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PERSPECTIVES ON VRI PRESCRIPTION MAP DEVELOPMENT WITH SATELLITE IMAGERY

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INTRODUCTION

Variable Rate Irrigation (VRI) prescription development is an active area of research (Hedley and Yule 2009; e.g., Evans and King 2012; Evans et al. 2013; McCarthy et al. 2014). Prescriptions may be static, unchanging or changing only a small number of times during a growing season. Prescriptions may also be dynamic, changing frequently, possibly every irrigation cycle. Static prescriptions are of utility in areas where a constant difference in applied irrigation is desired, e.g. avoiding irrigation in uncropped areas, or reduced application in areas prone to drainage problems (Evans et al. 2013). Static prescriptions can be problematic, however because factors effecting crop water stress may vary spatially and in time (Evans et al. 2013; O'Shaughnessy et al. 2015). Dynamic prescription map development is the subject of recent research (e.g. O'Shaughnessy et al. 2015; Stone et al. 2015).

Researchers have demonstrated the importance of many agronomic factors in VRI management (e.g. McCarthy et al. 2014; O'Shaughnessy et al. 2015). Such factors may include: soil root zone water holding capacity (RZWHC), topography, nutrient concentrations, disease, non-uniformity of agronomic inputs, and plant populations. These factors can be difficult to quantify, but all may ultimately affect evapotranspiration (ET) and irrigation water requirements. While many existing prescription models rely on uniform estimates of ET, it is apparent that accurate spatial estimates of ET may help improve VRI management (Sadler et al. 2005).

One tool to estimate ET spatially is remote sensing using aerial or satellite imagery. A benefit of using remote sensing ET estimates is that the cumulative effect of many factors on the crop condition can be indirectly sensed thus eliminating complicated models to incorporate all of the affecting factors. In this research, a water balance model using satellite imagery as an input for spatial ET estimation was tested for use in VRI management in a field in eastern Nebraska in 2015. The implementation and some results from that study are presented here. A simple static prescription development method is first presented. Finally, some considerations for VRI implementation are also discussed.

A SIMPLE ROOT ZONE WATER MINING METHOD

Before discussing some current research on dynamic prescription map development, it seems reasonable to present a relatively simple static VRI prescription methodology. One useful application of static prescription maps is the mining of spatially varying root zone water holding capacity (RZWHC). A number of research studies have been published focusing on delineating variable rate irrigation management zones (IMZs) based on RZWHC (e.g., Hedley et al. 2009; Haghverdi et al. 2015; Lo 2015; Miller 2015; Stone et al. 2015). Such IMZ delineation methods can be used as a baseline for a variety of management schemes; one simple scheme is described below. This method does not account for the impact of topography. Both ET and precipitation are assumed to be spatially uniform.

A simple VRI strategy using static prescriptions to mine RZWHC has been developed building on the work of Miller (2015). This method has recently been successfully incorporated into irrigation coursework at the University of Nebraska-Lincoln to introduce students to VRI management. The method requires a field map of RZWHC; this may be developed using soils maps, apparent electrical conductivity surveys (e.g. Veris mapping), etc. A simple method for generating IMZs is to round the mapped RZWHC values to the nearest whole inch of water over the total root zone depth. Such rounding will produce a map of RZWHC zones each with a different integer RZWHC value. A management allowable depletion (MAD) map, or table, is then generated. In applying the method to speed or sector control VRI, a sound strategy would be to select the sector RZWHC based on the lower 10th percentile of the RZWHC in that sector – in other words, the RZWHC for which 10% of the sector area has that or a smaller RZWHC. The MAD (%) versus total RZWHC is selected based on management preferences or following extension guidelines (e.g. Yonts and Klocke 1985; Rogers et al. 2014; Andales et al. 2015).

The number of irrigation events (N) required to mine the differences in RZWHC for all IMZs is:

$$N = \frac{(MAD_{max} - MAD_{min})}{I_{max,net}} \tag{1}$$

where MAD_{max} and MAD_{min} are the maximum and minimum MADs across all IMZs, in inches of water over the total root zone, and $I_{max,net}$ is the maximum desired net irrigation application depth during any single irrigation event. N is rounded up to the nearest whole number. The net applied irrigation depth for each IMZ ($I_{IMZ,net}$) is calculated as:

$$I_{IMZ,net} = \frac{1}{N}(MAD_{max} - MAD_{IMZ}) \tag{2}$$

where MAD_{IMZ} is the MAD for the IMZ of interest, in inches of water over the total root zone. $I_{IMZ,net}$ will be static for each IMZ until the differences in MAD have been mined (after N applications of the static prescription). The prescription map is developed based on gross applied irrigation depths for each IMZ ($I_{IMZ,gross}$), which can be determined by dividing $I_{IMZ,net}$ by application efficiency (E_{app}) as:

$$I_{IMZ,gross} = \frac{I_{IMZ,net}}{E_{app}} \quad (3)$$

Irrigation timing would be most simply based on the checkbook method (e.g. Yonts and Klocke 1985; Rogers and Alam 2003; Andales et al. 2015). Irrigation timing would be based on the IMZ having the smallest RZWHC. When that zone were expected to reach MAD, an irrigation event would be triggered considering cycle time. Thus, this method only requires tracking a water balance for the zone with the smallest MAD. ET and rainfall data can come from sources commonly used for local irrigation management. Two soil water sensor stations are recommended for the IMZ that is used for triggering irrigation events. Putting a soil water sensor station in each IMZ would give a producer additional confidence that each IMZ is being managed correctly.

After RZWHC has been mined (after the first N applications of the static prescription) uniform irrigation rates are applied to the entire field. RZWHC may be mined again later in the season, if a precipitation event (or series of events) is great enough to fill some, or all of the IMZs, back to field capacity. This scenario is uncommon in the central plains. Notice that the IMZ with the maximum root zone MAD will not receive irrigation until uniform irrigation commences. Large zero application zones may present a problem for irrigation pumping. Where such conditions exist, it may be necessary to apply some minimum depth of water to the zero application zones (e.g. 0.10 or 0.20 in.). These small application depths will be negligible in a water balance.

It is assumed, when applying this method, that the root zone depth is constant throughout the season. It is therefore best to apply the RZWHC mining after the rapid development crop stage. In eastern Nebraska and Kansas, irrigation may often not be necessary during the rapid development stage. In times or locations where irrigation is needed early in the season, it may be most practical to apply uniform irrigation until the full root zone has been established and then mine the RZWHC differences. The method includes the assumption that the depleted water depth is uniform throughout the field at the beginning of the static prescription map application. (Field capacity meets this requirement but doesn't have to be the starting point.) Therefore, if uniform irrigation is practiced before RZWHC mining begins, as long as soil water depletion can be assumed to remain uniform across the field (irrigation and precipitation are such that no zones exceed field capacity) then Equations 1 through 3 will still be valid. Irrigation timing will still depend on the zone with the smallest MAD. Similarly, in some situations, the irrigation system capacity may not be able to meet crop water use during peak ET demand, whether due to limited pumping rates, electric load control, or system down time (maintenance and repair). In these cases, it is advisable to apply uniform water early in the season to retain water in the soil reservoir, and then to mine the water later in the season with the VRI prescription map.

REMOTE SENSING BASED IRRIGATION SCHEDULING WITH DYNAMIC PRESCRIPTIONS

One method for modeling ET using remote sensing data is the reflectance-based crop coefficient approach. In this approach, crop ET is calculated by multiplying reference ET by a crop coefficient (K_c) as is common in ET modeling for irrigation scheduling. However, the K_c is obtained from satellite or aerial remote sensing imagery. Bausch and Neale (1987) demonstrated the use of vegetation indices (e.g. the normalized difference vegetation index, NDVI) from remote sensing surface reflectance data to determine a basal crop coefficient (K_{cb}, corresponding to plant transpiration only). The resulting K_{cb}s are referred to as reflectance based basal crop coefficients

(K_{cbrf}) and allow for spatial consideration of crop development rates, population densities, etc. Others have successfully coupled similar approaches with water balance models (e.g. Hunsaker et al. 2005; Campos et al. 2010) for uniform irrigation management. Required inputs for this type of model include spatial RZWHC, reference ET, precipitation, and irrigation, at relevant spatial scales.

Shortwave surface reflectance imagery necessary for the K_{cbrf} approach can be obtained from satellites. Landsat reflectance imagery is available at a 30 m resolution, which is about as fine of a resolution as can be managed using center pivot VRI with most sprinkler packages (as discussed later). A benefit of the K_{cbrf} approach is that general behavior of K_{cb}s in time is well documented (e.g. Jensen et al. 1990; Allen et al. 1998). Thus remote sensing imagery is not needed every day as K_{cbrf}s can be coupled with traditional time-based K_{cb} curves to interpolate between and extrapolate beyond image dates. Thus a daily spatial water balance can be maintained for irrigation scheduling.

All water balances are sensitive to inputs and can drift from reality. Often in irrigation scheduling, soil moisture monitoring is used as a check or truth. It is not practical to monitor soil moisture for every satellite image pixel within a field. However, it may be possible to monitor soil moisture at a few locations and make spatial inferences for the entire field. Another approach is to use multiple models as a self-correction system; neither of these methods are discussed further in this paper, but both are currently being tested by us.

With remote sensing-based ET estimates and spatial water balances, irrigation management can be similar to using single point water balances or a check-book method, thus allowing a water user to quickly make a decision on when to irrigate. By implementing the proper irrigation constraints, an irrigation prescription map could be generated. Thus a water user would still make the decisions on how and when to irrigate, in a manner that is similar to current best management practices, but would be able to do so with spatial variation.

REMOTE SENSING PRESCRIPTION TESTING

Irrigation management using a K_{cbrf} based water balance was tested during the summer of 2015 on a corn crop at the University of Nebraska's Agricultural Research and Extension Center near Mead, NE (N 41.165°, W 96.430°). A zone control VRI-equipped center pivot was used for irrigation. The field was managed as a corn-soybean rotation under no-till management and controlled wheel traffic. A description of the experiment and some brief results are presented below, along with some observations or considerations for VRI management and research.

Experimental Methods

The K_{brf} method was tested in an experiment with four treatments: VRI based on a K_{cbrf} water balance for each plot (using Landsat imagery as a model input), VRI based on within-plot neutron probe soil moisture measurements, non-VRI or "uniform" irrigation with neutron probe from only two locations within the field, and non-irrigated for a reference. Figure 1 is a map of the 2015 plot layout. The experiment in 2015 was performed on the north half of the field, which was planted to maize. Plot layout was determined based on an apparent electrical conductivity (EC_a) survey from a Veris MPS system (Veris Technologies Inc., Salina, KS). The EC_a was observed to roughly correlate to soil survey map units and topographical features at this site. No attempt was made to account for the radial variation in irrigation along the pivot lateral, although this source of error is acknowledged. Obvious gaps in the plot layout in Figure 1 are because of utility lines, a previous rail grade, and other spatial anomalies.

Experimental plots were oriented with crop rows and were 48 rows (120 ft) wide by 200 ft long. The size of the experimental plots was determined based on the estimated size of transition zones between plots and the ability to obtain reasonable yield data from a production combine and yield monitor. Hillyer et al. (2013) performed catch can tests on a VRI center pivot in Oregon. They found that the transition distance within each IMZ is about two-thirds of the wetted diameter of the sprinklers. This is shown in Figure 2, where a simple VRI prescription for three adjacent 120 ft by 120 ft. IMZs is considered. The average actual application depth as modeled following Hillyer et al. (2013) is also shown assuming a wetted diameter of about 45 ft. The total transition zone is about 60 ft, or 30 ft within each IMZ. After accounting for this transition zone there is an area of about 60 ft by 140 ft within each plot that should have received the intended irrigation application.

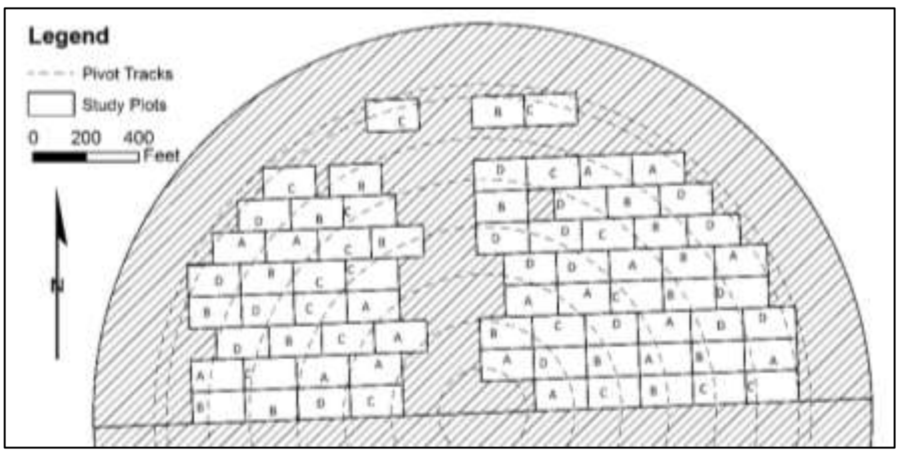

Figure 1. Plot map for the 2015 field study. Letters indicate treatments: A = VRI with K_{cbrf} WB, B = VRI with neutron probe, C = Uniform with neutron probe, D = not irrigated. Hatched areas were irrigated similar to the C treatment.

The plot dimensions further provided adequate width for about 3 to 4 adjacent combine passes for yield averaging from a combine with a 20 ft header. The plots were designed to have approximately 140 ft of length, within the buffer, along a combine pass to account for lags in the yield monitor. Thus yield, although not a primary measurement for this study, could be obtained from a calibrated production combine yield monitor. Further, the field was harvested with a single combine and using weighing grain carts to enable post-calibration of the yield monitor based on the total bushels harvested from the field. This pattern could be useful for farmers interested in their own field trials of VRI.

During the irrigation experiment, irrigation was triggered when any VRI plot, or either of the two monitoring plots for the uniform treatment, were projected to exceed a management allowable depletion (MAD) of 45% before completion of an irrigation cycle. Any irrigation treatment could trigger irrigation for the whole field, with each treatment only receiving the required depth to bring the respective plot (or plots) up to 1.5 in. above MAD. A minimum application depth of 0.1 to 0.2 in. was maintained to prevent running the pump at too low of a flow rate.

The primary measurement for each plot was soil moisture measured using a neutron probe. A neutron probe access tube was installed near the center of each plot. Soil moisture measurements were taken weekly between Jun. 24 and Oct. 7, 2015.

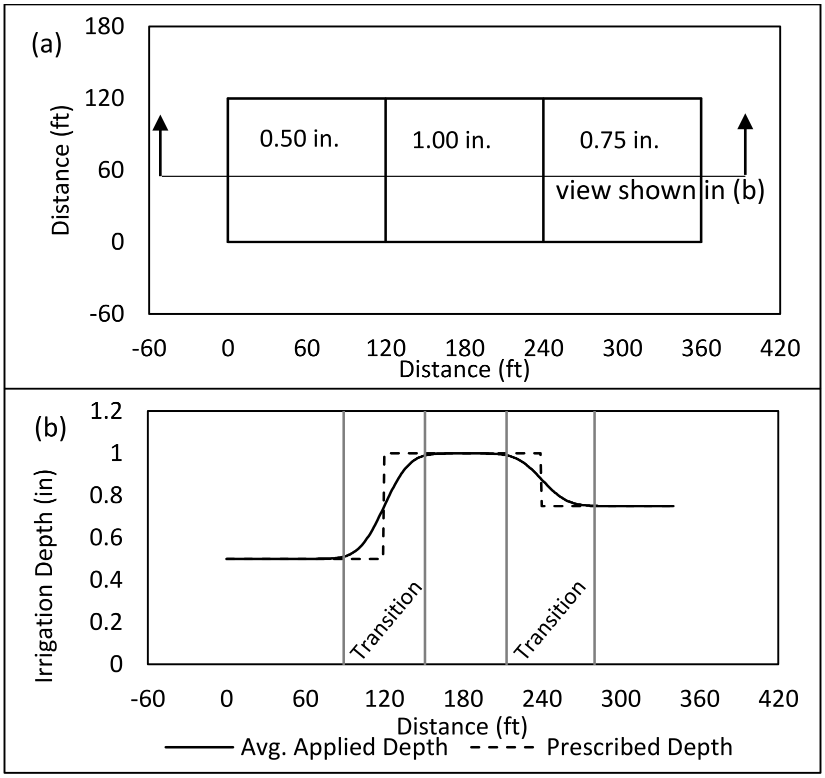

Figure 2. Plan (or aerial) view (a) and side view (b) of a VRI prescription in three adjacent 120 ft by 120 ft IMZs. The prescribed depth is shown in (b) with the estimated applied depth following Hillyer et al. (2013). Vertical lines indicate transition zones.

Current Results

During 2015, irrigation was applied four times, with gross application depths ranging from 0.0 to 1.2 in per application, depending on the treatment. The fourth event was required by the K_{cbrf} water balance model, which did not use soil moisture as an input, and was a result of over-estimating ET and model drift. The 2015 season was wet and thus little total irrigation was required. The relative seasonal irrigation application between the treatments is of interest, however. The remote-sensing-based water balance method resulted in the greatest average irrigation application, having nearly double the application of the other two treatments. The VRI treatment with individual plot soil moisture monitoring had the smallest average application. This treatment had about 14% less application on average than the uniform treatment. The effects of model drift in the remote sensing-based treatment indicate the importance of incorporating some other metric of soil moisture status in the model, which is the topic of current research. Others have also observed a need for incorporating soil moisture measurement into dynamic prescription map models (O'Shaughnessy et al. 2015; Stone et al. 2015).

PRESEASON SYSTEM EVALUTION

VRI system performance was evaluated throughout the growing season. The primary evaluation included system walk-throughs with the pivot set to a known pulse rate so that sprinklers that were stuck on or off could be identified. A catch can test was also performed under the study VRI system early in the 2015 growing season to test the accuracy of prescription application. One key observation from the test was the importance of pivot position specification and acquisition on the accuracy of prescription map execution. Single leg catch can tests are not adequate to capture the effects of transitions between IMZs and gridded catch can tests can be time consuming. Therefore a catch can layout and prescription map were strategically developed to capture the effects of transitions (see Figure 3). Of key importance was the inclusion of a zero application zone in the middle of the prescription map. Because of variations in uniformity and the size of buffer areas as described above, only the zero application zone would be field observable.

The catch cans were placed on a 10 ft spacing. The square IMZs were sized 120 ft by 120 ft to match the minimum dimension of the plots in the field experiment. IMZs were strategically positioned so that centers and transitions could be monitored. The center IMZs were offset east and west from the others to test the effects of those boundaries. The wedge shaped IMZs on the outside of the test were included for system "warmup" and to prevent zero application areas around the test IMZs. The prescription was applied in a clockwise direction. Catch cans were read as the pivot passed completely over them. It became evident during the test that the zero application did not match the prescription. The zero application zone was actually observed about 60 feet to the west of where it was expected, as shown by a circled group of cans in Figure 3. Upon further inspection it was discovered that the location of the pivot center point had been mis-entered in the system control panel. Thus the angular position of the pivot calculated by the control panel was incorrect and resulted in a shift in application. This shift would have been detrimental to the plot experiment. The position mis-entry was reconciled and no further positioning problems were identified.

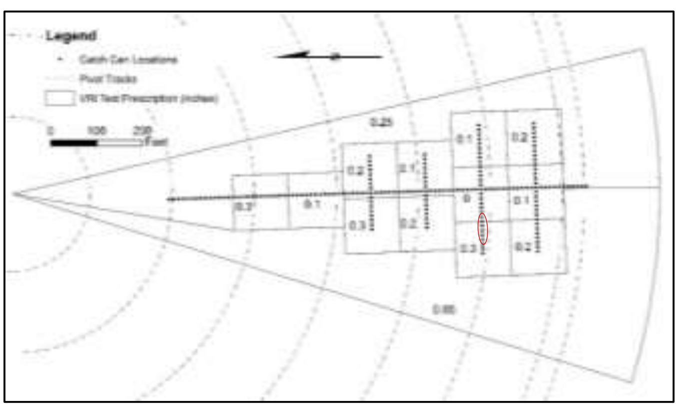

Figure 3. VRI system evaluation catch can layout and prescription map. Numbers are prescribed application depths (in.). Circled locations indicate zero catch, which was offset from expected because the location for the pivot center was incorrect in the control panel.

A simple similar test could be performed by a producer by placing a small number of catch cans in a cross pattern through a 100 ft by 100 ft zero application zone that was surrounded by full application zones. If the zero depth occurs at the center of the zone, then positioning errors would not be expected. Producers are also advised to do system walk-throughs as described above throughout the irrigation season. These simple evaluation tests can prevent mis-application of irrigation.

SUMMARY

Several VRI prescription map development strategies were developed and tested. A simple static prescription map methodology for mining differences in RZWHC was presented. This method is robust and easily adapted for VRI users. A satellite-imagery-based spatial water balance method was tested for dynamic prescription map development. The method was tested in a plot experiment in corn under a zone control VRI system in eastern Nebraska in 2015. The model was able to account for spatial variability in crop water use and RZWHC, but was biased high in seasonal applied irrigation when compared with treatments using neutron probe soil moisture measurements for irrigation scheduling. Finally, observations from a catch can test are presented wherein the pivot position in the system control panel was found to be mis-entered, resulting in a spatially shifted prescription map.

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