Integrating soil moisture measurements into pasture growth forecasting in New Zealand's hill country

Istvan Hajdu[1*], Ian Yule[1], Mike Bretherton[1], Ranvir Singh[1], Miles Grafton[1], Carolyn Hedley[2]
1New Zealand Centre for Precision Agriculture, Massey University, Palmerston North
2 Landcare Research, Palmerston North

Abstract

Forecasting pasture growth in hill country landscapes requires information about soil water retention characteristics, which will help to quantify both water uptake, and its percolation below the root zone. Despite the importance of soil moisture data in pasture productivity predictions, current models use low-resolution estimates of water input into their soil water balance equations and plant growth simulations. As a result, they frequently fail to capture the spatial and temporal variability of soil moisture in hill country soils.

Wireless Sensor Networks (WSN) are promising in-situ measurement systems for monitoring soil moisture dynamics with high temporal resolution in agricultural soils. This paper presents the deployment of a soil moisture sensing network, utilising WSN technology and multi-sensor probes, to monitor soil water changes over a hill country farm in the northern Wairarapa region of the North Island. Processed capacitance-based raw data was converted to volumetric water content by means of a factory calibration function to assess sensor accuracy and to calculate soil water storage within the pasture root zone.

The derived volumetric soil moisture data was examined in terms of its dependence on the variability and influences of hill country landscape characteristics such as aspect. The integration of spatially distributed sensors and multi-depth soil moisture measurements from various hillslope positions showed that slope and aspect exerted a significant impact on soil moisture values. Furthermore, considerable differences were identified in soil water profile responses to significant rainfall events and subsequent soil water redistribution.

Initial indications are that high-resolution time series of accurate multi-depth soil moisture measurements collected by a WSN are valuable for investigating root zone water movement. Sensor evaluation and data analysis suggest that these devices and their associated datasets are able to contribute to an improved understanding of drying and wetting cycles and soil moisture variability. Potentially, this will create an opportunity to generate improved pasture growth predictions in pastoral hill country environments.

Background

Soil moisture is the principal limiting resource for pasture growth and agricultural production in New Zealand's hill country (Bittelli, 2011, Woodward et al., 2001). Due to its high spatial and temporal variability (Brocca et al., 2007), obtaining soil water status data has been cost-prohibitive, labour-intensive and time-consuming at a practically useful resolution for farm management in hill country. Despite the importance of soil moisture in agricultural systems, pasture productivity simulations use low spatial resolution estimates of water input into their soil water balance component. Both slope and aspect have a significant influence on spatial and temporal soil moisture distribution; however there have been only a few studies investigating their role in New Zealand hill country soils (Bircham and Gillingham, 1986, Bretherton et al., 2010).

Systematic observations of water content within the root zone soil profile yields information about vertical water transfer and its variation with time. These readings can indicate certain soil water properties; the amount of profile available water and also drainage below the root zone (Fares and Alva, 2000). Besides the important role of accurate soil water status readings for irrigation scheduling, root-zone soil water data is also crucial for pasture yield prediction, forecasting the onset of drought conditions, selecting the right species for given soil conditions, fertiliser placement and timing, as well as decisions associated with feed supply and stock management.

Environmental monitoring has been a significant driver for WSN implementations. Its adaptable features and real-time data delivery, enable the continuous observation of highly variable (both in space and time) environmental parameters, such as soil moisture (Oliveira and Rodrigues, 2011, Barrenetxea et al., 2008).

A WSN is composed of a collection of spatially distributed, autonomous devices, called sensor nodes, organised into a cooperative network (Rawat et al., 2014). Electromagnetic techniques, such as capacitance methods, are commonly used for network-based in situ soil moisture observations for scientific and agronomic purposes (Brocca et al., 2017). The nodes can sense and gather information from the targeted area and transmit real-time data to the user (Rawat et al., 2014). A WSN enables improved spatial resolution and the acquisition of a temporally rich dataset, where traditional methods would not provide satisfactory coverage (Bogena *et al.*, 2010).

Pasture growth models use parameters that are dependent on soil water; moreover, the estimation of soil water deficit is a necessary input into these models (Woodward, 2001). Therefore, a clearer picture regarding temporal and spatial soil water storage variation will be of potential interest for pasture growth modellers in hill country farms.

The objective of this study is the investigation of the manner in which spatially distributed soil water measurements can contribute to an improved understanding of seasonal variation on pasture available water, and on water uptake from the rooting zone in NZ hill country soils. The long-term research aims are to mitigate the impact of uncertainty in the estimation of plant available water in the soil profile, and to investigate means of achieving this.

Methods

The study was conducted on a 2623 ha hill country property, located in the Wairarapa region of the North Island (40.74502º S, 175.88732º E, Fig. 1A). The slopes on the property were classified following the Land Use Capability (Lynn *et al.*, 2009) system. The property is equipped with a permanent weather station. Soil moisture sensing sites were selected from non-irrigated pastoral areas where the predominant plant communities are ryegrass species. The soils are predominantly silty clay loams (Landvision Ltd., 2009).

The deployed WSN architecture consists of a gateway, a repeater station, and twenty sensor nodes arrayed in a hybrid topology (Fig. 1B). This design enhances fault tolerance and allows inter-nodal communication within radio distance. These sensors and radios are powered by batteries recharged by a solar panel. An interface board, batteries, and wiring, are placed in a weatherproof enclosure mounted on a galvanised pole, in conjunction with a long range, omni-directional antenna (Fig. 1C). Data packages are passed through underground wires from the sensors to telemetry units which are linked via radio connection. The data is then uploaded to a server via cellular network and visualized by the online HALO Farm System, developed by Tag I.T Technologies Ltd (New Zealand, Hamilton).

As soil water extraction occurs to a depth of at least 350 mm in hill country (Bretherton *et al.*, 2011), a capacitance-based, AquaCheck Sub-surface Probe (AquaCheck Soil Moisture Management, Durbanville, South Africa) was chosen. It is a robust multi-sensor logging probe that is designed to be completely buried, and is able to estimate soil water status by measuring the electrical permittivity of the surrounding soil (Gardner et al., 2000, Bittelli, 2011). The probes are equipped with four moisture sensors spaced at 100, 200, 300, and 400 mm depths to monitor the rooting zone (Fig. 1D).

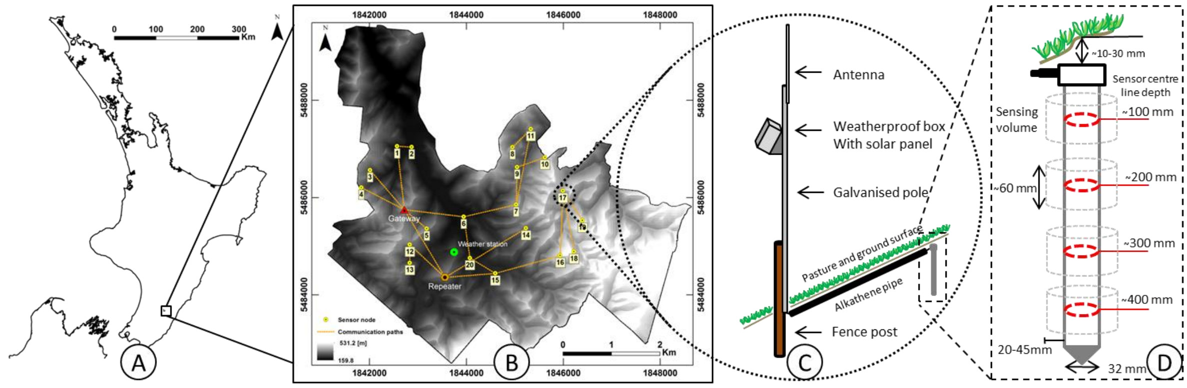

Figure 1. The research area location is shown on (A) and the farm extent is displayed with the WSN architecture and probe IDs on a DEM of the farm (B). The sensor node design is presented in (C) and the configuration of the AquaCheck Subsurface probe with the sensing range on the right (D).

The raw output data, given as a percentage (0% for air and 100% when the sensor is completely immersed in water) was collected from 20 sensor probes between 1st of November 2016 and 6th of June 2017, covering both drying and wetting cycles. The farm received a total rainfall of 642.2 mm during this period. In October 2016, total rainfall recorded was 67 mm, resulting in moderately moist soil conditions. Sensor readings were collected every 15 minutes and converted to volumetric soil water content (θ) by means of the factory calibration function.

To assess the accuracy of this calibration function, soil samples were collected from the sensor sites and the gravimetric soil moisture content measured (Gardner et al., 2000, Shukla, 2013) at each depth. These measurements were performed on a total of 230 samples collected from intact cores (25 to 50mm diameter, 450mm length covering all sensing depths). Bulk density values were determined from 80 samples and used to convert gravimetric soil water content to volumetric soil water content. The root mean square error (RMSE) was calculated to assess the relationship between the values obtained from the factory calibration function and those obtained from field samples.

As soil moisture is not measured continuously across depth, each of the monitored soil profiles (20) was divided into 7 discrete depths around the four sensors. Between each sensor, the trapezoid rule (Rahgozar et al., 2012) of numerical integration was used to approximate the region under the soil water profile curve, and to calculate the volume of stored water. It was assumed that soil moisture in the top 70 mm layer was similar to the topmost (100 mm) sensor reading. The daily soil water storage (SWS) was calculated for the top 430 mm soil layer based on the data from the capacitance sensors as described by the following equation (Equation 1):

$$\boldsymbol{SWS = \sum_{i=1}^{7} bi * \theta i}$$

Equation 1 Soil water storage (SWS) calculation formula integrating over 7 discrete segments, where *b* (mm) and θ (mm^3 mm^{-3}) are the depth and volumetric water content for soil layer *I*, respectively.

Soil water deficit (mm) was computed as the difference between soil water content on a given day at midnight, and field capacity (Woodward et al., 2001). Considering the depth of the soil profiles being monitored (400 mm), typical values for silty clay loam soils (Saxton and Rawls, 2006) of 160 mm and 95 mm were used for field capacity (FC, green line) and permanent wilting point (PWP, red line), respectively (Fig. 4A).

Results & discussion

As a preliminary result, Figure 2 illustrates that laboratory measurements and the corresponding sensed soil water content data correlate well. The raw data conversion to volumetric water content using the factory-based formula achieved an RMSE of 4.85% or 0.0485 $m^3 m^{-3}$. It was also observed that relative to the field data, the readings obtained by the topmost sensors contained the largest errors, and the bottommost readings showed the closest agreement to the laboratory measurements.

.

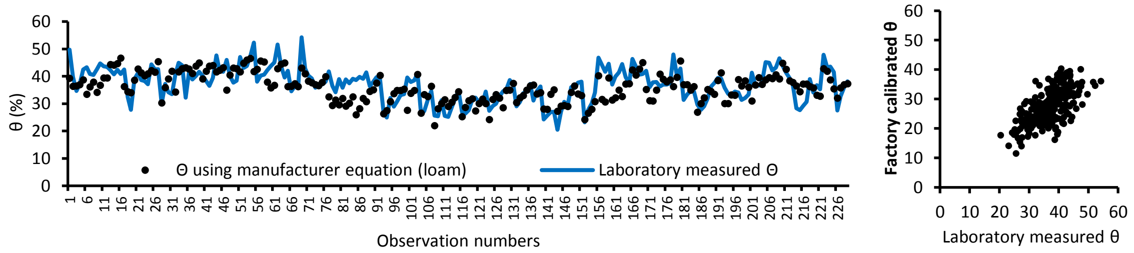

Figure 2. Comparison of factory calibrated values for silty clay loam soils and field volumetric soil moisture contents (*θ)* over all depths and at all times (230 observations)

Figures 3 and 4 show the variation of SWS (Fig. 3), soil water deficit (Fig. 4A), and daily SWS changes (Fig. 4B) for different slopes and aspects throughout the 7 month observation period. At the beginning and at the end of the observed time interval, the soil moisture conditions were near FC (Fig. 4A) for all aspects with a clear seasonal drying and rewetting trend in between. The lowest SWS value (107 mm) was reached in January for north facing slopes (PWP = 95 mm). The highest SWS values were observed on east facing areas (192 mm in the middle of April 2016). The average difference between the lowest and highest SWS was 72 mm, indicating that a typical value of available water holding capacity for silty clay loams at 400 mm depth (estimated as 65 mm by Saxton and Rawls (2006), holds up reasonably well for the soils at the sensor sites.

North facing slopes usually have the lowest amount of water in the profile, except during autumn months when slopes with a southern aspect were drier. When daily solar radiation was high, from December 2016 until the middle of January 2017, the difference between south and north facing slopes increased. Due to significant rainfall events (18/02/17, 05/04/17, 14/04/17), soil water redistribution down the soil profile indicated that the north facing slopes lost the received water slower, although they eventually became drier over the monitored last two months than the other aspects. Most of the water was quickly lost after the significant rainfall events (Fig. 3 and 4b). West facing slopes held significantly more water than any other slope orientation during the observed time interval, while east oriented and flat surfaces demonstrated similar behaviours and soil moisture contents.

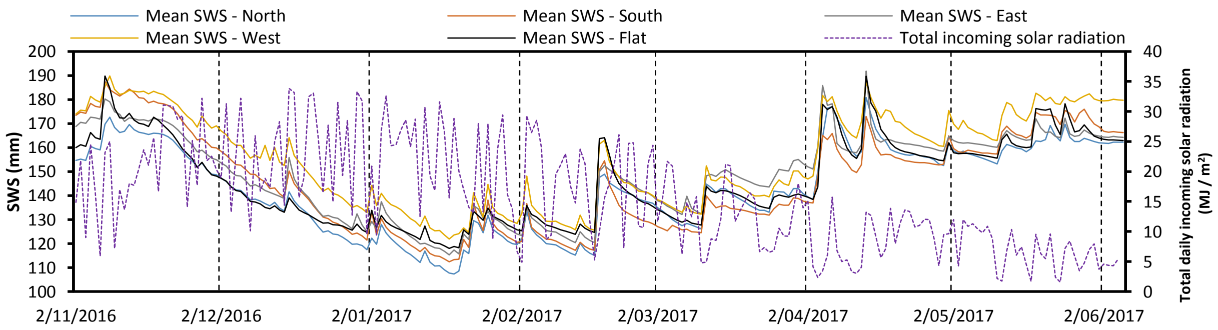

Figure 3. Time series of mean total soil water storage (SWS) for various aspects and daily total incoming solar radiation measured at the weather station's location during a 7 month period

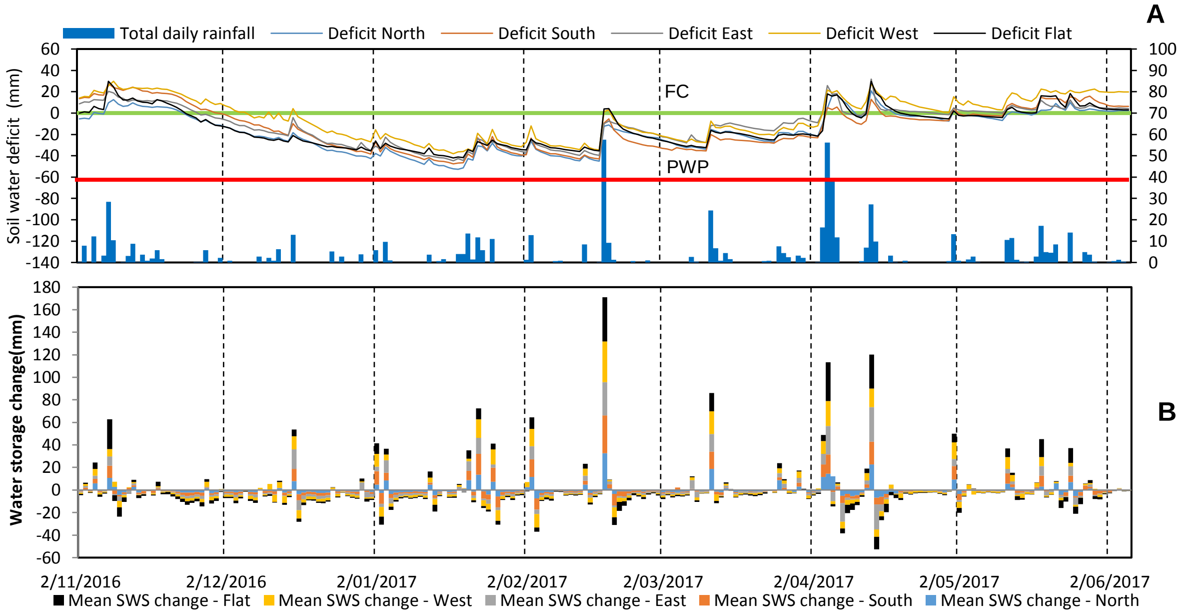

Figure 4. Time series of soil water deficit (A) and daily soil water budget for various aspects (B)

The AquaCheck probes are commonly used for soil moisture monitoring in agricultural systems. However, the performance of the AquaCheck probe has not been studied extensively in remote hill country conditions, especially in New Zealand soils. The correlation of depth with accuracy is most likely caused by three possible factors: 1) high organic matter content and root mass in the upper layers are likely to help retain water 2) highly variable soil moisture in the top 10-15 cm soil layer and 3) soil temperature variation. The influence of topography was significant during summer time when high incoming solar radiation values were prevalent, although the role of aspect dropped when large precipitation events occurred in autumn. As expected, silty clay loam soils have a high water holding capacity, which provided adequate water during the dry months in the year of measurement. Further work could include the estimation of daily evapotranspiration and the water drained from the root zone.

Conclusion

This research evaluated the performance of the AquaCheck Sub surface sensor under field conditions and investigated root zone soil water behaviour using data gathered over a seven-month period. Compared to measured field data, the sensor error was 4.85% for the RMSE but site-specific calibrations will be required to improve accuracy. The effect of soil temperature on data acquisition and surface soil moisture variation at 100 mm depth will need to be investigated to improve accuracy further. It can be concluded that seasonality and the effect of aspect are strongly linked. Calculated SWS variations provided a relatively good indication of the generally used soil water retention properties. It should be noted that the amount of precipitation is not evenly distributed within the property boundary and needs to be taken into account to achieve a better understanding of rainfall patterns on the farm. The suggested improvements will be potentially useful for a comparison or validation of pasture yield prediction results based on field soil water measurements versus modelled soil moisture.

Acknowledgments

The scholarship funding has been provided by Ravensdown and Ministry of Primary Industries (MPI) via the Primary Growth Partnership (PGP – Pioneering to Precision) research project. Moreover, we wish to thank the New Zealand Centre for Precision Agriculture (NZCPA), Agri Optics NZ Ltd and TAG I.T Technologies Ltd for providing their collaboration, labour and technical support.

References

Barrenetxea G, Ingelrest F, Schaefer G, Vetterli M 2008. Wireless sensor networks for environmental monitoring: the sensorscope experience. Communications, 2008 IEEE International Zurich Seminar on Pp. 98–101.

Bircham JS, Gillingham AG 1986. A soil water balance model for sloping land. New Zealand Journal of Agricultural Research 29: 315–323.

Bittelli M 2011. Measuring soil water content: A review. HortTechnology 21: 293–300.

Bogena HR, Herbst M, Huisman JA, Rosenbaum U, Weuthen A, Vereecken H 2010. Potential of wireless sensor networks for measuring soil water content variability Vadose Zone Journal 9: 1002–1013.

Bretherton M, Scotter DR, Horne DJ, Hedley MJ 2011. Water uptake by hill country pasture - more than you think. *In:* Currie LD, Christensen CL eds. Adding to the knowledge base for the nutrient manager. Fertilizer and Lime Research Centre, Massey University.

Bretherton MR, Scotter DR, Horne DJ, Hedley MJ 2010. Towards an improved understanding of the soil water balance of sloping land under pasture. New Zealand Journal of Agricultural Research 53: 175–185.

Brocca L, Ciabatta L, Massari C, Camici S, Tarpanelli A 2017. Soil moisture for hydrological applications: open questions and new opportunities. Water 9: 140.

Brocca L, Morbidelli R, Melone F, Moramarco T 2007. Soil moisture spatial variability in experimental areas of central Italy. Journal of Hydrology 333: 356–373.

Fares A, Alva AK 2000. Evaluation of capacitance probes for optimal irrigation of citrus through soil moisture monitoring in an entisol profile. Irrigation Science 19: 57–64.

Gardner CM, Robinson D, Blyth K, Cooper JD 2000. Soil water content. Soil analysis: physical methods Pp. 1–74.

Horne DJ, Scotter DR 2016. The available water holding capacity of soils under pasture. Agricultural Water Management 177: 165–171.

Landvision Ltd 2009. Pati Tapu Station whole farm plan. Palmerston North: Horizons Regional Council.

Lynn I, Manderson A, Page M, Harmsworth G, Eyles G, Douglas G, Mackay A, Newsome P 2009. Land use capability survey handbook–a New Zealand handbook for the classification of land. Hamilton: AgResearch.

Oliveira LM, Rodrigues JJ 2011. Wireless sensor networks: A survey on environmental monitoring. JCM 6: 143–151.

Rahgozar M, Shah N, Ross M 2012. Estimation of evapotranspiration and water budget components using concurrent soil moisture and water table monitoring. ISRN Soil Science. 15 p.

Rawat P, Singh KD, Chaouchi H, Bonnin JM 2014. Wireless sensor networks: a survey on recent developments and potential synergies. The Journal of Supercomputing 68: 1–48.

Saxton KE, Rawls WJ 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil science society of America Journal 70: 1569–1578.

Shukla MK 2013. Soil physics: An introduction. CRC Press. Woodward SJR 2001. Validating a model that predicts daily growth and feed quality of New Zealand dairy pastures. Environment International 27: 133–137.

Woodward SJR, Barker DJ, Zyskowski RF 2001. A practical model for predicting soil water deficit in New Zealand pastures. New Zealand Journal of Agricultural Research 44: 91–109.