

---

# A Demonstration of Energy & Water Savings Potential from an Integrated Precision Irrigation System

## **Charles Hillyer, Assistant Professor (Senior Research)**

Oregon State University, Dept. of Biological & Ecological Engineering, 116 Gilmore Hall, Corvallis, OR, 97333, [hillyer@enr.orst.edu](mailto:hillyer@enr.orst.edu)

## **Chad Higgins, Assistant Professor**

Oregon State University, Dept. of Biological & Ecological Engineering, 116 Gilmore Hall, Corvallis, OR, 97333, [chad.higgins@oregonstate.edu](mailto:chad.higgins@oregonstate.edu)

## **Marshall English, Professor**

Oregon State University, Dept. of Biological & Ecological Engineering, 116 Gilmore Hall, Corvallis, OR, 97333, [marshall.english@oregonstate.edu](mailto:marshall.english@oregonstate.edu)

## **Lori Rhodig, INITIATIVE Manager**

421 SW Sixth Avenue, Suite 600, Portland, OR 97204, 503.688.5400, [LRhodig@neea.org](mailto:LRhodig@neea.org), Northwest Energy Efficiency Alliance

## **Geoff Wickes, Product Development Manager**

421 SW Sixth Avenue, Suite 600, Portland, OR 97204, 503.688.5400, [GWickes@neea.org](mailto:GWickes@neea.org), Northwest Energy Efficiency Alliance

## **Jac le Roux, President**

Irrinet LLC, 910 E 10th Street, The Dalles, OR, [jac@irrinet.net](mailto:jac@irrinet.net)

**Abstract.** Optimal irrigation management is demonstrated on farms in Oregon, Washington, and Idaho, during 2012 and 2013 as part of a multi-year effort to demonstrate the effectiveness and profitability of an integrated irrigation management solution. Integration includes high-resolution soil mapping, variable rate irrigation, on-site ET (estimated), soil moisture monitoring, optimal irrigation methodologies, flow meters, energy use monitoring via smart meters and yield mapping of results. The objective of the demonstrations is to show increased profitability based on optimizing inputs. Initially the information from each of these sources is integrated into a decision support system, Irrigation Management Online, specifically designed to schedule irrigations when water supplies are limited. The management system provides optimized scheduling based on multiple information sources and includes the grower as a critical component of the decision process. This paper will present the results from the 2012 and 2013 seasons and describe plans for following years.

**Keywords.** Irrigation Optimization, Energy Efficiency, Variable Rate Irrigation, Deficit Irrigation.

## Introduction

In the United States irrigated agriculture accounts for approximately 80% of the consumptive use of fresh water. The demand for fresh water is projected to exceed renewable supplies by 2025 (Postel et al., 1996). The world demand for food is becoming greater because of increased population size and growing demand for resource intensive products (beef, poultry, etc.). For irrigated agriculture, at the intersection of these two resource limitations, water shortages will become standard operating conditions. This leads to the obvious conclusion that significant changes must occur, and agriculture, the largest consumer of fresh water, is expected to make big changes in water use. Part of the solution is expected to come from improvements in crop characteristics to reduce water needs and increase stress tolerance (Baulcombe, 2010). However, it is generally recognized that the developing water shortages will also force fundamental changes in the way irrigation is managed (English et al., 2002). Irrigation management will necessarily move from simple stress avoidance (a biological objective) to optimization based on net returns to water (an economic objective). Much more sophisticated irrigation management tools will be needed to support optimal decision-making in a water-limited future. However, the most recent Farm and Ranch Irrigation survey indicated that only 10% of farms used any type of advanced on-farm water management tools (Schaible and Aillery, 2012). This lack of use indicates that technology adoption will be a significant challenge for improving the efficiency of agricultural irrigation.

The complexity of optimal irrigation advisory tools and technologies will require a development foundation that facilitates integration of technologies and information from a variety of sources. These tools will be driven by technologies for environmental monitoring, operational monitoring, and precision irrigation. Adoption of these technologies will, as with any new technology, be limited by its economic viability. The objective of the project described here is to demonstrate the economic potential of optimal irrigation in general and variable rate irrigation in particular.

The Northwest Energy Efficiency Alliance (NEEA) has undertaken a demonstration program that will improve energy efficiency by accelerating adoption of precision irrigation technology. The goals demonstration project are:

- Demonstrate savings in water and energy associated with optimal, variable rate irrigation.
- Determine the cost-effectiveness of current irrigation technologies by balancing the capital investment against financial gains from energy and water savings.
- Determine the relative value of each data source (instrument), both in terms of decision-making power and dollars.
- Provide the foundation for development of data exchange standards and an API for irrigation management.

## Optimal Irrigation

Optimality in irrigation can mean different things. A grower could choose to optimize for yield, profit, efficiency, total land in production, or minimum water use. Economically optimum irrigation management is fundamentally different, and more difficult, than conventional irrigation because economically optimal irrigation implies some level of deficit irrigation (English et al., 1990), (English and Raja, 1996), (English and Nuss, 1982). The basic premise of deficit irrigation is illustrated by Figure 1: a production function developed for winter wheat at Hermiston, Oregon. The maximum income occurs when the water application is 16% less that that required for maximum yield. This reduction in water application results in a reduction of crop water use which is the “deficit” in deficit irrigation

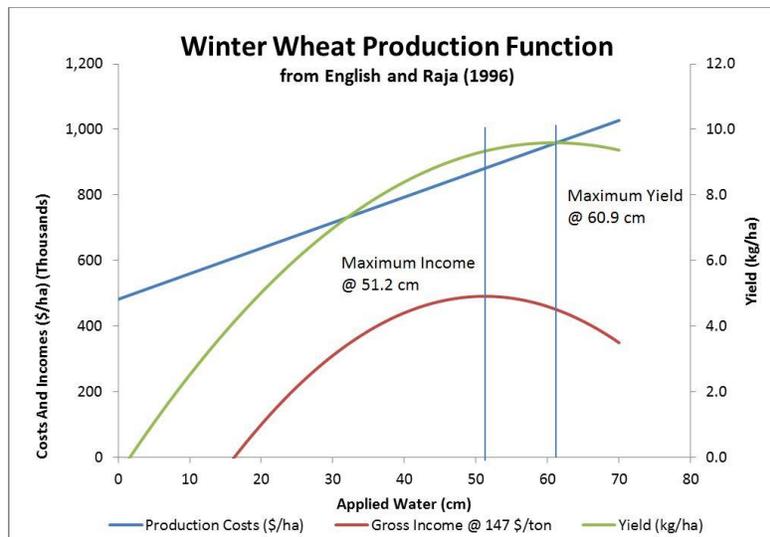


Figure 1 Water Production Function for Winter Wheat

While the conventional paradigm is to irrigate as needed to avoid crop stress, deficit irrigation involves controlling crop stress in spatially variable fields. The conventional method is essentially a balancing of irrigation and ET. Optimal irrigation scheduling is a decision process. The information needed to implement optimal scheduling is orders of magnitude more complex than conventional scheduling. The irrigation manager must account for soil heterogeneity, the spatial variability of applied water and crop responses to water stress. This management complexity is increased when the fields are not managed in isolation; the entire farm is considered when allocating water supplies. For this reason, sophisticated modeling and management tools are needed to implement optimal scheduling.

Irrigation affects and is affected by nearly all farm operations. Limitations on resource availability increase the complexity of the effects on irrigation management. To include these constraints in an optimization algorithm involves codifying the constraints in a manner appropriate for an optimization framework. Encoding all possible constraints is not an achievable goal because all constraints cannot be identified *a priori*. Including most of the constraints would still involve constructing quantitative representations of the different farm processes.

In this initiative, NEEA, working in collaboration with Oregon State University (OSU), uses an OSU-developed system known as Irrigation Management Online (IMO). Instead of building a simulation of the whole (or nearly whole) farm enterprise, IMO takes a different approach. The central thesis of IMO is that the best way to implement or express these constraints is to build a system that includes the only entity that is aware of all these constraints: the grower.

This system, known as Irrigation Management Online (IMO), explicitly analyzes irrigation efficiency and yield reductions for deficit irrigation, performs simultaneous, conjunctive scheduling for all fields in the farm that share a limited water supply, and employs both ET and soil moisture measurements in a Bayesian decision analysis to enhance the accuracy of the irrigation schedules. IMO is described in detail in (Hillyer, 2011), and (Hillyer et al., 2009); the complete details of its implementation are beyond the scope of this paper.

### An Integrated Approach

A wide variety of technologies and methods have been developed for precision irrigation management (Smith et al., 2010). The technologies for Center Pivot control have been reviewed by Kranz et al. (2012) and the potential for adaptive control was analyzed by McCarthy et al. (2011). Many of these technologies still operate in isolation. Integrating the information to produce an

irrigation schedule requires a significant time investment for the irrigation manager. This systems integration task is part of the focus of the demonstration and the overall project. The goal is to produce a system that demonstrates the potential time and effort savings obtainable from automating the data integration task. Furthermore, the data being integrated will be used to drive the IMO system to produce additional value in the form of more precision for irrigation management. Figure 2 shows a conceptual overview of the data sources that will be integrated.

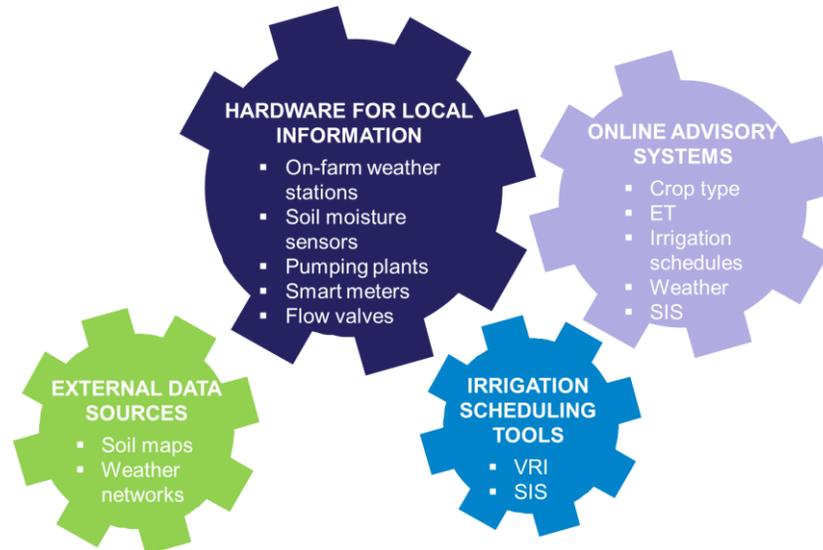


Figure 2 Conceptual overview of the integrated system

Data acquisition is only one part of the scheduling process shown in Figure 2. Making data easy to obtain and presenting it clearly is a valuable feature but the real power of irrigation schedulers lies in the potential for using the information to drive calculations. In this sense, an irrigation scheduler is also a decision support system. Mohan and Arumugam (1997) indicated that Expert Systems are viable and effective tools for irrigation management and stressed the need to include other aspects of irrigation management such as canal and reservoir operation. This need was also indicated by Clyma (1996) who concluded that scheduling services are not adequately integrated with other farm operations that hold greater importance than irrigation decisions.

One of the goals for this demonstration is for the benefits of system integration to transfer beyond the scope of the demonstration project. To that end, development of data exchange standards and an API for irrigation management is being developed in parallel with the demonstration projects. Once the demonstrations are complete, an open source version of the IMO system, including the systems integration features, will be made available. The open source release will serve as an example for other interested developers. Serve as a “guinea pig” for (rather than a competitor to) informing future development of irrigation management systems. NEEA is already collaborating with supply base partners to develop the data exchange standards (see Berne et al, 2013, these proceedings).

### Variable Rate Irrigation

Site-specific Variable Rate Irrigation (VRI) is a system where a center pivot irrigation system is equipped with the capacity to actuate valves for groups of sprinklers, or to regulate its speed during operation. A control system is used to open and close the valves at various rates (or change the speed) based on the position of the pivot and a desired application depth. VRI systems have been described in detail by (Evans et al., 2012), (Evans and King, 2010), and (Sadler et al., 2005). One aspect of VRI that has not been studied is the potential for mitigating some of the undesirable effects of deficit irrigation. When deficits are imposed on a field they are generally estimated based on an average for the whole field. Because no field is completely uniform, some areas of the field will experience more stress than the targeted amount. This can produce visible areas of crop stress even

though the overall yield response is still optimal. By using the VRI system, it may be possible to produce increased uniformity of yield response and improve the qualitative effect of visibly stressed areas in a field.

One requirement for performing deficit irrigation is that the depth of application may need to change given the timing of a particular irrigation event. For VRI this means that different prescriptions will be required for each irrigation event. Typical practice for VRI is to produce a single prescription that is calibrated to physical or chemical attributes of the soil and use this prescription repeatedly during the season. In this demonstration the prescriptions are based in the soil moisture status at the time of the irrigation event. The difference between prescriptions will likely be small in most cases but will be significant enough in certain cases to warrant generation of unique prescriptions.

## Demonstration Project

The demonstration project began in the spring of 2012 and is planned to be a multi-year effort. Three farms in the Columbia Basin agreed to participate in the demonstration. These farms were selected on the following bases: 1) high lift requirements for pumping (to ensure significant energy costs); 2) farm/irrigation managers willing to experiment with new technologies; 3) irrigation managers willing to act on the irrigation recommendation provided by the integrated system; and 4) greater than 500 acres in production. Each farm received the full complement of instrumentation, monitoring, and analysis described below effectively producing three replications of the demonstration. A summary of the fields used during the 2012 and 2013 seasons are shown in Table 1 and Table 2 respectively.

The following technologies were used at each farm:

**Variable Rate Irrigation:** At each site, one pivot was retrofitted with a variable rate irrigation system with zone control. Systems from two manufacturers were used. Two sites had systems from Valley Inc., and one site had systems from Lindsay Inc.

**Soil Mapping:** High-resolution soil maps were produced using the methods described by (Fulton et al., 2011). The soils data was used to produce data layers for several soil properties including holding capacity, field capacity.

**Flow Monitor:** Ultrasonic flow meters (GE Panametrics) were installed on the pivots equipped with VRI. Water use records for the other fields were derived from records kept by the software used to actuate the pivots.

**Weather Monitoring:** Each farm was equipped with a primary weather station with the sensors required to calculate reference ET. Additionally, each field had a secondary weather station placed well within the field boundary. This secondary weather station was equipped with temperature and relative humidity sensors and radio communication ET calculations were performed using the ASCE Standard equation (Allen, 2005). Two sites had weather stations produced by Automata Inc. and two sites had weather stations produced by Ranch Systems Inc.

**Soil Moisture Monitoring:** Each field was equipped with three soil moisture monitoring sites. At each site a neutron probe tube was installed. Additionally two of the sites had Decagon 10HS capacitance probes installed at three depths and one site a multi sensor AquaCheck probe. In each of the fields, the sites were chosen such that they represented the upper, lower, and middle quantiles of holding capacity

**Localized Yield Modeling:** At each site, a local calibration of the FAO33 yield reduction model was produced using historical yield records. This calibration will enable generations of more precise yield maps and enable consideration of the value of these maps relative to default or regionally estimated yield calibrations.

**Yield Mapping:** Harvest monitors with GPS tracking will be collected at each site. At two sites a John Deere Green Star 3 monitor was used and at one site a Case IH Pro 600 monitor was used.

To facilitate comparison of various combinations of technologies, the fields grouped into three different levels of integration. Each level represents a significant improvement in scheduling precision and potential for water and energy savings relative to the previous level. Level 1 is the equivalent to basic Scientific Irrigation Scheduling (SIS) where a water balance is used to drive irrigation scheduling. However, this capacity is enhanced by utilizing in-field temperature and relative humidity sensing to refine ET estimation, and neutron probe measurements to correct the water balance. Level 2 builds on Level 1 by adding additional soil moisture monitoring and high resolution soil maps. The soil maps enable explicit consideration of spatial variability which will lead to more accurate yield estimates and more robust management capacity. The additional soil moisture monitoring enables increased temporal resolution and the opportunity to assess data integration issues with different sensors, data loggers, and telemetry. Level 3, the final level, adds VRI capacity.

Table 1 Field designations for 2012 field demonstrations.

Field Number	Integration Level	Crop (2012)	Size (Ac.)	Pumping Lift (ft.)	Location
18	Level 3	Winter wheat	69		
11	Level 2	Winter wheat	82		
17	Level 1	Alfalfa	125.3	≈750	OR
25		(mature)	119.2		
102	Level 3	Alfalfa	125		
107	Level 2	Alfalfa	72	≈750	WA
109	Level 1	Alfalfa	125		
210	Level 1	Alfalfa	125		
2	Level 3	Winter wheat	136		
1	Level 2	Winter wheat	155	≈125	ID
3	Level 1	Sugar beet	147		
6	Level 1	Sugar beet	134		

Table 2 Field designations for 2013 field demonstrations.

Field Number	Integration Level	Crop (2013)	Size (Ac.)	Pumping Lift (ft.)	Location
M13	Level 1	Canola	124	≈750	OR
M22	Level 2	Canola	132		
M21	Level 3	Canola	121		
M10	Level 1	Field Corn	126	≈750	OR
M56	Level 2	Field Corn	123		
M54	Level 3	Field Corn	123		
B211	Level 1	Field Corn	97	≈750	WA
B116	Level 2	Field Corn	125		
B207	Level 3	Field Corn	102		
TD5	Level 1	Field Corn	125	≈125	ID
TD11	Level 2	Field Corn	125		
TD7	Level 3	Field Corn	125		

## **Results from 2013**

At the time of this writing the demonstration program is still ongoing and yield data for all fields from the 2013 season is not yet available. In lieu of full analysis, here we present some preliminary results and a discussion of the issues and complications that occurred during the 2013 season. Several of these issues are likely to have serious implications for further application of SIS on VRI irrigation systems.

### **System Calibration**

During the 2013 season, IMO was used to generate irrigation schedules for all of the Level 2 & 3 fields. Water use and neutron probe measurements were also tracked in IMO for the Level 1 fields. Simulation of soil moisture for each 12 demonstration fields is shown in the figures below. Overall the system calibrations were satisfactory. The calibrations will be used on the same fields in 2014 and will enable starting the next season with a well calibrated data set for each field.

There were two consistent problems during the season. The first is related to the soil mapping problems described later. The black squares in the graphs represent neutron probe measurements. Three measurements are taken on the same day each week. The measurement sites were selected so that they represented the 25th, 50th, and 70th percentiles of soil water holding capacity. During the season it became apparent that some of the sites did not correspond to those percentiles and were moved to more appropriate sites. The soil mapping issues are described further in the following section.

The second problem was related to the crop coefficients used for field corn. There were several periods where the crop water use (as observed by neutron probe measurements) was significantly less than what the crop coefficient indicated. There were no indications of disease, pest damage, or fertility issues that would have caused the reduction in crop ET. The consequence of this problem is the soil moisture estimates are lower than actual during the peak ET part of the season. This issue is still being explored at the time of this writing.

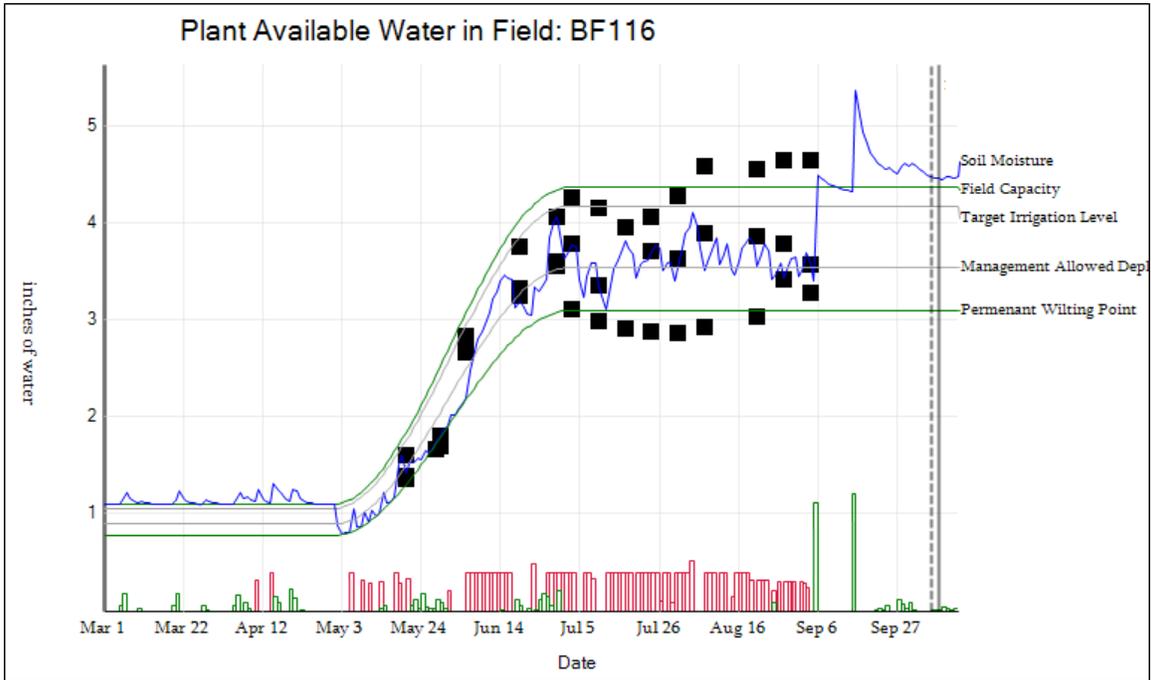


Figure 3 Soil Moisture Estimate for Field BF116

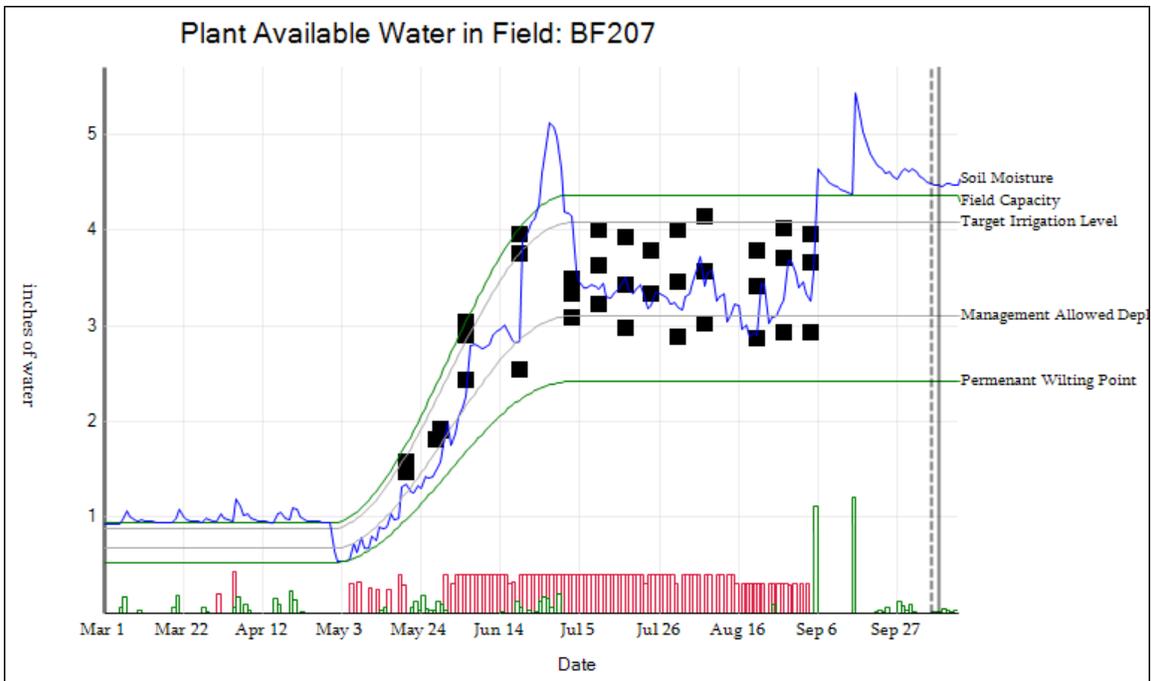


Figure 4 Soil Moisture Estimate for Field BF207

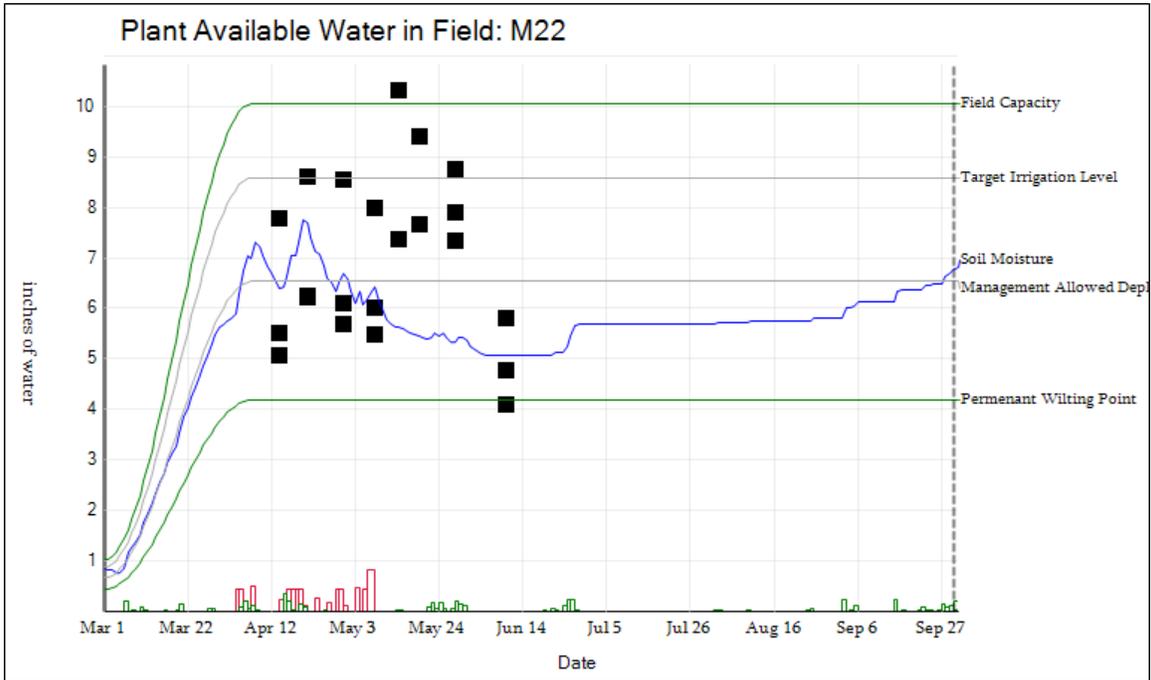


Figure 5 Soil Moisture Estimate for Field M22

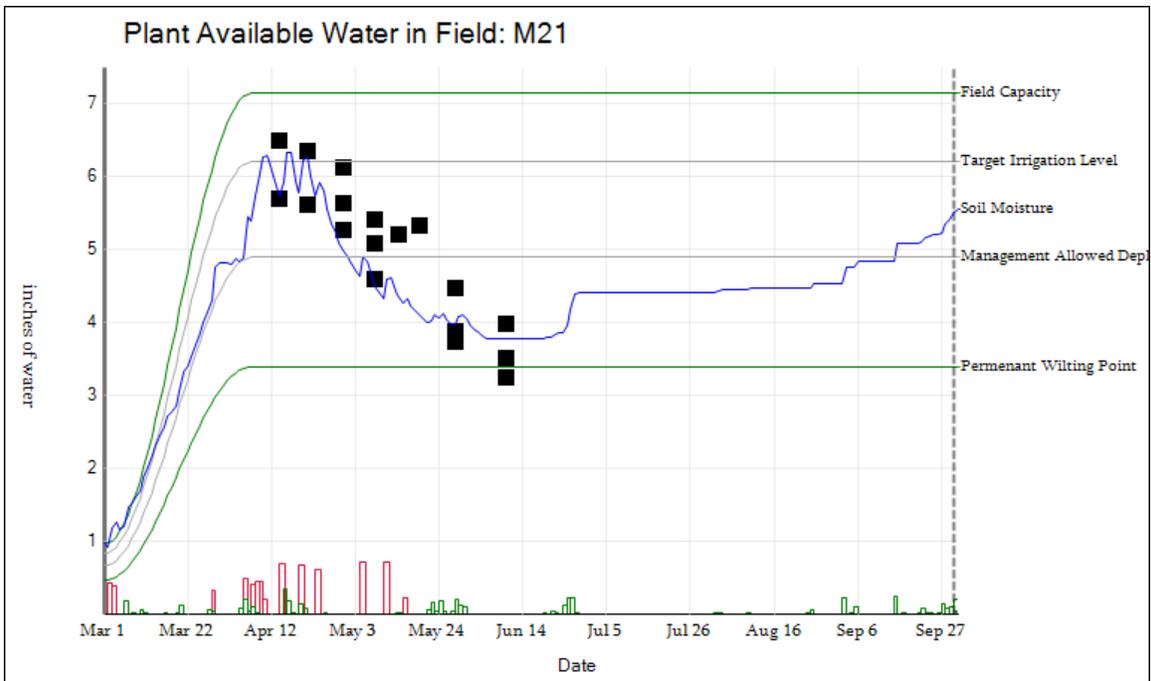


Figure 6 Soil Moisture Estimate for Field M21

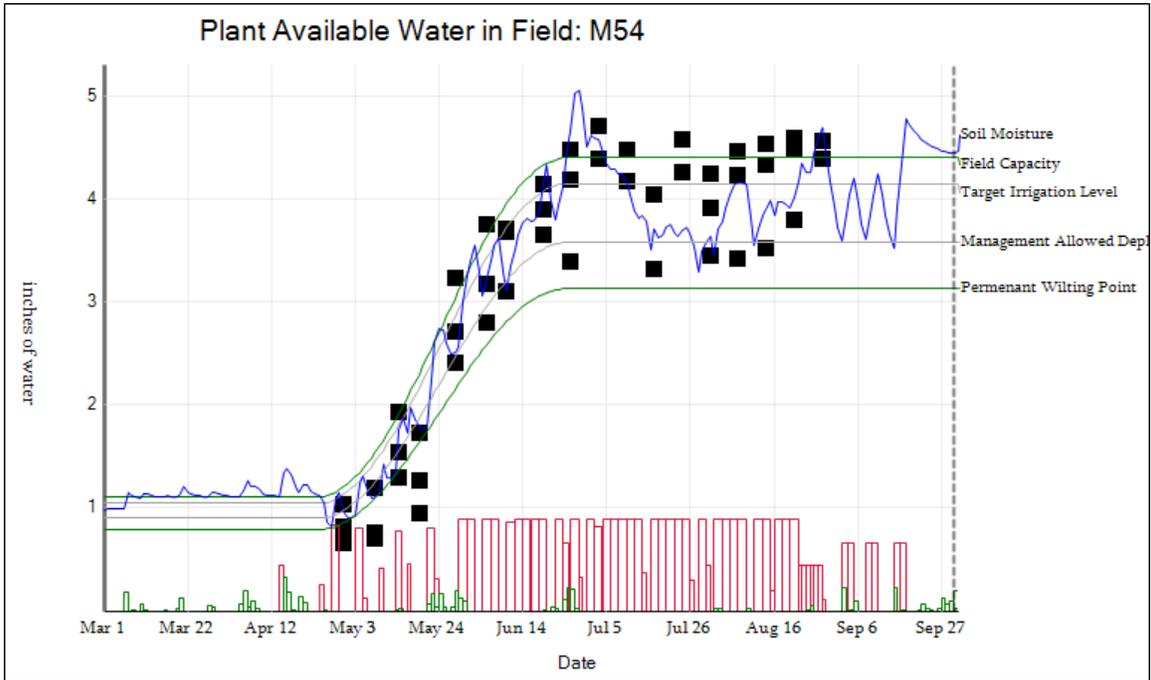


Figure 7 Soil Moisture Estimate for Field M54

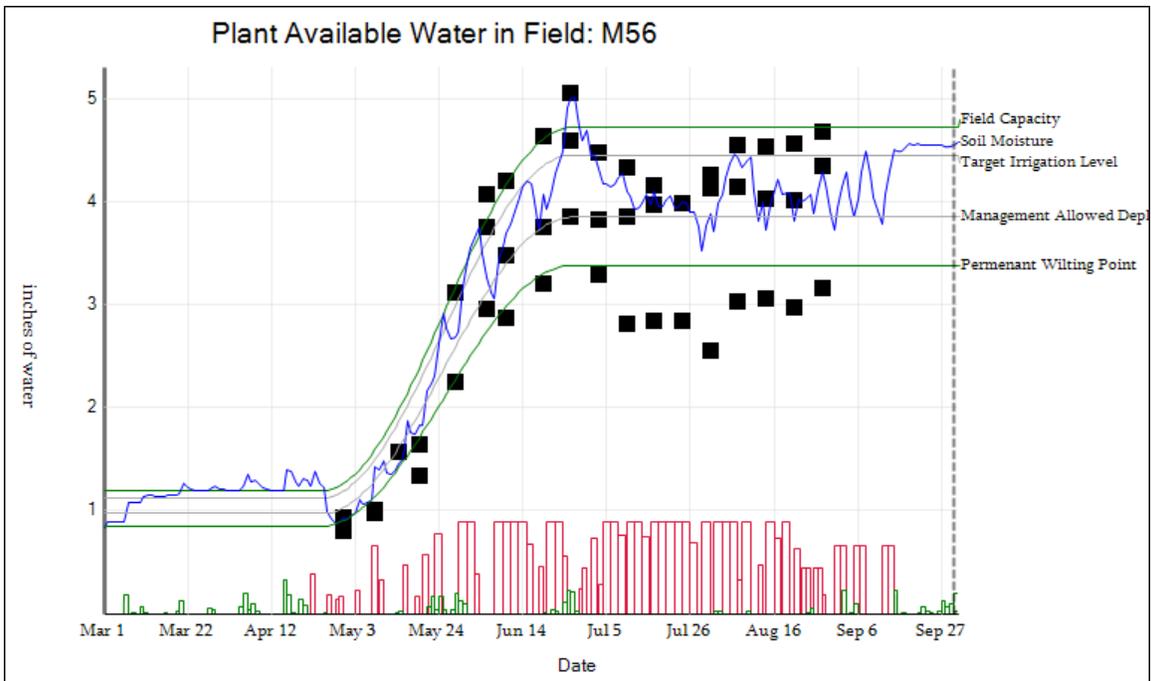


Figure 8 Soil Moisture Estimate for Field M56

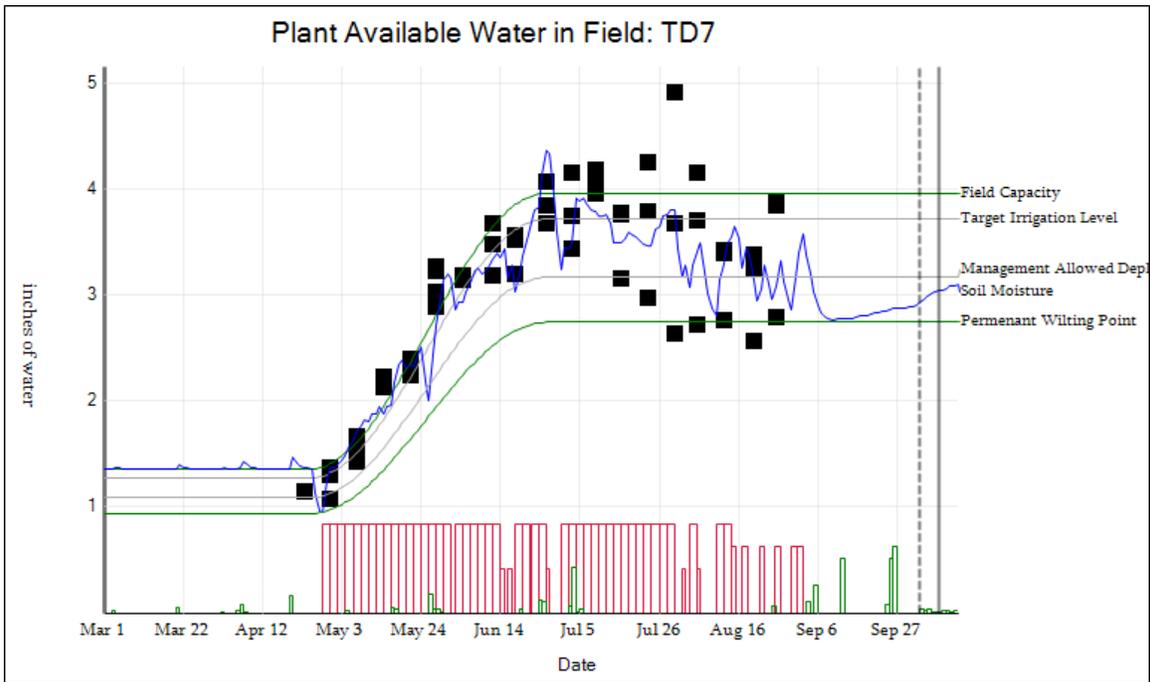


Figure 9 Soil Moisture Estimate for Field TD7

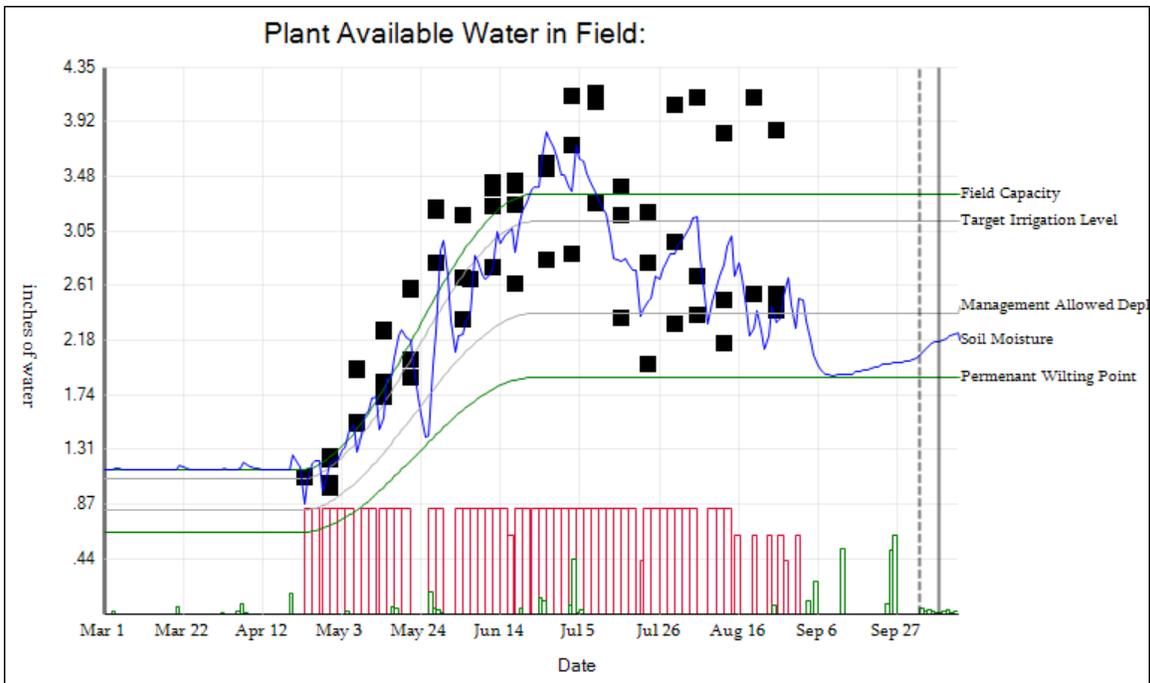


Figure 10 Soil Moisture Estimate for Field TD11

### Soil mapping

Scientific irrigation scheduling (SIS) requires the irrigator to know the soil's water holding capacity. To apply SIS with prescribed spatial variation (aka a prescription), the irrigator must have a map of water holding capacity. The methods described in (Fulton et al., 2011) were used to generate a map of field capacity and plant available water. The maps used spatial data from EM38 and Veris systems and soil texture analyses sampled shortly after the EM maps were acquired.

Figure 12 shows the map of surface layer EM readings for one of the Washington site's fields. Figure 13 shows the correlation between the measured soil texture and the modeled texture using the EM maps and a multi-model regression of surface EM, subsurface EM, and soil moisture content. Veracity of the maps was evaluated by correlation between observed soil texture and  $EC_a$ , cross validation using the estimated texture and observed texture at the soil sample points, and a qualitative evaluation by the grower. In several of the fields the cross validation indicated very poor correlation between observed  $EC$  and texture. The grower's evaluation of the soil maps further confirmed that the generated maps were not representative of observed conditions.

Initial analyses indicated that a potential cause of the poor correlation was recent tillage operations. A group of the fields were remapped first by a different contractor and then again by the first contractor. The resulting maps and cross validations are shown in figures 18 – 21. In several of the maps, correlations improved but not to degree that was fully acceptable.

The exact reason for the map's poor quality is still being examined. Some of the potential issues are:

- Sampling design correlated to tillage practices
- Frozen lens below surface ( may cause order of magnitude difference in  $EC$  readings)
- Formation of Silica layer (Becomes primary conductance pathway)
- Paramagnetic soil components (Needle formation from freezing may exacerbate EM readings)
- Micro topography effects (Furrows produce periodic effect)

The soil mapping issues have significant implications for further application of SIS with VRI. If reliable maps of PAW cannot be obtained then VRI's application is limited to spatially static prescriptions per field. An additional issue is the cost of the mapping procedure. Complete mapping and analysis cost several thousand dollars. If an accurate map cannot be determined then the field must be remapped, thus incurring further costs. While an accurate map will be valid for several years, a map is also required to evaluate if VRI is appropriate at a given site. The mapping cost and uncertainty of successful mapping are both issues that will need to be addressed.

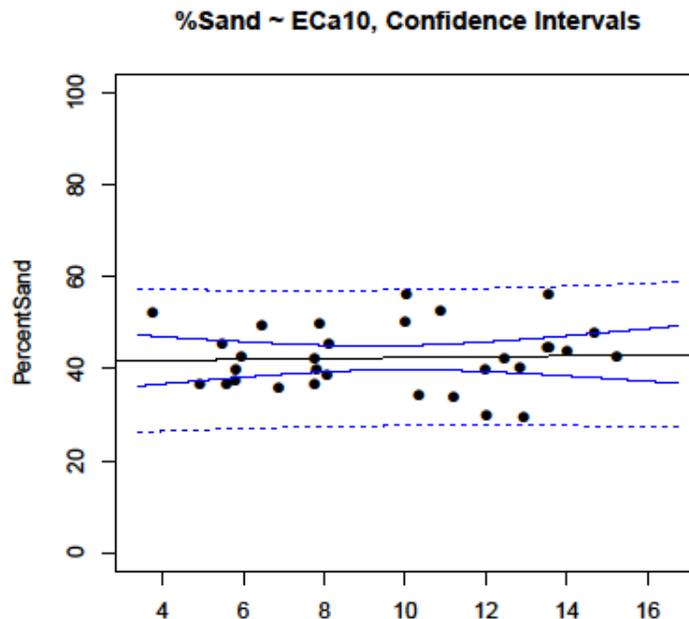


Figure 11 Example of correlation between observed 1m EM reading and measured soil texture. Nearly all the fields at the Washington site had similar levels of correlation.

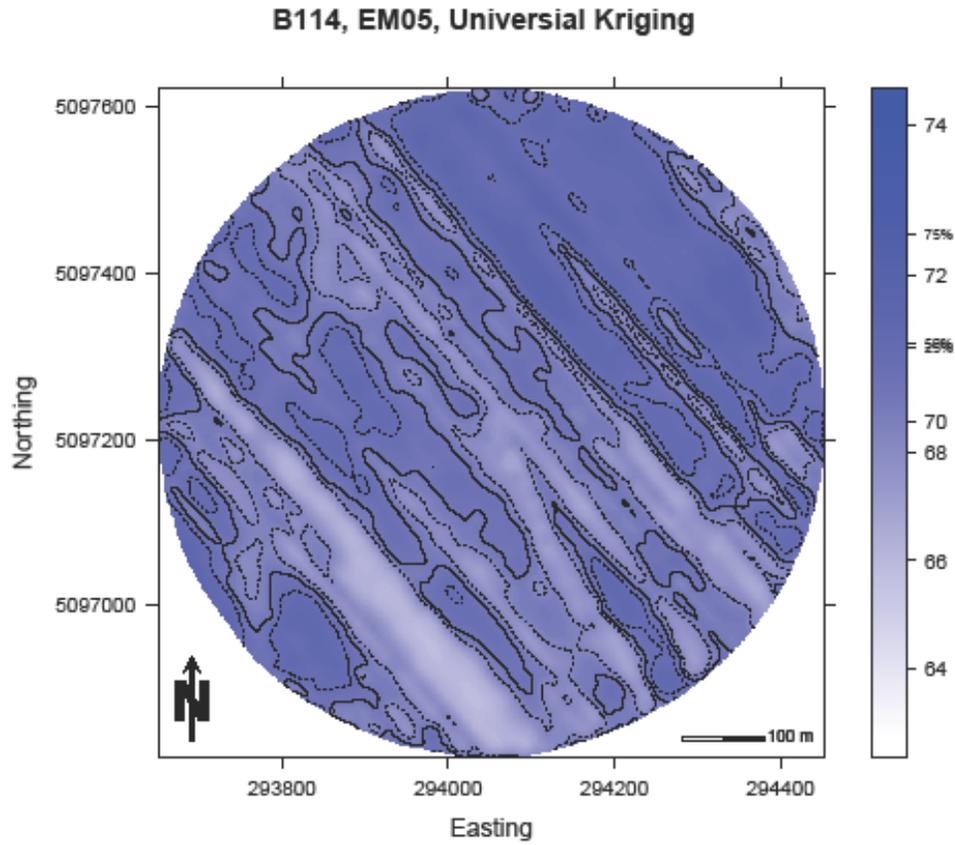


Figure 12 First map of 0.5 meter EM reading on field BF114

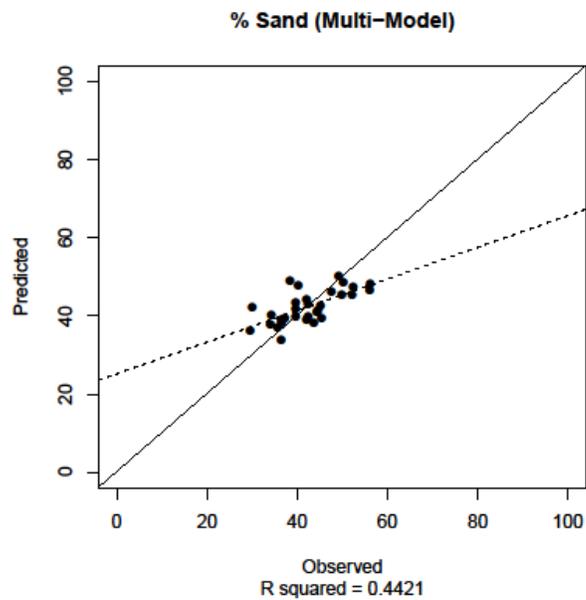


Figure 13 Expected and Observed %Sand derived from first mapping of field BF114. The dashed line is the best fit between observed and predicted.

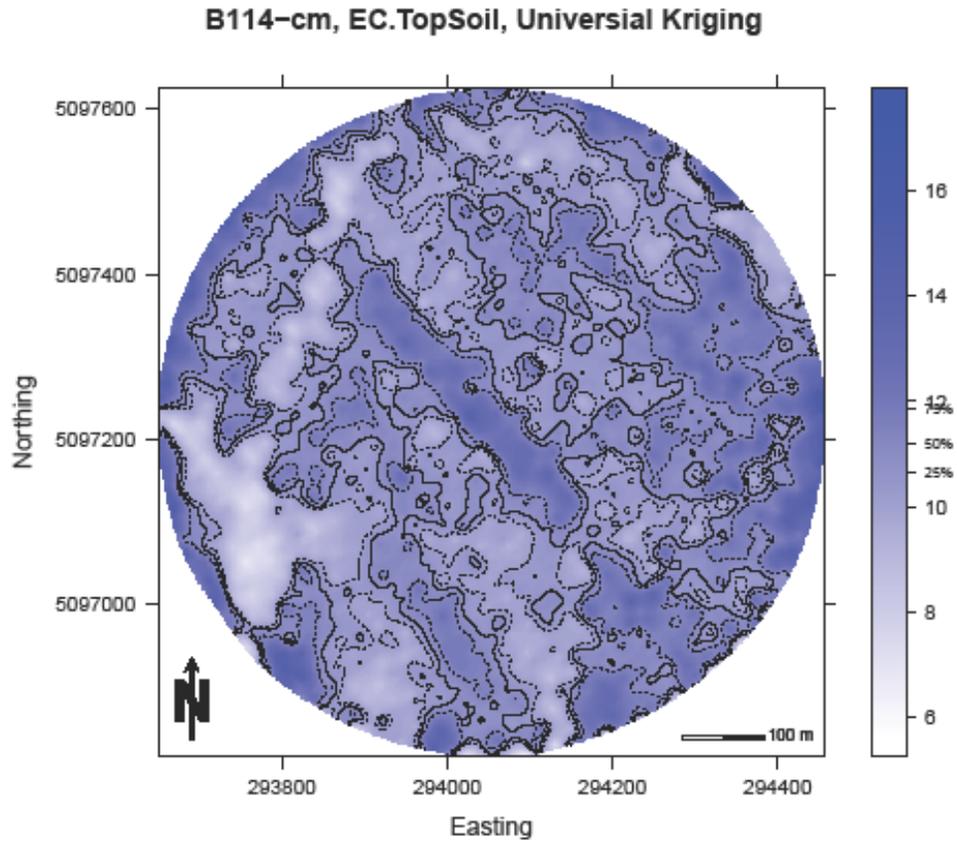


Figure 14 Map of 0.5 m EM readings from second mapping

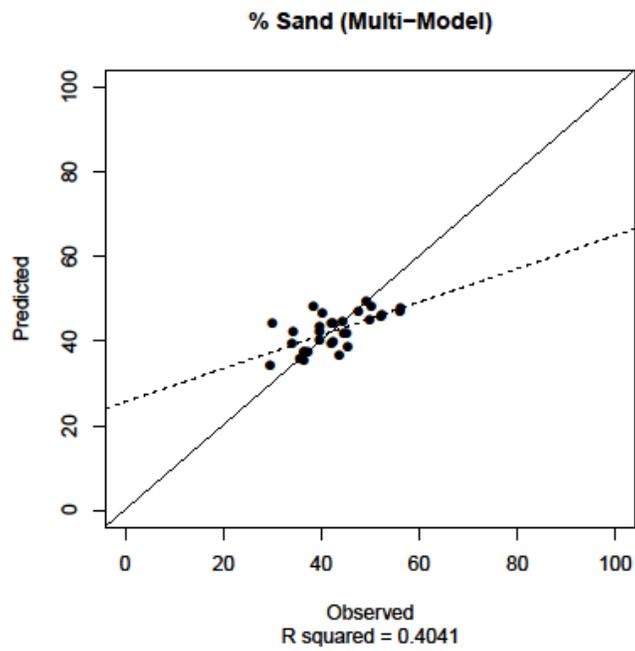


Figure 15 Expected and Observed %Sand derived from the second mapping of BF114

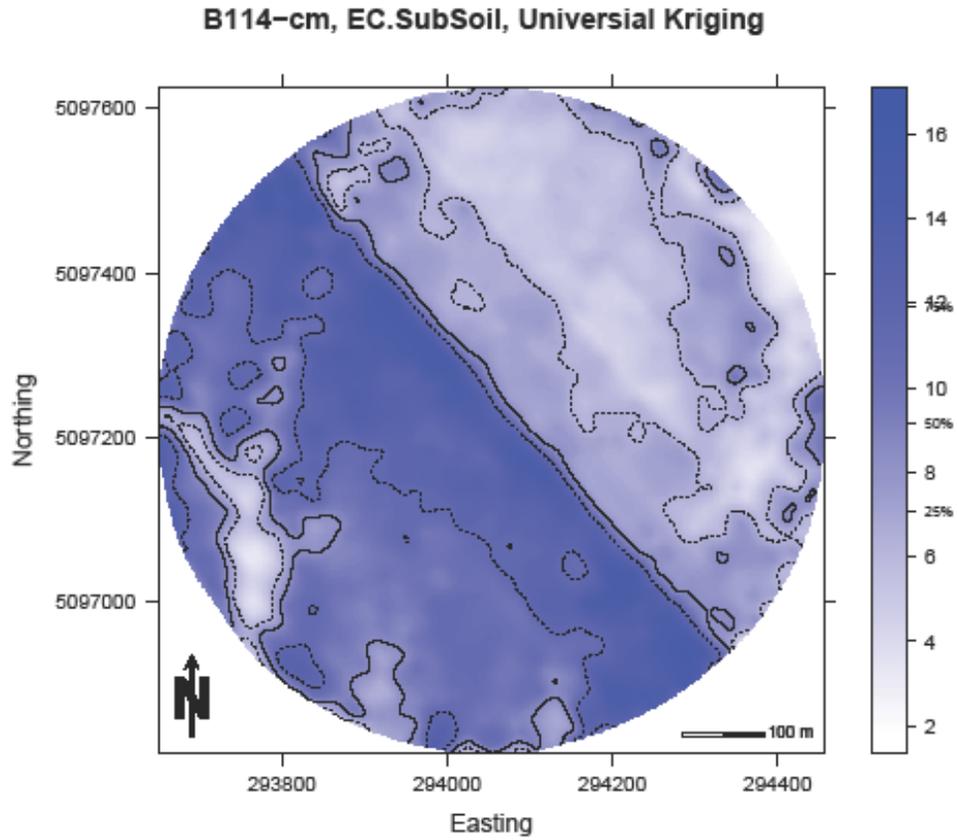


Figure 16 Map 0.5m EM readings from third mapping

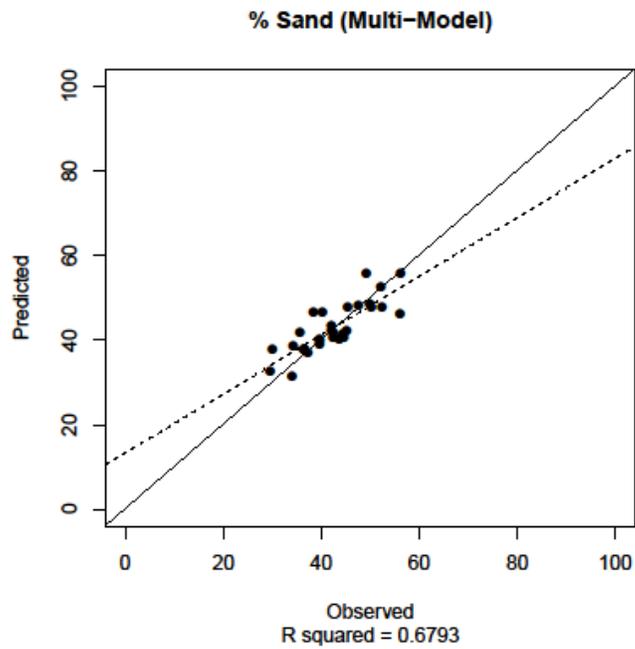


Figure 17 Expected and Observed %Sand derived from third mapping of BF114

## M21 Corn Trail

At the beginning of the 2013 season one of the participating growers had an opportunity to participate in a seed corn trial that required planting several small plots spaced far enough apart to satisfy trial requirements. The trial presented a unique opportunity to employ the VRI to combine one of the fields of Canola (M21) and the corn trail. Without the VRI system the grower would have been required to either over irrigate the Canola crop or plow under large sections of the Canola. By using VRI, the corn could be irrigated entirely separate from the canola and only the test plots were replanted. The plot layout and canola yield map are shown in Figure 18 and Figure 19 respectively.



Figure 18 Planting plan for corn trails in existing canola field

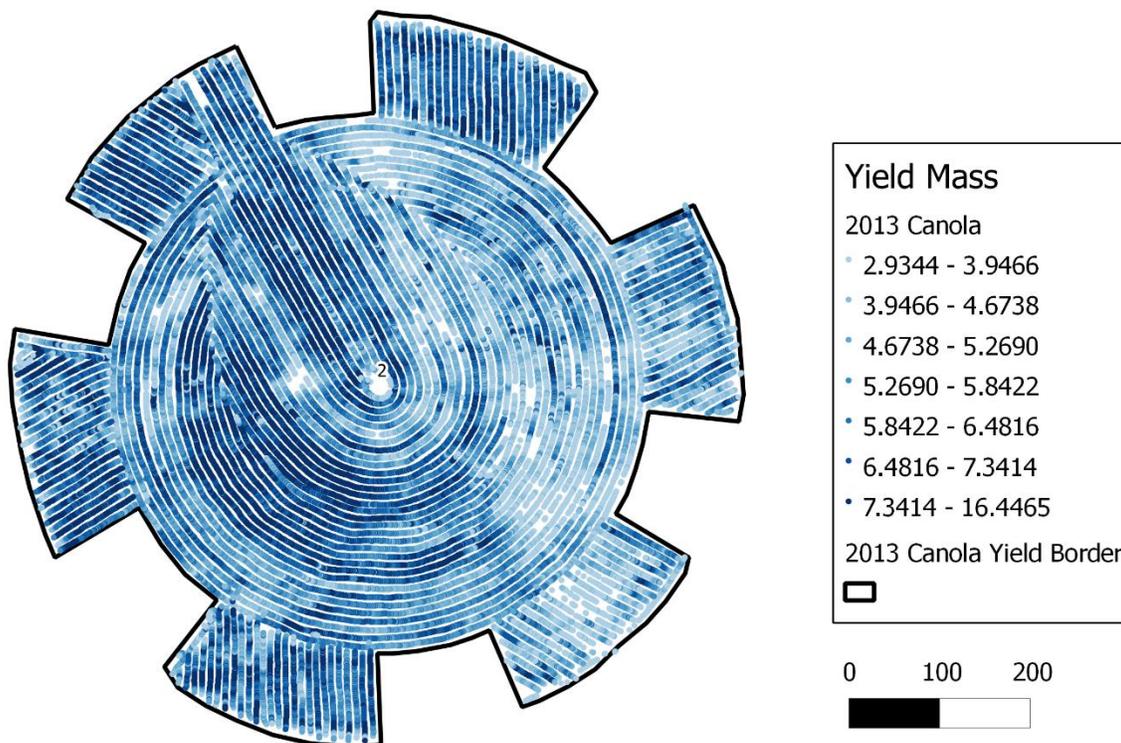


Figure 19 Canola yield map. Missing portions correspond to areas where corn trials were planted

## Field Station Telemetry problems

Field Corn was planted in all but three of the demonstration fields during the 2013 season. As plant height increased all of the in-field telemetry sites began to have signal strength attenuation. Figure 20 shows signal strength reported from three such sites. To restore communications the sites had to be moved or adjusted several times during the irrigation season. In some cases only the antenna needed to be raised, however many of these moves incurred nontrivial costs from labor.

Furthermore, the disruptions produced gaps in the dataset that prohibited reliable calculation of field specific reference ET. Accurate on-farm estimates of reference ET is a significant component of the integrated system. The repeated communication outages effectively reduced the value of the remote telemetry systems by limiting the quantity of data they produced. This issue is crop specific but still has important implications for precision management of irrigation. Without reliable communication the utility of infield instrumentation and telemetry is questionable.

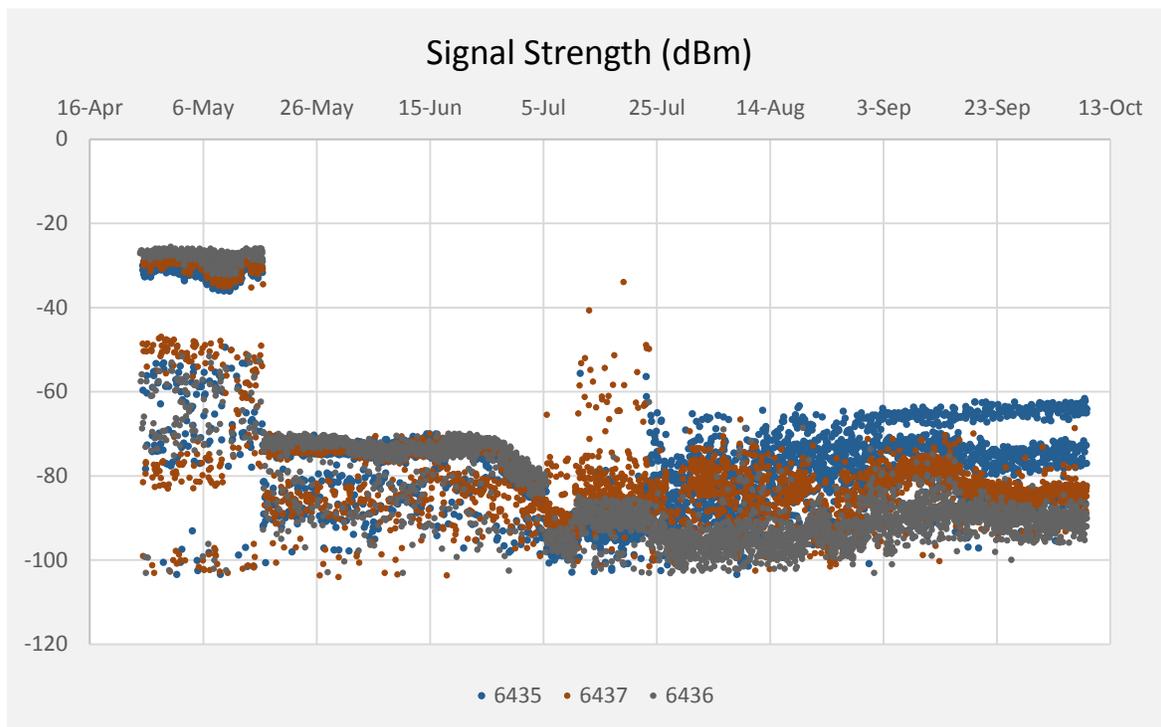


Figure 20 Field station signal strength during 2013 season

## VRI telemetry

VRI systems from two different manufacturer were used during the 2013 season. Since frequent revision of the VRI prescriptions is a critical component of the Integrated System, remote upload of prescriptions was needed. One of the manufacturers had a remote upload system however this system was not compatible with the grower's existing remote management system. The other manufacturer did not have a remote upload solution (that feature was still under development at the time). For the first manufacturer we were able to obtain remote access to the grower's office computer where the pivot control systems were installed. Obtaining this access was tentative because one grower has security and safety concerns regarding uncoordinated operation between the experiment team and the farm personnel. This method of access is not considered an effective long term solution. At the second manufacturer's site a cellular modem was installed to enable remote communication by the experiment team. Finding reliable cellular communication and

configuration of the communication was problematic but ultimately successful. This solution was considered acceptable long-term solution provided that reliable cellular communication is available. Both manufactures indicated that in-house solutions will be available in the future.

## Conclusion

A demonstration of the economic potential of optimal irrigation and variable rate irrigation was conducted on three farms in the Columbia Basin during the 2012 and 2013 irrigation season. This demonstration employed substantial environmental monitoring, integrated decision support systems, and precision irrigation systems. This demonstration is a multi-year effort and the subsequent years are anticipated to utilize a fully integrated management solution. In 2014, there will be additional cooperating farms across the Northwest testing this and other systems.

## References

- Allen, R. 2005. The ASCE standardized reference evapotranspiration equation. Environmental and Water Resources Institute, American Society of Civil Engineers, Reston Va.
- Baulcombe, D. 2010. Reaping Benefits of Crop Research. *SCIENCE* 327(5967): 761.
- Clyma, W. 1996. Irrigation Scheduling Revisited: Historical Evaluation and Reformulation of the Concept. *In* Evapotranspiration and Irrigation Scheduling, Proceedings of the International Conference. American Society of Agricultural Engineers, San Antonio, TX.
- English, M., L. James, and C. Chen. 1990. Deficit Irrigation. II: Observations in Columbia Basin. *J. Irrig. Drain. Eng.* 116(3): 413–426.
- English, M., and G. Nuss. 1982. Designing For Deficit Irrigation. *J. Irrig. Drain. Div.-Asce* 108(2): 91–106.
- English, M.J., and S.N. Raja. 1996. Perspectives on deficit irrigation. *Agric. Water Manag.* 32(1): 1–14.
- English, M.J., K.H. Solomon, and G.J. Hoffman. 2002. A Paradigm Shift in Irrigation Management. *J. Irrig. Drain. Eng.* 128(5): 267–277.
- Evans, R.G., and B.A. King. 2010. Site-Specific Sprinkler Irrigation in a Water Limited Future. *In* 5th National Decennial Irrigation Conference Proceedings. ASABE, St. Joseph, Michigan, Phoenix, Arizona.
- Evans, R.G., J. LaRue, K.C. Stone, and B.A. King. 2012. Adoption of site-specific variable rate sprinkler irrigation systems. *Irrig. Sci.* Available at <http://www.springerlink.com/index/10.1007/s00271-012-0365-x> (verified 8 October 2012).
- Fulton, A., L. Schwankl, K. Lynn, B. Lampinen, J. Edstrom, and T. Prichard. 2011. Using EM and VERIS technology to assess land suitability for orchard and vineyard development. *Irrig. Sci.* 29(6): 497–512.
- Hillyer, C. 2011. Optimal irrigation management : a framework, model, an application for optimizing irrigation when supplies are limited.

- Hillyer, C., M. English, C. Sayde, K. Hutchinson, and J. Busch. 2009. A Web-Based Advisory Service For Optimum Irrigation Management. *In* World Environmental & Water Resources Congress. ASCE, Kansas City, MO.
- Kranz, W.L., R.G. Evans, F.R. Lamm, S.A. O'Shaughnessy, and R.T. Peters. 2012. A REVIEW OF MECHANICAL MOVE SPRINKLER IRRIGATION CONTROL AND AUTOMATION TECHNOLOGIES. *Appl. Eng. Agric.* 28(3): 389–397.
- McCarthy, A.C., N.H. Hancock, and S.R. Raine. 2011. Advanced process control of irrigation: the current state and an analysis to aid future development. *Irrig. Sci.* Available at <http://www.springerlink.com/index/10.1007/s00271-011-0313-1> (verified 10 October 2012).
- Mohan, S., and N. Arumugam. 1997. Expert system applications in irrigation management: an overview. *Comput. Electron. Agric.* 17: 263–280.
- Postel, S.L., G.C. Daily, and P.R. Ehrlich. 1996. Human appropriation of renewable fresh water. *SCIENCE* 271(5250): 785–788.
- Sadler, E.J., R.G. Evans, K.C. Stone, and C.R. Camp. 2005. Opportunities for conservation with precision irrigation. *J. Soil Water Conserv.* 60(6): 371–379.
- Schaible, G., and M. Aillery. 2012. Water conservation in Irrigated agriculture: trends and challenges in the face of emerging demands. *USDA-ERS Econ. Inf. Bull.* (99).
- Smith, R., J. Baillie, A. McCarthy, S. Raine, and C. Baillie. 2010. Review of precision irrigation technologies and their application. National Centre for Engineering in Agriculture.