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Sustainable Irrigation

NPSI/IAL Travel Fellowship 2010

Sensor and control system development for autonomous site-specific irrigation

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Alison McCarthy
Postdoctoral Research Fellow (Mechatronic and Irrigation Engineering)
National Centre for Engineering in Agriculture
Faculty of Engineering & Surveying
University of Southern Queensland
Toowoomba Qld 4350
Australia

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Dr Troy Peters, Washington State University, Prosser, Washington
Mr Jake LaRue, Valmont Irrigation
Mr Nick Emmanuel, CropMetrics
Professor Robert Evans, USDA-ARS Northern Plains Agricultural Research Laboratory
Dr Kelly Thorp, USDA-ARS US Arid Land Agricultural Research Centre
Dr Susan O'Shaughnessy, USDA-ARS Conservation & Production Research Laboratory
Dr James Mahan, USDA-ARS Plant Stress and Germplasm Development Laboratory

Abstract

The NPSI/IAL Travel Fellowship 2010 aimed to investigate developments toward autonomous site-specific irrigation control systems. Site-specific irrigation systems offer improvements in water use efficiency and crop performance by differentially applying irrigation to the field when and where it is required. Commercially available variable-rate irrigation applicators have been developed which enable automatic adjustment of irrigation volumes from individual nozzles on centre pivot and lateral move irrigation machines. However, irrigation control strategies that determine site-specific irrigation application have not been as extensively researched as the applicators and require consideration of soil, plant, weather and management factors (e.g. climate, soil type, crop type, water availability, irrigation system). Irrigation control strategies require sensors to assess plant response to irrigation. Automation of this irrigation control system will potentially reduce labour and optimise crop performance with the available water.

One university, four United States Department of Agriculture agricultural research stations and two commercial variable-rate irrigation companies were visited in the USA during the fellowship in March 2011. These institutions are developing or evaluating variable-rate irrigation for centre pivots and lateral moves, researching automatic furrow irrigation control and/or developing plant sensors which may be applied to irrigation control strategies. There has been poor continued use of variable-rate technology purchased by growers in Georgia, USA. This has led Valmont Irrigation to also offer a system that determines site-specific irrigation application using soil moisture measurements. There has been extensive development of infrared thermometers to provide feedback to irrigation control strategies. Image-based plant sensors offer opportunities to monitor plant growth and provide plant measurement in irrigation control strategies. However, this use of sensors in an irrigation control strategy may not provide optimal feedback. Hence, it is possible that data requirements of optimal irrigation control strategies may also drive sensor development.

1. Introduction

Precise determination of irrigation requirements can improve the use of available irrigation water and variable-rate irrigation hardware. Research into variable-rate irrigation technology has spanned over 20 years and produced a number of commercial systems (e.g. Farmscan, Valmont, Zimmatic). However, the greatest limitation to the adoption of variable-rate irrigation is associated with developing optimal irrigation schedules (i.e. volume and timing of irrigation) or irrigation prescriptions (Evans et al. 1996).

The decision of irrigation application and timing requires consideration of interactions between irrigation management, environmental conditions and crop demands, and requires access to detailed measurements and information. A control engineering approach is one solution being developed to automate irrigation management. Figure 1 illustrates a generic irrigation control system that uses the full range of plant, weather and soil data for irrigation management. In Figure 1:

- the ‘decision support system’ embodies the control strategy;
- ‘actuation’ is the action of adjusting the irrigation volume and/or timing; and
- ‘application’ is the resulting physical amount and timing of water and fertiliser applied to the crop.

This process can be applied to both constant and spatially varied irrigation management at a range of time scales. The control strategy can be automatically implemented on an irrigation system to create a real-time, autonomous irrigation control system.

My PhD involved investigating the application of adaptive control strategies to site-specific irrigation using large mobile irrigation machines (centre pivots and lateral moves, LMIMs). A simulation control framework ‘VARIwise’ was developed to generate and simulate various control strategies (McCarthy et al. 2010). VARIwise enabled spatial scale variations down to $1m^2$ and input data at any temporal resolution. The soil and cotton model ‘OZCOT’ (Wells & Hearn 1992) was used to evaluate the performance of the strategies in simulation.

Control strategies developed in VARIwise were either: (i) ‘sensor-based’ strategies which directly adjusted the irrigation application according to the measurement response; or (ii) ‘model-based’ strategies which used a calibrated soil and plant model for irrigation management. These strategies are also applicable to surface irrigation by considering the application variability of irrigation water along the field.

The most appropriate control strategy depends on factors including sensor data availability and grower’s specific performance requirements. Without sufficient sensors, the state of the process cannot be determined or evaluated. The required scale and accuracy of sensors is also important, as it would not be practical to install and maintain a large number of sensors in the field. Hence, it follows that control strategy development will be driven by the available sensor technology, but also that control strategy options should drive future plant and soil moisture sensor development.

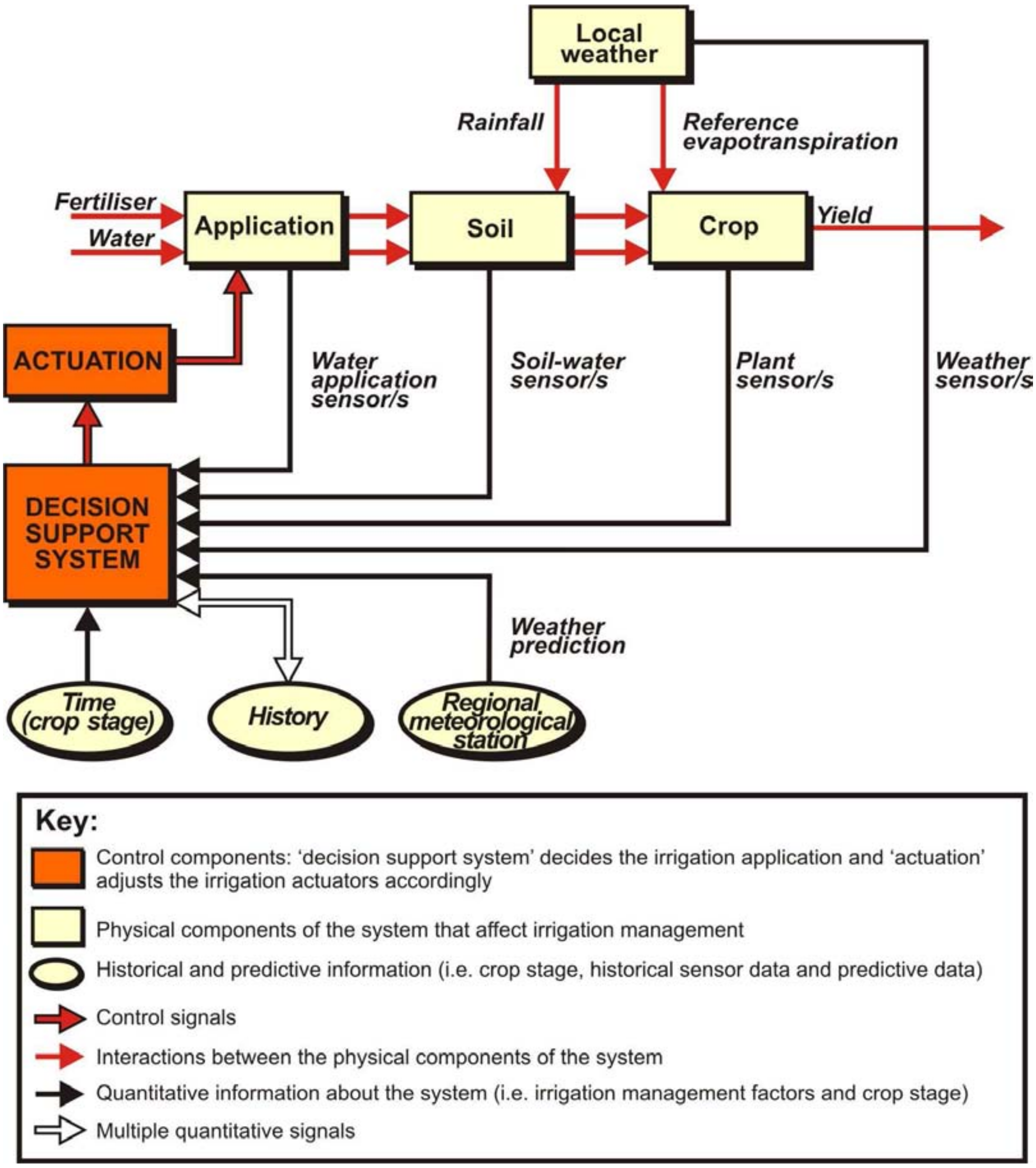

Figure 1: Generic control scenario for irrigation application (adapted from McCarthy et al. 2010)

1.1 Aims of travel fellowship

A study tour was conducted to evaluate the current state of sensor and control system development in the USA and opportunities for further research and application of these systems to Australian conditions. Research in variable-rate irrigation systems commenced about 20 years ago in the USA and led to the first commercialised variable-rate irrigation technology.

The specific travel aims of the fellowship were to:
(1) assess the state of development of spatial sensors for irrigation control systems;
(2) investigate work on autonomous irrigation systems to see other possible issues; and
(3) investigate implementation of LMIM variable-rate hardware.

The travel was completed in March 2011 (Appendix A). The study tour involved meetings with researchers from the United States Department of Agriculture – Agricultural Research Service (USDA-ARS), Washington State University and commercial irrigation hardware and software companies, Valmont Irrigation and CropMetrics. Current research identified to be at the forefront of autonomous irrigation system development includes:

- Automated agricultural sensors in Washington State University, Prosser, Washington
- Infrared thermometers in the USDA-ARS at Bushland and Lubbock, Texas
- Remote sensors and model-based irrigation control in the USDA-ARS at Maricopa, Arizona
- Commercial variable-rate irrigation companies in Omaha, Nebraska
- Variable-rate irrigation systems in the USDA-ARS at Sidney, Montana

2. Washington State University in Prosser, Washington

2.1 Irrigation in Prosser

Prosser is located in a valley with little rainfall, very cold nights and mild days (Figure 2). Prosser's water is sourced from the Yakima River and Sunnyside Canal which run through Prosser. This water is pressured because it is gravity fed from surrounding mountains. The pressure of the water is then often regulated on-farm. Power costs in Prosser are low because there are wind and water power plants to generate all the power for the town.

Figure 2: Valley in Prosser, Washington

Water is allocated using weirs that were built by the Irrigation District, a conglomeration of local farmers. The maximum allocation allowed per grower is determined by their acreage.

Prosser's climate limits the crops grown to perennials with frost requirements, e.g. apples, cherries, grapes and hops (Figure 3). Irrigation systems are traditional hand-line or frame-line (Figure 4) for pasture, and drip or sprinkler irrigation systems for orchards.

Figure 3: Structures for hops in Prosser, Washington (dormant during visit)

Figure 4: Frame-line irrigation system on pasture field

2.2 Research at Washington State University in Prosser

The Centre for Precision and Automated Agricultural Systems (CPAAS) is a research centre within Washington State University that conducts research projects on automation in agriculture and precision irrigation (Figure 5). The majority of projects were focussed on the automation of harvesting, disease detection and pruning in orchards. Harvesting is the most labour-intensive and expensive task in orchards.


(a) (b)

Figure 5: My visit with: (a) Troy Peters; and (b) Manoh Karkee

Although the automated systems developed at CPAAS were not applied to irrigation management, the technology is equally applicable to irrigation. For example, camera-based sensing systems were developed to detect grape suckers (Figure 6) and leaf diseases (Figure 7). The basis for these systems is that weeds and diseased plants emit a different spectral response to a healthy field crop. For irrigation management, such a system could be used to differentiate between healthy plants and weeds or diseased plants. Time-of-flight (3D) cameras were used to determine the structure of raspberry bushes for pruning. In an irrigation context, a 3D camera could be used to evaluate plant health in an irrigation control system.

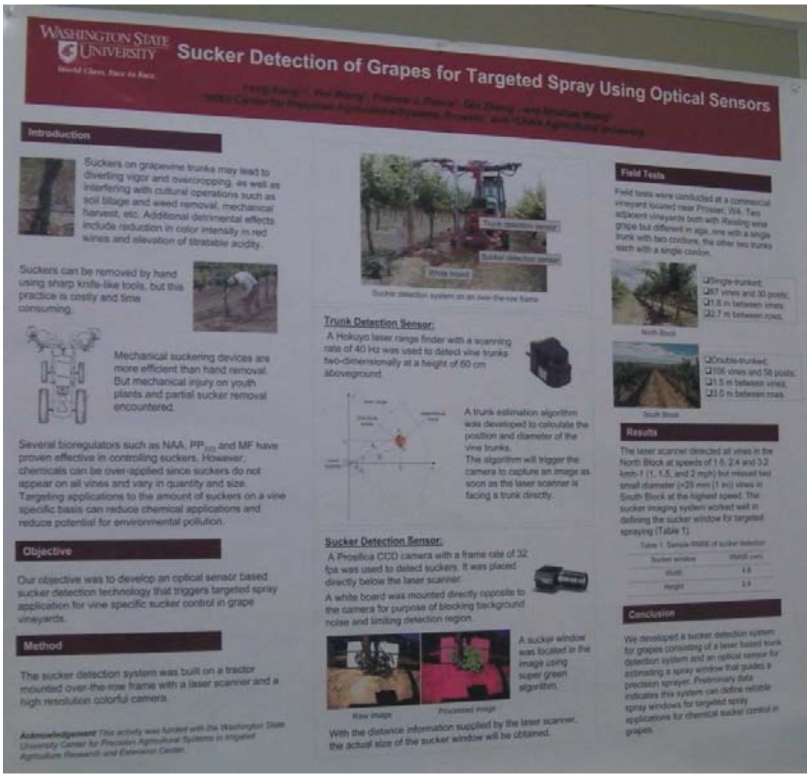

Figure 6: Camera-based sucker detection of grapes

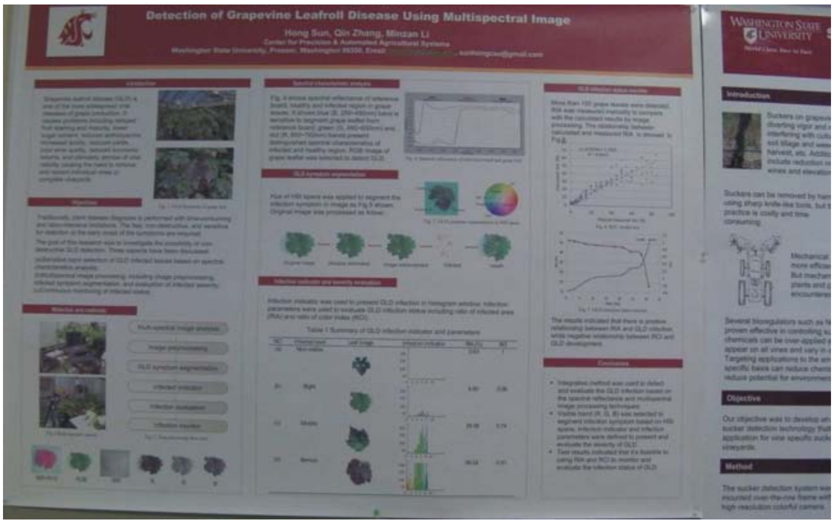

Figure 7: Camera-based leaf disease detection

The camera used in an irrigation control system could be fixed at one point in the field and collecting measurements of the plant status. Alternatively, the camera could be mounted on farm machinery (e.g. tractor) or an irrigation machine to collect measurements across the field.

Postgraduate research was being conducted to take an artificial intelligence approach to irrigation management. This involved using mathematical techniques to develop relationships between the control system inputs (e.g. fertiliser, irrigation) and outputs (e.g. yield, plant response), rather than using known relationships.

2.3 Summary of Washington State University in Prosser

Researchers at the Centre for Precision and Automated Agricultural Systems were developing image-based sensing technology primarily for automating orchard operations. This technology can potentially be utilised in automated irrigation to measure plant growth (e.g. change in structure) and health (e.g. detection of diseases and weeds).

The collected data can be used as inputs to response-based or model-based VARIwise strategies. For example, a response-based strategy that aims to achieve a set vegetative growth pattern may reduce the irrigation application to slow down vegetative growth. A model-based strategy may determine irrigation application using a model that had been calibrated using measurements from the camera (e.g. plant height, growth stage).

3. Valmont Irrigation and CropMetrics in Omaha, Nebraska

3.1 Irrigation in Nebraska

Large mobile irrigation machines were originally developed in Nebraska to deliver irrigation across fields with uneven topography. Valmont Irrigation is an irrigation machine company that is over 50 years old and is based in Valley, Nebraska (near Omaha, Nebraska). Valmont Irrigation has commercialised a variable-rate irrigation system and have recently began offering an additional site-specific irrigation prescription service 'CropMetrics' in early 2011.

3.2 Valmont Irrigation Variable-Rate Irrigation in Nebraska

All currently available commercial variable-rate irrigation hardware is based on pulsing technology. This involves continuously turning a solenoid (that is on each dropper) on and off to achieve time-proportional control (Figure 8). For example, the irrigation rate can be reduced by turning the solenoid off for a longer period of time.

Figure 8: Valmont Irrigation variable-rate irrigation hardware at the Triumph of the Ag Expo

Variable-rate irrigation hardware was originally commercialised by Design Feats (formerly Farmscan) and developed in conjunction with the University of Georgia, Tifton. Valmont Irrigation has recently also begun offering variable-rate irrigation hardware. The Valmont system uses power and data cables from the existing machine, whilst the Design Feats system uses additional cables for power supply and communication to each solenoid.

I met with Valmont Irrigation Project Manager, Jake LaRue (Figure 9). Mr LaRue said a recent survey had been conducted of 100 growers who had installed Farmscan variable-rate systems in Georgia over the previous 10 years. This survey revealed that only four of the growers who had purchased the variable-rate technology were still using the hardware for variable-rate irrigation. Mr LaRue suggested that growers are having difficulties understanding how to determine site-specific irrigation volumes. To improve the uptake of variable-rate irrigation and continued use of the systems by those who already have variable-rate technology, Valmont has also commercialised an irrigation prescription service (CropMetrics) to aid growers with irrigation decision-making.

Figure 9: Meeting with Valmont Irrigation Project Manager Jake LaRue

3.3 CropMetrics in Nebraska

I met with CropMetrics President, Nick Emmanuel, in Omaha, Nebraska. CropMetrics provides an irrigation prescription service for irrigation machines with either speed or full variable-rate irrigation control. This involves using ‘Virtual Agronomist’ software that generates irrigation prescription maps (Figure 10).

The derivation of these maps is driven by an imported field-scale map of topography and electrical conductivity and uses the following procedure:
1. Import topography and electrical conductivity maps from before the start of the crop season.
2. Overlay the available variability maps and identify the areas in the field with the most commonly occurring properties (e.g. the maroon-coloured area of Figure 11). These areas are deemed to be optimal for soil moisture sensor placement to represent the status of the majority of the field.
3. The measured soil moisture deficit is the irrigation volume that is applied to the areas which are most commonly occurring. The relative variation in irrigation application for all other areas is determined using a user-defined multiplier and the variability in the electrical conductivity map.
4. The site-specific irrigation volumes are then further adjusted according to the topography map. For example, the irrigation applied to low areas of the field is reduced by a user-defined fraction of the slope in that area.

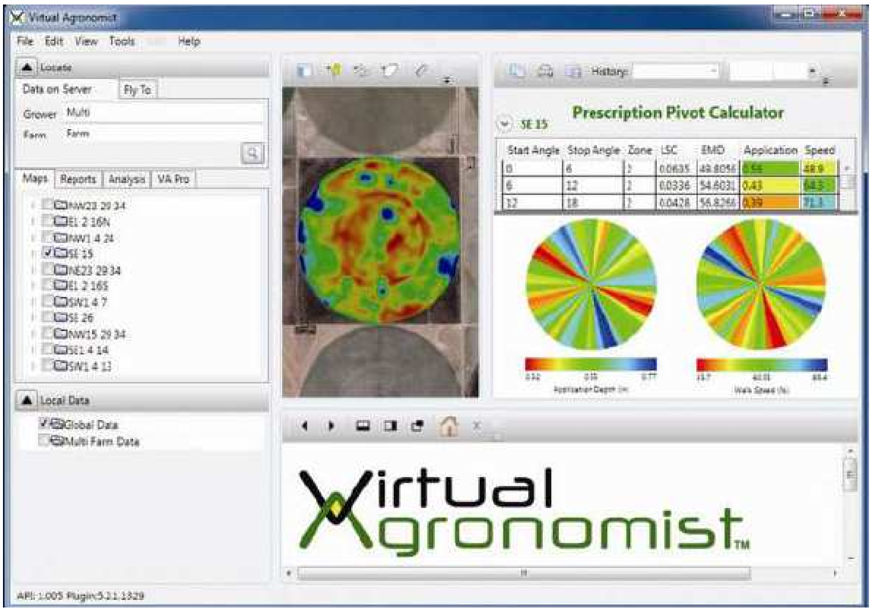

Figure 10: CropMetrics software with irrigation prescription maps for speed control (CM 2011)

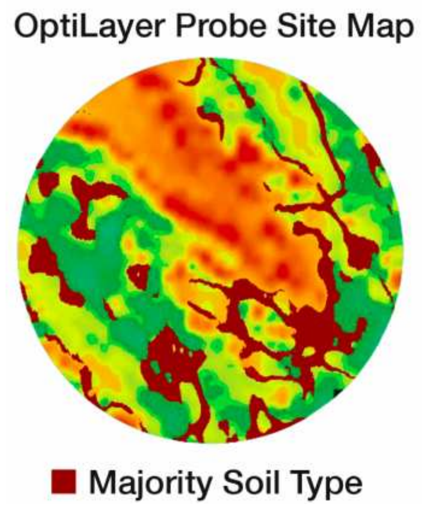

Figure 11: Field variability map used to aid in-field soil moisture sensor placement (CM 2011)

Additional variability maps (e.g. yield, NDVI) can be imported into the Virtual Agronomist software to develop the irrigation prescription map. The influence of these parameters on the irrigation application is manually set using a user-defined multiplier.

No validation was provided for placing a single soil moisture sensor in the most commonly occurring soil. Typically a single soil moisture sensor is installed where the soil has the lowest water holding capacity (and dries out first) to indicate irrigation timing. In contrast, the CropMetrics system irrigation prescription does not determine irrigation timing and the soil moisture sensor may not indicate irrigation timing if the most commonly occurring soil type has a high water holding capacity.

A single sensor was installed in the field to reduce cost and complexity and encourage uptake of the technology. This indicates that irrigation control strategies should minimise sensor requirements to increase likelihood of commercial success, while also ensuring adequate control performance.

The CropMetrics system does not use real-time spatial variability or plant data. This may restrict the performance of the irrigation strategies because the management zones in a field generally vary from year-to-year and often within a crop season (Plant 2001). The ‘optimal’ placement of the soil moisture sensor may also be temporally variable.

3.4 Summary of Nebraska

Valmont Irrigation has recognised the need to incorporate irrigation decision-making with variable-rate irrigation hardware. The current CropMetrics system uses a single fixed soil moisture sensor and underlying variability maps to determine irrigation application, without an evaluation of the previous irrigation application. Irrigation control strategies should have minimal sensor requirements to help improve uptake of the technology.

4. USDA-ARS Northern Plains Agricultural Research Laboratory in Sidney, Montana

4.1. Irrigation in Sidney

Sidney has a dry climate and limited water availability. These factors limit the crops grown to wheat, malting barley, soybeans and sugar beets. Irrigation systems were centre pivot irrigation machines, travelling guns and frame-line irrigation systems.

4.2 Research at USDA-ARS Northern Plains Agricultural Research Laboratory in Sidney

Irrigation research projects at the USDA-ARS Northern Plains Agricultural Research Laboratory involved evaluating deficit irrigation systems, dryland irrigation, alternate cropping systems, soil quality and properties and nitrogen management. Recent cuts to funding of USDA-ARS irrigation projects indicate that irrigation research is not currently a government priority.

Variable-rate irrigation actuators were developed by a postgraduate student at the USDA-ARS in the 1990s (Figure 12). These actuators vary the irrigation using pulsing technology similar to the Valmont variable-rate irrigation technology. Actuators have been developed for both LEPA (low energy precision application) and MESA (mid elevation spray application) emitters. The LEPA emitters are controlled using electrically operated control valves, whilst the MESA sprinklers are controlled using pneumatically operated valves to prevent contaminates in the water clogging the valves. This equipment is currently maintained by William Iversen and Professor Bob Evans (Figure 13).

(a) (b)

Figure 12: Variable-rate irrigation hardware on centre pivot irrigation machine

Each set of valves is controlled separately, and a pulley system has been developed to automatically retract the droppers up when the MESA sprinklers are in use (e.g. Figure 12b). This prevents the LEPA droppers from interfering with the MESA spray pattern. The valves are controlled using a programmable logic controller (Figure 14).

Figure 13: Visit to USDA-ARS lab in Sidney, Montana with Professor Robert Evans

Figure 14: William Eversen explains the programmable logic controller used to control the variable-rate applicators

Much of current research at the Sidney USDA-ARS uses the variable-rate irrigation machine as a research tool for comparing treatments of nitrogen, crop varieties and water stress, rather than for irrigation decision-making methods. The possibility of using VARIwise irrigation control strategies for dryland crop management was discussed with Professor Evans where the control variables could be nutrient application volume and timing (instead of irrigation application).

4.3 Summary of USDA-ARS Northern Plains Agricultural Research Laboratory in Sidney

Research in irrigation control strategies and sensors was not currently a priority with reductions in government funding. Funding was only available for variety, nutrient application and water deficit management trials.

5. USDA-ARS US Arid Land Agricultural Research Centre in Maricopa, Arizona

5.1 Irrigation in Maricopa

Maricopa is a traditional agricultural town near Phoenix, Arizona that is gradually being urbanised. Common agricultural crops in Maricopa are cotton, grains and alfalfa. The predominant methods of irrigation in Arizona are furrow and bay irrigation because of the large amount of water that is available and delivered by canals from the Colorado River in Arizona. A variable-rate lateral move irrigation machine was being installed at the USDA-ARS during the visit.

Figure 15: Furrow irrigation system from irrigation canal in the Maricopa USDA-ARS

5.2 Research at USDA-ARS US Arid Land Agricultural Research Centre in Maricopa

The main areas of research at the Maricopa USDA-ARS are remote sensing and SRFR surface irrigation modelling for irrigation management. SRFR is a one dimensional surface irrigation model (Strelkoff et al. 1998) that is currently being maintained by Dr Eduardo Bautisto (Figure 16b). SRFR can simulate variable inflow and infiltration rates. SRFR and similar furrow irrigation models (e.g. SISCO, Gillies et al. 2010) can be used in irrigation control strategies to aid predictions of furrow irrigation advance with variable infiltration along the furrow.

A current project by Dr Kelly Thorp (Figure 16) aims to use the SRFR irrigation model with a crop production model, DSSAT (Decision Support System for Agrotechnology Transfer, Jones et al. 2003) for irrigation management. DSSAT contains modules for the simulation of a range of crops. In this project, SRFR will predict the irrigation application along a furrow for a particular set of inflow, cutoff and infiltration parameters, whilst DSSAT will simulate the crop response to determine the influence of variability on the crop growth. Dr Thorp will evaluate different irrigation deficits for furrow irrigation in simulation and then evaluate these in the field for comparison.

(a) (b)

Figure 16: Visit with researchers at the Maricopa USDA-ARS: (a) Dr Doug Hunsaker and Dr Kelly Thorp; and (b) Dr Eduardo Bautisto

Estimation of evapotranspiration was a common method to estimate crop water use for irrigation management. This is because evapotranspiration dominates the water cycle in the Arizona's arid environment and hence is a highly accurate indicator of crop productivity. Two approaches to estimating evapotranspiration were being tested, namely: (i) Penman-Monteith equation of FAO56 (Allen et al. 1998); and (ii) energy balance.

For the FAO56 approach (i), the crop coefficient used in the evapotranspiration calculation was calibrated using the measured NDVI (normalised difference vegetation index). NDVI measurements were collected using tractor-mounted GreenSeeker sensors (Figure 17).

Figure 17: NDVI sensors on tractor for estimation of soil water depletion (French et al. 2011)

The energy balance method (ii) involves calculating the energy required to change the water from liquid to gas phase. This requires measurement or estimation of net radiation, soil heat flux and 'sensible' heat flux (e.g. French et al. 2007). Dr Andrew French at the USDA-ARS determined these heat fluxes by modelling the soil surface temperature and a vegetation index. The vegetation index was estimated using NDVI and remote sensing of the field, where images in the visible and infrared bands were acquired from satellites and aerial photography (e.g. Figure 18). The soil moisture content was then estimated depending on the crop coverage measurement from the infrared images, and the stress level from the NDVI readings. For example, if the crop had full cover and unstressed vegetation, then the soil water profile was assumed to be full.

Figure 18: Image of field obtained using aerial photography with reflectance panels to calibrate crop coverage images (French et al. 2011)

Remote sensing images were found to be sensitive to lighting conditions. Hence, if the day of data collection was cloudy then ground-based observations (e.g. NDVI) were the basis for crop water management.

NDVI measurements may be used in sensor-based irrigation control strategies to either apply a desired amount of stress, or aim for specific coverage measurements throughout the season. Similarly, the crop coverage measurements may be used to calibrate a crop model in model-based irrigation control strategies. However, crop stress is not commonly a parameter in crop production models. Because NDVI is proportional to leaf area index for some crops (e.g. for cotton before the canopy is closed), NDVI can be used to calibrate the modelled vegetative growth in model-based control strategies.

5.3 Summary of USDA-ARS US Arid Land Agricultural Research Centre in Maricopa

Although irrigation systems in Maricopa are currently predominantly surface irrigation, water availability is decreasing and water use efficiency of irrigation must be improved. This is being achieved at the Maricopa USDA-ARS by aiming to improve surface irrigation using models of crop production and surface irrigation application. Research using a variable-rate lateral move irrigation machine has commenced.

NDVI and image-based crop coverage sensors were being developed for irrigation decision-making based on the estimation of crop evapotranspiration. NDVI would be applicable to both sensor- and model-based irrigation control strategies.

6. USDA-ARS Conservation & Production Research Laboratory in Bushland, Texas

6.1 Irrigation in Bushland

Bushland's irrigation water is sourced from the Ogalla Aquifer. The Ogalla Aquifer supplies water across eight states in the USA from Texas to South Dakota and a total of 80% of the water pumped from the Ogalla Aquifer is used for agriculture. Agricultural crops grown in Bushland include cotton, corn and wheat.

The windy conditions of Texas are ideal for wind power generation. There are approximately 75 wind turbines in Bushland which produce 1.6 GW of electricity (e.g. Figure 19). This windy climate also means that the irrigation systems must be low pressure to minimise evaporation losses. Hence, irrigation systems in Bushland are typically either large centre pivots (some up to two kilometres long) with low pressure emitters (e.g. LEPA) or drip irrigation systems. Fluctuations in wind also cause fluctuations in the electricity produced which often leads to power outages. Hence electrical systems for irrigation control systems and data transfer have to be robust to loss of electricity.

Figure 19: Wind power plant in Bushland, Texas

6.2 Research at USDA-ARS Conservation & Production Research Laboratory in Bushland

Research at the Bushland USDA-ARS is being conducted to improve the efficiency of water use. Much of this work involves the development and evaluation of radiometers (e.g. infrared thermometers) to determine plant stress for crop water management.

One approach being researched by Dr Susan O'Shaughnessy (Figure 20) involves using infrared thermometers and the 'time temperature threshold' method to determine irrigation timing. Irrigation events are initiated one day after the crop has been above a threshold temperature for a set number of minutes. The thermometers are calibrated at five ambient temperatures in a controlled temperature room (Figure 21) before being mounted on a centre pivot irrigation machine.

Figure 20: Visit with Dr Susan O'Shaughnessy at the USDA-ARS in Bushland, Texas

Figure 21: Nine infrared thermometers being calibrated in controlled temperature room

Infrared thermometers have been installed at sixteen locations along a centre pivot at the research station (Figure 22). At each location, readings from three thermometers are averaged to reduce the measurement errors caused by the sensor variability and infield crop variability. This irrigation machine traverses the field daily and the thermometers collect canopy temperature during 'dry runs' to determine when to initiate the irrigation event. The current system does not determine irrigation application.

Figure 22: Three infrared thermometers on irrigation machine in Bushland, Texas

Dr Susan O'Shaughnessy is developing the next prototype sensing unit which measures the red, green and blue response as well as temperature (Figure 23). The colour response of plants will indicate plant condition (i.e. greenness) and possibly leaf diseases.

Figure 23: Prototype of infrared thermometer with colour sensor

Each infrared thermometer measures the average temperature over a 0.7 metre diameter circle when mounted on the irrigation machine. There may be both exposed soil and plant in the measurement area depending on the infrared thermometer placement (e.g. in a crop row), crop type and growth stage. For example, both soil and plant temperature will be measured by the thermometer for early season crops. This has been found to affect the accuracy of the temperature measured. However, for developed fodder crops or closed-canopy cotton, only the foliage would be measured by the infrared thermometer. Dr Paul Colaizzi at the USDA-ARS has investigated using radiometers to also determine soil cover and adjust the plant infrared thermometer measurement accordingly.

A weighing lysimeter with underground access is used to obtain crop coefficients for evapotranspiration calculations at the Bushland USDA-ARS (Figure 24, 25). A full-time scientist is employed to collect data from the lysimeter and maintain the equipment.

(a) (b)

Figure 24: Lysimeter and access at research station in Bushland, Texas

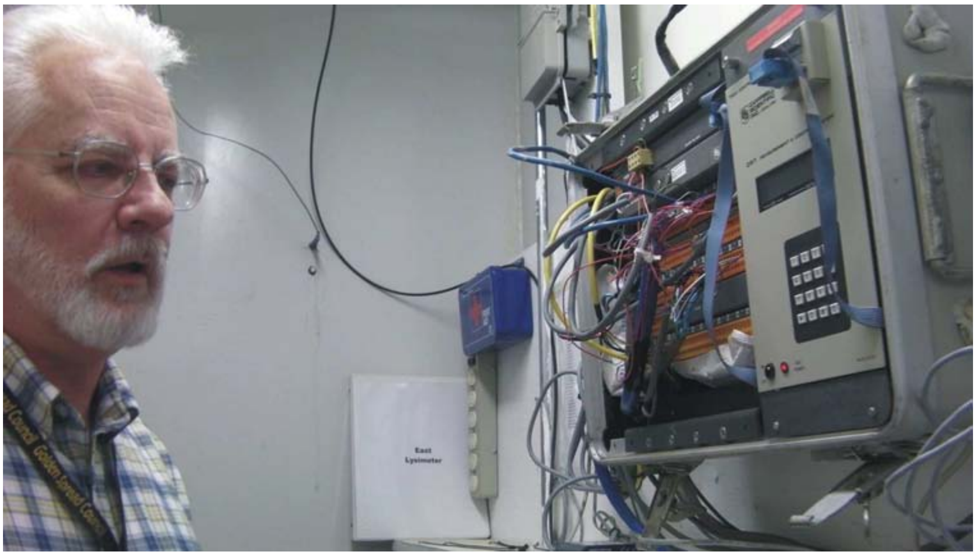

Figure 25: Dr Steven Evett and the lysimeter control panel

Crop models have been used by Bushland researchers for plant and irrigation management. Generally these models are used for comparison of irrigation timing, crops to grow, planting time and plant spacing. Research has shown good correlations between measured and modelled data for crop rotation. However, cotton models have been found to be inaccurate with narrow row spacing.

Mechanistic crop production models were found to be more accurate than empirical models for crop management. Mechanistic models are developed from known dynamics of the soil-plant-atmosphere system, while empirical models are derived from infield measurements of the weather, soil and/or plant. Mechanistic models may be extrapolated to other sites with different climatic and soil inputs because they are derived from known dynamics. The development of empirical models requires extensive data collection to accurately describe the modelled system which may not be practical for each new crop or field site. In addition, empirical models might not extrapolate to other sites with different climatic and soil inputs.

Dr Steven Evett has conducted comparisons of commercially available soil moisture sensors to aid selection of soil sensor technology. This research found that the performance of the soil moisture sensors depended on soil type, soil water content and amount of soil being measured by the sensor. Neutron moisture meters were the most accurate soil moisture sensor but require manual operation and a licence to operate (because they use radioactive material); hence, these sensors are not applicable to real-time irrigation control. However, soil moisture sensors that measure the dielectric constant of soil (e.g. capacitance) have a smaller measurement volume but do not require manual reading. Hence, these sensors are more appropriate for automatic irrigation control.

6.3 Summary of USDA-ARS Conservation & Production Research Laboratory in Bushland

Thermal sensors are being developed that can measure spatial variability but are currently only used for irrigation timing and not spatial crop water management. These sensors take daily measurements and are sensitive to the time of day that the measurement is taken. These sensors also take an average measurement over the measurement area which may include soil; hence, soil coverage is often also measured. Crop temperature is a variable that may be used in response-based irrigation control strategies. These are applicable to overhead irrigation systems because they can be mounted on irrigation machines to collect high resolution spatial information. Model-based irrigation control strategies may not be able to use temperature information because crop models are not typically parameterised by temperature.

Crop production models can be used for comparisons of crop management practices and indicate better performing irrigation management practices. Model-based irrigation control strategies require calibration using available soil moisture and plant measurements.

Neutron moisture meters are not appropriate for real-time irrigation control because they require manual operation. Hence, less accurate sensors must be used for spatial irrigation management.

7. USDA-ARS Plant Stress and Germplasm Development Laboratory in Lubbock, Texas

7.1 Irrigation in Lubbock

The irrigation water in Lubbock is pumped from the Ogalla Aquifer (which also supplies irrigation water to Bushland). Growers in Lubbock are allocated 305 millimetres over their cropping area, while the average annual rainfall is 457 millimeters. Common field crops grown are cotton, corn, peanuts and wheat. Crops must be deficit irrigated because the available water is not sufficient to deliver the crop water requirements. Hence, it is a priority for growers to best utilise the rainfall.

As for Bushland, sub-surface drip irrigation and LEPA centre pivot irrigation machines are the predominant irrigation delivery system because of the windy conditions. There are 13 000 centre pivots in Lubbock, typically with 15 to 25 spans (e.g. Figure 26). Crops are typically planted in a circular formation to minimise the exposure of plants to the wind and hence reduce wind damage.

Figure 26: Typical centre pivot irrigation machine up to 2 km long in Texas (Goldberg 2011)

Local growers commonly use a 'banking' irrigation strategy where water is applied before the crop is planted and less irrigation is applied at the start of the crop season to save water for the end of the season. However, for cotton crops this may lead to overwatering at the end of the season.

7.2 Research at USDA-ARS Plant Stress and Germplasm Development Laboratory in Lubbock

The Lubbock USDA-ARS has 40 acres of experimental plots and the main research themes involve investigating genetic drought tolerance of plants, acclimating plants to drought, and evaluating the critical irrigation times for cotton. Dr James Mahan is developing a system where only canopy temperature is used to determine crop water requirement (Figure 27). This follows a similar principle to the time temperature threshold method used in Bushland by Dr O'Shaughnessy. This is because the soil does not directly indicate crop condition.

Figure 27: Visit with Dr James Mahan at the USDA-ASRS in Lubbock, Texas

An infrared thermometer-based irrigation scheduling system 'Smart Crop' has been developed by Dr Mahan and commercialised (Figure 28). This system has been designed to be fixed in the field and analyses the sub-daily progression of crop temperature. Hence, this system requires a high temporal resolution of data. In contrast, thermometer readings in the Bushland system were recorded only once every day but at a higher spatial resolution because the sensors were mounted on the irrigation machine that traversed the field daily. To increase the spatial resolution of the temperature measurements, Dr Paxton Payton at the USDA-ARS was investigating using a thermal camera at the pivot point of an irrigation machine that rotates at short intervals to obtain near-continuous thermal data for the whole field.

Figure 28: Smart Crop infrared thermometer fixed in sorghum field

Postgraduate students were using crop models for spatially varied irrigation management. This involved integrating a spatial hydrologic model 'PALMS' (Moiling et al. 2005) with a cotton production model 'Cotton2K' (Marani 2000). PALMs is a weather-driven precision agriculture landscape modelling system with 15-minute precision which simulates the flow of energy, water and plant growth for different crops. PALMs is primarily used in mid eastern US terrain. Cotton2K is a cotton production model for aid climates with an hourly time step and has been validated in California, Arizona and Israel. The underlying soil properties were obtained from the US Government Geoscience website.

7.3 Summary of USDA-ARS Plant Stress and Germplasm Development Laboratory in Lubbock

An infrared thermometer-based irrigation scheduling system based on point-source plant measurements and developed at the Lubbock USDA-ARS has been commercialised. Response-based VARIwise control strategies could use feedback from the thermal sensors used in these systems. However, the optimal configuration of the sensor must be further considered. For example, the infrared thermometer may be fixed in the field to take a high temporal resolution of data for one plant, while a sensor mounted on an irrigation machine would measure the plants at a higher spatial resolution but lower temporal resolution (i.e. only as often as the machine passes over the field).

8. Conclusions

8.1 Achievement of aim 1
To assess the state of development of spatial sensors for irrigation control systems

Soil moisture, weather and thermal sensors are generally used for irrigation decision-making. Thermal approaches to plant sensing were commonly researched because they can collect daily data at a high spatial resolution if they are mounted an irrigation machine. However, these sensors are highly dependent on the time of day and sub-daily measurements may be more useful for irrigation control.

Sensor availability is a constraint on the automation of irrigation control. The most accurate soil moisture sensors are not practical for an automatic irrigation control system because they are can only be obtained manually and need a license to operate. Image-based sensors that have been developed for identifying plant growth and structure in orchards are potentially applicable to irrigation.

8.2 Achievement of aim 2
To investigate work on autonomous irrigation systems to see other possible issues

The majority of current irrigation research in the USA involves development of sensors rather than control systems or decision-making approaches. The models used in model-based strategies were different at each research station visited and each model may have different sensor requirements for model calibration. This may require the development of a broad range of sensors to measure the full range of variables required for each model. Each model that is part of an irrigation control system will also have to be specifically programmed to be integrated into the control system. It is anticipated that these factors will lengthen the time for both control system and sensor development.

8.3 Achievement of aim 3
To investigate implementation of LMIM variable-rate hardware

There has been a significant reduction in the use of Farmscan variable-rate irrigation technology by growers who purchased the technology in Georgia, USA. Commercial irrigation prescription software is being commercialised as part of the Valmont variable-rate irrigation system to help growers understand how to use variable-rate technology. The research station with a working variable-rate irrigation system is now only using the system as a research tool for variety and treatment trials rather than optimising irrigation application.

9. Recommendations

The design of variable-rate irrigation control systems should be holistic and consider the integration of appropriate sensors, control strategies and variable-rate hardware. Irrigation control systems should have low data requirements to be adopted more readily. It is anticipated that response-based strategies or strategies with low data inputs would be adopted before model-based strategies which have more extensive data requirements. A more integrated approach to model-based control strategy development will reduce the overlap in their development with each research station developing strategies using different models.

The suitability of thermal sensors and logging soil moisture sensors to irrigation control should be considered. Alternatively, control strategy options should drive future plant and soil moisture sensor development. This includes further development of sensors for model-based irrigation control strategies, e.g. camera-based plant sensors.

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Appendix A: NPSI/IAL Travel Fellowship itinerary

Table 1: NPSI/IAL Travel Fellowship itinerary

Date	Activities	Destination	Host
7-8 March	• Meeting with University researchers • Visited Centre for Precision and Automated Agricultural Systems • Field visit to hops farm, vineyard, orchards and racecourse irrigation machine trial site • Presentation at Whitstran Elementary School	Washington State University, Prosser, Washington	Dr Troy Peters
10 March	• Meeting with commercial irrigation company representatives to discuss commercial variable-rate irrigation systems	Triumph of Ag Expo, Qwest Centre, Omaha, Nebraska	Nil
11 March	• Meeting to discuss variable-rate irrigation and comparison of commercial site-specific irrigation technology	Valmont Irrigation, Valley, Nebraska	Mr Jake LaRue
12 March	• Meeting to discuss irrigation decision-making and sensor requirements	CropMetrics, Omaha, Nebraska	Mr Nick Emmanuel
14-15 March	• Meeting with variable-rate irrigation researchers • Meeting with North Dakota University postgraduate students • Attended opening of local Agri-Industries franchise and met with local growers and irrigation industry representatives • Presentation to local growers, and USDA-ARS and North Dakota University researchers • Field visit of experimental variable-rate irrigation machine	USDA-ARS Northern Plains Agricultural Research Laboratory, Sidney, Montana	Professor Robert Evans
17-18 March	• Meeting with furrow irrigation control and plant sensing researchers • Presentation to laboratory researchers	USDA-ARS US Arid Land Agricultural Research Centre, Maricopa, Arizona	Dr Kelly Thorp
21-22 March	• Meeting with laboratory researchers	USDA-ARS Conservation &	Dr Susan O'Shaughnessy

	• Field visit of site using infrared thermometers for irrigation management and testing of VRI • Presentation to laboratory researchers	Production Research Laboratory, Bushland, Texas	
24-25 March	• Presentation to laboratory researchers • Field visit of drip irrigation site	USDA-ARS Plant Stress and Germplasm Development Laboratory and Wind Erosion and Water Conservation Laboratory, Lubbock, Texas	Dr James Mahan