SUMMER SCHOLARSHIP REPORT

1. **Project Title** (Maximum 15 words)	:	US1902 "A novel approach to monitor soil moisture in an irrigated cotton system"
2. **Proposed Start Date**	:	10/12/2018
Proposed Cease Date	:	04/04/2019
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1. Executive Summary:

With water scarcity increasing due to a variable climate and increased demand across industries, water use efficiency must continue to improve. There are limitations with how moisture is currently measured and estimated on a field scale, with most growers relying on capacitance probes which measure a single point. Accurate paddock scale soil moisture measurements are required to improve irrigation schedules and reduce water loss due to evaporation throughout the farm, and field seepage beyond the root zone. This project looked at the suitability of cosmic ray probe technology in measuring soil moisture in irrigated cotton systems, using a case study in Narrabri (Appletrees, Auscott). While there was a clear correlation between the neutron count derived from the cosmic ray technology and field sampled soil moisture, it was difficult to predict actual soil moisture content using this technology. This is likely due to limitations in the model used to calibrate the results, which did not factor in biomass. Even though the results were inconclusive, the technology has potential, and could be further researched to bypass its limitations in irrigated cotton enterprises.

2. Background:

Soil moisture (SM) can highly vary in space and time, and this can have a significant impact on cotton crop yield and fibre quality. Irrigated cotton accounts for over a quarter of all irrigated agriculture in Australia. With water scarcity increasing due to increased demand across industries and climate change, water use efficiency must continue to improve. The Australian cotton industry is already a world leader in water use efficiency, improving whole farm water use efficiency from 57% to an estimated 70% in the past three decades. The remaining 30% of water is lost across the farm, due to field seepage and evaporation (Roth et al., 2014).

There are limitations with how moisture is currently measured and estimated on a field scale. Technologies such as capacitance probes are only capable of measuring SM in a small area directly around the probe, whereas large scale remote sensing technology such as satellites cannot measure beyond the soil surface. Especially with the rise of new irrigation systems such as bankless irrigation, accurate paddock scale SM measurements will allow growers to better determine their irrigation schedules.

The CosmOz Rover, developed by CSIRO, contains a large-scale cosmic ray probe. Primary cosmic rays from outer space, usually in the form of protons, interact with the atmosphere to form secondary cosmic rays; high energy neutrons. These collide with hydrogen atoms, losing energy, to become fast neutrons, and eventually reach a state of thermal equilibrium. Cosmic ray probes measure the flux of fast neutrons, which is inversely proportional to the amount of hydrogen atoms whether it be in air, water, or organic compounds. As water molecules are the dominant source of hydrogen atoms in soil, then close to the Earth's surface, SM content can be inferred from neutron fluxes (Desilets et al., 2010).

The CosmOz Rover has a 300 m radius horizontal footprint, and can measure to a depth between 0.1-0.7 m depending on SM content, with saturated profiles only measurable to shallower depths (Hawdon et al., 2014). Cosmic ray measurements are passive, non-invasive and mostly insensitive to variations in soil characteristics such as texture, surface roughness, bulk density and the state of water (Desilets et al., 2010; Zreda et al., 2008). Measurements can be taken at a fixed point for temporal data, or additionally moved around a field/farm for spatial data. Key factors that affect measurements include soil organic carbon.

This technology has been studied with success in natural vegetation and dryland agricultural systems, but has not been trialled with irrigated systems. This novel technology has the potential to provide more representative paddock-scale SM measurements compared to other technologies, as a tool to guide decision making for irrigation schedules and improve water-use efficiency.

3. Aims and Objectives:

- Test whether cosmic ray probe technology is a suitable method for measuring SM in irrigated cotton systems
- Corroborate the results with other related technologies, such as IrriSAT

4. Materials and Methods:

Field measurements of SM were taken from an Auscott property (Appletrees) in Narrabri between the dates 10 December 2018 and 13 January 2019 (Figure 1). The CosmOz rover was stationed between a fallow field and a cotton field sown on the 25th of October.

Figure 1. Location of sampling site, with the CosmOz Rover radius marked in red.

Field moisture samples were taken from 12 sites in rows across both fields (crop and fallow), at depths of 0-5 cm, 5-15 cm and 15-30 cm and measured using the gravimetric oven drying method. Samples were oven dried at 105°C for a minimum of 24 hours.

A particle size analysis was conducted to determine the clay content of all 36 sample sites, using sodium hexametaphosphate solution (5%, pH 8.5) and hydrometer method. The total carbon content was measured using the Dumas high temperature combustion method. Samples were heated to 1350°C and gases released are measured using an infrared sensor.

A farm-specific calibration for the CosmOz Rover was developed from the average SM across both fields. Neutron counts were corrected for atmospheric pressure, water vapour and neutron influx intensity to isolate the effect of SM. The calculations and constants used were developed from Australian sample sites by previous CSIRO studies (Hawdon et al., 2014; McJannet et al., 2017).

5. Results:

The average field moisture of the crop and fallow fields reflect the conditions observed. The moisture of the fallow field remained relatively constant throughout the span of the survey, with the exception of a major rainfall event on December 14. The crop moisture fluctuated with irrigation cycles.

There was a good correlation of -0.60 between the neutron count and field SM which reflects the negative relationship between neutron count and moisture (Table 1). This relationship is visible by a sharp decrease in neutron count during irrigations of the cotton crop, between December 17-19 and January 2-4, and an increase as the moisture evaporated (Figure 2).

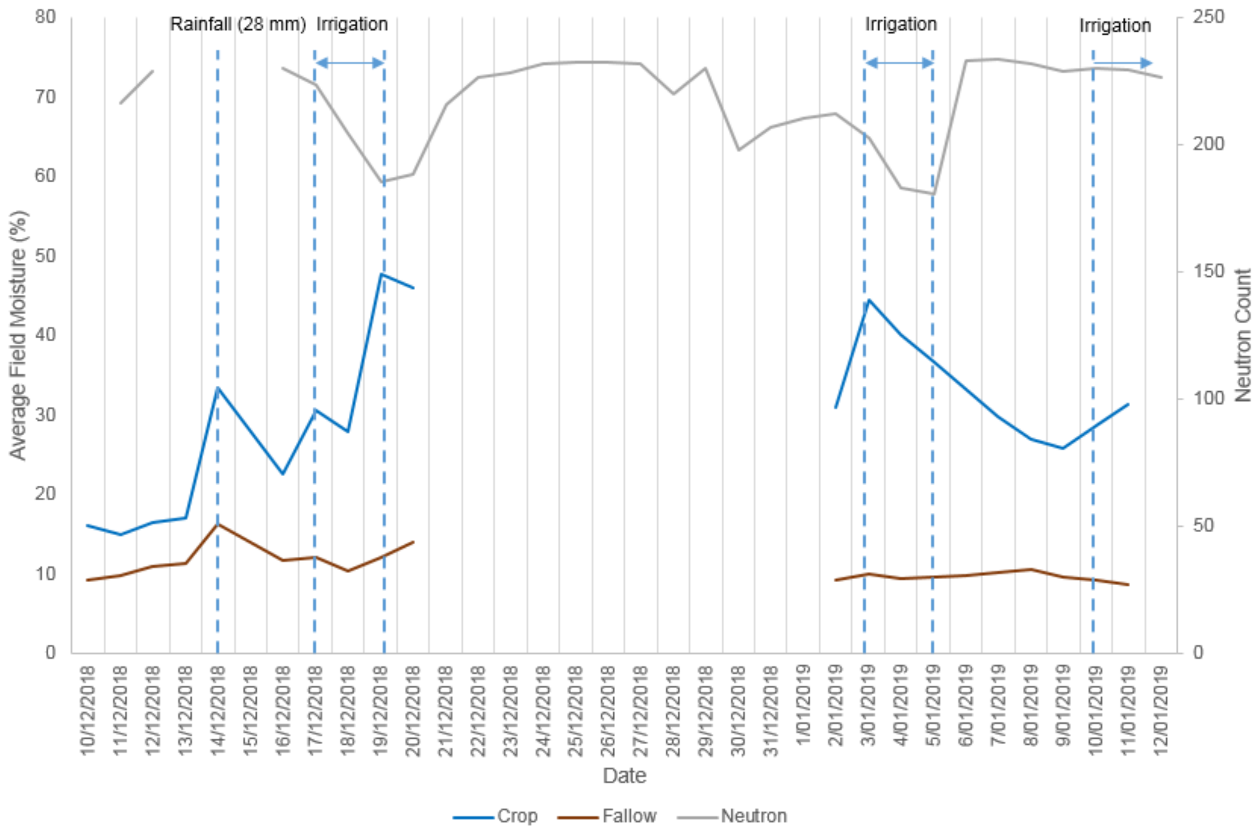

Figure 2. The change in neutron count over the study period, in relation to the crop and field fallow measurements, rainfall events and irrigation cycles.

Actual values of SM could not be calculated from the CosmOz data, which is likely due to limitations in the current methodology. This methodology was developed for dryland and natural vegetation systems that generally involve little change in plant biomass. Irrigated cotton can rapidly grow in summer, particularly between December and January, when measurements took place. The water within this plant biomass likely impacted the measurement from the CosmOz. A correlation matrix and several linear regression models were fitted to assess the relationship between biomass and the neutron count (Table 1, Table 2). The models that looked at SM separately for the irrigated and fallow field, as well as biomass variables like crop height and crop coefficient (K_c) had the highest R^2 (Table 2). The crop height, a simple measure of biomass, was a significant variable in all cases it was included in the model.

Table 1. Correlation matrix of the response (N count) and variables measured in field, or by Irrisat (average K_c).

	N Count	**SM**	**SM Crop**	**SM Fallow**	**Crop Height**	**Average K_c**
N Count	1	-0.6	-0.56	-0.34	0.32	0.17
SM	-0.6	1	0.99	0.36	0.24	0.33
SM Crop	-0.56	0.99	1	0.25	0.35	0.45
SM Fallow	-0.34	0.36	0.25	1	-0.56	-0.53
Crop Height	0.32	0.24	0.35	-0.56	1	0.96
Average Kc	0.17	0.33	0.45	-0.53	0.96	1

*Where SM Crop and SM Fallow are the separate soil moisture contents of the cotton and fallow fields respectively.

Table 2. Various linear regression models, with their R^2 and significant predictor variables.

Model	**R^2**	**Significant variables**
Neutron count ~ SM	0.34	SM
Neutron count ~ SM + crop height	0.58	SM, crop height
Neutron count ~ SM + crop height + Kc	0.66	SM, crop height
Neutron count ~ SM Crop + SM Fallow + crop height + Kc	0.70	SM Crop, crop height

6. Discussion and Conclusions:

The equation below characterises the relationship between neutron intensity and SM, where ρ_{bd} is the soil's bulk density, N is the corrected neutron count by the CosmOz, N_0 is the neutron count from field measurements, $w_{lattice}$ is the lattice water content, w_{soc} is the organic carbon content.

$$\theta = \left[\frac{0.0808}{\left[\frac{N}{N_0}\right] - 0.372} - 0.115 - w_{lat} - w_{soc}\right]\rho_{bd}$$

While a constant value for the calibration coefficient N_0 should be derived from the field SM samples, the N_0 changed on a daily basis. Using the average N_0 with the N count gave inconceivable values – negative and extreme SM values above saturation.

A further analysis of the extreme fluctuations in N count above (Table 1) has shown that biomass can significantly impact the N count. This was suggested in dryland studies (Chrisman and Zreda, 2013), even though these case studies did not exhibit high and rapid changes in biomass, as compared to an irrigated cotton system. While successful in predicting moisture in dryland and natural vegetation systems, this experiment has shown the need to include other factors in order to be used in an irrigated system.

During the span of these studies, there was a significant increase in biomass, as seen from images obtained from Irrisat (Figure 3). This in turn is reflected by an increase in water use and demands, as reflected by the increase in crop coefficient (Figure 4). While K_c was shown to improve the model, the simple but inaccurate and labour intensive method of measuring average crop height showed a higher correlation with the N count. Future studies could compare different measures of crop biomass, and trial existing satellite products such as NDVI.

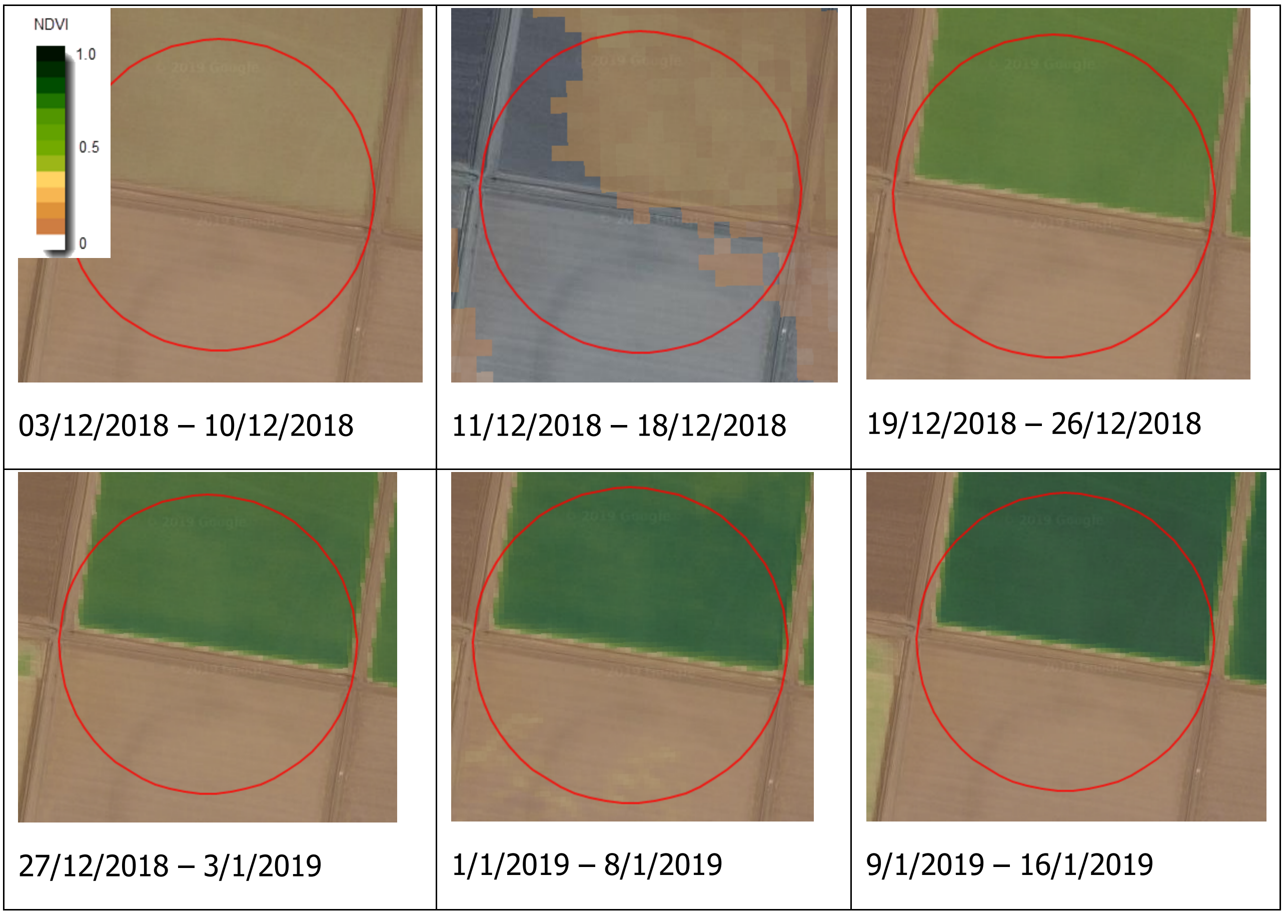

Figure 3. Change in NDVI (biomass from crop) over duration of sampling from (IrriSat), with the radius of the CosmOz Rover outlined in red. Note: cloud cover evident in the image derived from 11/12/2018-18/12/2018.

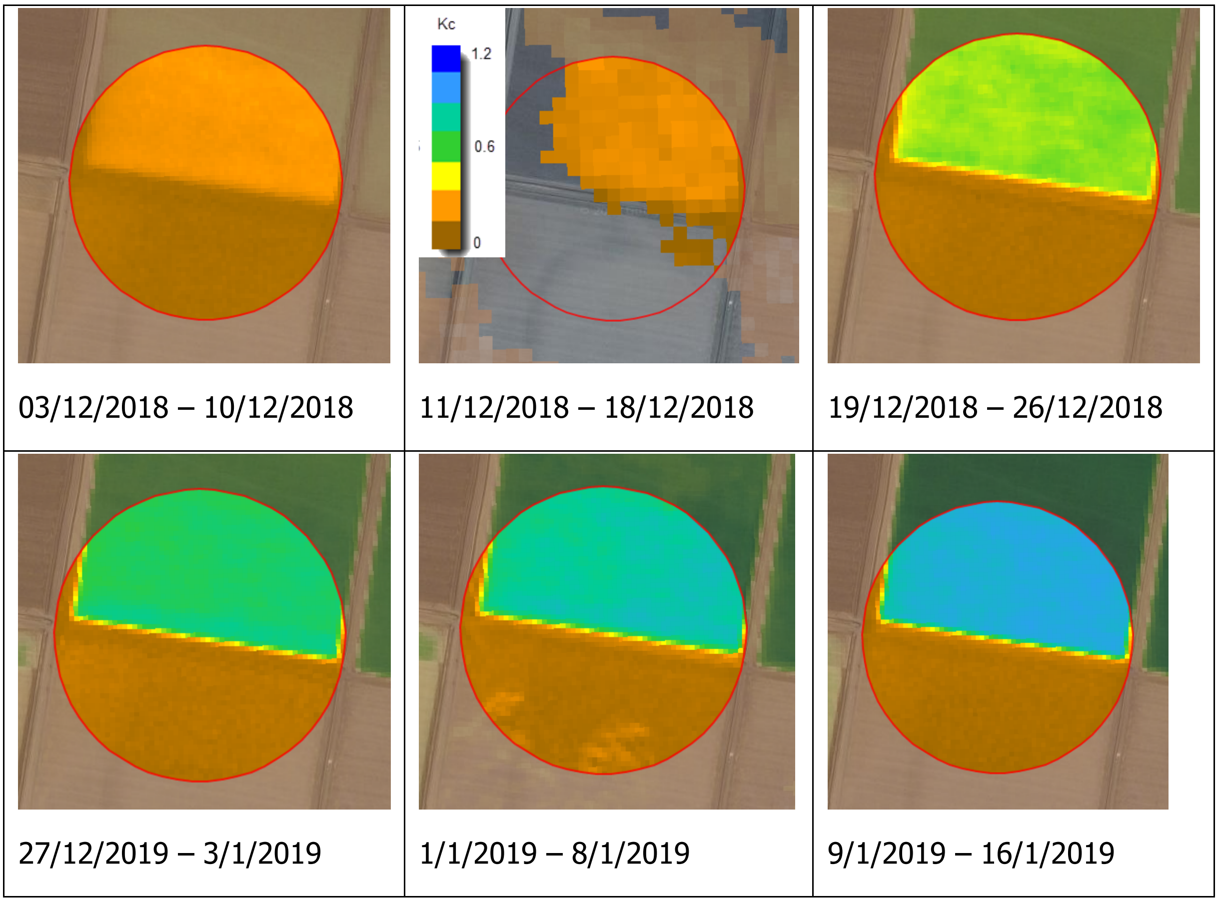

Figure 4. Change in crop coefficient (K_c), a measure of crop evapotranspiration, over duration of sampling from (IrriSat), with the radius of the CosmOz Rover outlined in red. Note: cloud cover evident in the image derived from 11/12/2018-18/12/2018.

Furthermore, as the CosmOz gives a single measurement for a large footprint, there is the issue of differentiation between non-irrigated and irrigated areas. Irrigation of the cotton field occurred in sections, several days apart. This is particularly an issue as not all the area covered by the CosmOz is weighted equally in calculations. Due to the short-term nature of this study, the placement of the CosmOz occurred post-planting and was consequently placed at the edge of a field, close to irrigation channels or head ditches, where variation in moisture and conditions were high. Future studies should avoid this.

These results suggest that the current model and method for cosmic ray probe technology is inappropriate for monitoring SM in an irrigated cotton system, and that a new methodology needs to be developed in the future for irrigated systems. However, these results also show that there is high potential for this technology, should they be calibrated.

7. Highlights:

- There was a good correlation (-0.60) between the neutron count derived from the cosmic ray technology and field sampled soil moisture
- N count measurements were significantly affected by biomass (crop height)
- Soil moisture content from the cosmic ray probe could not be derived due to limitations in the existing methodologies for analysis
- These limitations will be addressed in future studies by upgrading current methodology and including other important factors (e.g. crop biomass) to develop soil moisture models

8. Future Research:

To overcome the limitations and issues faced in this study, further research using cosmic ray probes to infer soil moisture content in irrigated cotton systems is required. Some improvements in the sampling required to calibrate existing methods is required and include:

i) Placement in the middle of a field to accurately calibrate for moisture fluctuations and increasing biomass
ii) Measurements of the changing plant biomass over time
iii) A longer time series to quantify relationships between neutron count and soil moisture content

Longer term trials could also use capacitance probes to replace lab testing field soil moisture, or measurements of NDVI from satellites.

9. Presentations and Public Relations:

The results from this work will also be presented by A. Prof Tom Bishop at Proximal Soil Sensing in the USA in June.

10. Reference List:

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