WIRELESS SOIL MOISTURE SENSOR NETWORKS FOR PRECISION IRRIGATION SCHEDULING

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Abstract

Advanced nutrient management aims to optimise plant nutrient use and minimise deleterious environmental effects. Precision irrigation tools tackle this issue by controlling soil moisture status related to irrigation events, minimising drainage and run-off events, and improving nutrient use efficiency. Precision irrigation hardware allows irrigation and nutrient inputs to be varied to small defined management zones under the irrigator. The management zones are derived from data layers obtained from electromagnetic (EM) surveys and yield maps. Wireless soil moisture sensor networks (WSNs) are then positioned into these zones to monitor wetting and drying events for precision irrigation scheduling.

Wireless sensor nodes used in this study operate on license free radio frequency with mesh networking capability (self-organising and self-healing). They are battery powered, recharged by solar energy, and able to operate without sunlight for four weeks. Appropriate sensors are attached to the wireless sensor nodes to measure soil moisture at two depths, soil temperature, soil matric potential and rainfall & irrigation. All these variables are measured at 15 minute intervals and relayed to the base station via the most energy efficient path. Each wireless node maintains a list of neighbour nodes in order to repair the communication path to the base station in case of one node failure. Data processed in real time at the base station is available to researchers, land managers and irrigator software controller packages via 3G cellular network or ADSL over the internet in real time.

Real time soil moisture data recorded from three zones under a wheat crop at our study site in the Manawatu Sand Country for the irrigation season 2011-2012 showed that volumetric soil moisture typically varied between 0.10 – 0.45 m^3 m^{-3} at any one time, because some areas remained saturated while other areas drained rapidly to a refill point of approximately 0.10 m^3 m^{-3}, when irrigation was used to avoid plant water stress. Zone 1 required regular irrigation during the summer months to avoid moisture stress, Zone 2 required occasional irrigation, and Zone 3 required no irrigation for the entire irrigation season. This information was used to update zone specific irrigation plans in customised software which controlled a variable rate irrigator.

Introduction

Efficient water management plays an important role in irrigated agricultural systems (Kim and Evans, 2009). Under conventional blanket irrigation (uniform rate irrigation across the land) many parts of irrigated fields are effectively over or under-irrigated due to spatial variability in soil available water-holding capacity, water infiltration and runoff. Under-irrigated areas are subject to water stress, resulting in production loss, while over-irrigated areas suffer from poor plant health and nutrient leaching.

Irrigation control systems based on WSN and real time soil moisture data are a potential solution to optimise water management by remotely accessing in-field soil water conditions and then site-specifically controlling irrigation sprinklers (Kim and Evans, 2009; Hedley and Yule, 2009). The systems require seamless integration of the real time soil moisture data via a 3G cellular or ADSL network to control individual sprinklers on a precision irrigation system (Hedley et al., 2011).

Soil moisture data can be collected using an autonomous wireless sensor network system (WSN), which then communicates with another autonomous wireless sensor network system controlling individual sprinklers on the irrigation hardware.

Strategic positioning of WSN sensor nodes into a field is enabled by interrogating the soil and landscape at high resolution and deciding on positions which sample all differences likely to influence irrigation scheduling. High resolution quantification of the soil and land resource for precision water management is enabled using electromagnetic (EM) surveys with geostatistical interpolation and ground-truthing of the datasets (e.g. Hedley and Yule, 2009). On-the-go EM mapping (Adamchuk et al., 2004) simultaneously collects georeferenced apparent soil electrical conductivity (EC) and accurate elevation data, and interpolation of this data allows quantitative description of relationships between soil and topographic factors in the landscape which influence water storage and movement, e.g. soil texture and slope. This geostatistical form of digital soil mapping acknowledges the importance of position in empirical descriptions of relationships of the soil resource to its environs, as described by McBratney et al., (2003).

Recent low-cost, low-power wireless mesh networking technology is well suited to replace wires as the communication medium in many agricultural applications (Coates and Delwiche, 2009). The networks consist of a number of wireless nodes, which are battery powered and backed up by solar energy, and attached to sensors in the ground; the nodes transmit data via other wireless nodes to a base station. The WSN which is capable of self-organising and self-healing (mesh networking) requires minimum maintenance. Although the WSN uses low power radios, mesh networking technology enables transmission of data from one node to any other node in the network, without using high power radios. The mesh network allow greater flexibility in node placement since inability for two nodes to communicate (e.g. due to a physical obstruction) is handled by re-routing through any other possible alternative route within the network. Another advantage is that a failed node does not disable the network, as the other dependent nodes re-route through other available nodes (self-healing). Once the wireless sensor nodes are placed in management zones and the base station is activated, the sensor network is self-formed by allocating unique addresses to each node and defining the most efficient communication path to relay data from each node to the base station. The base station which processes the data also acts as a web server. Interested parties can access the real time data by directing a standard web browser to the URL of the web server in the base station. The graphical user interface (GUI) enables one to look at the real time and historical data, download required data, backup application data and set alarms for pre-set variable values. Alarms send email alerts to notify the interested parties to warn about critical conditions

This paper presents our progress in developing a WSN to inform software which controls a variable rate irrigation system.

Methods

Site Description

The site is a 75 ha wheat field, situated in the Manawatu Sand Country, near Bulls, and irrigated by a centre pivot irrigator with variable rate (VRI) modification allowing individual control of each sprinkler by digital maps uploaded to a central controller (www.precisionirrigation.co.nz). The topography is a sand plain, with a microrelief of small crescent-shaped barchan dunes reflecting past aeolian movement of sand across the sand plain surface. Soils are Motuiti sands (Campbell, 1978) and are variably influenced by a high and fluctuating water table both in space and time. Some areas of the field remain wet in spring delaying cultivation, while other areas dry out very rapidly and require frequent irrigation to avoid becoming hydrophobic for the remaining summer season.

Defining the soil and land resource

Geonics EM38Mk2 and EM31 sensors were combined with RTK-DGPS and dataloggers mounted on an all-terrain vehicle to acquire high resolution EM38 and EM31 vertical mode datasets in two separate surveys in October 2010. The sensors measure a weighted mean average value for apparent electrical conductivity (EC) to 1.5 m depth (EM38) and 5.0 m depth (EM31). Survey data points were collected at 1-s intervals, at an average speed of 15 kph, with a measurement recorded approximately every 4 m along transects 10 m apart. EM surveys quantify soil variability largely on a basis of soil texture and moisture in non-saline conditions (e.g. Sudduth et al, 2005).

Defining the irrigation management zones

EC and elevation data were kriged on a five metre grid in the R 2.13.1 statistical environment (R Development Core team, 2011) using the gstat package (Pebesma, 2004) to produce the soil EC and digital elevation map (DEM). A soil wetness index (SWI) was extracted from the DEM in SAGA software (Olaya and Conrad, 2009). Yield data was also obtained for spatial data analysis. The spatial data analysis interrogates the datalayers overlaid onto a common interpolation grid, and derives management classes which partition the soil and landsurface into classes using the k-means clustering algorithm. Three management classes ("zones") were derived for this study (k=3).

Laboratory analysis of soil hydraulic and textural properties

Three replicate soil samples (at three depth intervals) were randomly collected from each of the three classes for laboratory analysis. The soil samples were intact soil cores (100 mm diameter and 80 mm in height) taken from the middle of three sample depths (0-200mm, 200-400mm, 400-600mm) for determination of field capacity (10kPa); and smaller cores (50 mm diameter and 20 mm in height) were taken for soil moisture release at 100 kPa. A bag of loose soil was also collected (0-200 mm, 200-400 mm, 400-600 mm soil depth) for laboratory estimation of permanent wilting point (1500 kPa) and particle size distribution. Percent sand, silt and clay was determined on these soil samples by organic matter removal, clay dispersion and wet sieving the >2-mm soil fraction and then by a standard pipette method for the <2-mm soil fraction (Clayden, 1989).

Installing the WSN

A wireless soil moisture sensor network (WSN) was installed into the irrigated field, with nodes placed into each of three management classes. The nodes (Crossbow Technology) with wireless mesh technology have a maximum communication range of up to 1 km in line of site, and are capable of acting as sleeping routers to conserve power. Sensors attached at each node were: (1) two Delta-T SM300 moisture sensors installed at 20cm and 50cm to monitor volumetric soil moisture content (v/v), (2) a Spectrum Technologies Watermark soil matric potential sensor installed at 20cm soil depth to monitor soil moisture tension (in cbar), and (3) a tensiometer equipped with an absolute pressure transducer, to assess depth of water table, installed at one metre soil depth (data not presented in this paper). A rain gauge was also attached to one node to monitor irrigation and rainfall events. Data is relayed to a base station every fifteen minutes, processed in real-time, converted to the necessary format and immediately made available through a 3G cellular modem via the Internet to a web page, available for simultaneous remote access by end users.

Results

Soil management zones

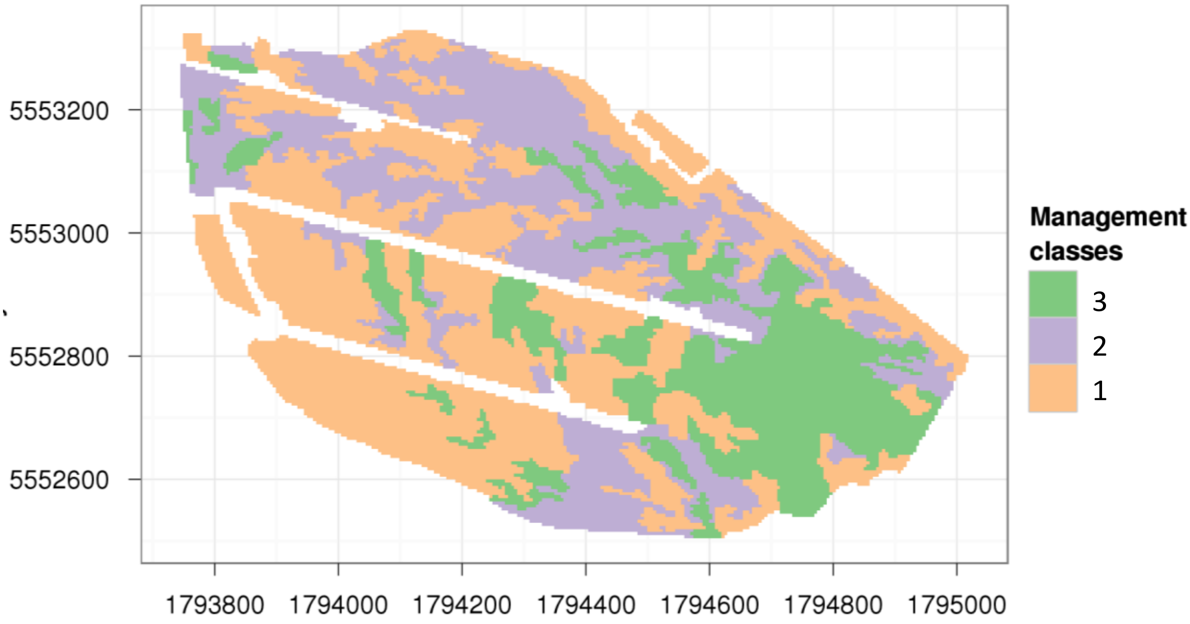

Fig. 1. Soil management zone map derived by spatial data analysis of EM, elevation and yield.

Figure 1 shows the graphical output of our spatial data analysis, delineating three major management classes. Figure 2 indicates the statistical difference of each co-variate datalayer (EM38, EM31, soil wetness index, yield) for each management class, derived by the k-means clustering algorithm. Ground-truthing of these classes confirmed that they accurately reflect management issues encountered at this site; which includes the fact that some areas (Class 3) remain too wet to cultivate in Spring, when other areas (Class 1) reach their ideal soil moisture status for cultivation. These differences reflect micro-topography and depth to water table. Crop yields closely reflect these soil wetness differences, and therefore the yield data was included in our determination of management classes.

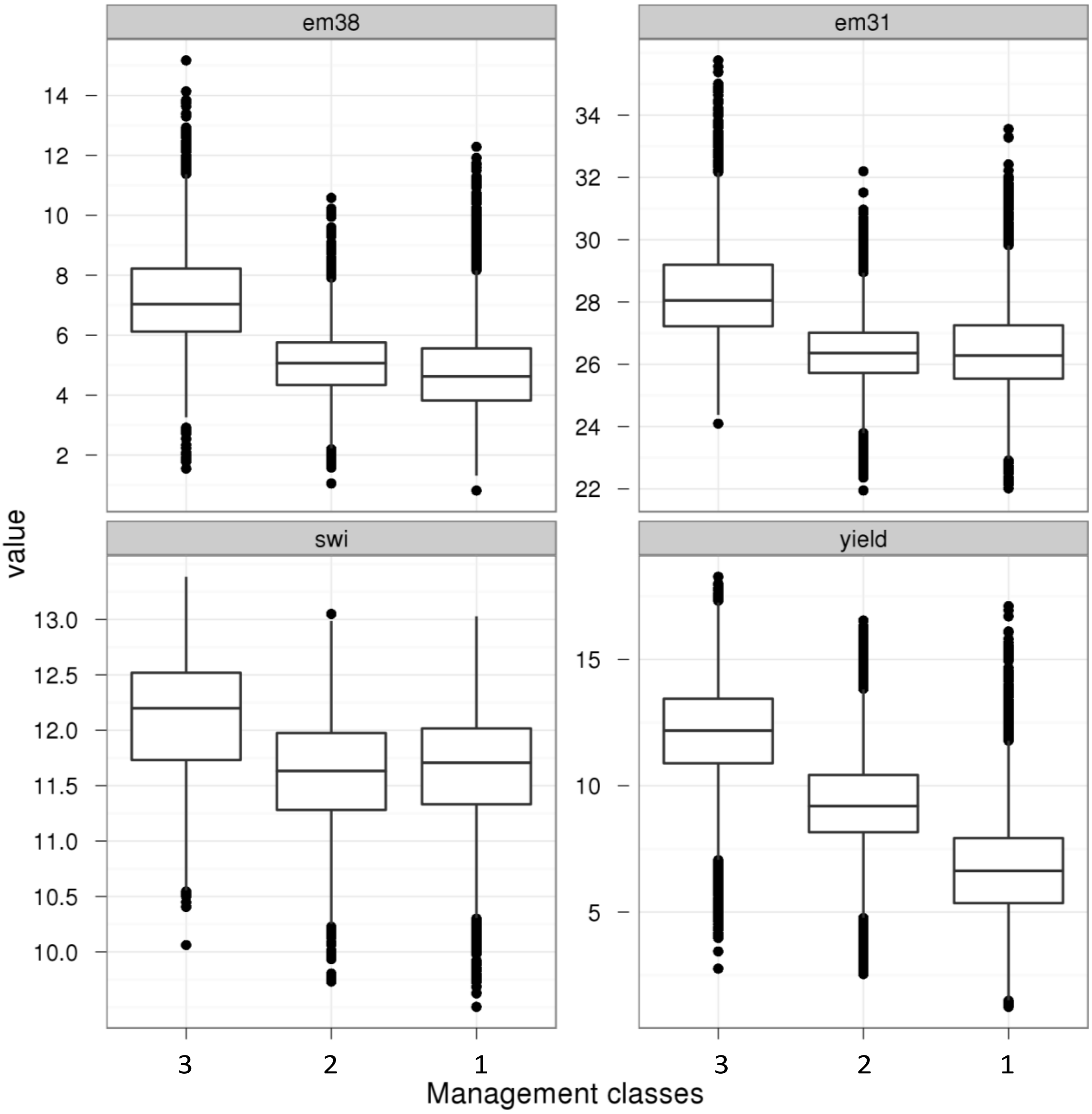

Fig. 2. Spatial data analysis of EM, elevation and yield was used to derive three soil management classes. The box plots show the statistical differences between each co-variate datalayer for the three management classes.

Laboratory analysis of soil hydraulic and textural properties in each class

Class 1 and 2 soils are classified as sands; Class 3 soils are loamy sands with larger available water-holding capacities (AWC) (Table 1). The larger AWC of Class 3 is often irrelevant with respect to irrigation requirements, as a high water table sub-irrigates the crop for much of the irrigation season in this class. The analyses indicate that Class 1 and 2 soils can only store and supply 50mm/m readily available water to the growing crop. Wilting Point (1500kPa) is at 0.03 $m^3 m^{-3}$ for Class 1 and 2 soils and 0.04 m^3m^{-3} for Class 3 soils.

Table 1. Laboratory analysis of soil hydraulic and textural properties

Class	Soil Description	Sand	Clay	10kPa	100kPa	RAWC	AWC
		%	%	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}	m^3m^{-3}
1	Excessively drained sand	96	2	0.11±0.02	0.06±0.01	0.05±0.02	0.08±0.02
2	Well drained sand	95	2	0.14±0.04	0.09±0.01	0.05±0.03	0.11±0.03
3	Imperfectly drained, loamy sand	90	4	0.24±0.02	0.13±0.02	0.11±0.02	0.20±0.02

The small textural difference of Class 3 soils reflects the low-lying position in the landscape where fine sediments tend to collect at times of surface run-off from adjacent areas. The fact that Class 3 soils tend to be wetter for longer periods, also reduces the winnowing effect of strong winds, and scalping effect of cultivation, and promotes organic matter stabilisation. Replicate WSN nodes were installed into each of the three management classes, because our ground-truthing supported the map classifications.

Wireless Sensor Network

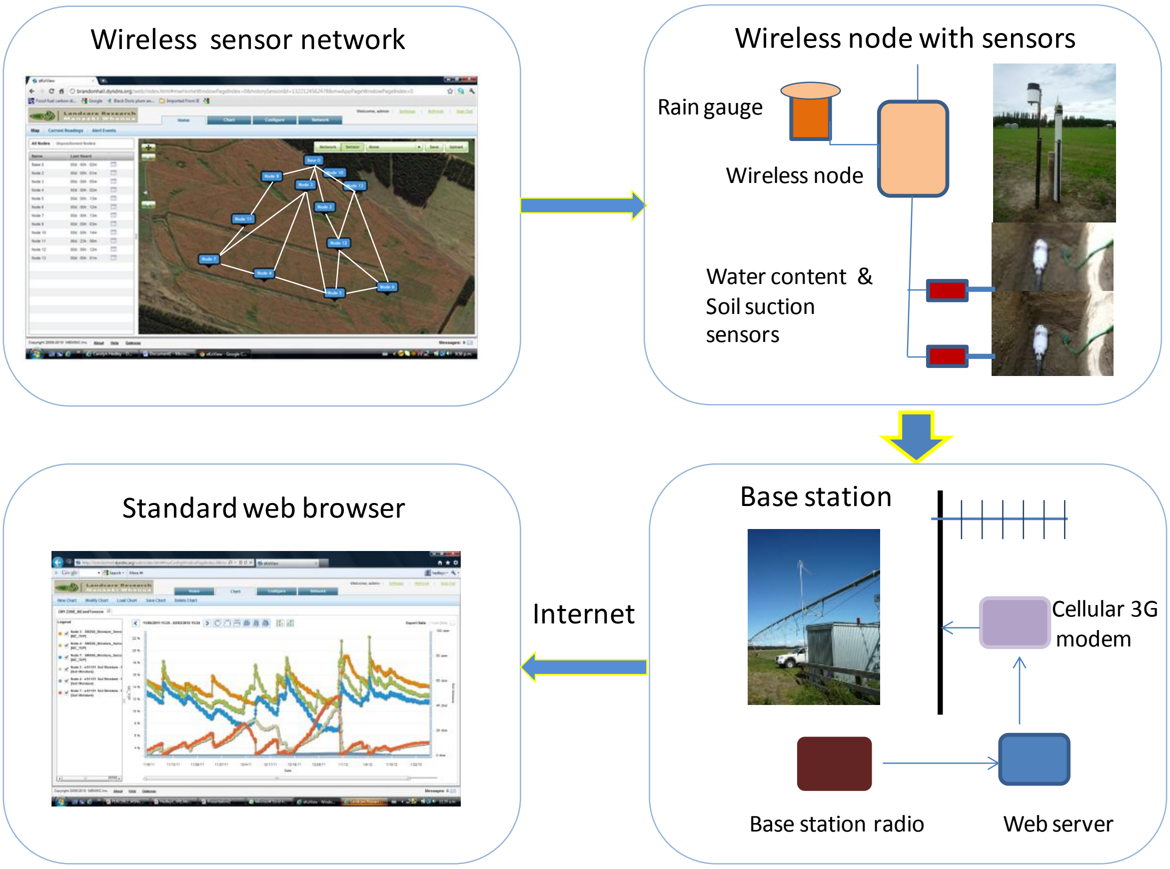

Fig. 3. Schematic flowchart of wireless soil moisture sensor network

Figure 3 provides a schematic flowchart of the WSN system installed at this site. The top left figure is the WSN homepage, indicating the position of the in-field sensors under the irrigator, the communication routes, and time since each node last transmitted data. The top right figure is a schematic of one node, with soil moisture sensors and a rain gauge attached. The nodes transmit to the base station positioned at the pump shed next to the pivot. A cellular 3G modem is used for accessing the data by remote computers. The data is displayed in a standard web browser.

Figure 4 provides a graphical display of in-field sensor data received from the nodes for the period 16 October 2011 (prior to irrigation) to 24 January 2012 (after irrigation completed). Class 1 volumetric soil moisture ranged between 0.08 – 0.16 m^3 m^{-3} indicating that rainfall, supplemented by irrigation, maintained the plant with no moisture stress (see Table 1). Class 3 soils were close to, or at saturation and therefore required no irrigation.

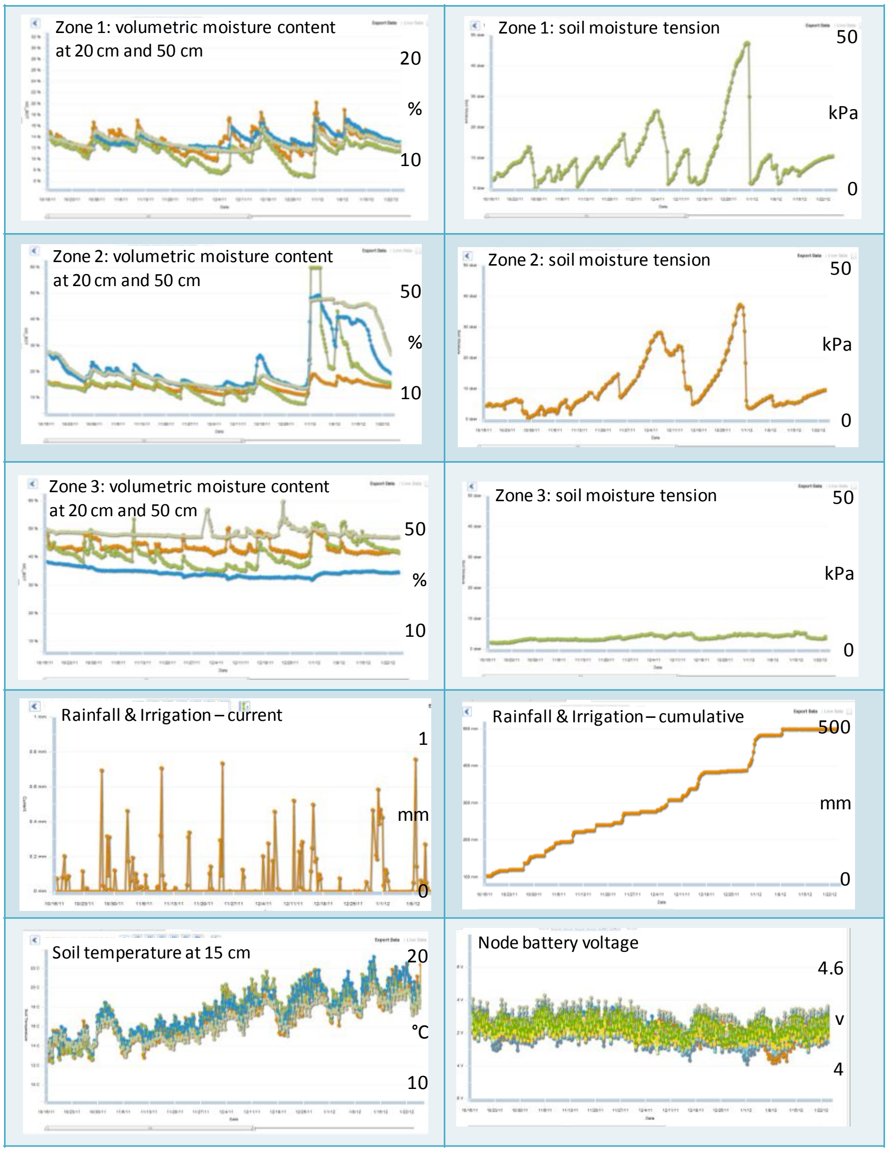

Fig. 4. Graphical display of in-field sensor data received from the wireless sensor network, for the period 16 October 2011 – 24 January 2012.

Irrigation was scheduled within the operational constraints of the pump. For the majority of the season Class 1 soils received 10 mm when they reached Refill Point, Class 2 soils received 5 mm, and Class 3 soils received 2 mm. Rainfall and irrigation, soil temperature (at 20 cm) and node battery voltage were also monitored. Monitoring node battery voltage provides opportunity for timely maintenance of nodes, e.g. checking power supply issues.

Discussion and Conclusions

The WSN continuously monitors soil moisture in spatially explicit management zones. Field Capacity (FC) is viewed in real time, after significant rainfall events; and effective irrigation is monitored by assessing if drainage occurs past 50 cm (see Fig. 4).

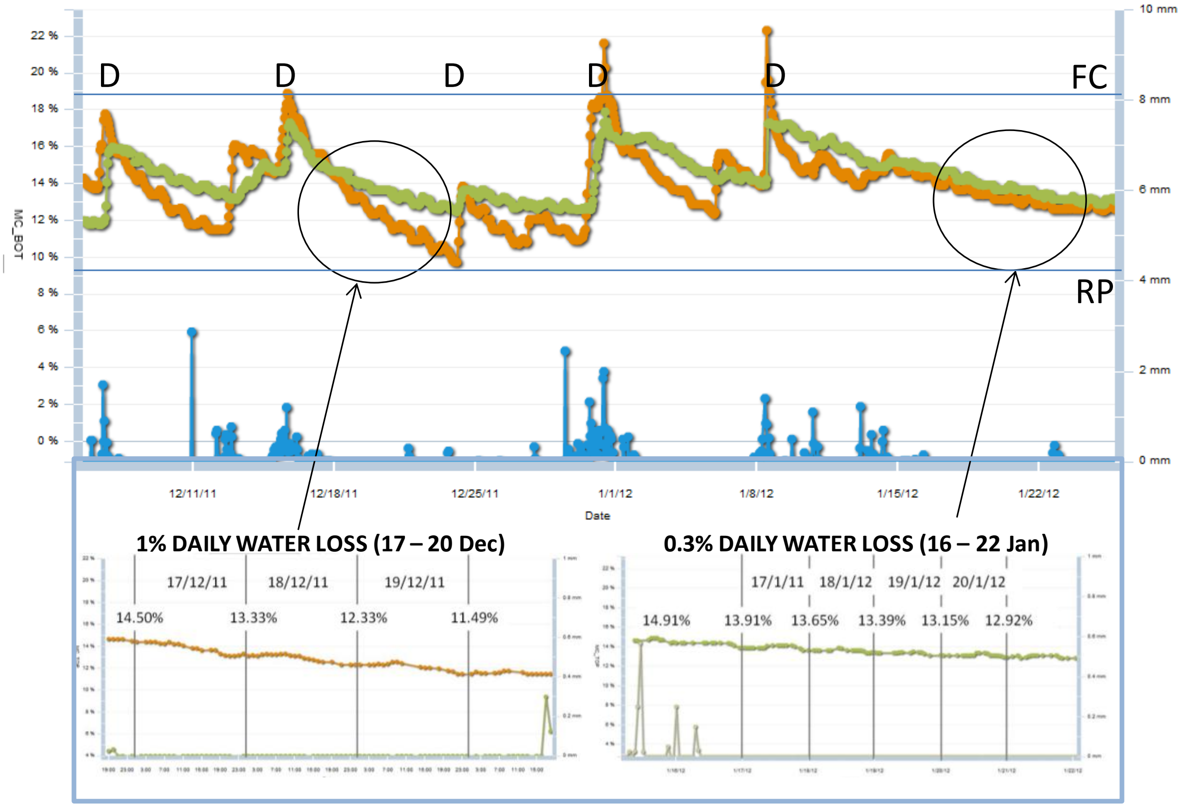

Fig. 5. Field Capacity (FC), Refill Point (RP), drainage (D) past 20 cm (brown line) and 50 cm (green line), and daily water use is directly monitored by the in-field sensors.

The shape and slope of the drying curves indicates whether drainage has occurred, and the rate of drying. Rapid drainage is indicated by a sharp fall in soil moisture after a rainfall or irrigation event. In contrast a gradual decrease in soil moisture will occur as crop roots take up water. Fig. 5 shows that soil moisture was decreasing at the rate of ~1% per day in mid-December, and 0.3% per day in mid-January. This reflects greater water demand by the wheat crop in mid-December, than in mid-January when vegetative growth had slowed, and grain ripening was occurring.

Fig. 6 shows a drying event (circled) in Class 1 soils, with soil moisture tension reaching ~50kPa, and volumetric soil moisture dropping to 7%, indicating that irrigation is required within the next day or two. The difference between 50 kPa and 100 kPa in these Motuiti sands is 2-3% moisture or 4-6 mm in the top 20 cm soil depth. The WSN soil moisture sensors therefore provide a direct measure of soil moisture status, for exact irrigation timing. Other methods used to guide irrigation scheduling include modelling approaches (regional or site-specific) (e.g. DeJonge et al., 2007; Humphreys et al., 2008) or crop stress measurement (Peters & Evett, 2007). Peters & Evett (2007) use a slight warming of crop leaf temperature to indicate water stress, and measure this on a fully automated centre-pivot irrigation system, using infrared thermocouple thermometers attached to the trusses of the pivot. This canopy temperature method provides a useful indicator of the initiation of water stress, however it does not indicate when a plant is approaching moisture stress, it can only indicate when the plant is suffering from stress, which could be too late for irrigation if we are aiming to eliminate water stress impact on yield reduction.

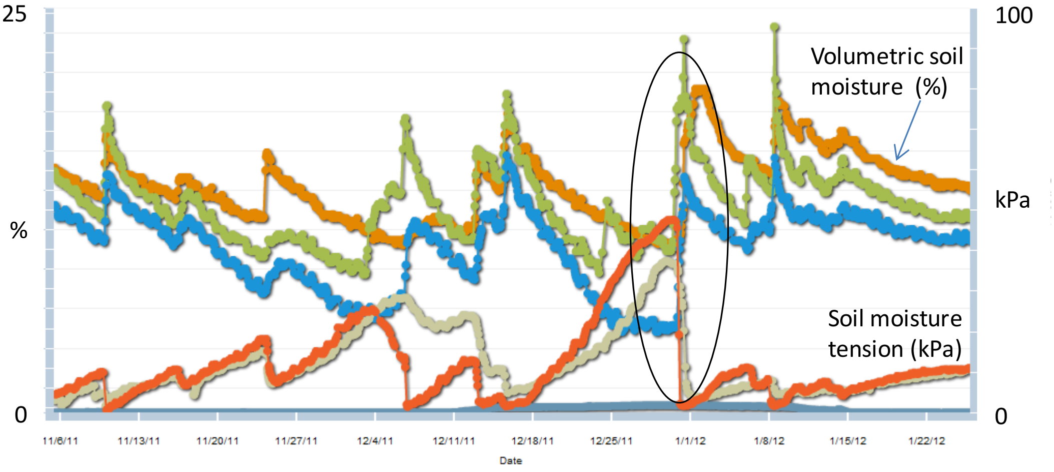

Fig. 6. Simultaneous monitoring of volumetric soil moisture and soil moisture tension is a direct sites-specific method to assess need for irrigation in each management class. The period shown above is for the 2011-2012 irrigation season: 6 Nov 2011 to 22 Jan 2012.

The WSN therefore provides a more effect direct method to monitor crop water use and need for irrigation.

The advantages of using site specific real time soil moisture data, affected by site specific climatic conditions, for irrigation scheduling are:

1. No need to know the plant type
2. No need to know the plant growth stage
3. Avoid uncertainties (errors) when estimating evapotranspiration (ET)
4. No need to know any of the variables needed to estimate ET such as
    a. Air temperature
    b. Relative Humidity (RH)
    c. Radiation
    d. Soil temperature
    e. Wind conditions ….and many more

Our spatially and temporally explicit soil moisture mapping and monitoring methods provide information for precision irrigation scheduling, and presents the data in a digital format for incorporation into the VRI controlling software.

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