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THE COSMIC-RAY SOIL MOISTURE OBSERVATION SYSTEM (COSMOS) FOR ESTIMATING THE CROP WATER REQUIREMENT: NEW APPROACH†

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ABSTRACT

Soil moisture is a crucial parameter to determine the crop water requirement for irrigation. Soil Moisture Deficit of the root zone (SMD) is an indicator that can be used to determine the exact crop water requirement. The application of the recent technology of COsmic-ray Soil Moisture Observation System (COSMOS) provides continuous, integrated, area based values, with a measurement radius of up to 400 meters, whilst being non-invasive.

In a field experiment in Italy, the Cosmos probe was used over a mixed crops area during the cropping seasons of 2014 and 2015. The results showed that soil moisture values obtained by Cosmos were comparable with those obtained for the top 0-60 cm layer soil moisture measured by sensors, soil cores, profile probes and with values simulated by the SALTMED model. This indicates that the Cosmos probe's effective depth of sensing is within the top 0-60 cm. Knowing that almost 80% of the crop root system is accommodated within the top 0-60 cm, the Cosmos measurement could be useful for monitoring the soil water status and SMD in the root zone in irrigated agriculture. The Cosmos system could be made operational for irrigation managers to determine when and how much to irrigate.

KEY WORDS: crop water requirement; COSMOS; soil moisture deficit; soil moisture

† Le système d'observation de l'humidité du sol (COSMOS) pour l'estimation des besoins en eau des cultures : une nouvelle approche

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measurement; SALTMED model; irrigation requirement.

RÉSUMÉ

L'humidité du sol est un paramètre crucial pour déterminer les besoins en eau d'une culture irriguée. Le déficit d'humidité du sol de la zone de racine (SMD) est un indicateur qui peut être utilisé pour déterminer le besoin en eau exact d'une récolte. L'application de la technologie récente du système d'observation de l'humidité du sol à rayonnement COsmic (COSMOS) fournit des valeurs continues, intégrées, zonales, avec un rayon de mesure de jusqu'à 400 mètres, tout en étant non invasive.

Dans une expérience de terrain en Italie, la sonde COSMOS a été utilisée sur une zone de cultures mixtes pendant les saisons de 2014 et 2015. Les résultats ont montré que les valeurs d'humidité du sol obtenues par COSMOS étaient comparables à celles obtenues pour les 60 premiers centimètres du sol par des capteurs, des prélèvements de sol, des sondes à profils humidimétriques, des résultats de simulation par le modèle SALTMED. C'est donc dans cette zone ou se situe la profondeur effective de détection de la sonde COSMOS ; sachant que près de 80% du système racinaire se situe également dans cette zone, la mesure COSMOS pourrait être utile pour surveiller l'état de l'eau du sol et le SMD dans la zone la zone racinaire en vue d'une application dans l'agriculture irriguée. Le système COSMOS pourrait être rendu opérationnel pour les gestionnaires de l'irrigation afin de déterminer quand irriguer et en quelle quantité..

MOTS CLÉS : besoins en eau de récolte ; COSMOS ; déficit d'humidité du sol ; mesure de l'humidité du sol ; modèle SALTMED ; besoin en eau pour l'irrigation.

INTRODUCTION

Conventional methods of measuring soil moisture generally provide either point-source or soil profile data at a specific point. In order to gain a better understanding of the effects of plant canopies and plant roots on soil moisture distribution, it has been necessary to undertake many point source measurements which are very costly and time-consuming. Alternative methods of 'new technology' are now available which make use of indirect sensing technologies to produce area based integrated soil moisture.

Soil moisture at a horizontal scale of around 400 m and depths of 12 to 70 cm can be inferred from measurements of naturally occurring cosmic-ray neutrons that are moderated mainly by the hydrogen atoms in water and back-scattered to the atmosphere. The count of the resulting slow-neutrons above the ground is sensitive to water content, largely insensitive to soil chemistry and inversely correlated with hydrogen content of the soil water. An integrated measurement of the average count over a few hours is made by a neutron detector placed above the ground known as Cosmos Ray Sensor (CRS). The method is completely non-invasive, does not require a radioactive source, and can be easily moved between different fields, or removed for crop harvesting. The large footprint makes the method suitable for monitoring average soil moisture conditions, whilst the measurement depth makes the detector suitable for studying plant/soil/atmosphere interactions (Shuttleworth *et al*., 2010).

Rosolem *et al*. (2014) used the cosmic-ray sensors in combination with satellite remote-sensing to map soil moisture for hydro-meteorological applications. Similarly, Dong *et al*. (2014) used Cosmos to map soil moisture of the top 5 cm of soil. The study recommended the use of Cosmos for calibration/validation of soil moisture obtained by satellite. This was in line with a study conducted by Chrisman and Zreda (2013) who confirmed the suitability of Cosmos for quantification of soil moisture at mesoscale. Köhli *et al*. (2015) conducted series of Mont Carlo simulation and found that the Cosmos system is more sensitive to soil moisture in the nearest tens of meters from the probe and the footprint radius ranges from 130 to 240 meters. This range depends on air relative humidity, soil moisture and vegetation. They reported that the effective depth of the sensed soil moisture varies from 15 to 83 cm, being shallow under wet condition. In addition, Franz *et al*. (2013) reported that the observations and simulation study indicated that the horizontal heterogeneity only has a small effect on the average soil moisture under natural conditions.

Bogena *et al*. (2013) investigated the accuracy of the cosmic-ray soil water content probe in humid forest ecosystems. Without considering the impact of the forest litter layer they obtained a reasonable soil moisture with root mean square error, RMSE, of 0.03. The accuracy could be improved once the litter layer is taken into consideration. Rivera Villarreyes *et al*. (2013) evaluated the Cosmos method applicability in cropped fields. The investigation proved the potential of the Cosmos method at field scale. They recommended the Cosmos method provided it is calibrated and adapted for seasonal variation in vegetation cover / growth in cropped fields.

MATERIALS AND METHODS

The Cosmos study was carried out at the experimental field (Figure 1a) located nearby the village of Mezzolara di Budrio (Bologna, Italy) in the plain of the Po valley (44º34´ N, 11º32´ E). The field is part of the CER's experimental farm. The Cosmos instrument has been installed (Figure 1b) and measurements started at the beginning of the 2014 irrigation season and continued for two years (2014-2015).

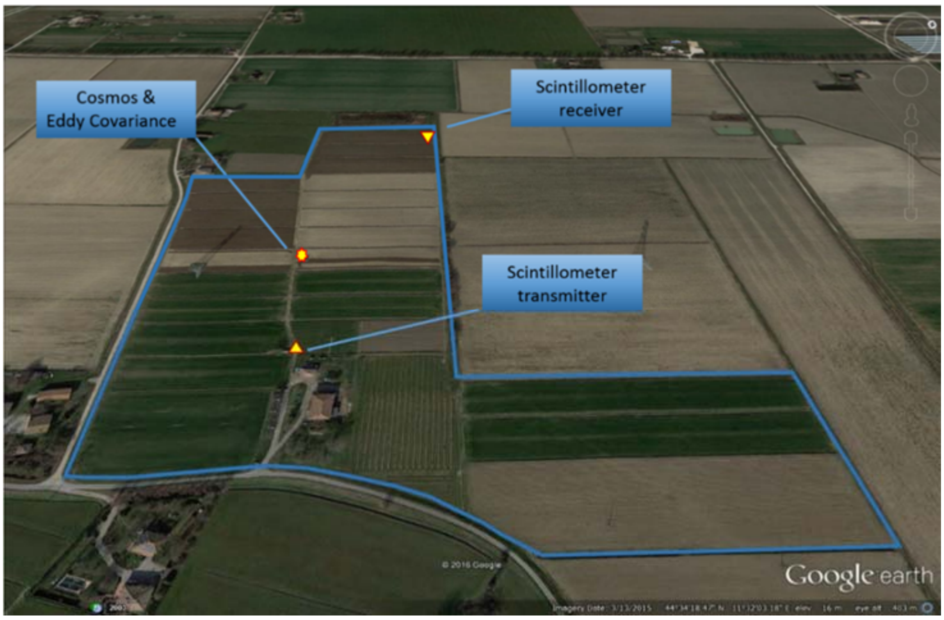


Figure 1a. Experimental site and COSMOS location

The soil is typical of the Po valley lowland with a high content of silt and fine sand. Those soils are normally deep and without noticeable soil particle size (> 2 mm). The detailed soil's physical and chemical parameters are given in Table I.

Figure 1b. COSMOS (Cosmic Ray Soil Moisture Observing System)

Table I. Soil physical and chemical parameters

Parameter, units	Average
Sand, %	32
Silt, %	50
Clay, %	18
pH, log H^-	8.27
$CaCO_3$ Total, %	13.5
$CaCO_3$ Active, %	3.1
N Total, %	0.06
K Exchangeable, meq/100g	0.34
P (Olsen), meq/100g	5.49
CEC, meq/100g	21.6

Crop rotation is typically bi- or tri-annual, including in sequence: winter wheat and a horticultural crop (potato or processing tomato) and maize or sorghum in case of a tri-annual rotation. The crops rotated in the period 2013-2016 are reported as percentage of the total cropped area in Table II. Additional soil moisture contents measurements were carried out using three different methods: Soil moisture sensors (WaterScout SMEC 300 Soil Moisture/EC/Temperature Sensor), Profile Probe (PR2- Delta-T) and soil cores. These measurements were taken to verify the soil moisture and effective depth of Cosmos. Profile probe measurements were taken at 10, 20, 30, 40, 60 and 100 cm depth. Soil cores were taken at the same depth of the Profile Probe. Soil moisture sensors were installed vertically at two depths to give average soil moisture of 0-60 cm depth.

Table II. The crop rotation during 2013-2016

Crop	Percentage of the total cropped area in			
	2013	2014	2015	2016
Winter Wheat	46.4	32.1	43.0	39.3
Maize	21.4	21.4	28.6	21.4
Sorghum	18.0	28.7	0.0	14.3
Processing Tomato	7.1	7.1	7.1	14.3
Orchards	0.0	3.7	3.7	3.7
Sunflower	0.0	0.0	10.7	0.0
Constructed Wetland	3.7	3.7	3.7	3.7
Weather Station	3.7	3.7	3.7	3.7
Total	100%	100%	100%	100%

The irrigation season normally starts end of May and ends late August/early September. The irrigation systems used were: reel sprinkler machine equipped with gun or boom; drip irrigation and solid set sprinklers (Table III).

Table III. The land cover and the method of irrigation

Crop	Sprinkler- solid set system	Drip system	Supplementary irrigation (reel-gun-boom sprinkler systems)	Not irrigated
Winter wheat				X
Sorghum			X	X
Sunflower			X	X
Orchards		X		
Maize	X	X		

Tomato	X	X

RESULTS AND DISCUSSION

The hourly neutrons counting rate was recorded, quality controlled and corrected for the effect of atmospheric pressure, background neutron flux (Evans *et al.*, 2016) and relative humidity (Rosolem *et al.*, 2013). The volumetric soil moisture content, θ (m^3 m^{-3}) was then calculated using Desilets *et al.* (2010) analytically derived equation. The equation takes into account the neutron counting rate (counts hr^{-1}), N, the corrected neutron counting rate over dry soil under the same reference conditions, No, and three fitting parameter factors that control the shape the soil moisture-neutron count rate relation, ao, a1, and a2, being 0.0808, 0.372 and 0.115, respectively. No is determined by field soil sampling and laboratory analysis within the Cosmos footprint.

$$\theta\ (N) = \frac{ao}{\left(\frac{N}{No}\right) - a1} - a2 \quad (1)$$

The effective depth of Cosmos measurement is defined as the thickness of soil from which 86% of counted neutrons arise (Zreda *et al.*, 2008). The effective depth, z (cm), was calculated according to the hypothetical equation of Franz *et al.* (2012) as:

$$z = \frac{5.8}{\rho\ \tau + \theta + 0.0829} \quad (2)$$

Where ρ is the soil dry bulk density (g cm^{-3}), τ is the weight fraction of lattice water of soil mineral grains defined as the amount of water released at 1000 °C (g g^{-1}) and θ is volumetric soil moisture content (m^3 m^{-3}).

The recorded data was transmitted in real time to the USA Cosmos web site: http://Cosmos.hwr.arizona.edu/Probes/StationDat/098/index.php. The data and plots can be retrieved and exported in different formats. Figure 2a shows part of the information that is displayed in real time for the field experimental site. These hourly Cosmos volumetric soil moisture content values, SWC calculated from equation 1 are shown in the top panel of Figure 2a. The bottom panel shows how the effective measurement depth of the Cosmos sensor (obtained from equation 2) varies with SWC, becoming deeper in drier periods. Figure 2b shows the hourly Cosmos volumetric soil moisture content values of the two cropping seasons 2014 and 2015. There are very clear responses of SWC to precipitation (excluding irrigation). The Cosmos sensor clearly shows a good sensitivity to the changes in rainfall.

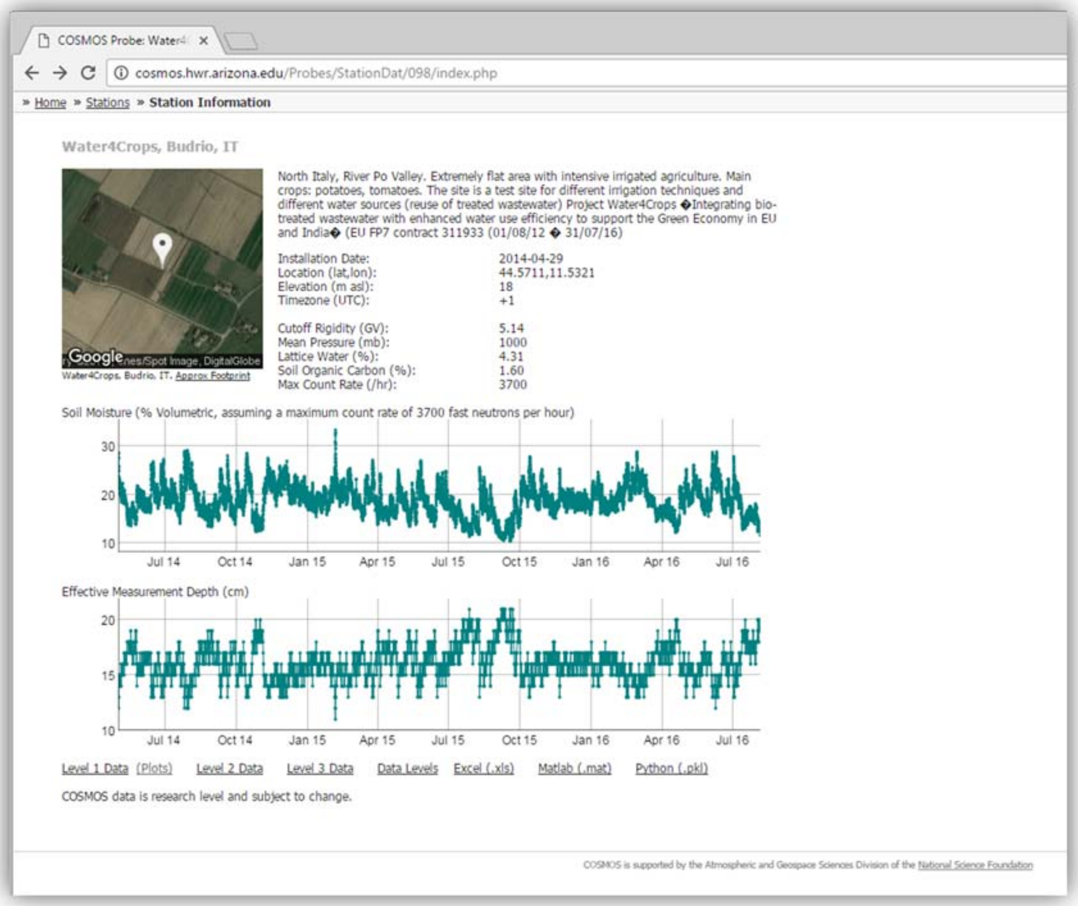


Figure 2a. On line real time soil moisture and effective depth of the study site continuously updated on the web site.

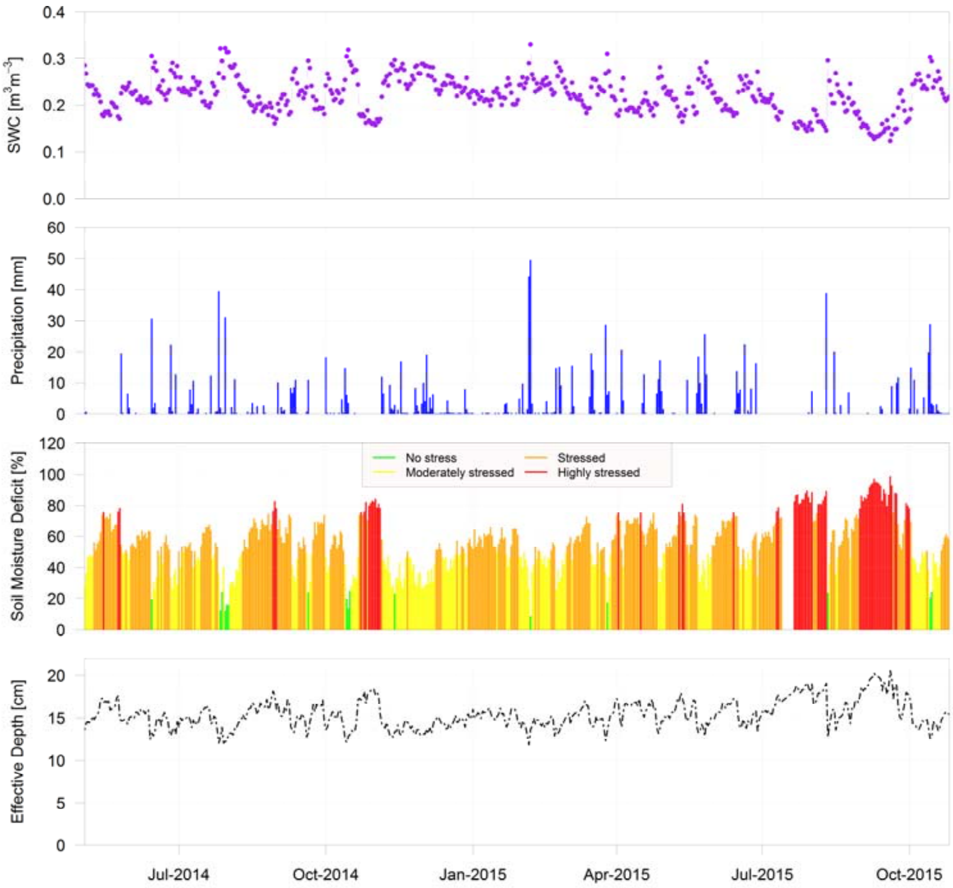


Figure 2b. Cosmos soil water content, effective depth and SMD for 2014-2015 seasons. (Cosmos water content was not adjusted for biomass water content at this stage)

The soil moisture deficit, SMD, for the rootzone depth is usually used as a good indicator of the need for irrigation and is used by the irrigation managers in a decision support system to decide when and how much water to apply. The SMD is calculated as:

$$SMD\% = [1- (SWC - SWC_{wp} / SWC_{fc} - SWC_{wp})]\ 100 \quad (3)$$

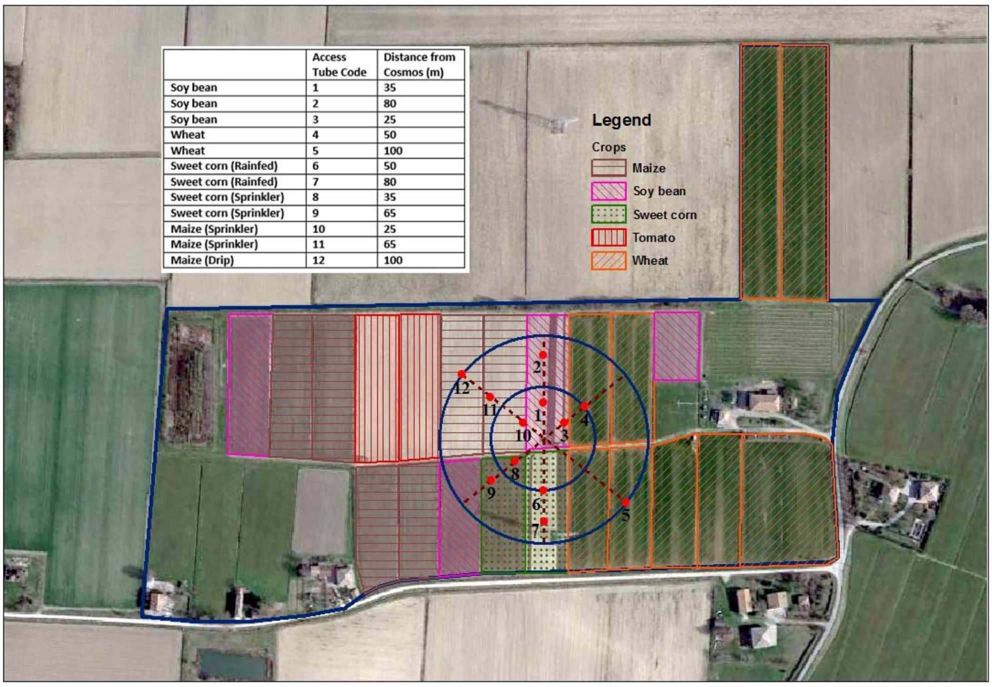
Where SWC_{fc} and SWC_{wp} represent, soil moisture at field capacity and wilting point, respectively. The term ($SWC_{fc} - SWC_{wp}$) represents the maximum available water for crops, while the term ($SWC - SWC_{wp}$) represents the actual available water on a certain day (FAO - Allen *et al*., 1998).

The question here is whether the Cosmos sensor provides accurate and useful measurements that cover the rooting depth for which the SMD and irrigation water requirement are estimated. However, should the Cosmos prove to be measuring a shallower depth, that does not extend to the full root zone, there will be a need to apply a water balance model such as the two-layers model (Ragab, 1995) to obtain soil moisture and SMD of deeper layers (root zone) from the knowledge of the shallow/surface layer and soil physical properties. However, Figure 2b shows a shallow depth of no deeper than 20 cm as calculated from the theoretical equation of Franz *et al*. (2012).

Figure 2b shows the colour coded SMD to demonstrate the level of crop water stress to show how these data can be used to indicate the need for irrigation. The different level of water stress is based on FAO guidelines as given in Allen *et al*. (1989): SMD ≤ 25% no water stress, 25 < SMD ≤ 50% moderately water stressed, 50 < SMD ≤ 75% water stressed and SMD > 75% highly water stressed. In Figure 2b, the green colour represents no water stress, the yellow colour represents moderate water stress, the orange colour represents water stressed and red colour represents highly water stressed conditions.

Cosmos effective depth verification

The recent literature reported the hypothetical effective depth to vary from 12 to 70 cm (Franz *et al*., 2012) and from 15 to 83 cm (Köhli *et al*., 2015). In this study, an attempt was made to derive the effective depth from field measurements. Therefore, a calibration process using profile probes, was conducted in 2015 using the scheme shown in Figure 3. In addition, soil moisture sensors and soil cores values obtained in 2014-2015 were also used in the verification process.



	Access Tube Code	Distance from Cosmos (m)
Soy bean	1	35
Soy bean	2	80
Soy bean	3	25
Wheat	4	50
Wheat	5	100
Sweet corn (Rainfed)	6	50
Sweet corn (Rainfed)	7	80
Sweet corn (Sprinkler)	8	35
Sweet corn (Sprinkler)	9	65
Maize (Sprinkler)	10	25
Maize (Sprinkler)	11	65
Maize (Drip)	12	100

Figure 3. Cosmic ray probe calibration: Profile Probe access tubes distribution over the Cosmos probe dominated area in 2015

This scheme aimed to provide information about the exact depth and horizontal extent of Cosmos measurements. Moreover, additional efforts were carried out to correct the neutron counts due to the contribution of the water in the crop's biomass. The correction for biomass water was based on the equation obtained by Baatz *et al*. (2015) from field experiments. Their equation suggested a 0.9% reduction in fast neutron intensity per 1kg of dry matter per m^2. As the dry matter was not collected on a daily basis, SALTMED model (Ragab, 2015) was applied to simulate the daily dry matter for all crops. Examples of the model results are shown in Figures 4 and 5 for maize and tomato, respectively. Figure 6 shows the Cosmos soil water content after correction for biomass water content according to Baatz *et al*. (2015). The corrected neutron counts were used to adjust the soil moisture of Cosmos. The correction for biomass water resulted in a soil moisture difference up to 7%.

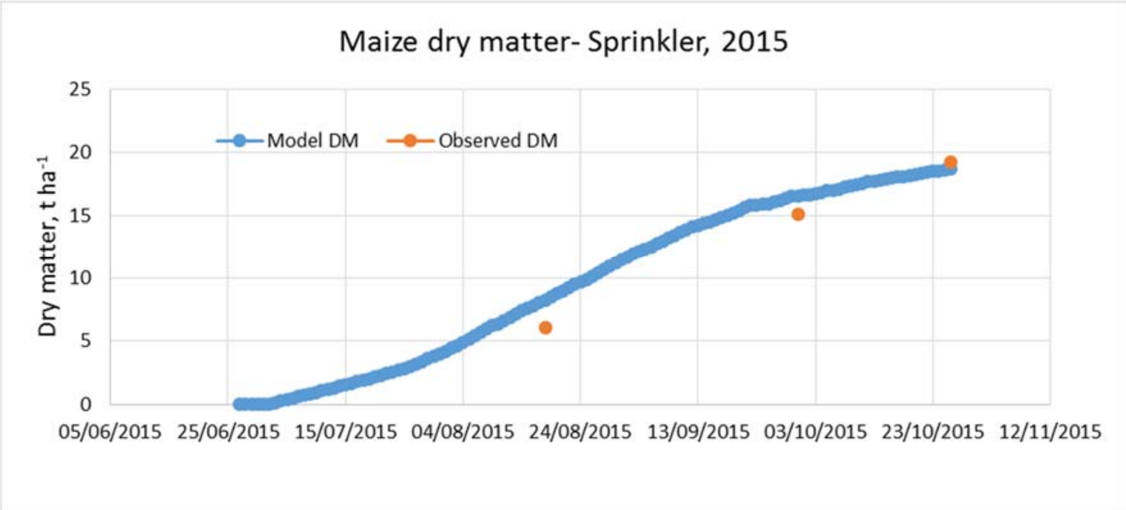


Figure 4. SALTMED model simulation of dry matter of maize, 2015

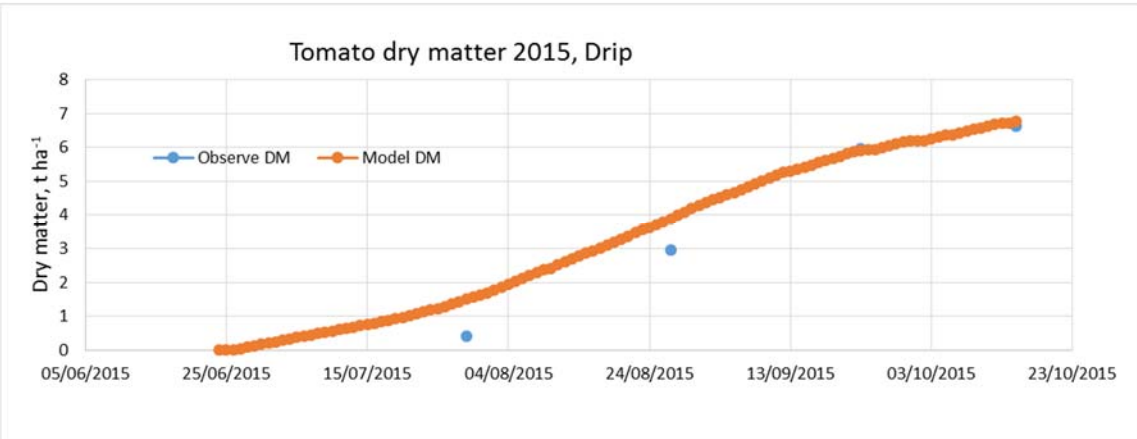


Figure 5. SALTMED model simulation of dry matter of tomato, 2015

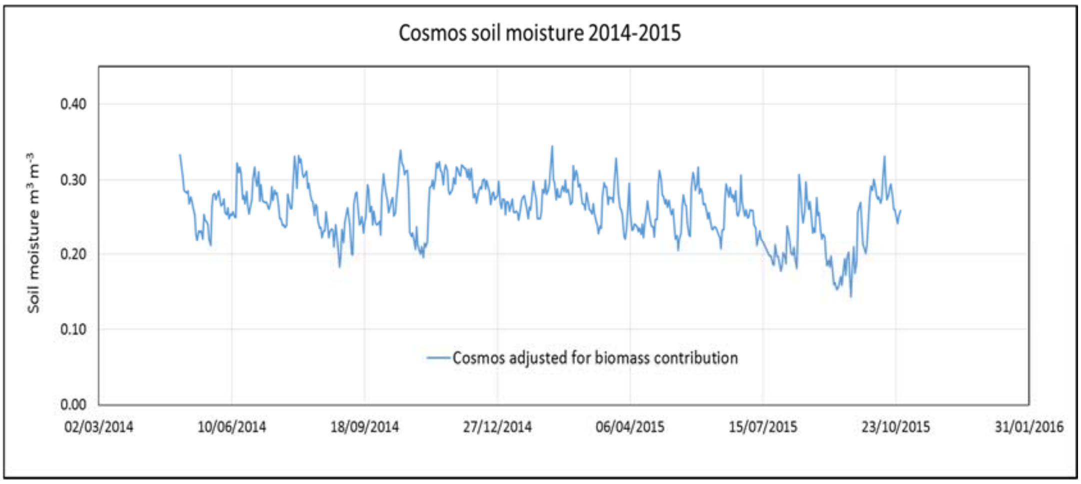


Figure 6. Cosmos soil water content after correction for biomass water content

Cosmos versus cores soil moisture content

Soil cores were taken up to a depth of 50 cm in 2014-2015 cropping seasons. Soil moisture contents were determined by oven drying in the lab and converted into volumetric soil moisture content using the measured bulk density of each soil depth. Figure 7 shows the comparison of Cosmos with the soil cores soil moistures (averaged over 50 cm) under all plots of drip and sprinkler irrigated maize in 2014-2015, while Figure 8 only shows two plots of maize, sprinkler and drip irrigated in 2015 with good matching as indicated by the Root Mean Square Error, RMSE of 0.0290 (Table IV). Figure 9 shows a comparison between the Cosmos soil moisture and the average soil moisture of all soil cores with RMSE of 0.0393 (Table IV). The three figures hinted at the possibility that Cosmos is sensing soil moisture of up to 50 cm deep.

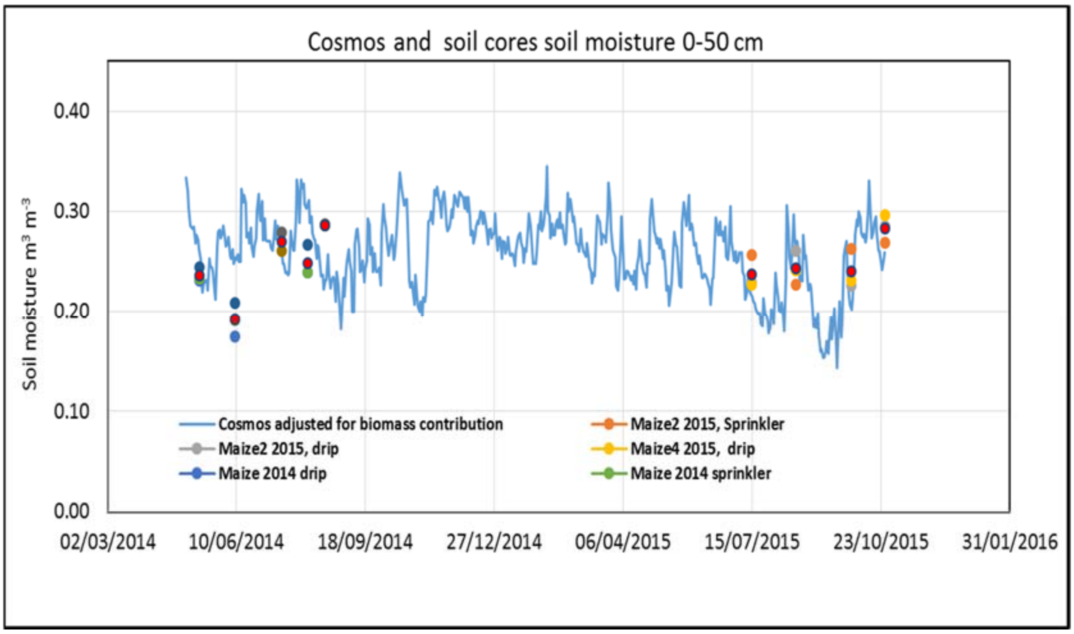


Figure 7. Cosmos soil water content compared with cores soil moisture (0-50cm average) under maize crop, sprinkler and drip irrigated in 2014-2015

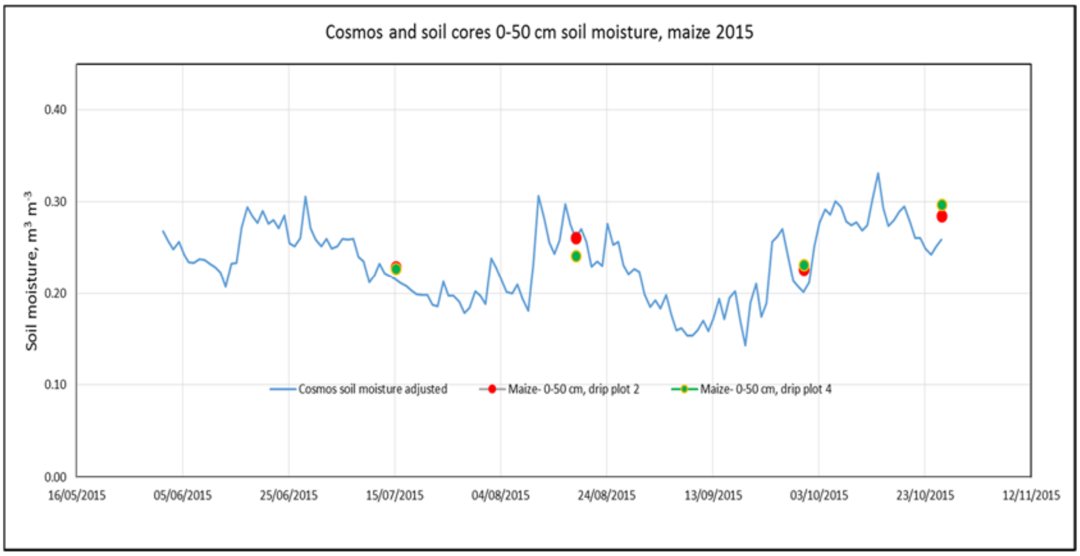


Figure 8. Cosmos soil water content compared with cores soil moisture (0-50cm average) under maize crop, drip irrigated in 2015

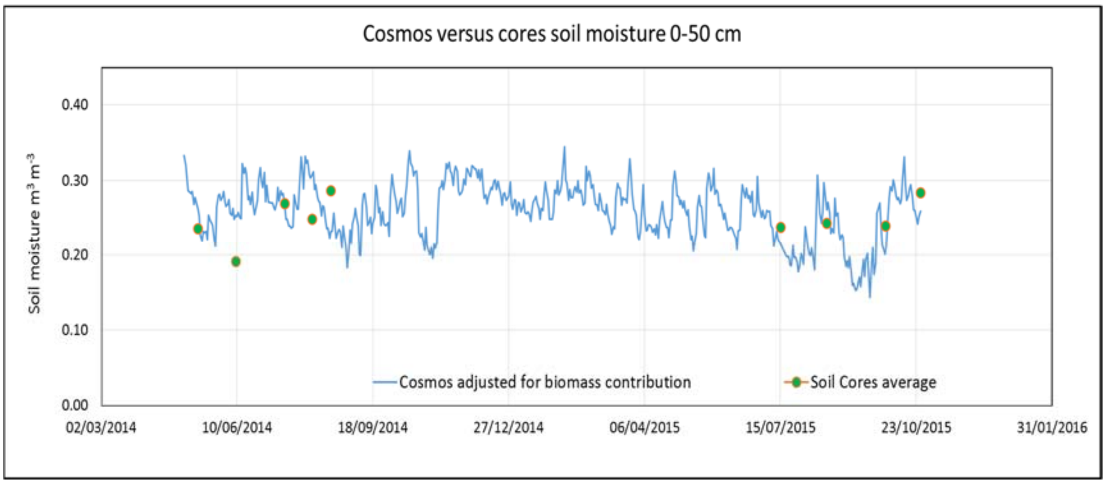


Figure 9. Cosmos soil water content compared with cores soil moisture (0-50cm average) under all crops sprinkler and drip irrigated in 2014-2015

Cosmos versus profile probe soil moisture content

The scheme shown in Figure 3, provided 12 locations around the Cosmos probe with distances ranging from 25 to 100 m. Soil moisture measurements were taken every 10 cm up to 60 cm then a deeper measurement at 100 cm was made. The first comparison was carried out using the most distant access tube at 100 m (Figure 10). The figure shows that the 100 cm depth soil moisture is out of Cosmos depth range of sensing. Nearer access tubes to the Cosmos probe such as plot 10 (25 m) and plot 11 (65 m) along the same transect with plot 12 (100 m) were also compared with Cosmos soil water content as shown in Figures 11 and 12, respectively. The figures of the three access tubes along the same transect at 25, 65 and 100 m distance from the Cosmos probe indicated that, most of the measurements up to 60 cm depth are within the Cosmos sensing depth while the 100 cm depth is out of the Cosmos range. Therefore, the 100 cm profile probe measurements were excluded from further comparisons.

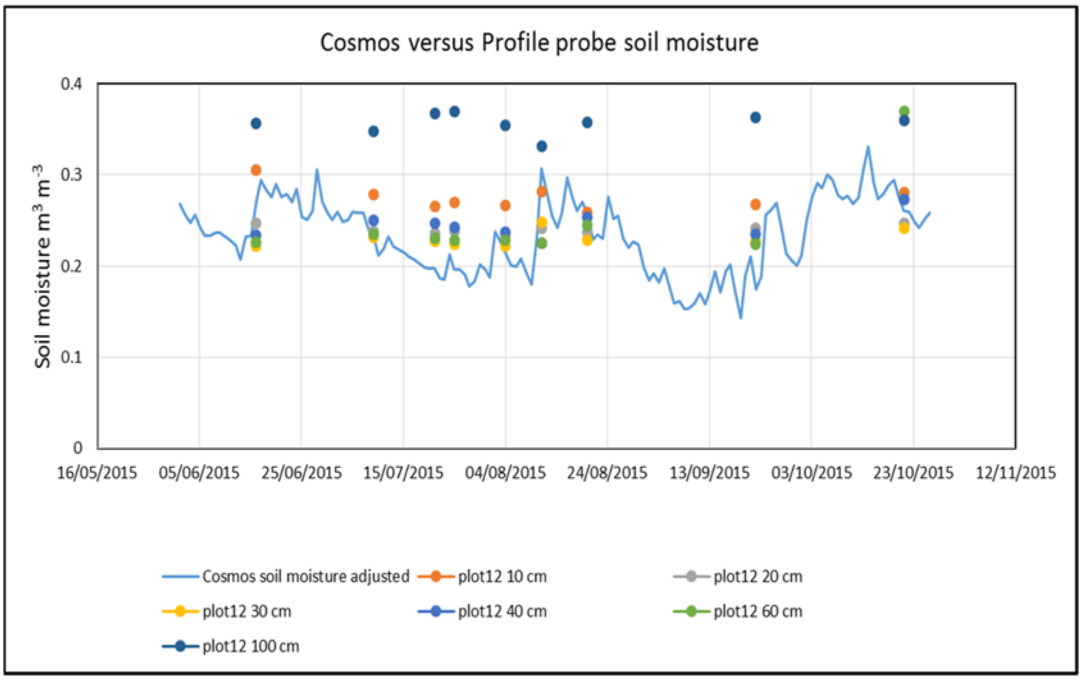


Figure 10. Cosmos soil water content compared with Profile probe soil moisture for plot 12 (100 m from Cosmos probe) at different depths up to 100 cm.

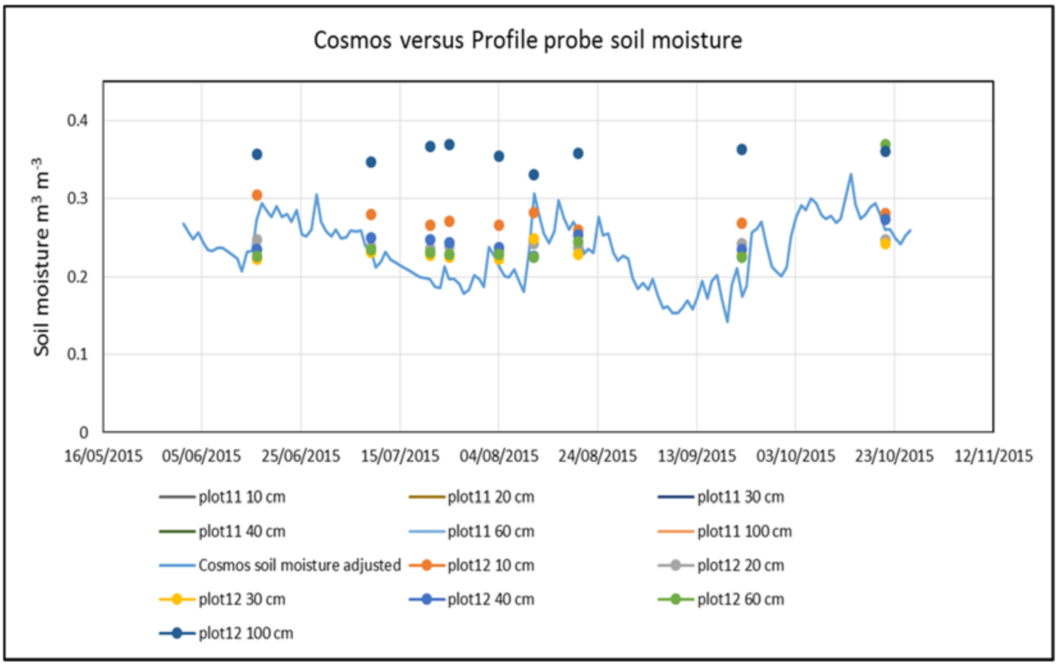


Figure 11. Cosmos soil water content compared with Profile Probe soil moisture for plots 11 (65 m from Cosmos probe) and 12 (100 m from Cosmos probe) at different depths up to 100 cm.

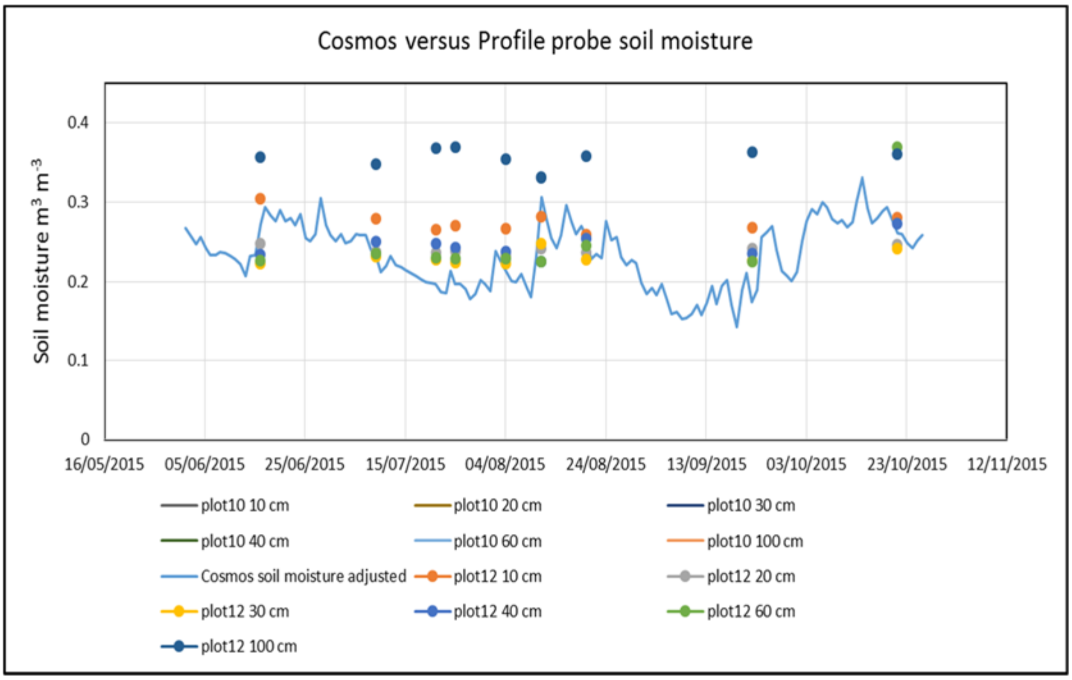


Figure 12. Cosmos soil water content compared with Profile probe soil moisture for plots 10 (25 m from Cosmos probe) and 12 (100 m from Cosmos probe) at different depths up to 100 cm.

The comparison of Cosmos soil moisture with all the 12 access tube measurements up to 60 cm depth, Figure 13, shows once again the possibility that the Cosmos probe is sensing a depth up to 60 cm.

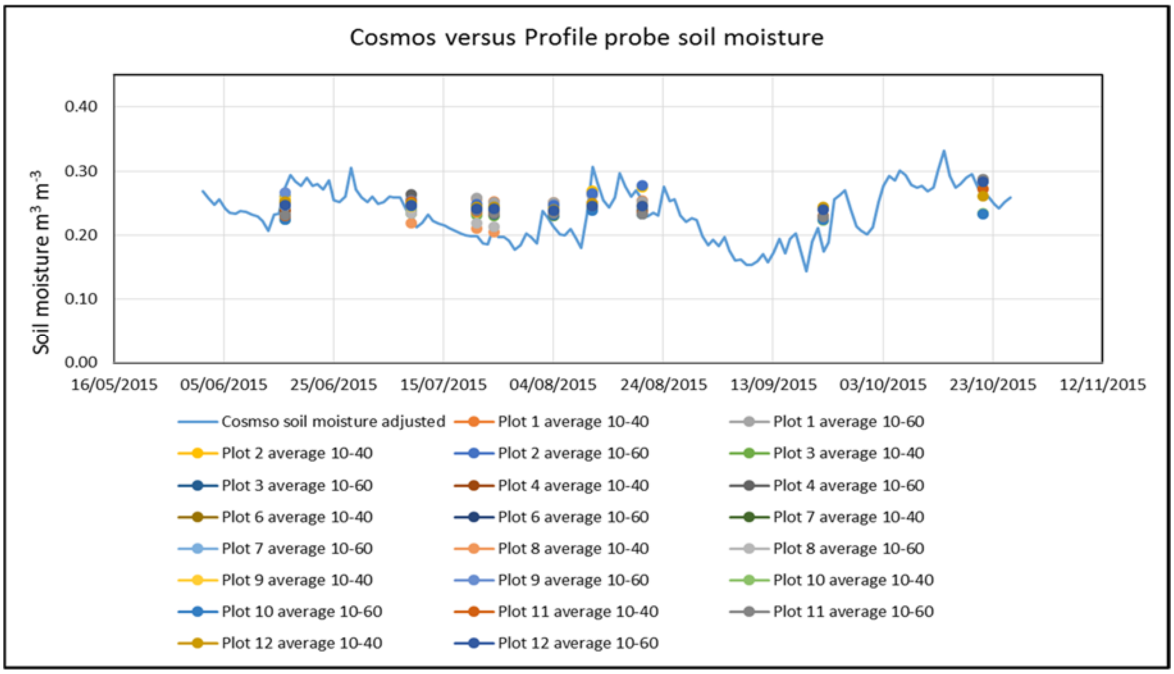


Figure 13. Cosmos soil water content compared with Profile probe soil moisture for all plots at different depths up to 60 cm

Following these findings, the Cosmos soil moisture was compared with average soil moisture for 0-40 cm and 0-60 cm layers of the three plots along the transect plot 10 (25 m), plot 11 (65 m) and plot 12 (100 m) as shown in Figure 14.

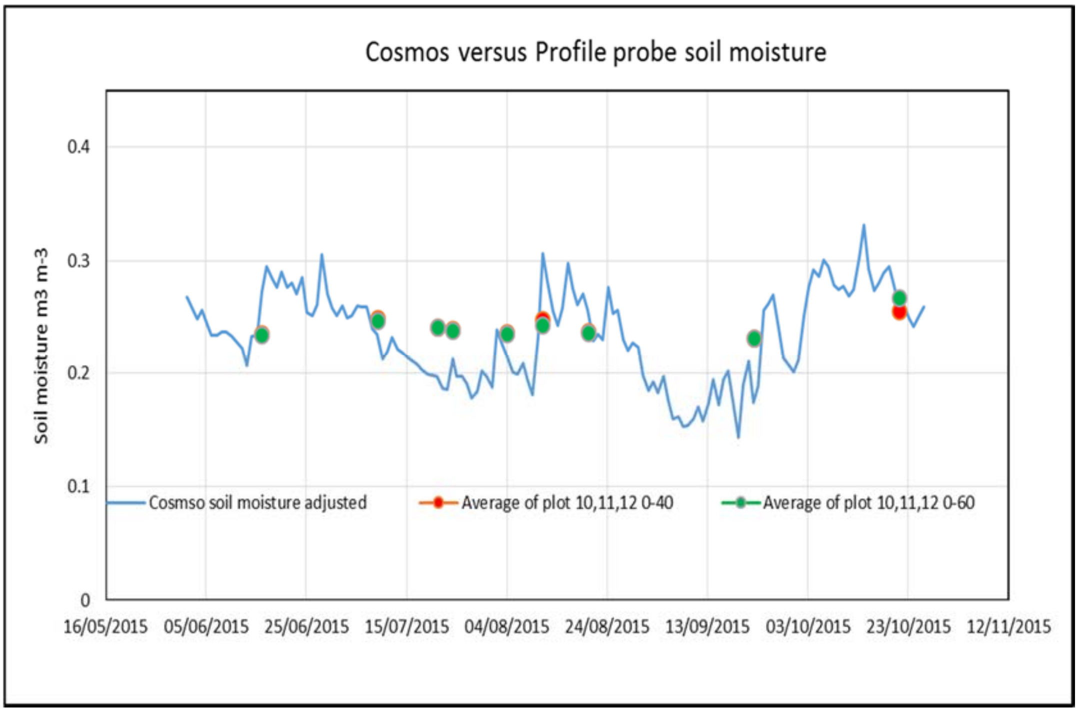


Figure 14. Cosmos soil water content compared with Profile probe soil moisture averaged for plots 10, 11 and 12 for 0-40 cm and 0-60 cm depths

Figure 15, shows that the average soil moisture of all plots of the profile probes for 0-40 and 0-60 cm layers are close to each other and within the sensing depth of the Cosmos with reasonable RMSE of 0.0363 and 0.0369, respectively, Table IV. Comparing the Cosmos soil moisture with the average of 0-40cm and 0-60 cm layers of all the 12 tubes indicated similar results with RMSE of 0.0330 and 0.0339, respectively (Table IV).

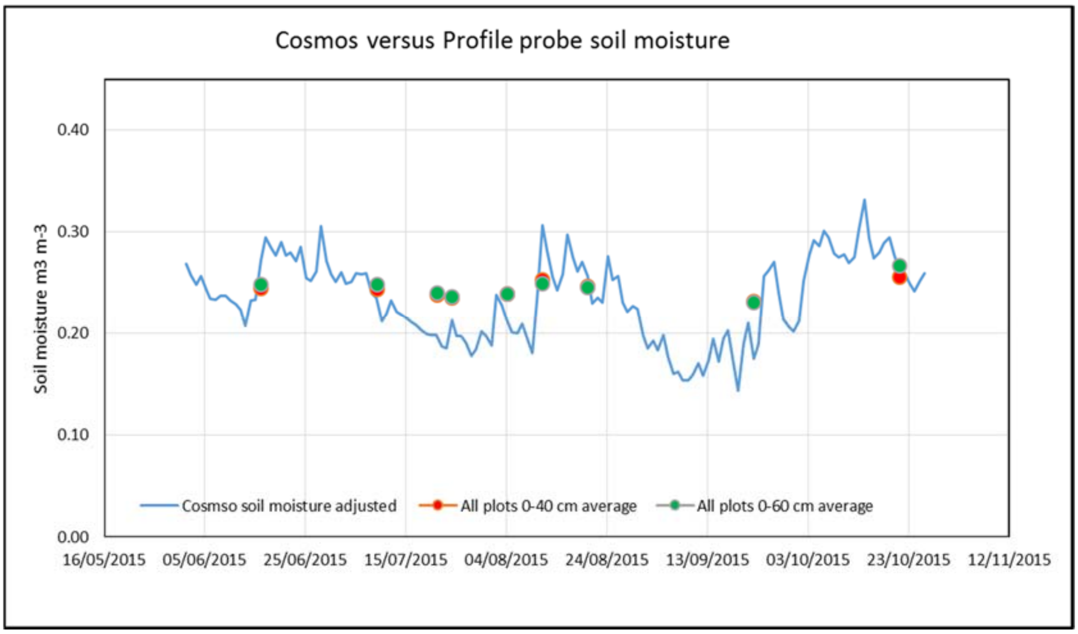


Figure 15. Cosmos soil water content compared with Profile probe soil moisture averaged for all plots for 0-40 cm and 0-60cm depths.

Cosmos effective horizontal extent verification

In comparison with the Cosmos soil moisture, plot 12 soil moisture obtained by the Profile probe at 100 m distance from the Cosmos probe shows that the soil moisture at such distance affect the Cosmos values and within the range of Cosmos sensing range. However, it is possible that Cosmos could sense a distance beyond the 100 m and that needs to be verified in further study.

Cosmos versus sensors soil moisture content

A third comparison between Cosmos and soil sensors soil moisture was carried out. The sensors were buried under the soil surface at different depths. The average of sensors soil moisture for layer 0-60 cm was obtained and compared with Cosmos soil moisture. Figure 16 shows a good agreement between Cosmos soil moisture and the average of all sensors for all plots for 2014 with RMSE of 0.0423 (Table IV).

Overall comparison

The Cosmos soil moisture was compared with the average soil cores and average sensors soil moisture, as shown in Figure 17 for cropping season 2014.

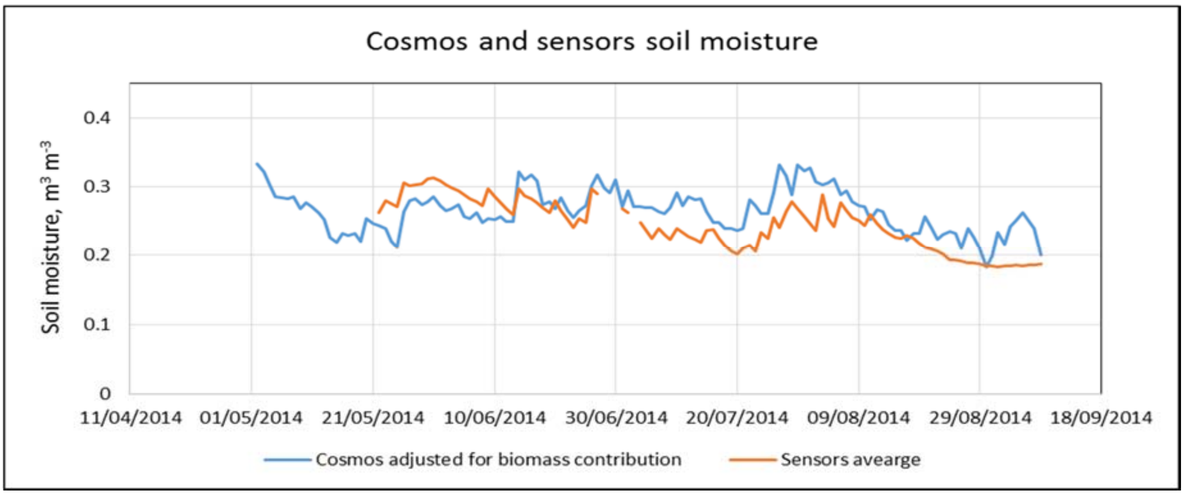


Figure 16. Cosmos soil water content compared with soil moisture sensors averaged for all plots and for 0-60 cm depth. 2014 cropping season

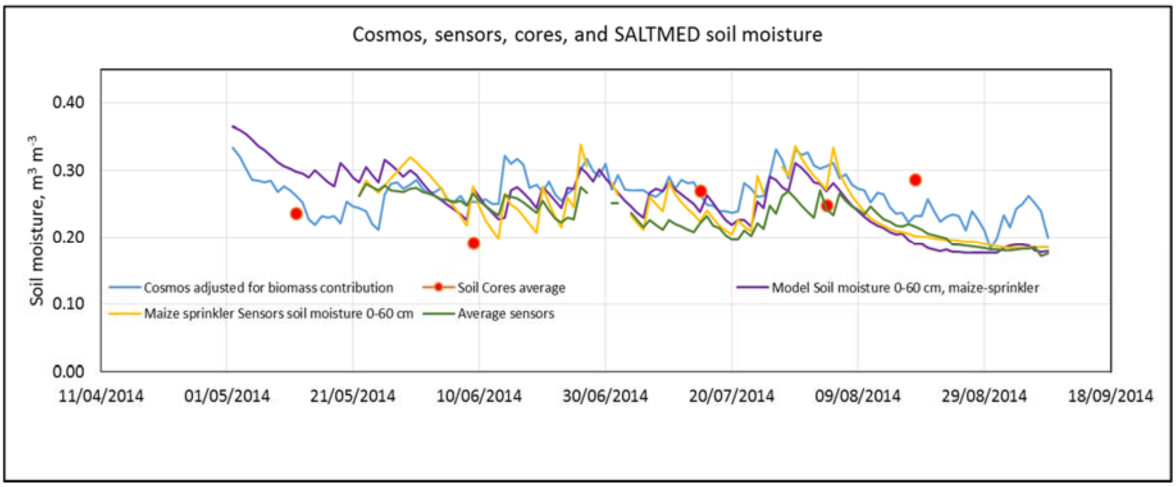


Figure 17. Cosmos soil water content compared with averaged soil moisture sensors, averaged soil cores and SALTMED simulated soil moisture for maize, 2014

The above results show that Cosmos soil moisture falls within the band of the top 0-60 cm soil layer soil moisture measured by sensors, soil cores and Profile probes, supported by the SALTMED model. This could indicate that there is a possibility that Cosmos probe's effective depth could be within the top 0-60 cm of the irrigated lands, particularly during the summer crop seasons. In such case, knowing that almost 80% of the crop root system is accommodated within the top 0-60 cm, the Cosmos measurement could be useful for monitoring the soil water status and subsequently soil moisture deficit in the root zone. As soil moisture deficit is also used as indicator for irrigation water need, crop irrigation requirement could also be based on soil moisture deficit of the root zone or the top 0-60 cm of soil when measured by Cosmos probes. As for the horizontal extent of sensing, the current study shows the soil moisture measured by profile probes at a distance of 100 m is close to those measured by Cosmos. Given there were no further access tubes beyond 100 m, it is possible that Cosmos is able to sense a larger horizontal extent beyond 100 m which warrants further investigation in the future. Table IV shows the RMSE obtained by sensors, soil cores, and by profile probes when compared with Cosmos. The range of the RMSE is reasonable and with overall average of 0.0394, the results support the use of Cosmos as area based, non-destructive and hazard free method of measuring soil moisture and subsequently, crop water requirement.

Table IV. Root mean square error for soil moisture obtained by soil cores, sensors and Profile probes compared with Cosmos soil water content

Method description			Measurement details				RMSE
Method	Measurement	Year	Selected plots	Number of values	Depth, cm	No of depths averaged	
Profile probe	In situ- Non-continuous	2015	1 to 9	324	0-40	4	0.0426
			1 to 9	405	0-60	5	0.0452
			10, 11, 12	108	0-40	4	0.0363
			10, 11, 12	135	0-60	5	0.0369
			10	36	0-40	4	0.0384
			10	45	0-60	5	0.0394
			11	36	0-40	4	0.0356
			11	45	0-60	5	0.0370
			12	36	0-40	4	0.0374
			12	45	0-60	5	0.0376
			1 to 12	432	0-40	4	0.0330
			1 to 12	540	0-60	5	0.0339
Sensors	In situ- continuous	2014	4 plots	388	0-60	2	0.0423
		2014-15	8 plots	792	0-60	2	0.0667
Soil cores	Laboratory	2014-15	45 spots	930	0-50	5	0.0393

		2015	40 spots	800	0-50	5	0.0290
Overall average							0.0394

Revisiting the effective soil moisture depth

Given the fact that Cosmos soil moisture is in reasonable agreement with the soil moisture of cores and sensors for a layer 0-50 cm and for a layer 0-60 cm measured by the profile probes, SMD has been re-calculated for the 0-50 cm layer. Figure 17 shows the soil moisture and SMD of Cosmos when using the hypothetically calculated effective depth (max ~20 cm), while Figure 18 shows the Cosmos soil moisture corrected for biomass water content and for a verified and tested depth of 50 cm. The SMD calculations could be made operational from a Cosmos system to help irrigation managers to determine when and how much to irrigate to avoid harmful water stress (red colour areas, Figure 18). Figure 18 also show the sensitivity of Cosmos to rainfall events where the most stressed periods (red coloured) are mostly rain free periods.

Figure 18. Water content adjusted for biomass for 50 cm effective depth as verified and tested by field measurements

CONCLUSION

The Cosmos technology is one step in the right direction as it provides continuous, integrated, area based values and solves the problem of spatial variability often found in point measurements in relation to the soil spatial heterogeneity. This method could also be used to determine the soil moisture deficit, hence determine when and how much to irrigate. The RMSE obtained by sensors, soil cores, and by profile probes when compared with Cosmos was reasonable, with overall average of 0.0394.

The results showed that Cosmos soil moisture falls within the top 0-60 cm soil layer verified by the soil moisture measured by sensors, soil cores and profile probes supported by the SALTMED model. This indicates that there is a possibility that the Cosmos probe's effective depth could be within the top 0-60 cm of the irrigated lands, particularly during the summer crop seasons. In such case, knowing that almost 80% of the crop root system is accommodated within the top 0-60 cm, the Cosmos measurement could be useful for monitoring the soil water status and subsequently soil moisture deficit in the root zone.

The Cosmos technology could be made operational for irrigation managers to determine when and how much to irrigate to avoid harmful water stress. In summary, these results support the use of Cosmos as an integrated area based, non-destructive and hazard free method of measuring soil moisture and for crop water requirement determination.

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