Energy and Water Savings from Optimal Irrigation Management and Precision Application

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ABSTRACT

With a goal of 20% savings by 2020, the Northwest Energy Efficiency Alliance's (NEEA) *Agriculture Irrigation Energy Efficiency* initiative is focused on increasing grower profitability through lower energy use and reduced costs. The concept – a flexible approach combining optimal irrigation techniques with soil, moisture, and weather data in an integrated, easy-to-use decision support solution – was demonstrated on three farms in Oregon, Washington and Idaho during 2012 as the beginning of a multi-year effort in collaboration with growers, utilities and industry partners.

To accelerate progress, NEEA is collaborating with industry supply base partners to leverage existing technologies. Integration includes soil mapping, variable rate irrigation, on-site evapotranspiration (ET), capacitance and neutron probe soil moisture measurements, optimal irrigation methodologies, flow meters, smart meter energy use monitoring and yield-mapping of results. Information is integrated in a decision support solution; the key is a common software platform with an application programming interface (API) to receive real-time data for irrigation scheduling decisions. NEEA is working with AgGateway, a non-profit consortium of businesses serving the agriculture industry to promote, enable and expand eBusiness, to develop industry-wide data exchange standards. These standards will be submitted for adoption to the American Society of Agricultural and Biological Engineers (ASABE) and presented at November 2013 Irrigation Association conference. Also included is a data analysis engine able to recommend optimum irrigation for maximum profit, and a simulation program to test different scenarios and plans.

Results from 2012 included: manual solution integration; identification of barriers to the automated system; documentation of equipment limitations and requirements; development of yield-specific calibration requirements; informal validation of water savings; and demonstration of optimal irrigation techniques versus overwatering. With increased demonstrations, 2013 will test the automatic solution and continue collaboration with vendor partners.

Introduction

The demand for fresh water is projected to exceed renewable supplies by 2025 (Postel et al., 1996). The world demand for food is swelling 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 not only common but even standard operating conditions. This leads to the obvious conclusion that 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. These tools will be driven by technologies for environmental monitoring, operational monitoring, and precision irrigation. The complexity of such optimal irrigation advisory tools will require a development foundation that facilitates integration of technologies and information from a variety of sources. However, adoption of these technologies will, as with any new technology, be limited by its economic viability. The object of the project described here is to demonstrate the economic potential of optimal irrigation in general and variable rate irrigation in particular.

The demonstration project will achieve the following:

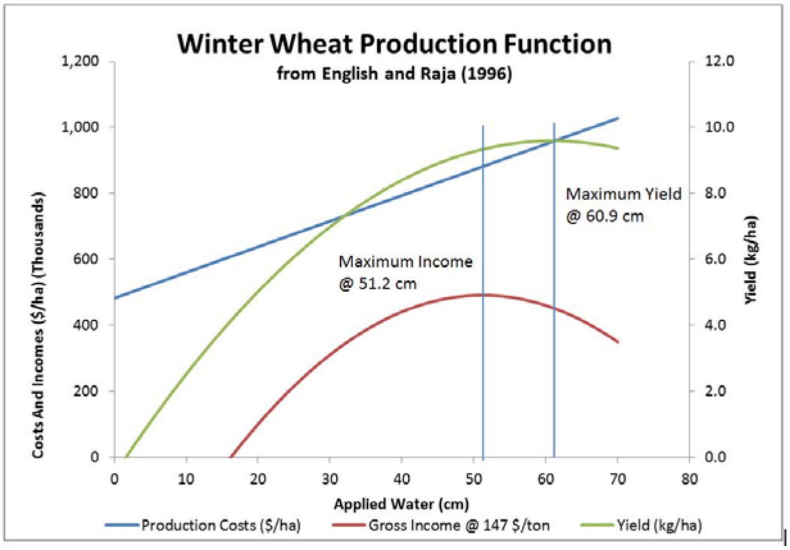
1. Demonstrate savings in water and energy associated with optimal, variable rate irrigation.
2. Determine the cost-effectiveness of current irrigation technologies by balancing the capital investment against financial gains from energy and water savings.
3. Determine the relative value of each data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

Optimal Irrigation

Economically optimum irrigation management is fundamentally different, and more difficult, than conventional irrigation. Economically optimal irrigation implies some level of deficit irrigation (English et al., 1990), (English and Raja, 1996),(English and Nuss, 1982). 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 complexity is increased by the fact that fields are not managed in isolation; the entire farm is considered when allocating water supplies. Accounting for these factors will require: (i) explicitly characterizing field heterogeneity, the uniformity of applied water; (ii) modeling the disposition of applied water; (iii) estimating crop yields under variable water stress conditions; and (iv) quantifying the marginal costs of crop production (largely energy costs in the case of the farms that will be the focus of this project). 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.

Figure 1. A Production Function Developed for Winter Wheat at Hermiston, Oregon. The Maximum Income Occurs When the Water Application is 16% Less Than 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.



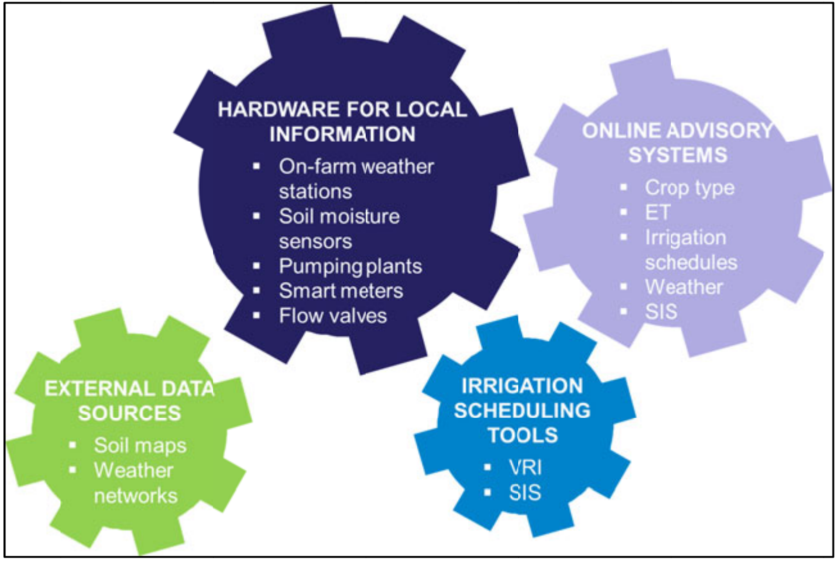
In this initiative, NEEA, working in collaboration with Oregon State University (OSU), uses an OSU-developed system known as Irrigation Management Online (IMO). Instead of building a simulation of the whole (or nearly whole) farm enterprise, IMO takes a different approach. The central thesis of IMO is 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 irrigation management. 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. The need for combining irrigation tools with crop growth models has been emphasized in the past (Wolfe, 1990) and continues to be emphasized more recently (Woodward et al., 2008). The cost of developing the yield response functions that are needed for optimal management is a limiting factor, however variable rate technology does make this more feasible (Bullock et al., 2009).

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.

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 visibly bad areas of yield response 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 bad areas in a field.

To test this theory the IMO system will manage two fields (with the same crop) at the same. One of the fields will be managed with a VRI system and the other with a uniform system. After harvest the shape of the statistical distribution of yield (rather than the overall magnitude) will be compared between the two fields. This comparison will be replicated at each of the demonstration sites. If the shape of the distribution produced by the VRI system is significantly less correlated to the limiting soil physical properties, it may be possible to show that the VRI system has produced more uniform yields relative to a non-VRI system. This yield normalizing feature could enhance the economic viability of VRI and improve the qualitative performance in the form of better looking fields.

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 season is shown in

.

The following components were installed or conduced at each farm:

- **Variable Rate Irrigation:** At each site, one pivot was retrofitted with a Valley Variable Rate Irrigation System (Valmont Industries, Inc.) and the panels were upgraded where necessary. The system was installed with 30 sprinkler banks. Valmont engineers supervising the installation selected the bank locations. Two of the farms were using re-use water (one from a potato processing plant, the other from animal waste). Because of concerns about potential valve clogging, these two sites were equipped with pneumatic valves rather than the typical hydraulically actuated valves.
- **Soil Mapping:** High-resolution soil maps were produced by a soil mapping service (Soil and Topography Information, Inc.) using a combination of electromagnetic sensing and physical soil sampling. The soils data was used to produce data layers for several soil properties including holding capacity, field capacity, and root zone restriction depth.
- **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 (Automata, Inc.) with the sensors required to calculate reference ET. Additionally, each field had secondary a 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).
- **Soil Moisture Monitoring**: Each field was equipped with two neutron probe tubes and readings were taken on a weekly basis. In the fields where soil mapping occurred, the tubes were sited such that the tubes were approximately in the upper and lower quartiles of the Plant Available Water. In two fields at each farm, two types of capacitance probes were also installed (AquaCheck and Decagon 10HS). These probes were connected to the weather stations to take advantage of their telemetry 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 the end of each season wherever possible (technical issues limited the collection of yield maps during the 2012 season). These data will be used to compare the spatial variability expected from the yield model. In the alfalfa fields, infrared photographs were used and alfalfa yield distributions were estimated using the methods described by (Mitchell et al., 1990; Pinter et al., 2003; Hancock and Dougherty, 2007).

Table 1. Summary of Demonstration Sites

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

To facilitate comparison of various combinations of technologies, the fields were, and will continue to be, 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.

Preliminary Results

All of the instrumentation was installed during the spring of 2012. Although a series of logistical issues and technical problems prevented the full implementation that was originally planned irrigation scheduling, there was significant relevant progress towards the goal of a robust demonstration.

- The logistical and technical issues highlighted several "bottlenecks" to data integration and have informed the development on the API.
- A majority of the environmental monitoring instrumentation was installed and operational for a significant portion of the irrigation season. These data enabled a robust calibration of the IMO system. A soil moisture graph, produced by IMO, is shown in Figure 3. The black squares are neutron probe measurements taken during the latter half of the irrigation season.
- The localized yield models were constructed for winter wheat and alfalfa.
- A "catch can" test was conducted at one of the VRI sites.
- An informal demonstration of deficit irrigation was conducted.

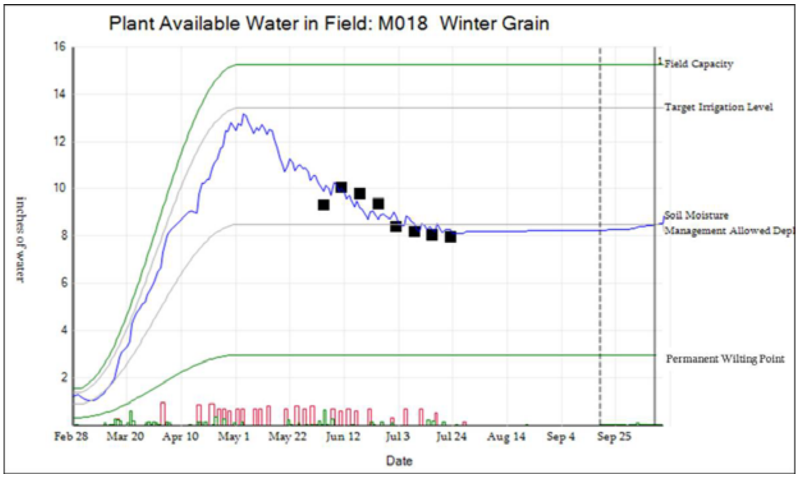
Data Bottlenecks

One of the goals of this project is to demonstrate the value of having a fully automated system where data inputs are assimilated and VRI prescriptions are delivered without effort by the user. At present, there is no acceptable method to load VRI prescriptions without human intervention. This was considered a significant roadblock and will be actively addressed prior to the start of the 2013 season. A secondary roadblock was the lack of automated methods for extracting the pivot's operational history. These data are critical to accounting for how much water has been used. Each of the manufacturers has a proprietary method to extract this information but no uniform reporting mechanisms are available. This issue will also be addressed prior to the 2013 season.

Calibration

The IMO model has been shown to accurately simulate the soil moisture status in a given field. The accuracy is predicated on a robust calibration derived from soil moisture measurements collected during the season. The measurements collected during the 2012 irrigation season facilitated calibration of the IMO model.

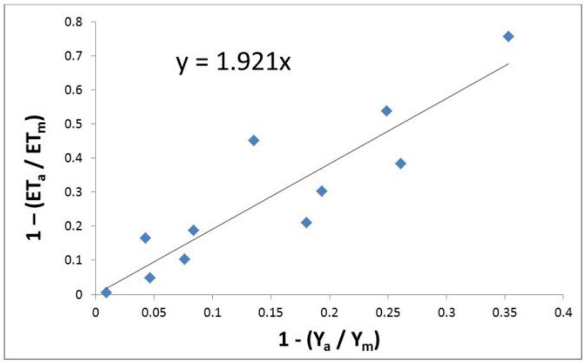
Figure 3. Trace of Estimated Soil Moisture Produced by Integrating Soil Moisture Measurements, Weather Data, and Water Use Records



Yield Model Calibration

Yield modeling is an essential component of optimal irrigation. In order to accurately estimate yield consequences an on-site calibration of the FAO33 model was developed. Historical wheat yields were collected from the cooperating producers and these data were used to estimate the FAO33 parameter k_y. Results of this calibration are show in Figure 4. Developing the calibration was complicated by the yields obtained during the 2012 season. The highest yields that are typically observed at the study site are approximately 120 bu/ac. This maximum yield value is a critical component of the FAO33 model because it defines the upper boundary for yield estimates. During 2012, the cooperator obtained 150 bu/ac, the highest yield ever. This yield required significant revision of the FAO33 parameters.

Figure 4. Yield Model Calibration Results



Yield modeling is an essential component of optimal irrigation. In order to accurately estimate yield consequences an on-site calibration of the FAO33 model (Doorenbos, 1979) was developed. Historical wheat yields were collected from the cooperating producers and these data were used to estimate the FAO33 parameter ky. The ky parameter relates the relative yield reduction to the relative reduction in ET and is the slope of the line shown in Figure 4. Results of this calibration are show in Figure 4. Developing the calibration was complicated by the yields obtained during the 2012 season. The highest yields that are typically observed at the study site are approximately 120 bu/ac. This maximum yield value is a critical component of the FAO33 model because it defines the upper boundary for yield estimates. During 2012, the cooperator obtained 150 bu/ac, the highest yield ever. This yield required significant revision of the FAO33 parameters.

Catch Can Testing

To evaluate the spatial precision of the VRI system a large catch can test was conducted at one of the cooperating farms. This test involved nearly 500 buckets arranged in a dual grid pattern. The grid spanned three management zones in the angular direction and spanned all but two spans in the radial direction. A "checker board" prescription map was loaded with high/low rates set to 30%/70% of nominal application depth. The prescription was chosen because it would be isotropic, alleviating wind direction effects. Two tests were conducted after harvest when the field was bare. The first test occurred during the daytime when wind speeds never exceeded 4.7 m/s. The second test occurred during the night when wind speeds where essentially 0 m/s.

Figure 5. Catch Can Bucket Layout

The results of the test were surprising as the expected pattern of water application was not observed. The reasons for this discrepancy are still being investigated. Two potential explanations are: 1) wind drift distorted the application pattern; and/or 2) the management zone sizes were small relative to the sprinkler overlap. The sprinklers installed on this system used serrated spray plates which are known to have wind drift problems. Both of these issues will be investigated during a second catch can trial scheduled for the 2013 season.

Deficit Irrigation Demonstration

Deficit irrigation's potential for water savings was demonstrated at one of the cooperating farms. One of the participating growers was skeptical that deficit irrigation would produce the expected water reductions without significant yield loss. Because no variable rate irrigation was conducted during the 2012 season, there was an opportunity to demonstrate deficit irrigation during the end of the season. This demonstration was only possible because of the VRI system. Using a specially designed prescription, five different deficit levels (with two replications) were applied but only on a small portion of the field. The small treatment area meant that very little of the field was jeopardized, alleviating of the grower's trepidation about experimenting with deficit irrigation.

The experimental layout is shown in Figure 6 and the yield results are shown in Figure 7. The results indicate that a 20% reduction of applied water would produce negligible reduction of yield. The two replications also confirmed suspicion that the north side of that field tended to perform better than the south. This north-south relationship was not directly obvious from visual inspection of the field but was likely caused by a combination of wind effects. The wind-induced yield differential effect will be investigated further during 2013 using a pair of Eddy Covariance systems.

Figure 6. Deficit Irrigation Plot Layout

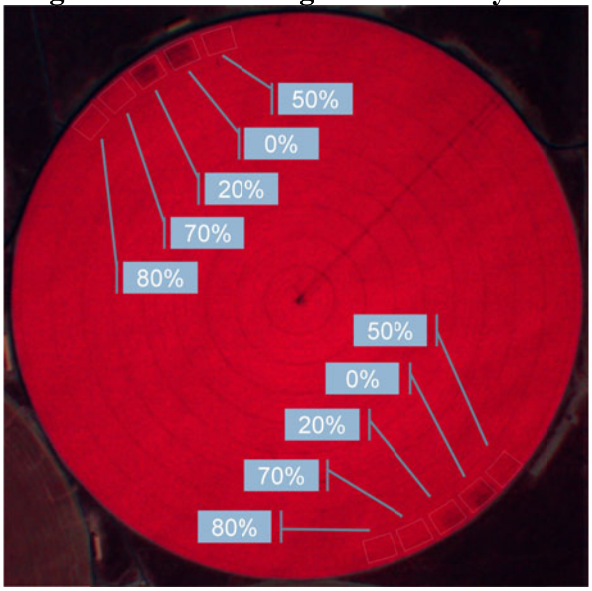
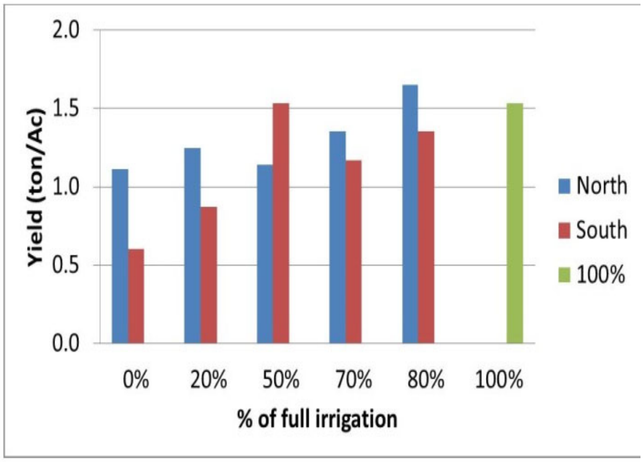


Figure 7. Deficit Irrigation Trial Results



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 irrigation season. This demonstration employed substantial environmental monitoring, and was integrated into a decision support system that generated irrigation recommendations. This demonstration is a multi-year effort and the subsequent years are anticipated to utilize a fully integrated management solution. In 2013, there will be additional cooperating farms across the Northwest testing this and other systems.

One limited test of deficit irrigation suggests that a 20% (perhaps even 50%) reduction in applied water produces negligible reductions in crop yield. This preliminary observation suggests the potential for substantial opportunities in irrigation optimization and water conservation across the region and beyond.

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