Project Title	Water Productivity mapping and assessment of irrigation performance for irrigation water conservation: a study in Al-Kharj region of Saudi Arabia
Principal Investigator	Prof. V.C. Patil
Institution	Precision Agriculture Research Chair, King Saud University
Strategic Technology Area	Space and Aeronautics; Track: Earth Observation
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Project Budget	(SR) 1,988,060
Website	http://rp.ksu.edu.sa

The National Plan for Science & Technology (NPST)

Precision Agriculture Research Chair (PARC)

Precision Agriculture Research Chair (PARC) successfully implemented a research project entitled "**Water Productivity mapping and assessment of irrigation performance for irrigation water conservation: a study in Al-Kharj region of Saudi Arabia**". This project was funded by the National Plan for Science and Technology (NPST).

About the Project

Water used for irrigation in the Kingdom of Saudi Arabia is mainly pumped from deep aquifers (up to 1000 m) to feed the center-pivot irrigation systems at enormous economic and environmental costs. This situation warrants an urgent need for attaining sustainability of agriculture. However, it is becoming increasingly difficult to maintain equilibrium between water and food securities. This critical equilibrium emphasizes the Kingdom's need for strategic technologies and methods to drastically reduce the current depletion rate of groundwater resources and optimize water consumption without reducing agricultural production. This can be achieved through efficient use of irrigation water.

In view of the above and a felt need for assessing water productivity (WP) of agricultural fields irrigated through center pivot irrigation system, this study was undertaken with the goal of developing Water Productivity Map (WPM) using Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery across spatial-temporal domains.

Project Objectives:

1. To develop and evaluate maps of crop types, cropping intensity and crop productivity.
2. To evaluate energy balance algorithms for mapping daily and seasonal crop water use at field, landscape and regional scales.
3. To develop and evaluate water productivity maps of major irrigated crops of the region over space and time.
4. To study the accuracies and errors involved in WPM across scales, radiometry and bandwidth.

Team members

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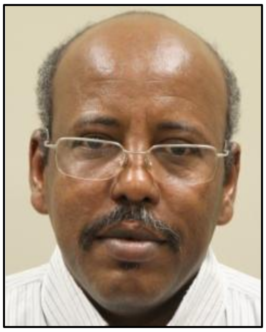

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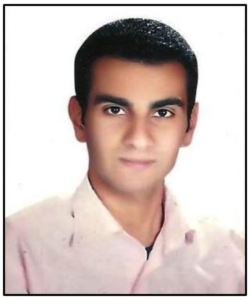

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Research Methodology

1. Study Area

The experimental site, Todhia Arable Farm (TAF), comprising 47 center pivots spread across 6,967 ha is located between Al-Kharj and Haradh and lies within latitudes 24°10' 22.77" and 24°12' 37.25" N and within longitudes 47°56' 14.60" and 48°05' 08.56" E (**Fig. 1**).

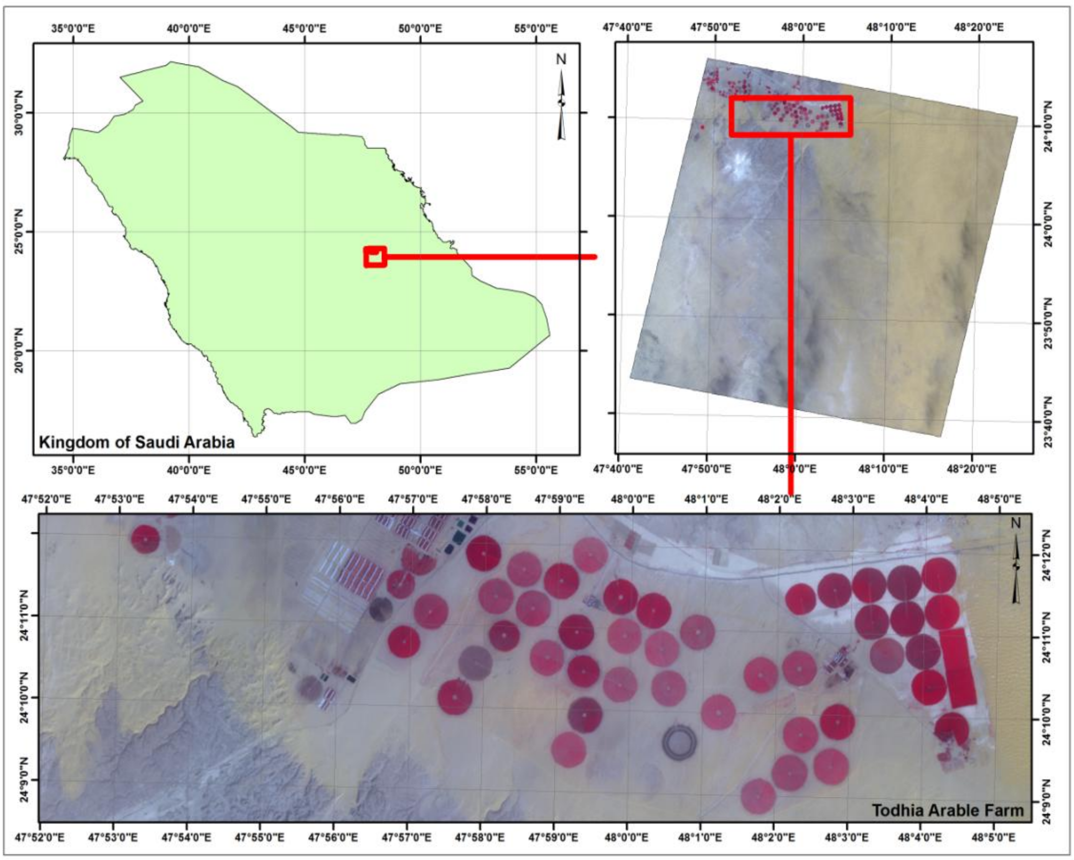

Figure. 1: Location map of Todhia Arable Farm, Saudi Arabia

2. Satellite Images

Time series satellite images of ASTER (Advanced Space borne Thermal Emission and Reflection radiometer) a Japanese sensor which is one of five remote sensory devices on board the Terra satellite *(http://ims.aster.ersdac.jspacesystems.or.jp)* were procured. The images were used to generate project outputs such as crop intensity, evapotranspiration, crop productivity and water productivity maps.

3. Ground Data collection

Ground truth data on crop biophysical parameters such as plant height, Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI) and crop canopy temperature were recorded for the major crops (wheat, alfalfa, Rhodes grass and corn).

(i) Normalized Difference Vegetation Index (NDVI)

$NDVI_{(G)}$ was measured in the field at 1m above the 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 at a baud rate of 9600 (**Fig. 2)**.

Fig. 2: Field data collection using Crop Circle..

(ii) 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), **Fig. 3**, of Licor 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).

Fig. 3: Field data collection using Plant Canopy Analyzer.

(iii) Crop canopy temperature (ºC)

Canopy temperature measurements were made using a hand-held infrared thermometer of Spectrum Technologies, Plainfield, IL, USA. The mean of three measurements was recorded at the centre of the plot and approximately 0.5 m above the canopy with a 30 angle of view, detecting radiation in the 8–14 µm wave bands.

(iv) Growth and Yield parameters

Periodic ground truth data on bio-physical parameters of four crops (wheat, alfalfa, Rhodes grass and corn) were collected.

4. Image pre processing

Acquired ASTER images were radiometrically (Top of Atmosphere) calibrated by applying sun elevation correction and earth-sun distance techniques. Radiative transfer equation was used to compute the at-sensor radiance (L_{rad}) to surface radiance ratio (i.e. absolute radiance value) utilizing pre-launch calibration constants of ASTER sensor on board TERRA satellite.

5. Water Productivity Mapping (WPM)

Water Productivity (WP) is defined as either the amount of yield produced per unit volume of water (kg of yield/m^3 of water) or as a monetary value of the yield produced per unit volume of water. WPM was achieved in three steps: (i) Crop Productivity Mapping (CPM), (ii) Water Use (ET) Mapping (WUM), and (iii) Water Productivity Mapping (WPM). Field-measured crop productivity data were related to the NDVI to obtain Crop Prodcutivity (CP) models. The best fit CP models were extrapolated to larger areas by using remotely sensed data to obtain CPM. WUM was prepared by using crop evapotranspiration (ET). The ET_{24} (per day) was obtained from ASTER data by applying the SEBAL model. WPM was generated for the entire farm by dividing the CPM by the WUM.

(i) Crop Productivity Mapping (CPM)

CP is a very important end-of-season observation that integrates the cumulative effect of weather and management practices over the entire crop growth season. Previous studies showed significant linear relationships between CP and the NDVI at the crop heading stage. Therefore, a scatter plot for each crop was drawn between the corrected ASTER derived NDVI (x-axis) and CP (y-axis) for the development of CP prediction models. The NDVI at the ear-head emergence stage in wheat and barley, the flag leaf stage in corn and the flowering stage in alfalfa and Rhodes grass were considered for CP estimations. The CP models were developed using Equation (1).

$$\mathbf{Y = aX \pm b} \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

Where, Y = the predicted CP (t/ha), X = the NDVI, and a and b are constants.

The actual (measured) CP (CP_A) data were collected from TAF records and correlated with the respective NDVI values derived from ASTER images. Remote sensing-based (predicted) CP (CP_P) of corn, barley and wheat was computed by multiplying the above ground biomass (AGB) by the harvest index (HI) – which is a function of the NDVI. While for alfalfa and Rhodes grass crops, a hay yield monitor (Model 880 of Harvest Tech., USA) was installed on a large square baler (Claas 3200) for recording the CP data (hay yields) at the time of baling. The hay yield maps were prepared by interpolating the filtered point data to 4 m×4 m grids using an ordinary kriging tool of ESRI GIS (Ver. 2010).

(ii) Water Use Mapping (WUM)

WUM was accomplished by using crop ET and assuming that the amount of water used by crops was equal to seasonal ET (ET_{actual}). The satellite-based SEBAL model was used for the estimation of ET on a pixel-by-pixel basis for the instantaneous time of satellite image as the residual amount of energy remaining from the classical energy balance, **Equation (2)**.

$$\lambda_{ET} = R_n - G - H \ldots\ldots\ldots\ldots\ldots (2)$$

Where, λ_{ET} = the latent heat flux, R_n = the net radiation at the surface, G = the soil heat flux, and H = the sensible heat flux to the air. The unit for all fluxes was $W/m^2/day$.

Research Results

1. Normalized Difference Vegetation Index ($NDVI_{(G)}$) and Leaf Area Index ($LAI_{(G)}$)

The $NDVI_{(G)}$ and $LAI_{(G)}$ were examined across the selected crops during the study period. It was observed that the average $NDVI_{(G)}$ values of alfalfa were 0.62(± 0.17) and 0.51(± 0.12) for the years 2012 and 2013, respectively. Meanwhile, Rhodes grass recorded high average $NDVI_{(G)}$ value in 2012 (0.65) and least average value in 2013 (0.22). The average $NDVI_{(G)}$ values of seasonal crops ranged between 0.63 (wheat) and 0.71 (corn) in 2012; however, it varied from 0.53 (barley) to 0.63 (corn) in 2013. The average $LAI_{(G)}$ for alfalfa crop was 4.51(± 1.74) and 4.02(± 1.33) for the years 2012 and 2013, respectively; while for Rhodes grass, the average $LAI_{(G)}$ was 4.50(±1.54) and 1.00(±0.24) for the years 2012 and 2013, respectively. For the seasonal crops, the highest $LAI_{(G)}$ was observed for wheat (4.74±1.31), followed by corn (4.37±1.48) during the year 2012. However, in 2013, corn recorded the highest $LAI_{(G)}$ (4.43±1.46) compared to barley (3.40±1.28) and wheat (2.60±1.05).

2. Crop Productivity (CP) Models

The best relationship between CP and NDVI was obtained when the crops were in mid-season (growth stage), as presented in Table 1. For the annual crops, the best response was observed on the Julian days of 43 (2013), 169 (2012) and 64 (2012) for barley, corn and wheat crops, respectively, when the crops were at their peak growth stage. While for the biennial crops (alfalfa and Rhodes grass), which have a growth period of 30 to 45 days between two harvests, the best response was observed on the Julian days 201 and 281 of 2012 for Rhodes grass and alfalfa, respectively.

The CP models were validated against the actual CP data recorded for the farm; there was good correlation (Table 1), with a root mean square error (RMSE) of 24% for Rhodes grass, followed by alfalfa (21%), corn (18%), and barley (16%), with the least RMSE observed for wheat (15%).

Table 1. NDVI models used for predicting Crop Productivity (CP).

Crop	Julian day	Model	Correlation (R^2, P>F)		RMSE, t/ha (%)	
			Modeled	Cross-validated	Modeled	Cross-validated
Alfalfa	281 (2012)	Y = 9.6754 * NDVI - 0.1097	0.5821, 0.028	0.6821, 0.047	986 (21%)	1211 (19%)
Barley	43 (2013)	Y = 8.8221 * NDVI - 1.1621	0.6214, 0.021	0.6682, 0.034	1567 (16%)	1687 (19%)
Corn	169 (2012)	Y = 21.4579 * NDVI -1.6884	0.5647, 0.031	0.711, 0.038	2218 (18%)	2788 (21%)
Rhodes grass	201 (2012)	Y= 11.3946 * NDVI - 0.3807	0.5211, 0.046	0.5711, 0.039	1087 (24%)	1372 (22%)
Wheat	64 (2012)	Y = 13.821 * NDVI - 6.0231	0.6211, 0.021	0.6822, 0.038	1086 (15%)	1124 (17%)

The results of the predicted and actual CP, ET (crop water use) and WP for both annual and biennial cops are presented in **Table 2**. It was observed that the predicted CP (CP_P) varied significantly in both temporal and spatial scales. For annual crops, the average CP_P (kg/ha) for corn was 13,510 and 14,060 for seasons 1 & 2 (2012), respectively, and 12,690 in 2013. However, the actual recorded CP (CP_A) for corn was 10,930 and 11,190 (kg/ha) for seasons 1 & 2 (2012), respectively, and 10,900 in 2013. Meanwhile, the average CP_P (kg/ha) for wheat crop was 6,000 and 7,370 for season 1 in 2012 and 2013, respectively. But, the CP_A (kg/ha) for wheat crop was 5,530 and 6,510 for season 1 in 2012 and 2013, respectively. In the case of barley, the farm recorded mean CP_A was 7,210 kg/ha, while the CP_P was 6,910 kg/ha, resulting in a mean error of 4.16%.

For the biennial crops, the CP_P (kg/ha/year) for alfalfa was 42,450 for 2012 and 15,530 for 2013 (up to May 19th). The CP_A (kg/ha) for alfalfa crop was 35,100 for 2012 and 21,000 for 2013. While the average CP_P (kg/ha) for Rhodes grass was 58,210 for 2012 and 24,580 for 2013 (up to May 19th). But the CP_A for Rhodes grass was 60,390 for 2012 and 15,140 for 2013.

Table 2. Predicted and actual Crop Productivity (kg/ha), ET/water use (m^3/ha) and Water Productivity (kg/m^3).

	Crop	Year/ Season	Predicted			Actual		
			CP_P (kg/ha)	ET_P (m^3/ha)	WP_P (kg/m^3)	CP_A (kg/ha)	WA (m^3/ha)	WP_A (kg/m^3)
Seasonal	Corn	2012-Season 1	13510(±3020)	9050	1.49(± 0.14)	10930(±1940)	9892	1.11(± 0.09)
		2012-Season 2	14060(±2710)	14013	1.00(± 0.12)	11190(±2090)	18242	0.61(± 0.08)
		2013-Season 1	12690(±2980)	22962	0.55(± 0.16)	10900(±2710)	21580	0.51(± 0.12)
	Wheat	2012-Season 1	6000(±520)	7517	0.80(± 0.02)	5530(±680)	4831	1.15(± 0.03)
		2013-Season 1	7370(±380)	3667	2.01(± 0.03)	6510(±620)	3982	1.63(± 0.02)
	Barley	2012-Season 2	7210(±420)	10648	0.68(± 0.04)	6910(±1120)	12594	0.55(± 0.02)
Biennial	Alfalfa	2012	42450(±6230)	94890	0.46(± 0.04)	35100(±5840)	84852	0.41(± 0.04)
		2013	15530(±3160)	40566	0.38(± 0.01)	21000(±2720)	48641	0.43(± 0.02)
	Rhodes grass	2012	58210(±10430)	168224	0.36(± 0.03)	60390(±5440)	163294	0.37(± 0.04)
		2013	24580(±4220)	23022	1.07(± 0.07)	15140(±3220)	22053	0.69(± 0.02)

CP_P = ASTER predicted crop productivity, ET_P = ASTER predicted evapotranspiration, WP_P = ASTER predicted water productivity, CP_A = Actual recorded crop productivity, WA = Actual quantity of water applied, WP_A = actual water productivity.

3. Water Use (ET) Mapping

ET values were estimated in this study through the analysis of ASTER images using the SEBAL model. The accuracy of the predicted ET (ET_P) was tested against the weather station recorded ET (ET_W). The distribution pattern of ET_P and ET_W is illustrated in **Fig. 4**. Both the ET_P and ET_W followed a similar pattern throughout the study period.

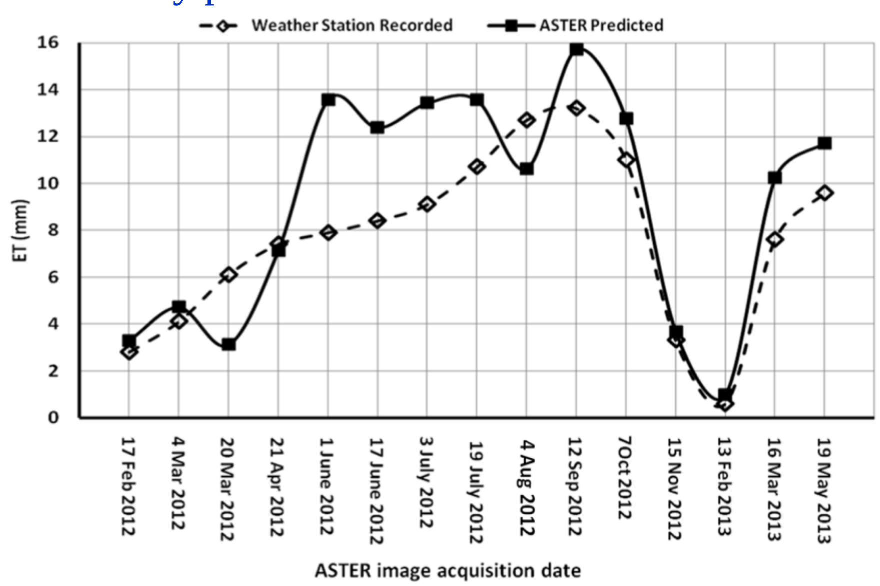

Fig. 4. Temporal variation in ASTER predicted (ET_P) and weather station recorded (ET_W).

The results showed a strong linear relationship between ET_p and ET_w with R^2 of 0.778 (**Fig. 5**). The mean deviation of ET_p from ET_w was found to be 10.49%. The ET_P (**Fig. 6**) was then used to assess irrigation performance (IP) for all of the test crops. The mean values of both ET_p and the actual quantity of irrigation water applied (WA) are presented in **Fig. 7** and **8**.

During the 2011-2012 season, the WA to alfalfa, Rhodes grass and wheat crops was lower than the required quantity as per the ET_p. However, during the 2012-2013 season, alfalfa, wheat and barley crops were irrigated with more than the required quantity of water. Conversely, corn received a higher than required quantity of water during 2011-2012 and a lower than required quantity during 2012-2013.

The deviation of ET_p from the WA to all of the crops was determined in terms of overall mean error (**Fig. 9**). The results indicated that the accuracy of ET_p was higher for alfalfa, corn, and Rhodes grass crops and lower for wheat and barley.

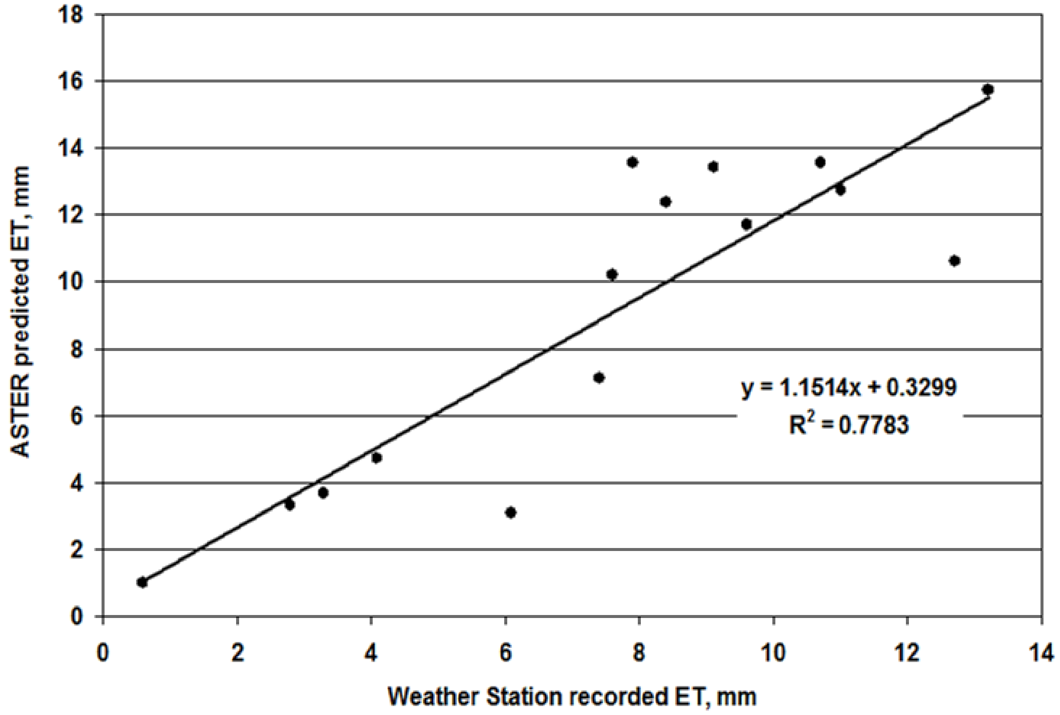

Fig. 5. Linear regression analysis between ET_P and ET_W.

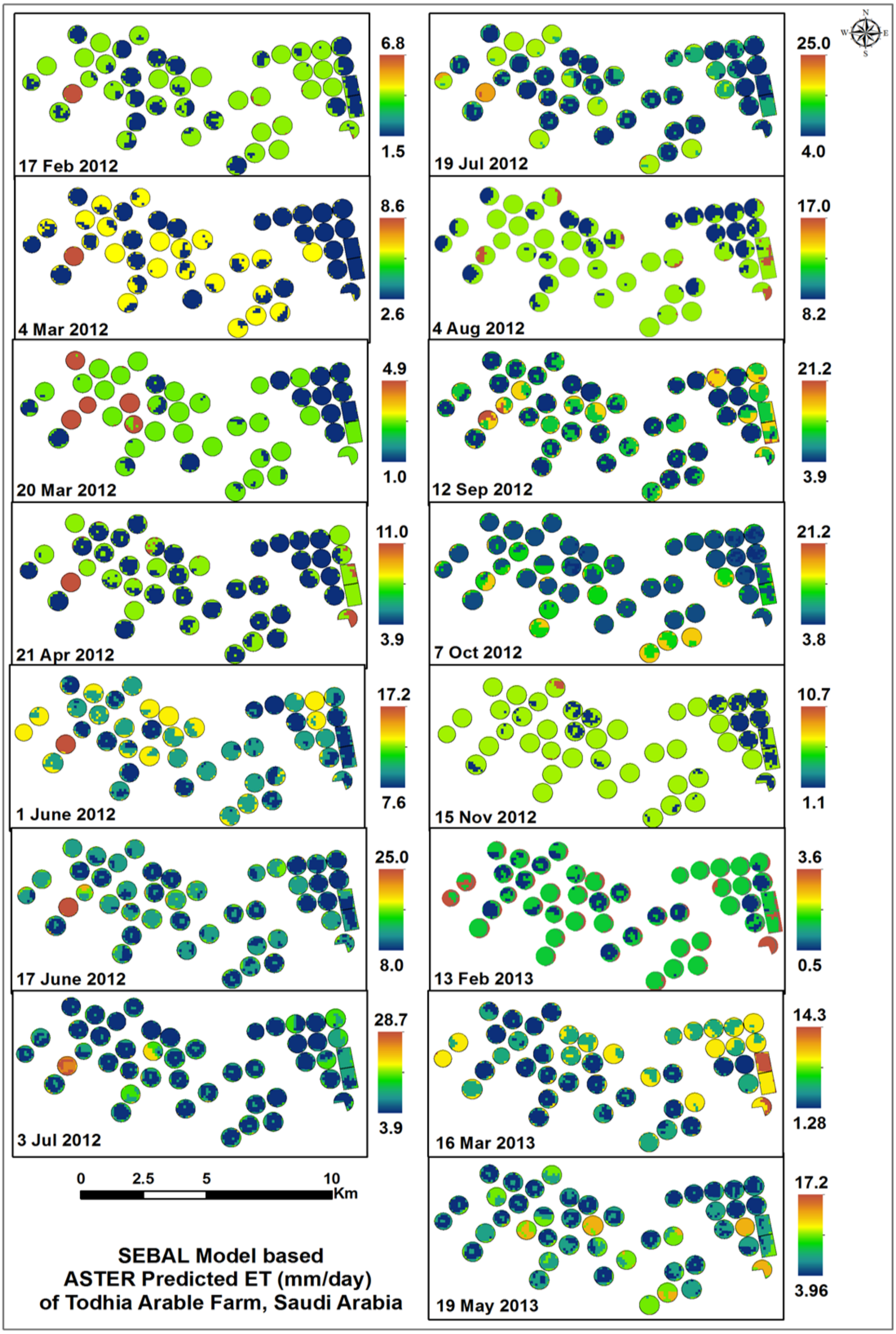

Fig. 6. SEBAL Model-based ASTER predicted ET (mm/day) for the study site.

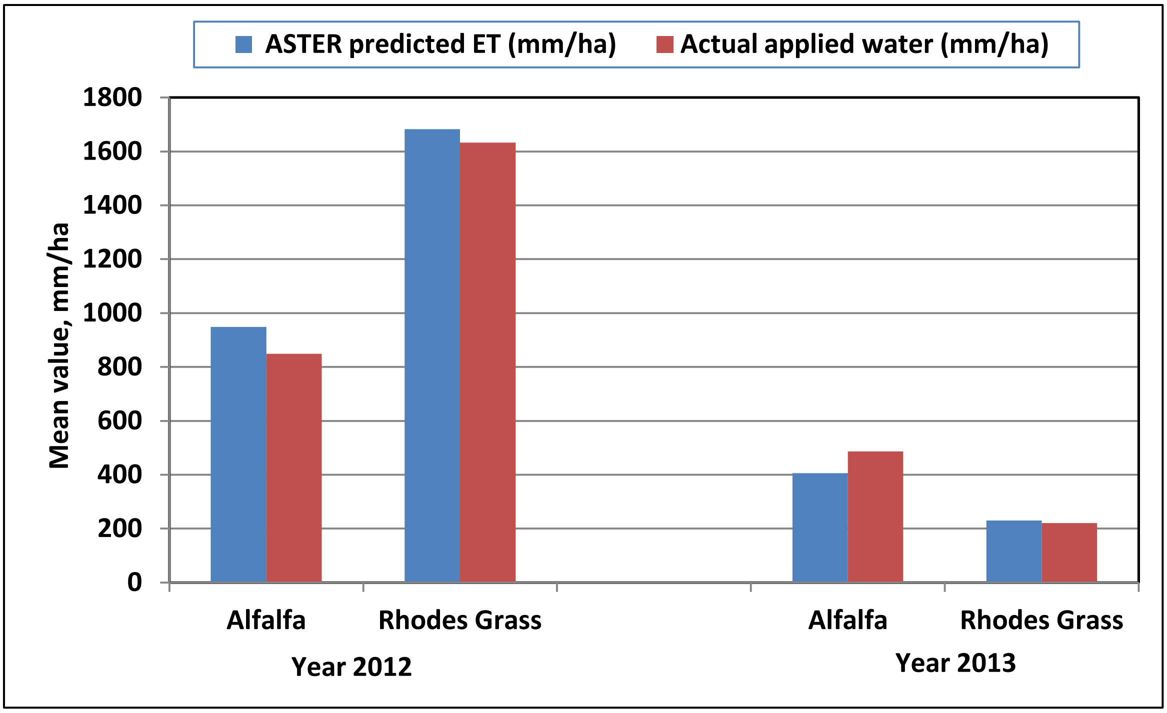

Fig. 7. ASTER predicted ET (ET_P) and the water applied (WA) to biennial crops.

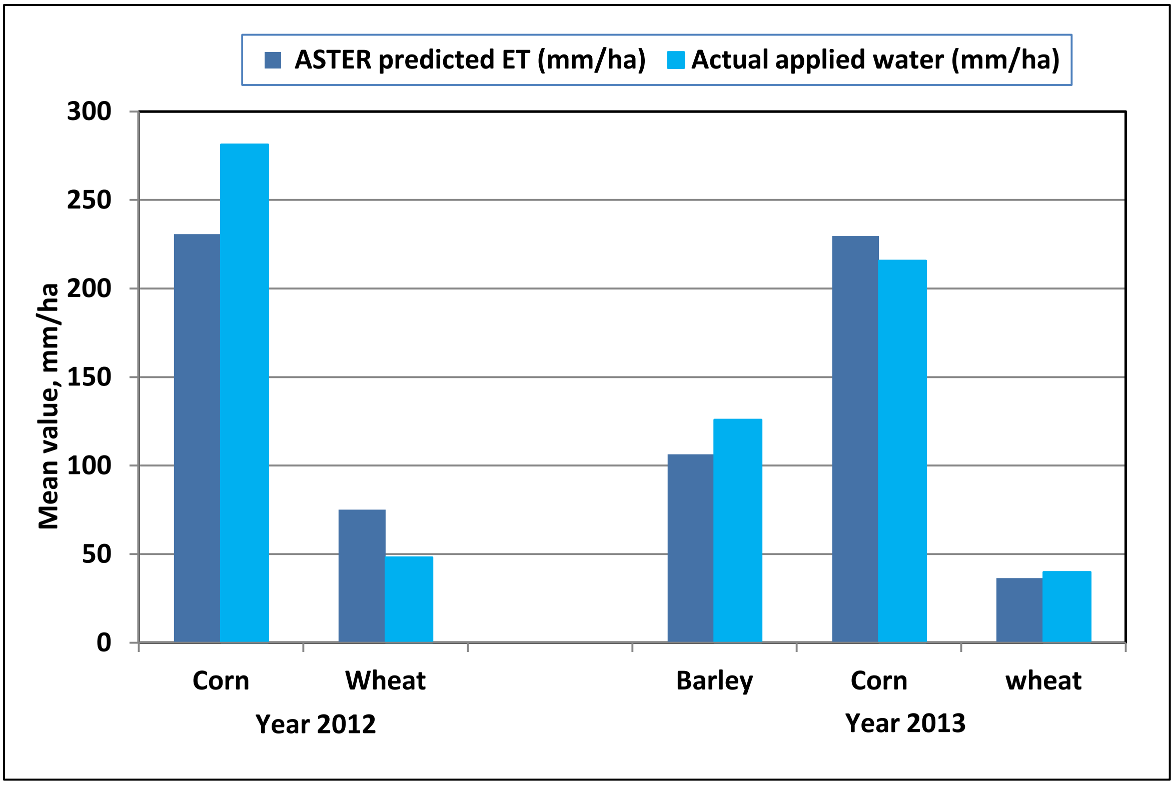

Fig. 8. ASTER predicted ET (ET_P) and the water applied (WA) to annual crops.

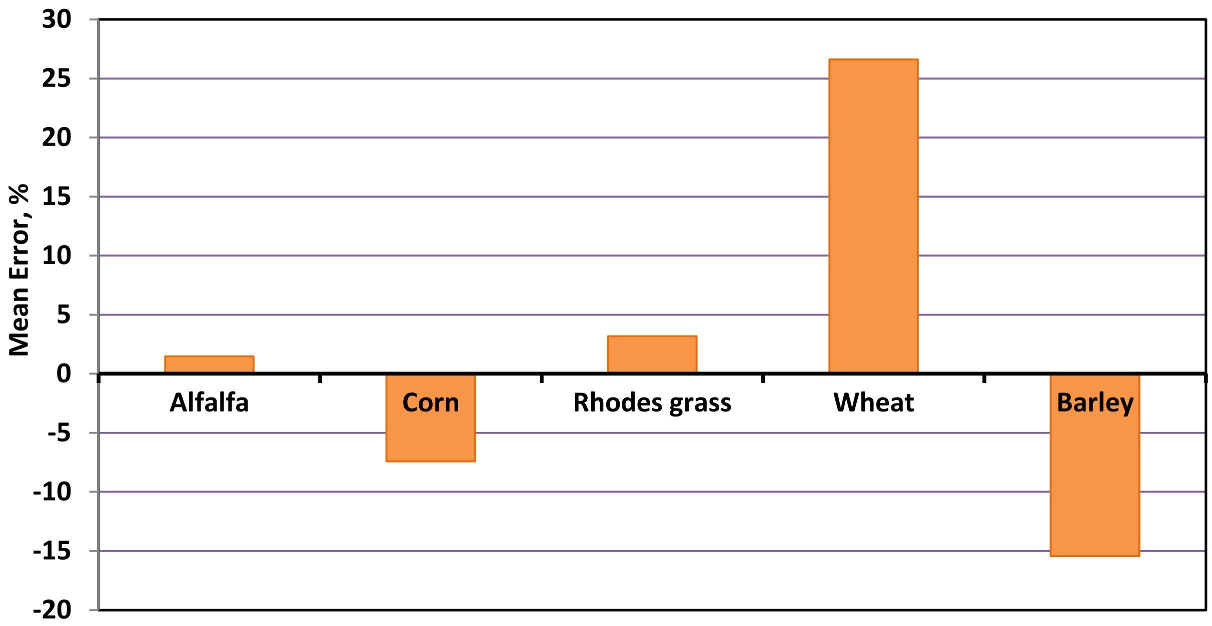

Fig. 9. Accuracy assessment of the predicted (ET_P) against the water applied (WA).

4. Water Productivity (WP)

As depicted in **Fig. 10**, the prediction of WP (WP_p) was more accurate for alfalfa and Rhodes grass crops in 2012. In alfalfa, the WP_p was 0.46 kg/m^3 versus an actual WP (WP_A) of 0.41 kg/m^3. Meanwhile, the WP_p for Rhodes grass was 0.36 kg/m^3 versus a WP_A of 0.37 kg/m^3. In 2013 (**Fig. 11**), the WP_p was 2.01, 1.07, 0.68, 0.55 and 0.38 kg/m^3 for wheat, Rhodes grass, barley, corn and alfalfa, respectively, versus WP_A values of 1.63, 0.69, 0.55, 0.51 and 0.43 for the same sequence of crops.

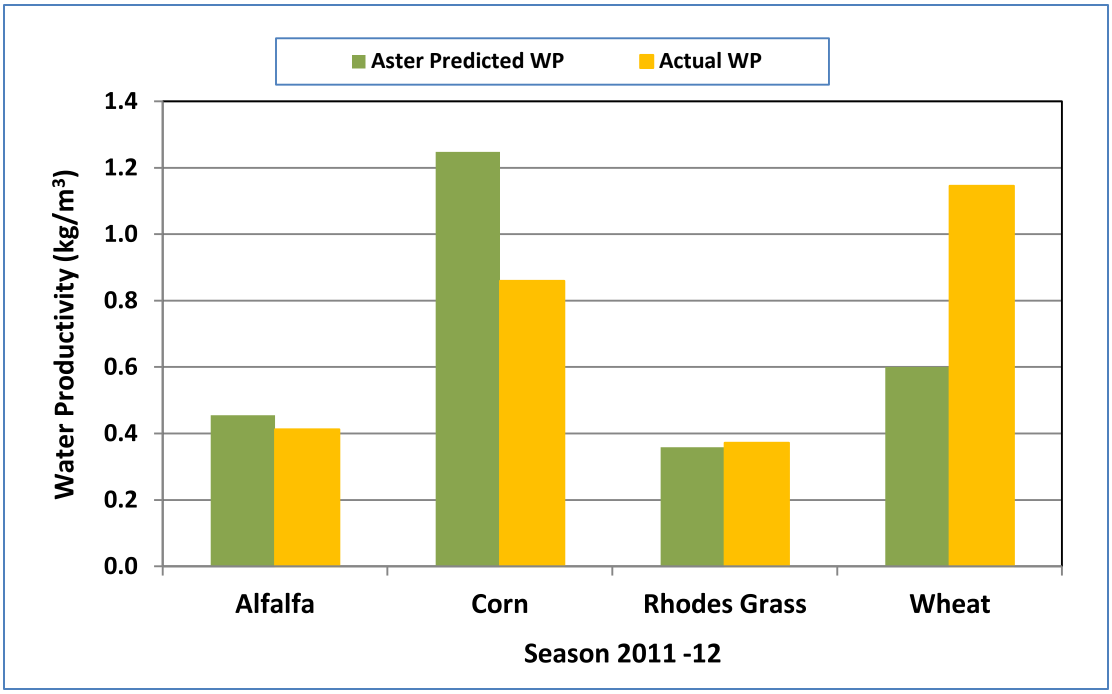

Fig. 10. ASTER predicted (WP_P) vs. Actual (WP_A) water productivity for 2012.

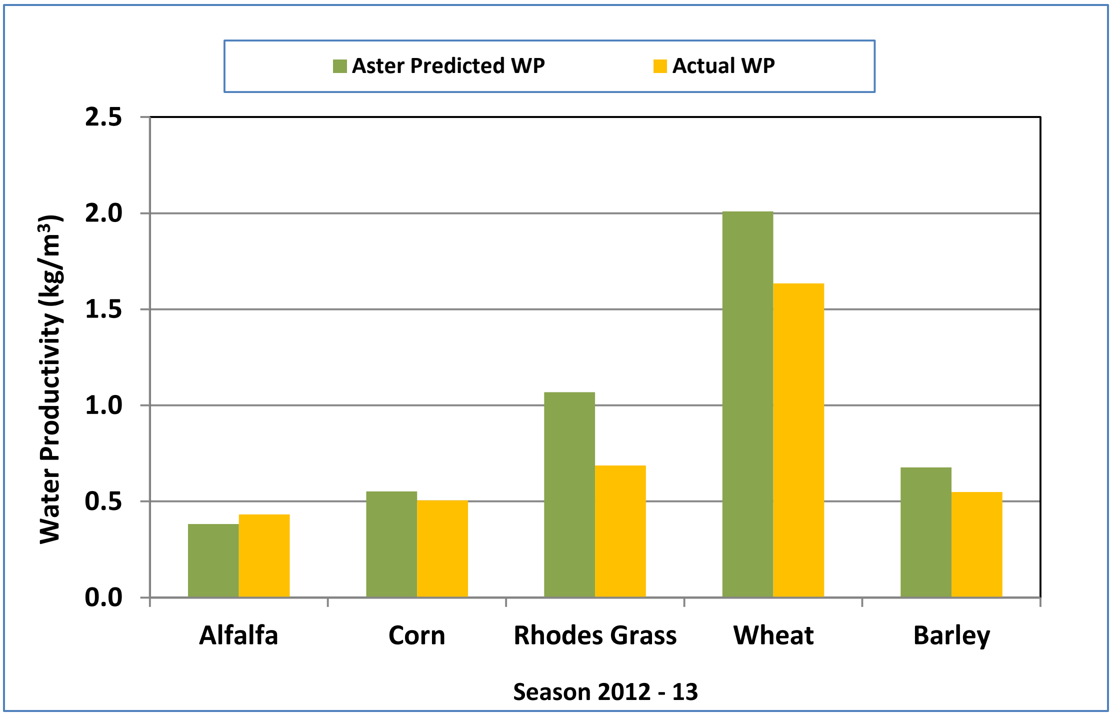

Fig. 11. ASTER predicted (WP_P) vs. Actual (WA_A) water productivity for 2013.

Benefits to the Country

Agriculture in general and irrigation in particular, consumes over 80% of the total quantity of water used in the Kingdom of Saudi Arabia. Therefore, increasing Water Productivity (WP) in agricultural sector is crucial to save water for other competitive and critical needs, such as for domestic, industrial, environmental and recreational purposes. WP study was conducted for the test fields located in Al-Kharj governorate, Riyadh region, Saudi Arabia concentrated on two main issues. The first was to map the irrigation water productivity, obtained from crop productivity (CP) and Evapotranspiration (ET) maps, at a field scale in order to visualize the spatial distribution of the WP involved. The second issue, however, involves establishing methods for extrapolation of findings to larger areas for the purpose of assessing irrigation performance. Advanced time-series satellite sensor data and Remote Sensing (RS) techniques were employed for the development of consistent, comparable, reliable, timely, and cost-effective CP, ET and WP maps and delineation of crop zones based on water use efficiency at different scales and levels.

The key contribution of this project into the efforts for sustainable agriculture in Saudi Arabia was the technology-based methodologies and the developed maps for the determination of irrigation WP and for the delineation of crop zones based on water use efficiency at the field, regional, and province levels. Strategies for considerable saving in irrigation water can be formulated using the results of this study.

This project was implemented through collaborative efforts made at national level (Precision Agriculture Research Chair and Department of Geography, King Saud University, Saudi Arabia) and international level (University of Oklahoma and USDA-ARS, USA).

In addition to the prediction of ET using the satellite-based SEBAL model, ET measurements were achieved using both Eddy Covariance (EC) and Surface Layer Scintillometer (SLS) systems. However, the EC and SLS data are not presented here, but were used for publications in peer reviewed Journals.

(a) Eddy Covariance (EC) system

Eddy Covariance system of "Li-COR, USA" was installed over a selected alfalfa field (**Fig. 12**). The eddy flux tower has been set up at a height of 3.67 m. The tower is equipped with slow and fast response sensors. Continuous fast responses of CO_2, H_2O and heat fluxes above the alfalfa canopy were measured at a frequency of 10 Hz using eddy covariance based open path Infrared Gas Analyzer (IRGA-LICOR 7500) and 3D Ultrasonic Anemometer (GILL), and then the collected observations were averaged for 30 minutes.

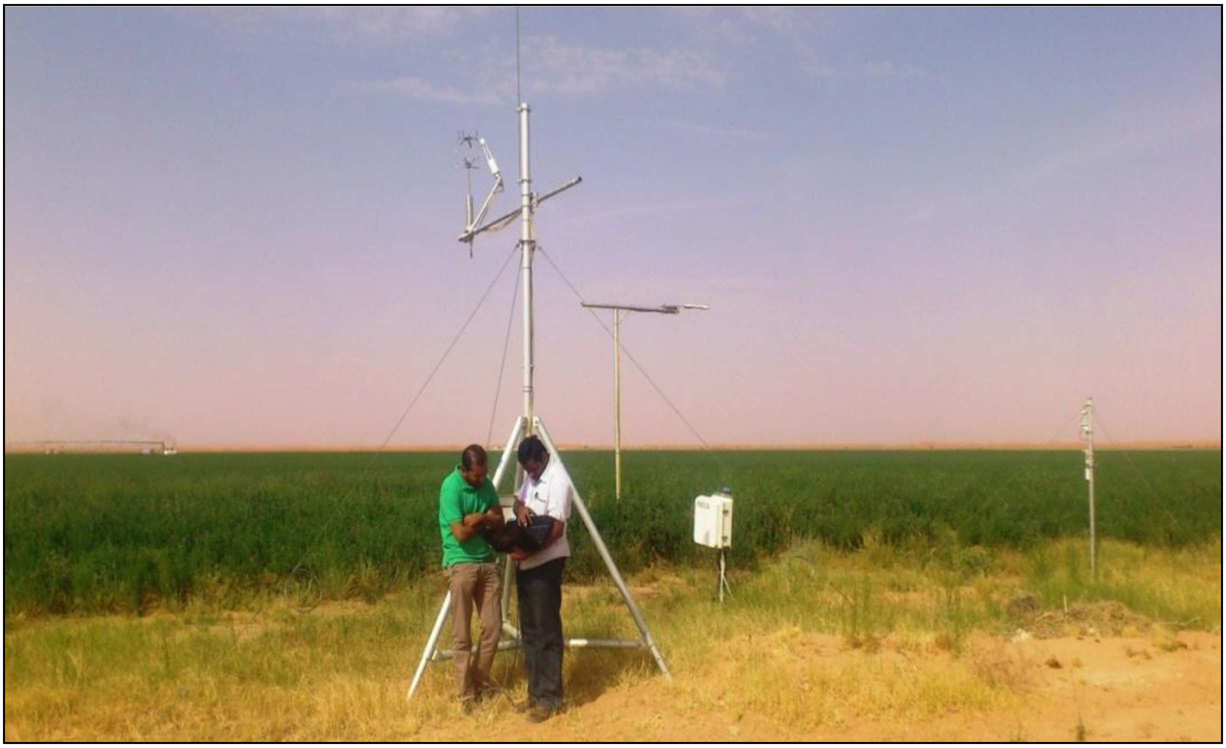

Fig. 12. Eddy Covariance (Li-COR, USA) installed over alfalfa field.

(b) Surface Layer Scintillometer (SLS)

A Surface Layer Scintillometer (SLS) of Scintec AG, Germany was installed on the same field where EC system was installed, **Fig. 13**.

Fig. 13. Surface Layer Scintillometer (Scintec AG, Germany) installed over alfalfa field.

Field Visits, Training and Workshops

Project Team collecting ground truth data in wheat crop.

Project Team and Licor Biosciences representatives during LAI Workshop.

Project Co-I: Prof. Dr. Al-Gaadi (right) and Co-I: Dr. Al-Dosari (middle) in wheat field.

Project Team and Licor Biosciences representatives during Eddy Covariance Workshop.

Licor Biosciences representatives demonstrating Eddy Covariance System.

Dr. C.M. Biradar "Project Consultant" during the Workshop on "Advances in Remote Sensing Techniques for Precision Agriculture".

Project Team while discussing research results with Dr. C.M. Biradar, Project Consultant (seated first on the left).

Water Productivity workshop in collaboration with the "Water Desalination and Reuse Center of King Abdullah University of Science & Technology (KAUST), Thuwal, Saudi Arabia" represented by Prof. Dr. Matthew McCabe (Third from right) and Dr. Rasmus Houborg (Second from right).