CREATING PRESCRIPTION VARIABLE RATE IRRIGATION AND FERTILIZATION ZONES: WATER AND NUTRIENT MANAGEMENT INTERACTIONS

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ABSTRACT

Variable rate irrigation (VRI) and variable rate fertilization (VRF) technologies allow irrigation and fertilization rates to be spatially customized. VRF is widely adopted, but VRI is an emerging technology with minimal adoption. As water is often the driving force in nutrient cycling, our overall objectives are to evaluate VRI influences on VRF and vice versa; and to combine these technologies to significantly increase crop yield and quality, conserve water, and minimize environmental impacts from fertilization. Phase One of this study occurred in 2016 with a characterization of the VRI system in a 46-acre (19-ha) portion of a field near Grace, ID, USA split into three zones (0% of full rate, 90%, and 100%) used to grow winter wheat (*Triticum* spp.). VRI zones were determined by the grower based on field knowledge. Average yields for the VRI zones were 122 and 116 bu ac^{-1} (8.2 and 7.8 Mg ha^{-1}) for the 90 and 100% VRI zones, respectively. The crop water productivity (CWP) map layer was based on a water balance made by measuring seasonal precipitation, irrigation, and pre- and post-season soil moisture at 80 sampling locations in the field to a depth of 3 feet (1.2 m) in 1-foot (0.31 m) increments. The CWP map reflects the crop efficiency of converting water use into yield. The CWP ranged from 1.5 – 9.4 bu $acre^{-1}$ $inch^{-1}$ (0.40 – 2.5 kg m^{-3}) with an average of 6.3 bu $acre^{-1}$ $inch^{-1}$ (1.7 kg m^{-3}). Irrigation zone averages for CWP were 6.8 and 6.3 bu $acre^{-1}$ $inch^{-1}$ (1.8 and 1.7 kg m^{-3}) for the 90 and 100% irrigation zones, respectively. This analysis allows an evaluation of the current water management and evaluate locations in the field where factors, other than water, limited yield; as well as areas that may need more water. There was a strong correlation between the CWP and the historic yield maps. Adjustments for the 2017 VRI maps were determined based on the CWP and historic yield maps. Fertilizer rates were uniform across the field for 2016 but VRF zones were developed for Phase two in 2017 based on the field prescription results shown herein. The prescription was based on spatial analysis of yield history and soil nutrient and CWP maps. It is reasonable to assume based on the spatially variable CWP and yield history maps, that some nutrients were over applied at low yield locations and under applied at high yielding areas. This will be addressed using the field prescription in 2017. The VRF map for 2017 is spatially variable—with rates ranging from 0 to 180% of average nutrient applied. The VRF and VRI data for Phase Two are presented here as proposed methodology and, no doubt, will require further refining. These prescriptions will be evaluated in 2017 and further refined in subsequent years.

INTRODUCTION

To produce profitable yields, crops require fertilizer nutrients and in semi-arid regions, such as the western United States, irrigation water is crucial for crop production (Khan et al. 2006). Irrigation and fertilization needs vary per environmental and soil conditions—with excesses or deficiencies often resulting in negative impacts for yield and crop quality. Furthermore, these inputs can result in negative environmental impacts, especially when irrigation water and N and P fertilizers are applied in excess. With increasing water scarcity and degrading water/air quality comes a need for improvement in irrigation and nutrient management practices.

Conventional management practices are applications of uniform rates of irrigation and fertilization regardless of field topography or natural soil variability. Due to spatial variability within fields, uniform applications result in excesses and deficiencies as a function of variation in yield potential and soil storage capacities. Variable rate irrigation (VRI) and variable rate fertilization (VRF) allow specific irrigation and fertilization rates to be spatially customized. VRF is widely adopted, but VRI is an emerging technology with minimal adoption. Each of these technologies rely on the development of management zones with unique application rate requirements.

Measuring spatially variable soil properties and, historic yield history are common methods of developing VRF zones (Khosla et al. 2008). Although VRF has been studied intensively, the most effective ways of developing VRI zones has not. We propose that VRI would take a similar approach and that VRI and VRF have interacting effects which should be accounted for to maximize crop production. VRF zones are established through intensive soil nutrient analysis. Somewhat similarly, we suggest that a possibly superior method of establishing VRI zones is to evaluate yield produced per unit of applied water or crop water productivity (CWP). CWP analysis has been used in various cropping systems, but has not been used in a VRI system. A spatial analysis of CWP determines the efficiency of a crop converting water use into yield--giving insight into areas where water was over or under applied with associated insight of where the yield was or was not limited by water. As yield is related to nutrient use, the interacting effects are also important to consider in tandem.

We are at the forefront of learning to use these technologies together and do not present the findings thus far as any sort of conclusion, but rather as a first attempt at doing so. The objectives of this study were to: Phase One – determine water management zones through CWP analysis in 2016 and a yield history over the 2013 to 2016 seasons under uniform fertilization and Phase Two – develop VRF and refined VRI zones based on CWP, yield history, and soil chemistry analysis for use in 2017.

MATERIALS AND METHODS

The study site location is near Grace ID, USA (42.607634, -111.788568) elevation 5535 feet (1687 m) above sea level. A variable rate center pivot (Growsmart ® Lindsey Precision VRI, Omaha, NE, USA) was installed in a 112 acre (45 ha) field in 2015. Approximately half of the field (46 acres or 19 ha) was planted to wheat (*Triticum* spp.) in 2016. Variograms, models of spatial variation needed for kriging, were developed for the geostatistical estimation process. To obtain reliable variograms to characterize the spatial variation in soil properties, a total of 80 cores (Webster and Oliver, 1993) were collected with 46 of the sampling locations aligned on a grid every 230 feet (70 m) and the remaining 34 samples collected at random points to allow more reliable variogram estimation at short lag distances (Webster and Oliver, 2007). The location of sample points are shown in Figs. 1 and 2. On April 20-21, at wheat green-up, and again on August 17-18, after harvest, soil cores were taken at these field locations to a depth of four feet (1.2 m) in one foot (0.31 m) increments—as soil conditions allowed (shallow bedrock inhibited taking the lowest depth at many sampling locations). Soil moisture was determined gravimetrically for each sample by drying at 150 ^{o}F (65 ^{o}C). Bulk density was measured gravimetrically from the spring soil samples and then used to calculate the volumetric soil water content. The CWP for 2016 was estimated by calculating yield over seasonal evapotranspiration

$$CWP = Y \,/\, ET$$

where ET was calculated using a seasonal water balance:

$$ET = P + I + \Delta S - RO - D$$

where ET is the amount of total water use during the growing period, P is precipitation, I is irrigation, ΔS is change in soil water content from spring to harvest, RO is runoff, and D is drainage from the root zone. Runoff and drainage were considered negligible as the field is mostly level (average slope < 3%) and there were no large rain events to create runoff or drainage out of the root zone during the study period. Change in soil water content was calculated by subtracting volumetric water content at spring green up from that at the post-harvest sampling time and then summed across depths for total ΔS at each sample site.

Yields were spatially collected with a commercial New Holland combine equipped with an IntelliView 4 yield monitor (CNH Industrial, Turin, Italy). Soil management zones were determined by evaluation of the CWP and yield maps, topography, aerial visual bare soil imagery, and grower experience (data not shown). Residual soil from the August soil moisture sampling of the surface layer was analyzed for soil nutrient analysis using standard methods (BYU Environmental Analytical Laboratory, Provo, UT, USA; http://eal.byu.edu/).

Values of key variables were interpolated in between sampling points using ordinary kriging in ArcMap's Geostatistical Analyst [Environmental Systems Research Institute (ESRI) 2011, ArcGIS desktop: Release 10, Redlands, CA, USA] and used to determine the 2017 VRI and VRF maps.

RESULTS AND DISCUSSION

Change in Soil Moisture (Δ*S*)

Change in seasonal soil moisture from spring until harvest is represented in Fig. 1. The removed soil moisture for the season ranged from 5.5-7.9 inches (0.14-0.20 m) demonstrating the spatial variation of soil moisture. As confirmed by the grower, zones with the most water removal were located where snowpack melted the latest in the spring, suggesting spring soil moisture is driving the spatial variability of this layer. The areas of lowest water removal are near field edges and areas of 'rock piles' covered in native vegetation. The absence of crops and low yields are responsible for the limited change in soil moisture for these areas.

There appears to be little similarity when comparing the change in soil moisture layer to the season's yield. The absence of an apparent correlation suggests, that in this instance, the change of soil moisture map is limited in predicting seasonal yield. Many factors influence yield outside of soil moisture, which may be the reason for the limited predictability of this layer. While this map is limited in yield prediction, it is a vital part of the CWP layer calculations and should be included when creating VRI management zones. Identifying zones with the most water demand and availability will influence management decisions.

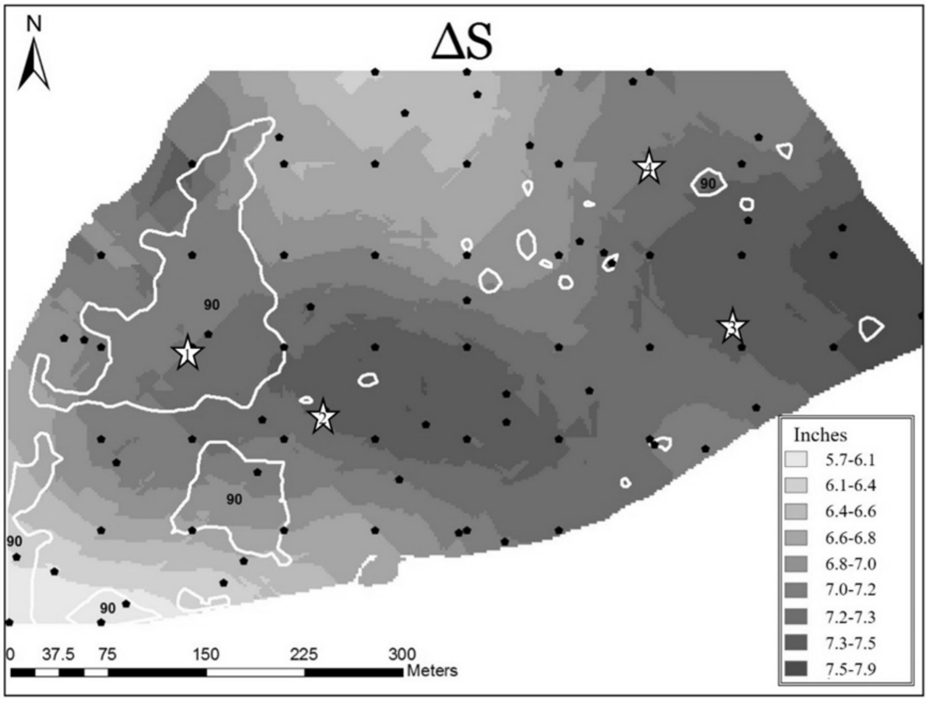

Figure 1: Interpolated map of Delta S, change in soil moisture from wheat green up to harvest, with grower designed VRI 90% zones outlined in white. Numbered stars are used as sample management areas as discussed relative to Table 1.

Crop Water Productivity (CWP)

Spatial analysis of CWP gives insight into areas which most efficiently converted used water to grain yield, with relatively high values equivalent to a high yield per unit of water applied (Fig. 2). The CWP ranged from 1.5 – 9.4 bu acre^{-1} inch^{-1} (0.40 – 2.5 kg m^{-3}) with an average of 6.3 bu acre^{-1} inch^{-1} (1.7 kg m^{-3}). Irrigation zone averages for CWP were 6.8 and 6.3 bu acre^{-1} inch^{-1} (1.8 and 1.7 kg m^{-3}) for the 90 and 100% irrigation zones, respectively. The lowest CWP are located at field edges and near non-planted ‘rock pile’ areas (top middle of Fig. 2) and, as such are likely artifacts of border edge effects.

The most striking low CWP area, which appears to divide the field just off center to the west in a line north to south (in line with the #2 star), is the location of an eroded ridge. This ridge may influence the high CWP to the west at the base of the ridge (area around the #1 star) due to an accumulation of relatively high water holding capacity top soil and/or water accumulation from subsurface movement from the ridge above. The grower, previously aware of this effect, intentionally reduced the irrigation in this area to be one of the 90% irrigation zones.

Another main area of high CWP is found in the south central portion of the field to the east of the ridgeline. This high CWP largely follows the wheel track of the center pivot and is due, at least in part, to extra water that was not used in the CWP calculations. This water came from a leak in the irrigation system at the second pivot joint and had a surprisingly large impact on the CWP. Moderate CWP areas are found in many locations, including the #3 and #4 stars (Fig. 2).

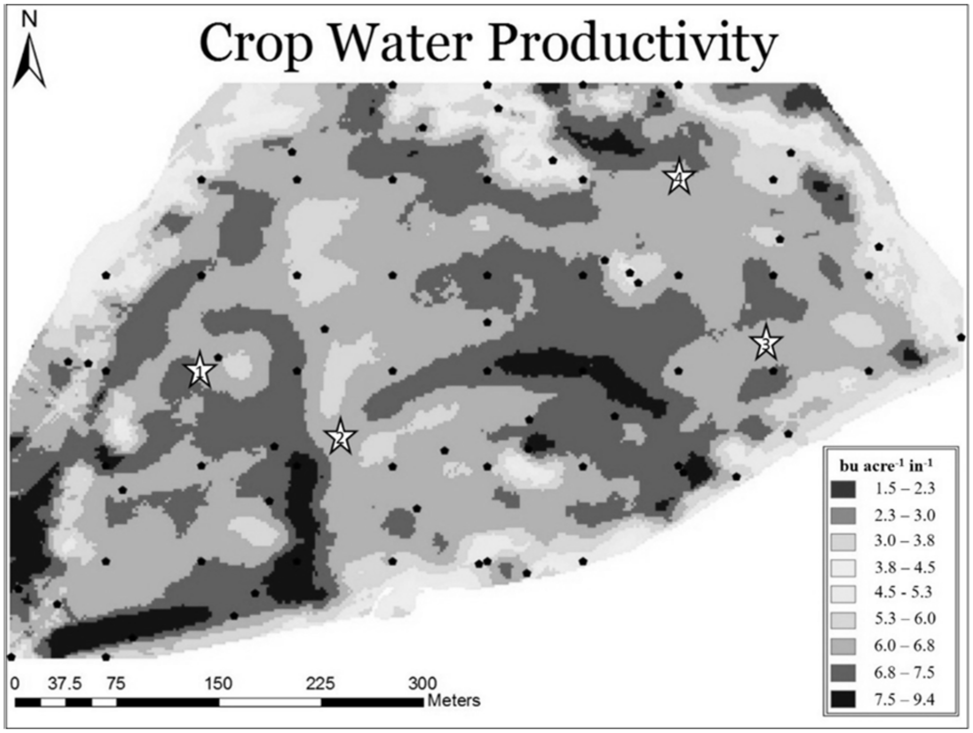

Figure 2: Interpolated map of the 2016 season crop water productivity (CWP). Numbered stars are proposed management areas as identified by Table 1.

Historic Yield

The compiled historic yields are shown in Fig. 3. One of the most interesting findings of this work is the apparent strong correlation between the CWP (Fig. 2) and the historic yield maps (Fig. 3). This would suggest that, on average, water is the limiting factor in the areas with relatively lower yields. For example, above average yields follow the leaky second pivot track in the south-center of the field. One would suppose that if the leak was not present that both yield and CWP would be lower. Also, we hypothesize that the above average yields and high CWP at the western edge of the field is likely related to irrigation overlap from a neighboring field—with the effect much larger than originally supposed. Furthermore, there is a distinct line of high yield and CWP on the west side of the field parallel to the southern boundary—where we hypothesize that the effect is due to irrigation system drainage. This is the area where the pivot system is typically stopped at the end of an irrigation cycle—with extra water being deposited into the soil as the center pivot pipes drain. In all three of these cases, the CWP map is not accurate due to non-measured water inputs, but all three result in higher historical yields—with the impact much larger than predicted. These give evidence that the field is somewhat water limited from year to year, as the yield responds positively from the supplementary water.

It is also possible a similar effect explains the relatively high yields in the zone downslope and to the west of the ridgeline—that is to say that subsurface water movement resulted in this area being more productive. However, the effect is also likely due to, at least partially, the fact that this soil has an accumulation of nutrient rich, high water hold capacity topsoil.

The ridgeline zone, despite having the full 100% irrigation, yielded poorly AND had low CWP. Two scenarios are possible. First, the water applied did not stay resident in the soil, but rather moved downslope. If so, the question is whether or not this ridgeline should receive an amount greater than 100%, which will be evaluated in 2017. Second, this area has shallow soil with relatively poor fertility. As such, it is possible that water was not the limiting factor in this zone, but rather nutrition and/or soil depth. If nutrition is the limiting factor, can VRF increase the yield and CWP in this zone? However, it is also possible that the soil depth and quality has degraded to the point that this area is just not productive and the inputs, including water and/or fertilizer need to be reduced in increase the CWP and similar for nutrients. There other zones of interest as well—with a need to develop similar test questions for each.

Creating 2017 VRI and VRF Zones

With regard to VRI, there are four generic scenarios (Table 1).

Table 1. Four generic Variable Rate Irrigation (VRI) zones based on historic yields (Yield Category) and 2016 Crop Water Productivity (CWP). The VRI rate for the majority of the zone will be adjusted as noted in the "VRI Rate" column. However, Test Strips within these zones will also be included for scientific evaluation.

	Yield History	CWP	VRI Rate	Test Strip VRI Rate	Explanations
1	Low	Low	<90%	100%	Low yields and low water efficiency. The low yields are probably due to a factor other than water
2	Low	High	>100%	100%	Low yields possibly due to water and/or other factors being limiting. Investigate nutrients and other possible limitations.
3	High	Low	100%	<90%	High yields, but poor water efficiency. Would reducing water also reduce yields?
4	High	High	100%	>100%	High yields with good water efficiency, but could yields be pushed higher with more water?

Due to the sheer volume of data, we aren't able to fully represent each unique area of this field in terms of proposed VRI and VRF maps. Rather, we selected four representative points for demonstration and only show N and P values (Table 2).

At field site 1, this is one of the most productive areas of the field in terms of both yield potential and CWP. The slope is moderate and the soil is relatively deep with higher organic matter (OM) and soil test P. We suspect, based on preliminary trials, that the yields could be pushed even higher with increases in both N and H_2O. The area is large enough that a strip trial can be inserted in this field to test these hypotheses alone and combined. However, our data would also strongly support not applying any P fertilizer to the grain in 2017 due to the very high soil test P values (data not shown).

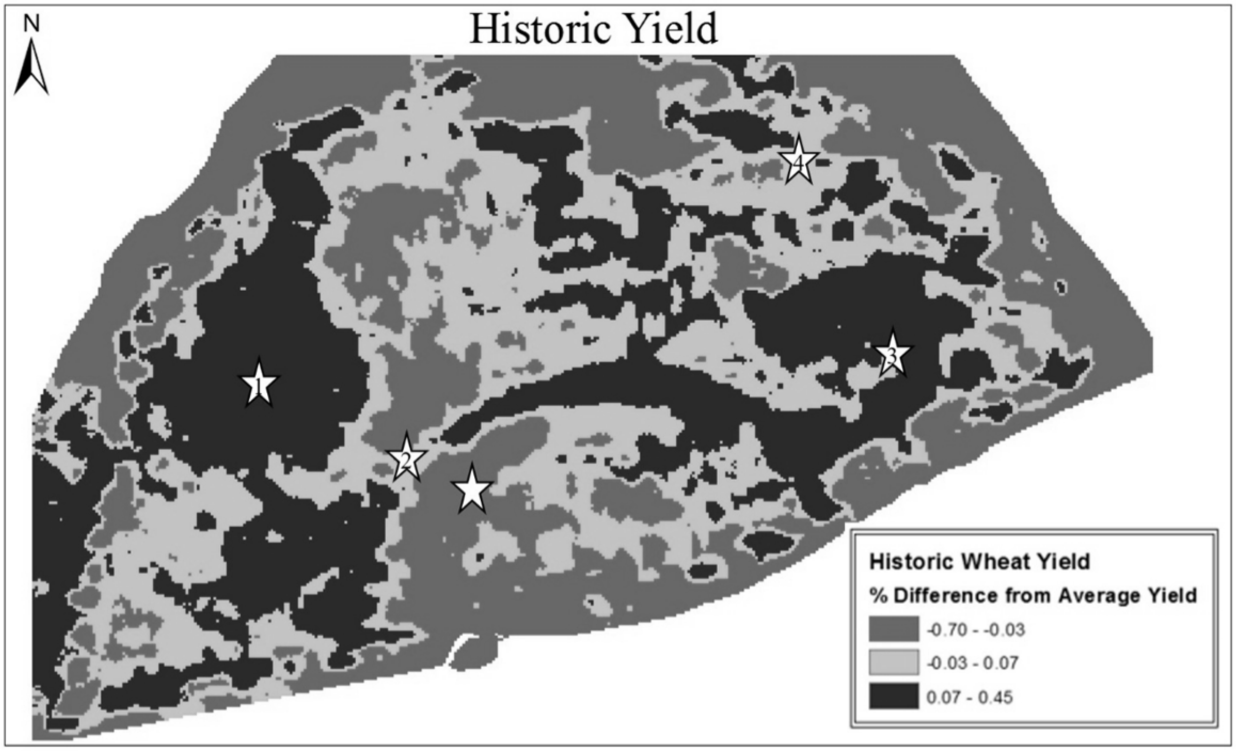

Figure 3: Historic wheat yields relative to the field average for the respective year. Year's included are: 2013, 2014, and 2016. Numbered stars are proposed management areas as identified by Table 1.

Table 2. Relative rates for irrigation water and N and P fertilizer applications for 2017 based on yield potential, CWP in 2016, and soil test values (not shown) for four example locations (numbered stars on Figures 1, 2, 3). Actual rates are not shown, but rather are expressed as relative to the field average.

Field Site	Yield Potential Rating	2016 CWP	Relative Proposed Rate for 2017, %		
			N	P	H_2O
1	High	High	120	0	100
2	Low	Low	80	180	<90
3	High	Moderate	120	50	100
4	Moderate	Moderate	100	0	>100

Field site 2 is essentially the opposite of site 1 in that it is one of the least productive areas of the field in terms of both yield potential and CWP. This site is an eroded ridge with low OM, high calcareousness, and low soil test P. And, the soil is relatively shallow. As such, this site has lower water holding capacity. We suspect that the N and H_2O need to be reduced relative to the rest of the field due to these conditions. However, this soil would likely benefit from increased P fertilization to this site as it is likely one of the most limiting factors for production. Once again, this area is large enough that strip trials can be installed.

As with field site 1, site 3 has a high yield potential, but the CWP wasn't as great as site 1. We suspect that this site's soil does not have as good of N supplying capacity and, as such, we feel that applying increasing levels of both H_2O and N would increase the CWP and yield. As with site 1, this area has high soil P and the fertilizer rate for this nutrient can be reduced.

Site 4 is "average" in many ways. We propose that both water and N may be combined limiting factors based on the moderate CWP. This site has relatively high soil P and does not need application.

SUMMARY

Precision agriculture seeks to match the inputs to natural spatial variations to maximize yield and limit excess applications. Variable rate fertilization and irrigation allow this to occur, but decision support systems are needed for proper implement of VRI management technology (Sadler et al., 2005). There is limited research in how VRI and VRF zones should be developed when used together, and how variable rates in VRI will influence VRF. In our first year of this study, we have learned much regarding how this field behaves regarding VRI and have proposed alterations for 2017, as well as adding VRF to attempt to enhance the efficiency of water and yield production. The 2016 CWP layer helps to create zones based on the efficiency of the crop to produce yield from the applied water. This indicates zones where variables, other than water, limit yield.

The historic yield layer gives insight into yield potential zones for the field. Yield potential is determined by factors such as topography, soil texture, low organic matter, etc. The yield history gives insight into areas where variable rate management will be a useful management tool. The historic yield and CWP layers are response variables from the soil properties that vary across the field. Understanding the variation in these properties allows the adjustment of nutrient and water application. We present this data collected for this field as an intensive view of the water and soil relations. We propose that this grower, equipped with tools to variably apply water and nutrients and to spatially measure grain and potato yields can use this data to begin to fine tune the VRI and VRF in this field. Measurements in future years will fine tune the proposed adjustments we make in general herein.

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