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The Applicability of VRI for Managing Variability in Infiltration Capacity and Plant-Available Water: A Preliminary Discussion and GIS Study

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Abstract. *Although variable rate irrigation (VRI) has been researched and marketed for a number of years, research that quantifies the magnitude of VRI's potential benefits and that are translatable to unmonitored fields is lacking. The potential reduction in seasonal irrigation is proposed as the criterion for beginning to evaluate the use of VRI to improve agricultural water management when infiltration capacity and plant-available water are spatially variable inside a field. An initial geographic information system study using publicly available geospatial data was conducted to examine soil and topographic properties associated with such variability within 1100 center pivots across 11 counties. The current results only indicate that the extent of variability may be different between counties, but with the acquisition of more accurate and site-specific data as well as the development of a model that enables multi-year comparisons of seasonal irrigation between VRI and uniform irrigation for an individual field, the public could be finally informed about the applicability of VRI by regional assessments of VRI potential and field-specific VRI investment decision tools.*

Keywords. *spatial variability, gis, irrigation, variable rate application, precision agriculture.*

Introduction

Site-specific irrigation, as currently implemented with center pivots, relies on modifying the "on" time of the last tower's motor (known as speed control, sector control, or variable depth irrigation) and/or pulsing solenoid valves upstream from one or more sprinkler nozzles (known as zone control or variable rate irrigation (VRI)) to vary intentionally the intensity and/or the depth of irrigation applied to different parts of a field. Over the years, engineers around the world from both industry and research institutions have contributed to the development of VRI's hardware and control systems (Evans et al., 2013) and have explored the effects of VRI in particular fields through simulations and/or experiments (Evans and King, 2012). The advancements that have been made thus far are summarized in reviews such as Evans and King (2012) and Evans et al. (2013).

Despite studies demonstrating positive potentials for conservation, adoption of VRI has been slow (Evans et al., 2013). Because VRI has higher initial capital costs and the magnitude of its benefits is less obvious than some other precision agriculture technologies, farmers may want customized projections of the impact of VRI to make a well-informed choice for each of their irrigated fields. While field-specific VRI investment decision tools would serve this purpose, regional assessments of VRI applicability could provide "big-picture" information to policymakers, researchers, and extension educators as well as irrigation equipment manufacturers and dealers. Regardless of scale, though, there is demand for quantitative estimates of the magnitude of VRI's benefits.

It should be mentioned in passing that at least two VRI management strategies can already be evaluated quantitatively and put into practice with much confidence. The first strategy is the avoidance of uncropped areas (Sadler et al., 2005). The second strategy is the pulsing of oversized nozzles in the first span, which enables irrigation to be applied at the design rate inside the innermost circle without risking the clogging of small nozzles or forfeiting uniformity with large sprinkler spacing. Under some contexts (e.g., high-value crops that are sensitive to over-irrigation, enforcement of harsh penalties for violating stringent chemigation regulations), one or both of these strategies may attract farmers to consider VRI.

This paper, on the other hand, focuses on two VRI management strategies—based on fundamental agricultural water management principles—that may affect larger portions of a field but may require further research to assess and implement: 1) minimizing runoff when infiltration capacity is variable and 2) maximizing the capture and consumptive use of stored natural precipitation when plant-available water (*AW*) is variable. These uses of VRI and the evaluation of their potential benefits are discussed, and subsequently, an initial study of field variability in several eastern Nebraska counties using a geographic information system (GIS) and publicly available geospatial data is presented. Insights from this work would hopefully inform regional assessments of VRI potential and the development of field-specific VRI investment decision tools.

1. Runoff and Variable Infiltration Capacity

With uniform irrigation (UI), irrigation runoff is minimized by decreasing center pivot timer setting and sprinkler spacing as well as increasing sprinkler wetted diameter. If runoff is already negligible, VRI may be able to decrease head requirements for pumping because the sprinkler wetted diameter requirement for minimizing runoff can now be shorter. Yet when accommodating the areas with least infiltration capabilities would result in undesirable or impractical UI center pivot designs and/or operations, VRI provides the option of lowering application rates over soils with less infiltration capacity. Application depth, too, can be adjusted if VRI and speed control are jointly utilized, as illustrated in fig. 1. In this example where uniform depth is intended, when both the average application rates and the machine rotation speed are lowered by 40%, only 6%—instead of 19% originally—of the applied amount would run off (approximately a two-thirds reduction).

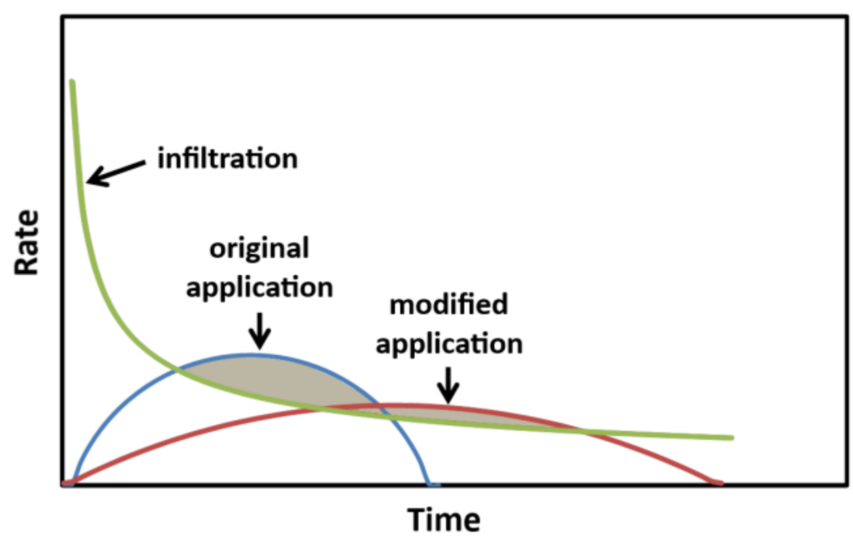

Figure 1. Runoff (grey area) caused by two different applications of the same irrigation depth

Since this combined practice decreases application rates over entire center pivot sectors, energy and system capacity might be sacrificed. However, these losses can be mitigated if variable frequency drive is available and if the infiltration capabilities are relatively homogeneous within sectors. The center pivot could catch up by increasing application rates and machine rotation speed over sectors whose soils have greater infiltration capabilities.

2. Natural Precipitation and Variable *AW*

The amount of *AW* in the soil immediately before an irrigation event can be different throughout a field. The part of this variability that is due to land properties can be attributed largely to spatial heterogeneity in surface hydraulic conductivity (i.e., the capacity to infiltrate water), in root zone water holding capacity (*RZWHC*; i.e., the ability to retain infiltrated water), and in topography (i.e., the access to surface and subsurface lateral flow generated upslope). Where a negligible fraction of *AW* is derived from natural precipitation, UI with high application uniformity will result in relatively uniform *AW* as long as application intensities are appropriate and irrigation is scheduled according to the area of the field with the least *RZWHC*. However, where natural precipitation not only constitutes a major source of *AW* but also adds significantly non-uniform amounts of *AW* across a field due to differences in runoff and deep percolation, VRI can conserve irrigation by lowering applications over areas that store more *AW* from precipitation and thus promote the consumptive use of this extra water. Further irrigation savings could be obtained when VRI is managed to maximize the capture of natural precipitation—generally by maintaining *AW* as close to site-specific critical soil water depletion thresholds as practically possible during the growing season and by withholding irrigation when AW is expected to be sufficient for the remainder of the growing season. Besides soil attributes, terrain contributes to *AW* variability as well. By determining net fluxes of subsurface lateral flow and by controlling opportunity times to infiltrate surface runoff whether from upslope areas with less infiltration capacity or during the recession phase of rainstorms, topography tends to concentrate water in flat, convergent areas where soils also often have higher *RZWHC*.

Evaluation of Potential Benefits

Improving agricultural water management with the two highlighted VRI strategies could bring a variety of benefits. As the applicability of these strategies are starting to be assessed at the regional scale and the field scale, attempting to quantify the magnitude of one benefit first, rather than all of them at once, may shorten the time before the research community can begin to release scientific information on this subject to the public. A benefit that is fitting for this purpose is the potential reduction in seasonal irrigation. Its primary advantage is that whether irrigation water is pumped from aquifers or is purchased from surface water diversion projects, the conserved amount has a known financial value to farmers.

The irrigation water savings, however, must not be interpreted as consumptive use changes for watersheds since the decrease in evapotranspiration of irrigation water is generally being substituted with an equivalent increase in evapotranspiration of precipitation water. An exception is any decreases in soil evaporation enabled by VRI. Otherwise, unless the surface runoff, deep percolation, and lateral subsurface flow are no longer usable because of their contaminant levels or the poor quality water bodies they enter, cutting down on these “water exports” does not make surplus water available for downstream users.

VRI’s impacts on yield would be assumed to be negligible for this phase of the analysis. In situations where over-irrigation does not lead to problems such as salinity, waterlogging, disease, or nutrient deficiency, full irrigation with VRI—as opposed to UI—is unlikely to affect yield for plants like corn because once they are fully irrigated, yield becomes relatively insensitive to additional water applications. Yet, if yield is limited by irrigation water supply due to low well capacities or regulatory water allocations, then increasing efficiency with VRI may deliver appreciable yield gains.

Environmental benefits that are concurrently achieved as VRI raises farm profits would be temporarily ignored as well. Tailoring irrigation application rates to site-specific infiltration capacities of the soil and lowering soil water content in the root zone by letting evapotranspiration consume captured natural precipitation lessens the risk of eroding topsoil and losing agricultural inputs (e.g., fertilizers and pesticides) through runoff or leaching. Furthermore, conserving irrigation water also implies conserving the fossil fuels that power its transportation and pressurization.

In order to quantify the potential reduction in seasonal irrigation, site-specific soil and topographic data could be incorporated into continuous and process-based hydrologic models to simulate the differences between URI and VRI over multiple seasons. A simple one-dimensional soil water balance may be employed at the early stages of development before progressing to a more sophisticated three-dimensional distributed model. As a complement to the modelling effort, field research that monitors infiltration, runoff, and redistribution would assist with model selection and parameterization. The model, when ready, would be applied both to regional assessments of VRI potential and field-specific VRI investment decision tools.

Methods

11 counties were selected from the parts of eastern Nebraska that have the highest densities of center pivots (fig. 2). These counties have average annual precipitation ranging between 600 and 800 mm (PRISM Climate Group, 2012), and the majority of them are not subjected to any regulatory limit on irrigation water supply (Nebraska Association of Resources Districts, 2013). All of the subsequent analysis was conducted on 100 center pivots in each of these counties (1,100 total), which were randomly sampled without replacement from a shapefile that maps Nebraska's center pivots in 2005 (CALMIT, 2007).

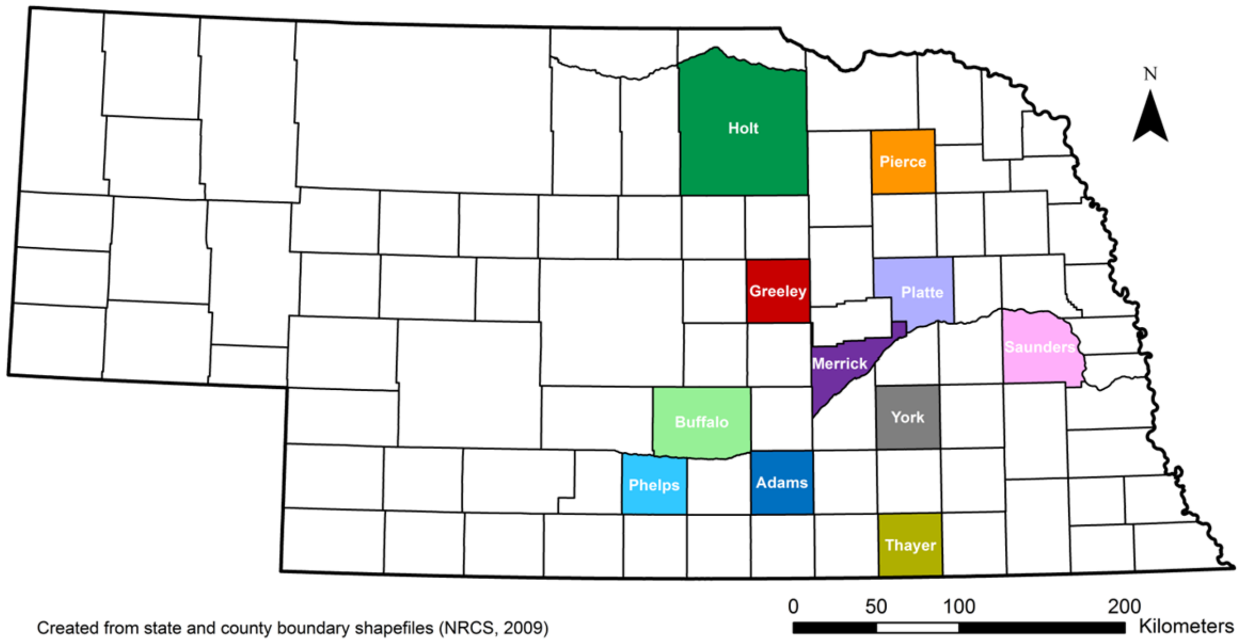

Figure 2. Map of the 11 eastern Nebraska counties included in this study

Three land attributes that are related to infiltration capacity and *AW* were obtained from publicly available data: *RZWHC*, soil surface saturated hydraulic conductivity (surface K_s), and topographic wetness index (*TWI*; Beven and Kirkby, 1979). Using Soil Survey Geographic (SSURGO) database (Soil Survey Staff, accessed 2013-2014), *RZWHC* and surface K_s were first calculated for every map unit component, and then every map unit was assigned the averages of the values for its constituent map unit components—each weighted by the percent composition of the particular component. As for *TWI*, 10 m National Elevation Dataset digital elevation models (DEMs; Gesch et al., 2002) were mosaicked together and resampled to 30 m resolution by the nearest neighbor method to generate a smoother surface for flow direction computations, and the index was calculated for each 900 m^2 square cell within the sampled center pivots loosely following Morris (2013) and using the TauDEM 5.1.2 toolbox (Tarboton, 2014) that can be added into ArcGIS.

To summarize the variability of these three attributes in one number for each field, excess *RZWHC*, excess surface K_s, and excess *TWI* were defined as:

$$Excess\ RZWHC = \sum\left[\left(\frac{A_i}{\Sigma A_i}\right) RZWHC_i\right] - RZWHC_{min} \quad (1)$$

$$Excess\ surface\ K_s = \sum\left[\left(\frac{A_i}{\Sigma A_i}\right)(surface\ K_s)_i\right] - (surface\ K_s)_{min} \quad (2)$$

$$Excess\ TWI = \overline{TWI} - TWI_{min} \quad (3)$$

where A_i, $RZWHC_i$, and (surface $K_s)_i$ are the area, *RZWHC*, and surface K_s of map unit *i* within the particular field.

Map units with zero *RZWHC* were assumed not to be farmed and were not included when calculating excess *RZWHC* and excess surface K_s. However, the area occupied by these map units were not excluded when calculating excess *TWI*, which introduced significant error whenever these unfarmed areas have substantially different *TWI* values than the rest of the field in which they belong. Typically, these unfarmed areas have high *TWI*, in which case excess *TWI* would be overestimated.

Additionally, since map units were not filtered by area, those that only occupy an inconsequential fraction of the pivot area were included in the excess *RZWHC* and excess surface K_s calculations even though UI is typically designed and managed based on a reasonably low percentile value of *RZWHC* and surface K_s instead of the minimum value found within the field. This error would lead to the overestimation of excess *RZWHC* and excess surface K_s.

A Microsoft Visual Basic for Applications macro was repeatedly executed to run a set of SQL queries on each county's (SSURGO; Soil Survey Staff, accessed 2013-2014) database within Microsoft Access. Then, the remainder of the procedure was completed using a Python script within ArcGIS.

Results

The cumulative distribution of excess *RZWHC*, excess surface K_s, and excess *TWI* for each of the 11 counties are plotted in figures 3-5. All of the distributions are bounded by zero at the lower end because of how these three statistics were defined, and many of the distributions are right-skewed due to the occurrence of uncommonly large values. Among the 1100 center pivots sampled, excess *RZWHC*, excess surface K_s, and excess *TWI* varied from 0 to 201 mm, from 0 to 29.8 cm/h, and from 1.52 to 6.33, respectively.

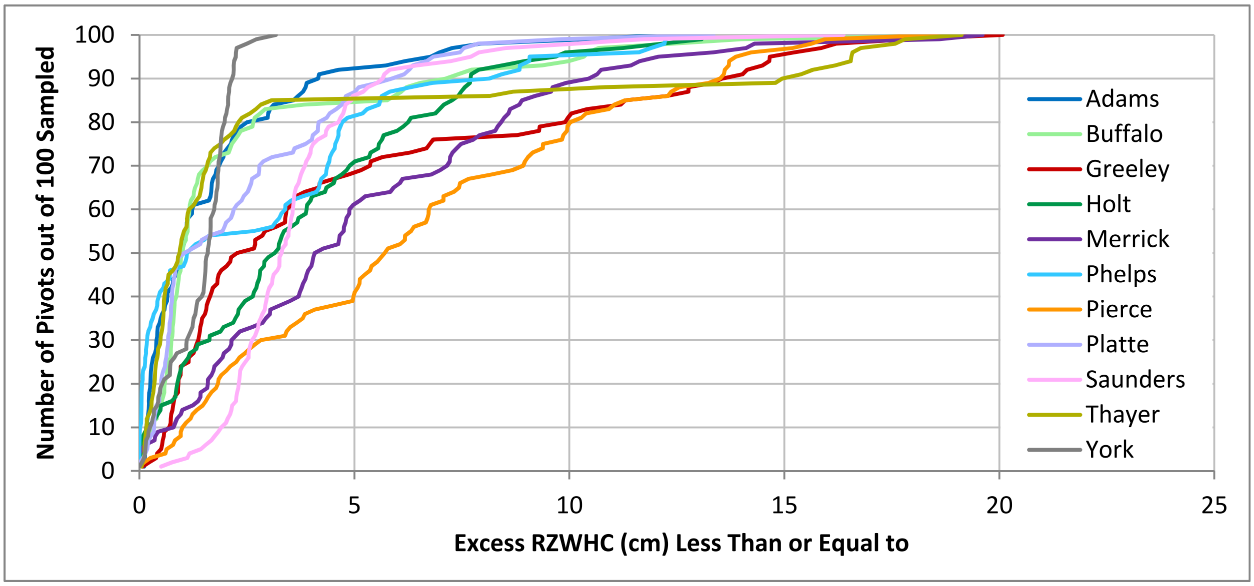

Figure 3. Cumulative distribution function of excess *RZWHC* for the 11 sampled counties

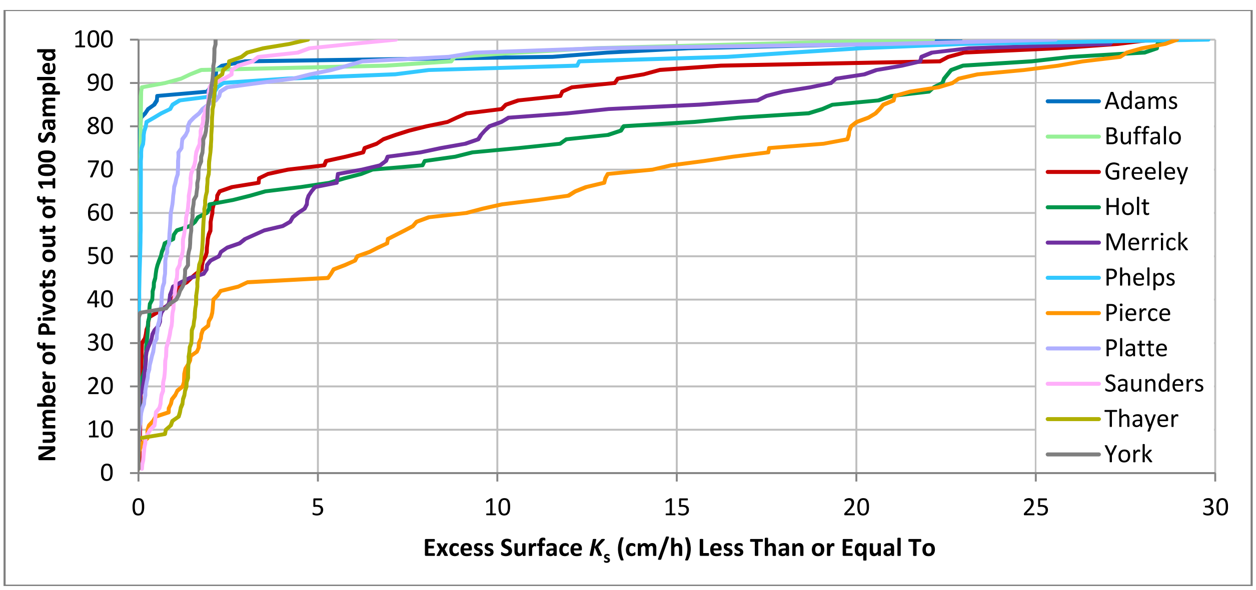

Figure 4. Cumulative distribution function of excess surface K_s for the 11 sampled counties

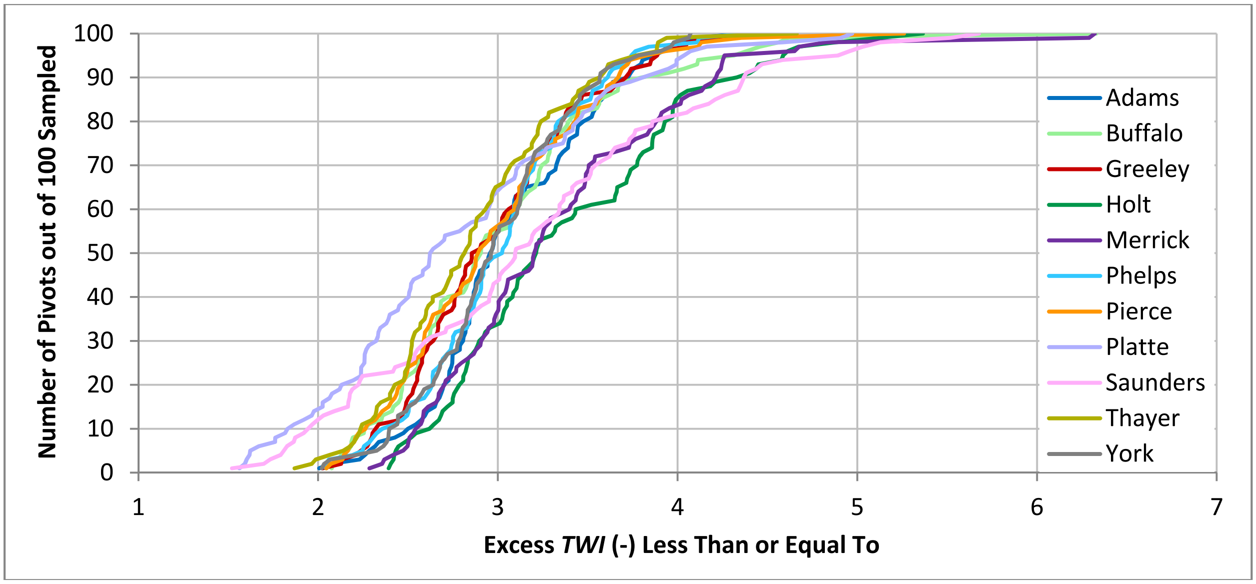

Figure 5. Cumulative distribution function of excess *TWI* for the 11 sampled counties

From figures 3 and 4, it appears that the sampled center pivots in York County (grey) have the most uniform *RZWHC* and surface K_s. Those in Adams (dark blue), Platte (light purple), and Saunders (pink) Counties also tend to be relatively homogeneous in terms of these two soil properties. In contrast, the sampled center pivots in Pierce County (orange) have the most non-uniform *RZWHC* and surface K_s. Those in Greeley (red) and Merrick (dark purple) Counties, overall, are relatively heterogeneous in terms of these two soil properties. From figure 5, it seems that the sampled center pivots in Holt (dark green), Merrick (dark purple), and Saunders (pink) Counties have the most non-uniform *TWI* while those in Platte (light purple) and Thayer (dark yellow) Counties have the most uniform *TWI*.

Discussion

To offer an example of how this rudimentary study can be interpreted, the authors would suggest that the center pivots of Merrick County—each with larger variations in capacity to infiltrate and store water and more gently convergent terrain—might, in general, benefit more from VRI than center pivots in Platte County—each with greater homogeneity in capacity to infiltrate and store water as well as steeper and/or more divergent terrain. It is interesting to note that these counties border each other but yet their results in this study are found to be on the opposite ends of the spectrum.

Nonetheless, it would not be advisable to use these preliminary results directly to provide VRI investment recommendations for individual fields. Although county-scale trends may be visible from the graphs, readers should keep in mind that for many of the 11 counties, the sampled center pivots span a large range of values. This observation underscores the necessity of evaluating VRI applicability on a field-by-field basis, which is consistent with common practices in precision agriculture.

Although it is unknown whether VRI center pivots would ever become a mainstream product, what can be claimed more safely is that this technology has the potential to bring benefits to the irrigated fields in eastern Nebraska that are most difficult to manage well with uniform irrigation. Just looking at excess *RZWHC*, for instance, 85 (about 7.7%) and 23 (about 2.1%) of the 1100 sampled center pivots have excess *RZWHC* over 100 mm and over 150 mm, respectively. If one assumes that the root zone starts every season at field capacity and that management allowed soil water depletion fraction is 0.5, these center pivots can respectively pump 50 mm less and 75 mm less per year by installing VRI and properly managing it to let more of the stored soil water be extracted in areas with higher *RZWHC*.

This preliminary evaluation of VRI applicability would have been impossible without the accessible and convenient geospatial data. Nevertheless, for the purpose of estimating field-specific potential irrigation water savings resulting from VRI installation, this data is limited in several aspects. First, the soil surveys were not conducted for precision agriculture. Their scale makes the delineation of map unit boundaries and the quantification of composition percentage very challenging as soils often vary along gradual gradients rather than across distinct lines. Additionally, the values in tabular SSURGO databases (Soil Survey Staff, accessed 2013-2014) are actually summary statistics for measurements of different samples taken from one or more areas where the particular soil series occurred, which means that the numbers are not specific to each occurrence of this soil series and thus would not reflect local deviations from typical values as well as natural and/or manmade changes that happened after soil survey sampling. Perhaps apparent soil electrical conductivity (EC_a) mapping followed by directed soil sampling within different EC_a zones would be one solution to this problem (e.g., Hedley and Yule, 2009).

Second, the accuracy of some of the soil data, especially surface K_s values (D.E. Eisenhauer, personal communication, 2014), can be a concern. Since surface K_s is sensitive to a wide variety of dynamic surface processes (e.g., tillage, traffic, biological activity, shrinking/swelling, impact of water droplets, erosion and sediment deposition), it has been reported to be extremely variable in space (e.g., Nielsen et al., 1973) and even in time (e.g., Cassel, 1983) for supposedly uniform soil, which would hinder its prediction especially in the absence of site-specific data.

Third, runoff direction is uncertain. In this study, since runoff direction is predicted by comparing elevation values of one cell with those of its neighbors, the predictions might be more frequently incorrect when elevation differences are small relative to DEM errors. Resampling DEMs to a coarser spatial resolution and TauDEM's pit removal routine both help create runoff direction predictions that better match what would be expected based on macrotopography, but then the influences of microtopographic features such as terraces, depressions, ridges/furrows and wheel tracks of center pivots—all of which can alter runoff movement—would not be simulated.

Conclusion

Publicly available geospatial data serves as a starting point for examining within-field variability in soil and topographic properties. However, the accuracy of its values and their representativeness of site-specific conditions may limit their use in final decision-making for VRI investment and policy. Although this study suggests county-level differences in the distribution of three variability indices (i.e., excess RZWHC, excess surface Ks, and excess TWI), it must be reiterated that these trends are not valid when comparing individual center pivots. Future research that develops a model to quantify the magnitude of potential irrigation water savings and of other potential benefits would be necessary to analyze the applicability of VRI both at the regional and the field scale.

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