University of Nebraska - Lincoln
DigitalCommons@University of Nebraska - Lincoln

Biological Systems Engineering: Papers and Publications

Biological Systems Engineering

2017

A geospatial variable rate irrigation control scenario evaluation methodology based on mining root zone available water capacity

K. A. Miller
Hastings Utilities, Hastings, NE

Joe Luck
University of Nebraska-Lincoln, jluck2@unl.edu

Derek M. Heeren
University of Nebraska-Lincoln, derek.heeren@unl.edu

T. Lo
University of Nebraska-Lincoln West Central Research and Extension Center

Derrel Martin
University of Nebraska-Lincoln, derrel.martin@unl.edu

See next page for additional authors

Follow this and additional works at: https://digitalcommons.unl.edu/biosysengfacpub

Part of the Bioresource and Agricultural Engineering Commons, Environmental Engineering Commons, Hydraulic Engineering Commons, and the Other Civil and Environmental Engineering Commons

---

Miller, K. A.; Luck, Joe; Heeren, Derek M.; Lo, T.; Martin, Derrel; and Barker, J. B., "A geospatial variable rate irrigation control scenario evaluation methodology based on mining root zone available water capacity" (2017). *Biological Systems Engineering: Papers and Publications*. 553.
https://digitalcommons.unl.edu/biosysengfacpub/553

This Article is brought to you for free and open access by the Biological Systems Engineering at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Biological Systems Engineering: Papers and Publications by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

Authors

K. A. Miller, Joe Luck, Derek M. Heeren, T. Lo, Derrel Martin, and J. B. Barker

This article is available at DigitalCommons@University of Nebraska - Lincoln: https://digitalcommons.unl.edu/biosysengfacpub/553

University of Nebraska Lincoln
digitalcommons.unl.edu

Published in *Precision Agriculture,* 2017
doi 10.1007/s11119-017-9548-z
Copyright © 2017 Springer Science+Business Media, LLC. Used by permission.
Published 7 November 2017.

A geospatial variable rate irrigation control scenario evaluation methodology based on mining root zone available water capacity

K. A. Miller,[1] J. D. Luck,[2] D. M. Heeren,[3] T. Lo,[4]
D. L. Martin,[5] and J. B. Barker[6]

1 Hastings Utilities, 618 East 5th St., Hastings, NE 68901, USA
2 University of Nebraska-Lincoln, 204 Chase Hall, Lincoln, NE 68583, USA
3 University of Nebraska-Lincoln, 241 Chase Hall, Lincoln, NE 68583, USA
4 University of Nebraska-Lincoln West Central Research and Extension Center,
402 West State Farm Road, North Platte, NE 69101, USA
5 University of Nebraska-Lincoln, 243 Chase Hall, Lincoln, NE 68583, USA
6 University of Nebraska-Lincoln, 102 Chase Hall, Lincoln, NE 68583, USA

Corresponding author — J. D. Luck, *email* jluck2@unl.edu

Abstract

Increasing concern for sustainable water use has the agriculture industry working toward higher efficiency in use of irrigation water. Recent advancements have improved the capabilities of center pivot irrigation systems to vary water application depths across the field, a technology known as variable rate irrigation (VRI). The goal of this study was to provide a geospatial method for potential VRI technology adopters to evaluate control scenarios and potential water savings using freely available datasets. Root zone available water capacity (R) was estimated spatially across two case study fields using the Natural Resources Conservation Service Gridded Soil Survey Geographic Database. The difference in application depth between conventional irrigation (CI) and both sector and zone control VRI was then estimated based on R. Prescription maps were developed to mine undepleted soil water from each irrigation management zone based on a soil water balance approach with a management-allowed depletion of 50%. For CI management, the areal 10th percentile (PCTL) of R for the field was used, while for VRI the 10th PCTL of R for each management zone was used. The highest reduction in irrigation depth was 18 mm where higher values of *R* were estimated; however, field average reductions ranged from 0 to 12 mm. The greatest improvements in pumpage reduction resulted from converting from sector control to zone control, while increasing the angular resolution only had a minor impact. Energy savings generally increased with higher VRI control resolution. Conclusions support previous notions that VRI may result in small pumping water reductions for some fields; however, improved water distribution may be achieved throughout the field.

Keywords: Irrigation management, Precision irrigation, Spatial variability, Variable rate application

Introduction

Water applied for plant survival and production, including horticultural and agricultural purposes, is considered irrigation water. Irrigation withdrawals in 2010 were estimated at 159 billion m^3 per year over 25 Mha in the United States alone (Maupin et al. 2014). As of 2010, irrigation withdrawals in the United States account for about 66% of all freshwater withdrawals excluding thermoelectric power. Nebraska irrigation withdrawals totaled nearly 7.8 billion m^3 in 2010 with the total irrigated land being 3.5 Mha, of which 2.6 Mha were sprinkler irrigated (Maupin et al. 2014). Irrigation water is becoming more limited, whether hydrologically or through regulation, as a result of increasing concern for the sustainability of fresh water resources. Irrigation water use efficiency, which is the ratio between yield increases due to irrigation and the amount of water applied should be improved to increase the sustainability of irrigated agriculture. In addition, irrigation application efficiency, or the percentage of water applied that is actually used by the crop, also should be maximized to promote this sustainability effort. Improved management through site-specific crop management (i.e., precision agriculture) may be more sustainable and efficient than current practices.

Variable rate irrigation (VRI) is a technology developed in recent decades to apply water more efficiently to irrigate crops. VRI has the potential to do so by varying the rate or depth of water applied to different crops and soils within a field (Hedley and Yule 2009; Evans et al. 2013). It has been estimated that pumpage of well-managed conventional irrigation (CI) could be reduced by 25 mm year-1 or more for 13% of the center pivot irrigated fields in Nebraska by using VRI to mine undepleted water in higher root zone available water capacity

(*R*) soils(Lo et al. 2016). Variable rate application of crop inputs has been studied for decades as a method to improve crop input use efficiency (Hedley 2015). Improving irrigation practices to reduce water pumped and lower pump energy requirements has recently become a topic of interest for producers. VRI technology allows producers to apply water precisely in sub-field scale irrigation management zones (IMZs) to improve efficiency (Daccache et al. 2015). Reduced pumping reduces deep percolation and surface runoff, which often carries contaminants from the field to groundwater or surface water.

To use VRI, the producer must define a prescription map and manage VRI throughout the irrigation season to meet crop water needs. Technology advancements have provided the necessary hardware, software and communication systems to successfully manage and apply prescriptions to irrigated fields. The major limitation lies not in the mechanical operation of the pivot but the management of spatial data and writing of prescription maps to address the numerous factors that affect yield and plant-available water (Evans et al. 1996). One necessity for writing a prescription map is defining IMZs. Of the different methods for delineating IMZs, a common one is based on observed changes in soil properties (Lo et al. 2017). The range in *R* determines the number, size and distribution of IMZs (Daccache et al. 2015). *R* is defined as the depth of water between field capacity (FC) and permanent wilting point (WP) within the managed root zone; this is also considered to be the water available for plant uptake. Field capacity is the amount of water in the soil, after the downward flow of water due to gravity that is negligible. Permanent wilting point occurs when plants can no longer readily extract water from the soil (Scherer et al. 1999). Field capacity can be determined with different laboratory techniques where the matric potential of the soil is between −10 kPa and −33 kPa. A good estimate can be determined from field sampling following a thorough wetting event one to three days prior (Martin et al. 1990).

Current VRI options include sector control and zone control. Sector control is the simplest form of VRI; this system has the capability to change irrigation rotation speed throughout the field, thus applying different amounts of water in angular sectors. Different manufacturers offer zone control with various capabilities. Zone control has the capability to pulse sprinklers, either individually or in banks where a group of sprinklers is controlled together. The ability to pulse sprinklers offers the option of varying irrigation application depth along the lateral and as the lateral rotates across the field. Currently, VRI is likely under-utilized with most zone control VRI systems being used to address regions of a field that do not receive irrigation. These regions are often waterways, ponds, roads, drainage ways or rocky outcrops (Evans et al. 2013).

CI for a field cannot adapt to in-field variation in soil texture or terrain since there is no ability to vary rates throughout the field, but variability between fields exists and requires each field to be managed independently. CI is commonly managed for the lowest R regions within the field to prevent under-irrigation (Daccache et al. 2015). VRI has the potential to manage in-field variation. At the sub-field level, many factors may vary, including topography, soil texture, cropping practices (e.g., tillage and soil compaction), fertility differences and localized pest distributions (Kranz et al. 2012; Evans et al. 1996).

Spatial yield maps from precision agriculture technologies have revealed relationships among field properties such as topography and soil physical properties related to water distribution rather than to soil nutrients (Sudduth et al. 1996). Obtaining accurate soil physical properties is challenging, often requiring intense fieldwork and laboratory analyses. As a result, the spatial resolution of these data has been relatively low, historically because of the difficulty of collecting the data. The scale at which they need to be collected has made it impractical to map sub-field variations (Sudduth et al. 2001; Hezarjaribi and Sourell 2007). Understanding geospatial variability in soil texture distribution and how R is related may assist in making site-specific management decisions (Godwin and Miller 2003).

Topography affects the hydrologic response of a rainfall catchment and the available water for crop production. Access to more accurate digital elevation models (DEMs) such as LIDAR has become easier through public datasets and real time kinematic (RTK) GPS elevation data recorded during field operations. Computerized terrain analysis tools have made it possible to readily quantify topographic attributes (Kitchen et al. 2003). Topographic wetness index (TWI; Bevin and Kirkby 1979) is widely used in precision agriculture and has been used in modeling the spatial distribution of soil moisture and surface saturation. Its most common use is to quantify topographic control on hydrological processes. Topography also affects soil formation processes, resulting in erosion of fine sediments and consequent colluvial deposits with higher available water capacity (AWC) at the lower portions of hillslopes. Soil texture and its relationship with AWC have been thoroughly studied and documented. Useful tools have been developed such as pedotransfer functions, which allow for prediction of wilting point and field capacity based on more easily measured properties (i.e., texture, bulk density and soil organic matter), allowing for the determination of AWC (Saxton and Rawls 2006). Additionally, the Gridded Soil Survey Geographic (gSSURGO) Database from the U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) can provide soil property data for a field. Information about soil boundaries and textural properties can lead to further understanding of variability within a field. Although gSSURGO data were not collected with precision agriculture management in mind, the data can be useful for a preliminary analysis of a field site. Thus, several data layers could be used to estimate spatial variability in R across a field; however development of a common geospatial evaluation methodology (as presented in this paper) would allow for comparisons based on in-field variability.

While great advances in irrigation technology have occurred with VRI systems, irrigation decision support systems have not developed at a similar pace. Knowledge of plant available water on a spatial, daily timescale throughout the soil is critical for optimal VRI management. Work has been done on modeling plant available water using a water balance approach or by soil moisture sensing. Using R and soil apparent soil electrical conductivity (ECa), researchers have developed daily soil water status maps that could assist in VRI management (Hedley and Yule 2009). Adoption of VRI has been relatively slow, indicating a need for increased management support and estimates of potential economic impact (Feinerman and Voet 2000; Evans et al. 1996, 2013).

When a producer is considering whether to adopt VRI for a specific field, the potential economic impact depends on the geospatial control scenario used for the prescription map. Previous researchers have developed and evaluated various control scenarios for VRI (Boluwade et al. 2016; Daccache et al. 2015; Haghverdi et al. 2015; Huang et al. 2015), but have not quantified reductions in irrigation pumping and energy use by developing prescription maps based on mining undepleted R. Boluwade et al. (2016) and Haghverdi et al. (2015) compared zone delineation algorithms and determined the optimum number of IMZs for different control scenarios, but did not create prescription maps. Daccache et al. (2015) developed prescription maps based on AWC to simulate the effect of grid resolution on application uniformity within IMZs, but the prescribed irrigation depths were arbitrarily chosen. Huang et al. (2015) developed an economic model to evaluate VRI control scenarios which accounted for ECa, TWI, yield impacts and reductions in pumping costs. However, the effect of AWC on seasonal irrigation was based on production functions. Lo et al. (2016) estimated pumpage reductions from using VRI to mine undepleted *R*, but did not evaluate control scenarios.

Goals and objectives

The goal of this study was to provide a method for potential VRI technology adopters to evaluate potential reductions in irrigation using readily available gSSURGO data for various control scenarios. The proposed method was based on estimating *R* spatially across two case study fields and treating each with CI and both sector and zone control VRI. Specific objectives were to (1) develop *R* maps using gSSURGO data, (2) develop prescription maps based on a soil water balance approach and simulate irrigation events for different irrigation control scenarios (i.e., CI and sector control and zone control VRI), and (3) estimate potential irrigation reductions and energy savings for different levels of VRI control for the study fields.

Materials and methods

Field study site descriptions

Two field locations in Nebraska, USA were identified for VRI control scenario assessment based on publicly available datasets. The first field study site (Field A) consisted of a 42-ha center pivot irrigated field located in Saunders Co., Nebraska (41.1648° N, 96.4304° W) that consisted of Fillmore, Filbert, and Tomek silt loams and Yutan silty clay loam soil types (NRCS 2014). The field has been managed as two 21-ha fields in which crops were rotated on north and south halves (typically soybeans and corn) from year to year in a no-till system (Barker et al. 2017). Some historic earthworks, including a former railway, affect the topography of the field. The 1981–2010 normal annual precipitation for a nearby station was approximately 750 mm (NCEI n.d.).

An additional study field (Field B) was located in Hamilton Co., Nebraska (40.7927° N, 98.1733° W) and consisted of a 25.6-ha field irrigated by a wiper center pivot. This pivot does not travel 360 degrees in one direction but, rather, travels a partial circle and then generally travels in the opposite direction for the next irrigation pass. The field was also on a corn-soybean rotation and was subject to conventional tillage practices. The field consisted of Crete and Hastings silt loam soil types (NRCS 2014) with minimal slopes. The 1981–2010 normal annual precipitation for a nearby station was 680 mm (NCEI n.d.). For both field sites, the seasonal net irrigation requirement is approximately 200 mm for corn and 150 mm for soybean (Sharma and Irmak 2012).

Development of root zone available water capacity maps

The gSSURGO data were used to understand variations in field soil texture properties at each site (Figs. 1, 2). The gSSURGO data were also used to develop *R* maps for the two study fields since *R* could be spatially estimated without the need for field data collection (Lo et al. 2017). The gSSURGO data include AWC values for soil horizons, along with their depth. Previous work done by Lo et al. (2016) summed the AWC to a depth of 1.20 m from gSSURGO (NRCS 2014) to represent the root zone on a 10-m grid which was then resampled to a 1-m grid. This previous work provided access to *R* data layers for the two study fields. For additional details, refer to the methods section of Lo et al. (2016).

VRI prescription maps for mining differences in R

With CI, a field that has spatial variability in *R* is typically managed to avoid stress in the most drought-prone portion of the field (e.g. 10th PCTL of *R*; it would be impractical to manage for the 1st PCTL of *R* assuming a normal distribution of *R*). In this case, some portions of the field will have undepleted soil water (Lo et al. 2016). Undepleted *R* correlates with water stored in the root zone from off-season precipitation that would not be depleted with CI. Therefore, static

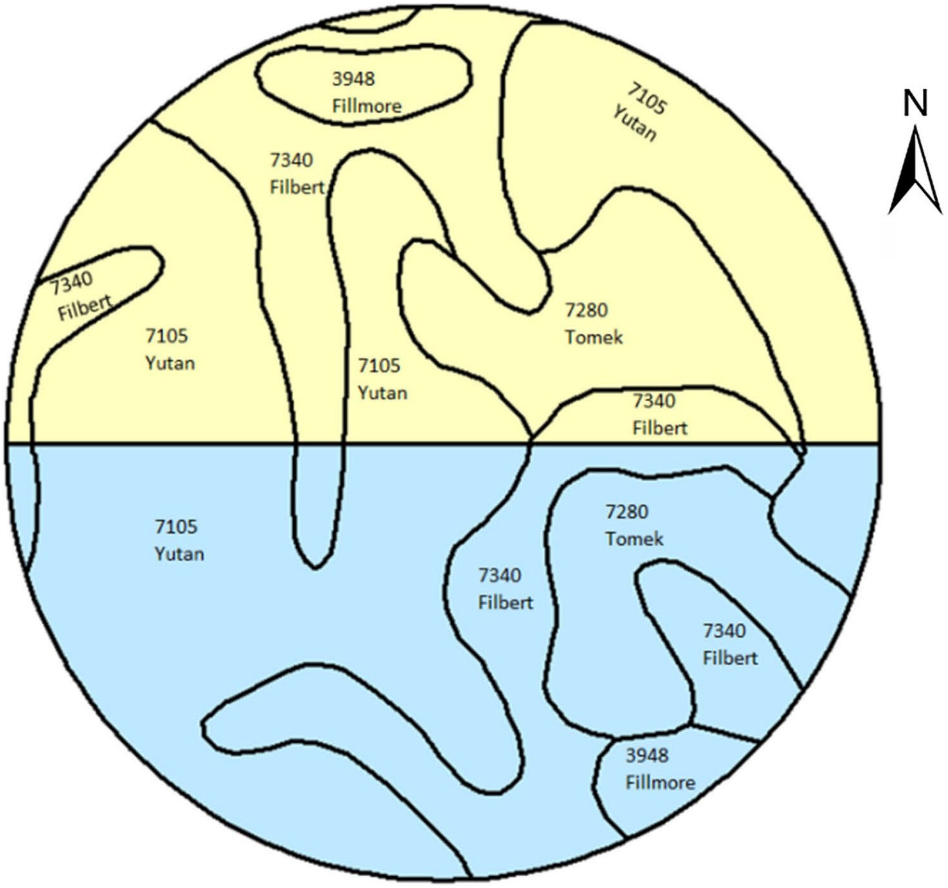


Fig. 1. Field A soils and their corresponding boundaries (NRCS 2014) and the separately managed halves of the field.

prescription maps were developed, similar to Barker et al. (2016), which were used to mine undepleted *R* based on a soil water balance approach to irrigation scheduling. This method is simple and could be easily adopted by producers. With this method, the entire field was assumed to begin the irrigation season with spatially uniform depletion (e.g., the entire field is at field capacity). Spatially uniform ET, drainage, runoff and precipitation were also assumed. The IMZs were defined by a control scenario correlating to irrigation equipment capabilities, with IMZ dimensions of angle and length along the pivot lateral. Utilizing the *R* map calculated from gSSURGO, a single *R* value for each IMZ was selected by using the 10th PCTL *R* for the IMZ. Managing irrigation based on the 10th PCTL *R* resulted in 90% of the IMZ receiving adequate irrigation (Lo et al. 2016).

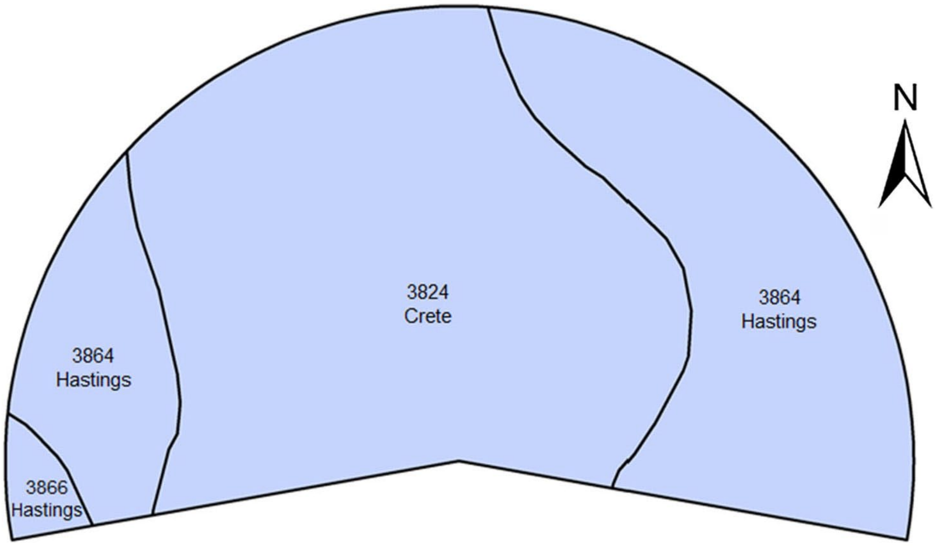


Fig. 2. Field B soils and their corresponding boundaries (NRCS 2014).

For a given control scenario, the minimum number of irrigation events needed to mine the differences in R throughout the field was calculated based on the static map of R for that control scenario (Eq. 1). The minimum R (R_{min}) is the R for the IMZ with the lowest R; therefore this IMZ would be the first to need irrigation in order to avoid crop water stress. The IMZ with the maximum R (R_{max}) would have the most precipitation stored in the root zone and would be the last IMZ to need irrigation.

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

where N = minimum number of irrigation events
R_{max} = maximum R assigned to an IMZ (mm)
R_{min} = minimum R assigned to an IMZ (mm)
MAD = management allowed depletion (fraction)
$I_{\text{net,max}}$ = maximum desired net depth for a single irrigation event (mm)

The N would be rounded up to the nearest integer. A static (or unchanging) prescription map was developed, with the irrigation depth for each IMZ calculated as:

$$I_{net,p} = \frac{1}{N}(R_{max} - R_{10th-PCTL,I}) \times MAD \tag{2}$$

where $I_{\text{net,p}}$ = prescribed net irrigation depth for one application event (mm)

$R_{\text{10th}-PCTL,\text{i}}$ = the 10th PCTL of all R in the ith IMZ (mm)

The resulting prescription map (a composite of $I_{\text{net,p}}$ for all IMZs) would remain unchanged until the differences in R between IMZs had been mined (a process that would take N irrigation events). Once the differences had been mined, CI was assumed to be practiced. Simulation of irrigation timing was not needed for the present analysis. In practice, the limiting IMZ (i.e., with the lowest R) would be selected for irrigation timing. Barker et al. (2016, 2017) discussed further operational considerations for applying this methodology and monitoring soil water content for VRI, which are not detailed here. In this study, this method was applied assuming a fully developed root zone.

Development of VRI center pivot control scenarios

Commercially available options for VRI control resolution vary by manufacturer. For this project, sector control was limited to 2°, 5°, and 10° resolution, while zone control added irrigation zones to the sectors at the scales of lateral spans and twice the wetted sprinkler diameter (taken to be 12.5 m), which was assumed to be the smallest independent scale following the work of Hillyer and Higgins (2014). Various irrigation control scenario polygons were developed by building polygons in AutoCAD (Autodesk, San Rafael, CA, USA) to simulate VRI IMZs. An example of the pivot polygon control scenarios for 10° sectors, and the corresponding zone control scenarios, is displayed in Fig. 3. It is important to note that the innermost zone was removed due to the lack of data for the zone scenarios with a distance of 12.5 m. The control scenarios were used to sample the spatial R maps developed from the gSSURGO data. Methods used to complete the sampling procedure in ArcGIS 10.2 (ESRI, Redlands, CA, USA) were first defined by developing a manual procedure in ArcGIS. Once the methodology was finalized (Fig. 4), programming code was written in Python to automate the process.

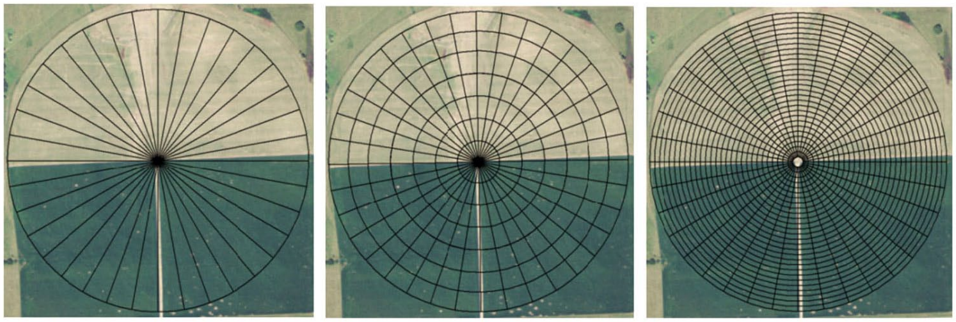
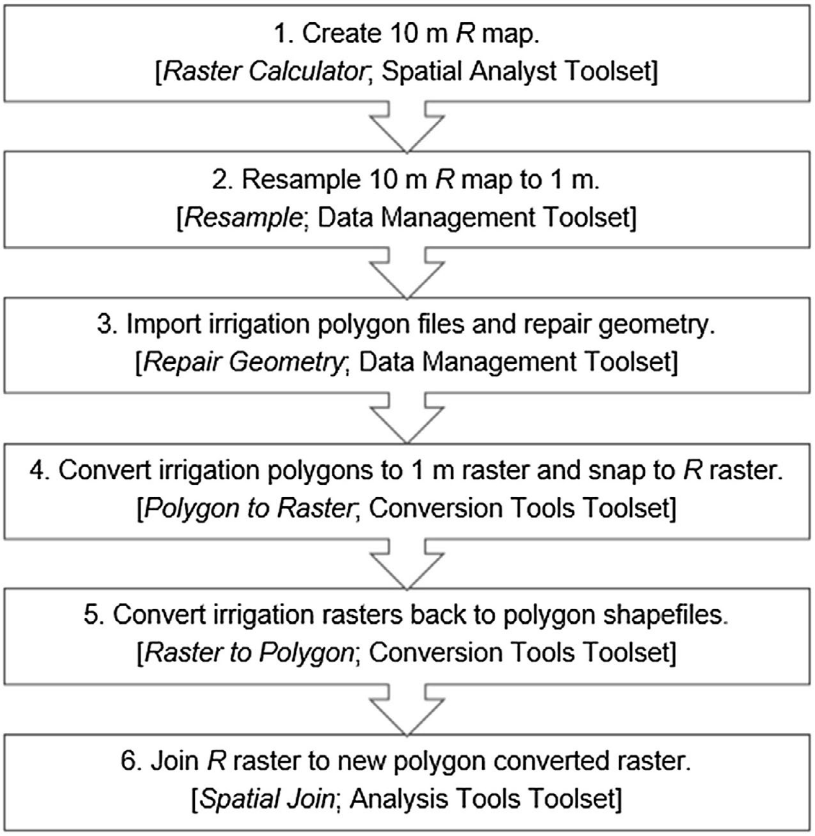


Fig. 3. Pivot polygon control scenarios for 10° sectors, including sector (left), span (middle), and 12.5 m laterals (right).



1. Create 10 m *R* map.
[*Raster Calculator*, Spatial Analyst Toolset]

2. Resample 10 m *R* map to 1 m.
[*Resample*; Data Management Toolset]

3. Import irrigation polygon files and repair geometry.
[*Repair Geometry*; Data Management Toolset]

4. Convert irrigation polygons to 1 m raster and snap to *R* raster.
[*Polygon to Raster*; Conversion Tools Toolset]

5. Convert irrigation rasters back to polygon shapefiles.
[*Raster to Polygon*; Conversion Tools Toolset]

6. Join *R* raster to new polygon converted raster.
[*Spatial Join*; Analysis Tools Toolset]

Fig. 4. Steps used in ArcGIS to sample geospatial data layers [brackets contain specific ESRI Toolsets].

Seasonal reductions in irrigation pumping

Simulated irrigation was based on a MAD of 50%, and it was assumed that the entire field was at field capacity at the beginning of the growing season. CI was simulated based on irrigating when the field's 10th PCTL *R* reached MAD. It was assumed that neither irrigation nor precipitation caused any zone to exceed field capacity; in other words, zero in-season deep percolation was assumed. The seasonal irrigation depth can be understood with Eq. 3:

$$I_{net,CI} = ET_{c} - P_{eff} - R_{10th-PCTL,field} \times MAD \quad (3)$$

where $I_{\mathrm{net,CI}}$ = seasonal net irrigation for CI (mm)
$\mathrm{ET_c}$ = seasonal crop evapotranspiration (mm)
$\mathrm{P_{eff}}$ = seasonal effective precipitation (mm)
$R_{\mathrm{10th-PCTL,field}}$ = the 10th PCTL of all *R* in the field (mm)

To simulate VRI, irrigation for the control scenarios was based on irrigating each zone individually which did not account for edge effects. It was assumed that the static prescription maps (Eq. 2) were used to mine undepleted *R* once during the season. If the soil water profile was refilled by rain mid-season, it might be possible to mine undepleted *R* again, resulting in additional reductions in pumping. Seasonal net irrigation for VRI was calculated with Eq. 4:

$$I_{net,I} = \mathrm{ET_c} - \mathrm{P_{eff}} - \mathrm{R_{10th-PCTL,i}} \times \mathrm{MAD} \quad (4)$$

where $I_{\mathrm{net,i}}$ = seasonal net irrigation for the *i*th IMZ (mm)
$R_{\mathrm{10th\text{-}PCTL,i}}$ = the 10th PCTL of all *R* in the *i*th IMZ (mm)

As mentioned, the 10-m *R* grid was resampled to 1 m; therefore each grid cell was made up of 100 points of the same value. This allowed for improved sampling resolution near zone boundaries compared with using 10-m grid cells. To quantify potential irrigation reduction with a VRI approach, the VRI control scenarios were compared with CI by combining Equations 3 and 4, resulting in Equation 5. A negative reduction in irrigation would indicate that VRI increased the water application above the CI application for that IMZ. To determine the irrigation reduction over the entire field, the area weighted average irrigation reduction (Eq. 5) was quantified.

$$\Delta I_{net,i} = I_{net,CI} - I_{net,i} = (R_{10th\mathrm{PCTL},i} - R_{10th\mathrm{PCTL},field}) \times MAD \tag{5}$$

where $\Delta I_{\mathrm{net,i}}$ = depth of reduction in seasonal irrigation for the *i*th IMZ (mm).

$$\Delta I_{net,field} = \sum_{\mathrm{i}}^{\mathrm{m}} \Delta I_{net,i} \times \frac{\mathrm{n_i}}{\mathrm{n_{total}}} \tag{6}$$

where $\Delta I_{\mathrm{net,field}}$ = depth of reduction in seasonal net irrigation for the field (mm).
m = number of IMZs in the field
$\mathrm{n_i}$ = number of 1-m cells in the *i*th IMZ
$\mathrm{n_{total}}$ = total number of 1-m cells in the field

Energy analysis

An energy analysis was performed to quantify potential savings directly related to the depth of water pumped using an electric motor. Gross pumpage reduction was determined by:

$$\Delta I_{g,field} = \frac{\Delta I_{net,field}}{\mathrm{E_a}} \tag{7}$$

where $\Delta I_{g,\mathrm{field}}$ = depth of reduction in seasonal gross irrigation for the field (mm)
E_{a} = irrigation application efficiency (fraction)

The E_a was assumed to be 0.85 for center pivot irrigation. A variable frequency drive was not considered. Pumping well information was obtained through the Registered Groundwater Wells Data Retrieval (Nebraska Department of Natural Resources 2015) along with irrigation operating requirements. Methods for calculating the energy usage for pumping water were chosen based on the findings of Martin et al. (2010). The cost of a kWh of electricity was estimated to be $0.10 USD and pump efficiency was determined from the manufacturer pump curves.

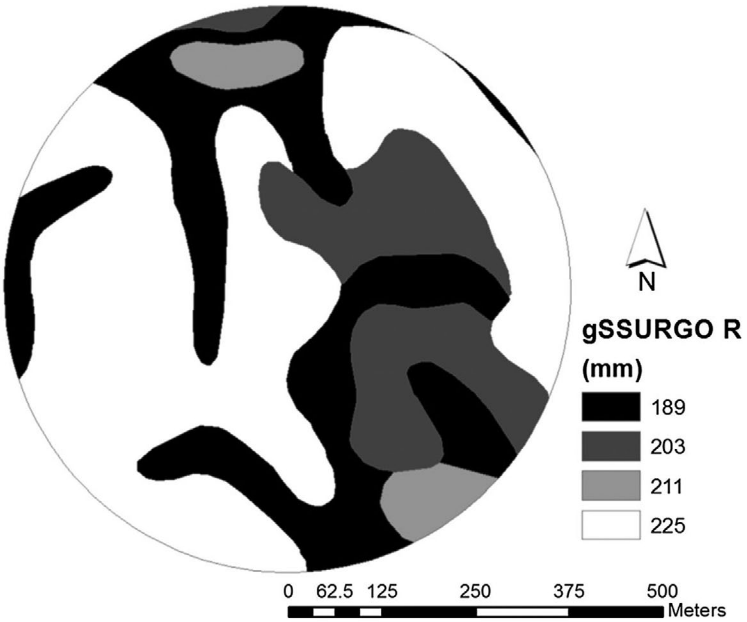


Fig. 5. *R* (mm) map created for Field A based on gSSURGO data downloaded from NRCS (2014).

Results and discussion

The *R* map created for Field A based on the gSSURGO data layer is illustrated in Fig. 5. It should be noted that only four distinct values were estimated based on this method. The histogram highlights the distribution of *R* versus field area for Field A (Fig. 6). These data indicate that substantial portions of the field may contain soil profiles where *R* values differ by more than 25 mm. Based on the amount of variation exhibited within this field, VRI could prove useful in addressing this imbalance in *R*.

Field B *R* results based upon gSSURGO showed three varying regions throughout the field with a total range in *R* from 210 to 229 mm (Fig. 7). The lowest *R* (210 mm) contained the most area in the field (Fig. 8). VRI opportunities were presented to address the different water needs among soils with different *R* (about 20 mm different) to mine the water as effectively as possible.

VRI prescription maps were developed for both field sites. For Field A, the $R_{10\text{th-}PCTL,\text{i}}$ assigned to each IMZ ranged from 189 to 225 mm for all control scenarios. Based on this range, a prescription map would

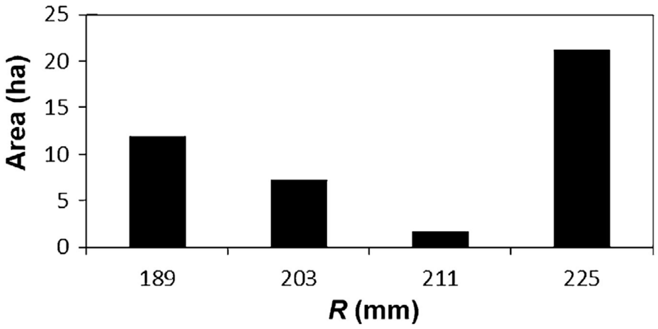


Fig. 6. Field A area represented for the corresponding gSSURGO defined *R*

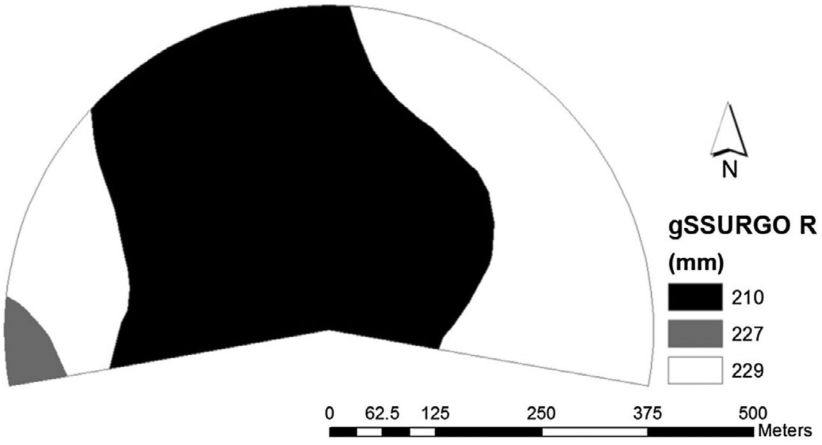


Fig. 7. *R* (mm) map created for Field B based on gSSURGO data downloaded from NRCS (2014).

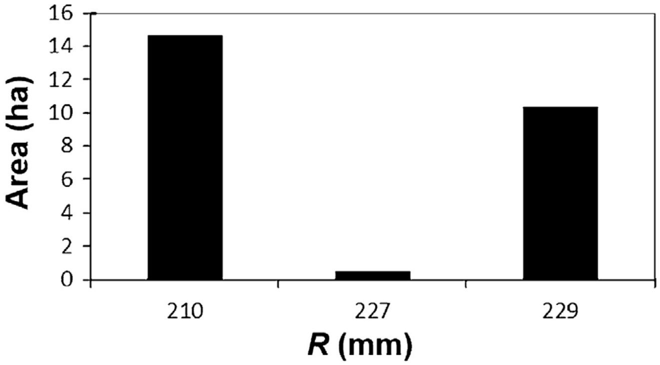


Fig. 8. Field B area represented for the corresponding gSSURGO defined *R*.

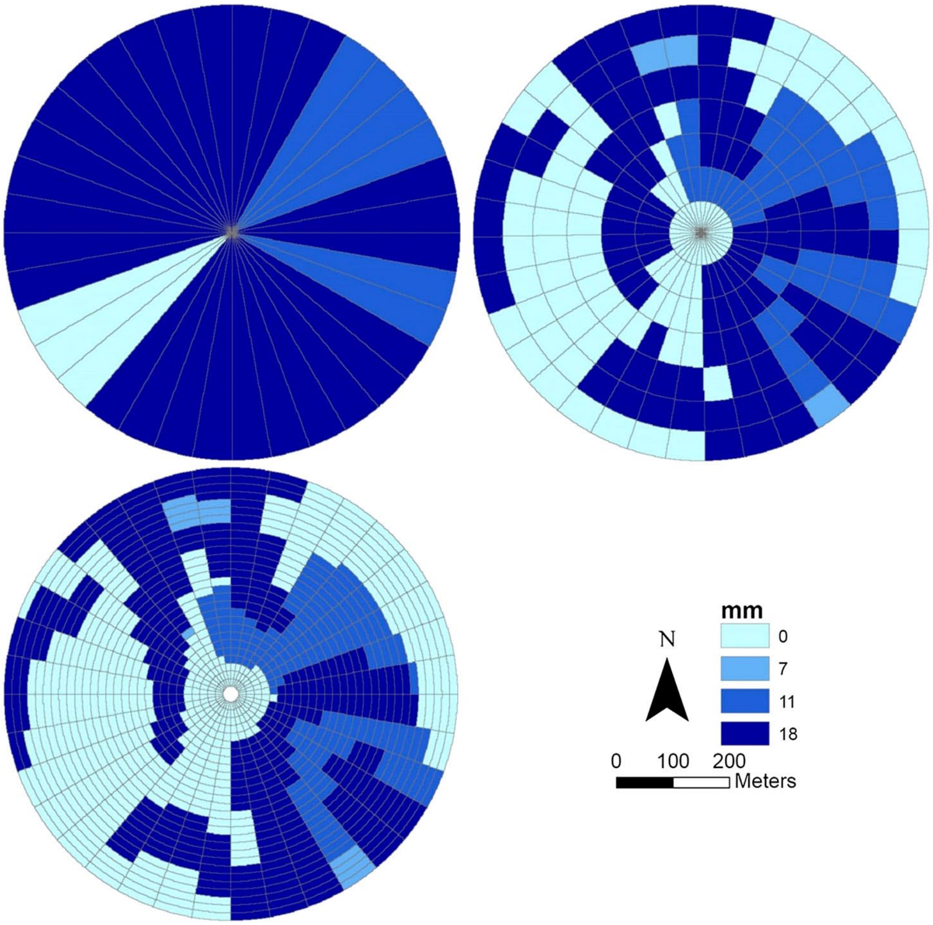


Fig. 9. Irrigation prescription maps (*I*net,p) for Field A for 10° control scenarios: sector (top left), tower-zone (top right), and 12.5 m lateral zone (bottom left).

only need to be used once during the season (N = 1) to mine the undepleted *R* if the $I_{\mathrm{net,max}}$ was 25 mm (Eq. 1). The $I_{\mathrm{net,p}}$ for the prescription maps ranged from zero to 18 mm (Fig. 9). The IMZs with no irrigation were in the soils with the highest *R*; IMZs with the maximum $I_{\mathrm{net,p}}$ were in the soils with the lowest *R,* which would be the first soils to reach MAD and trigger the irrigation event. As mentioned previously, after the prescription map was applied, it was assumed that irrigation was spatially uniform for the rest of the season. This method is focused on managing for spatial variability in soil properties; updating prescription maps throughout the season based on spatio-temporal variability in crop growth and evapotranspiration (e.g. Stone et al. 2016) was outside the scope of this research.

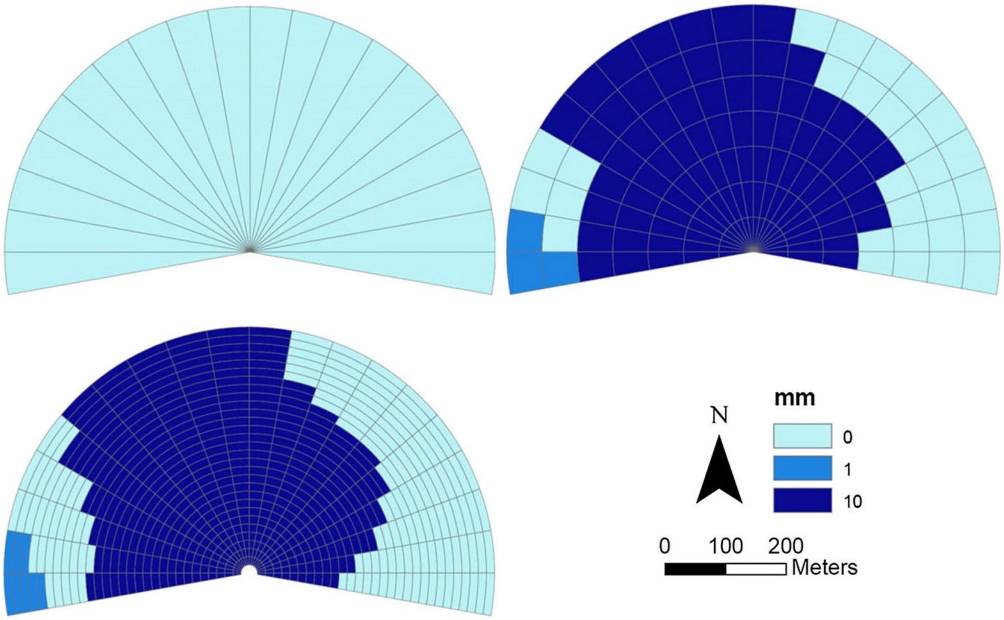


Fig. 10. Irrigation prescription maps (*I*net,p) for Field B for 10° control scenarios: sector (top left), tower zone (top right), and 12.5 m lateral zone (bottom left)

For Field B, the $R_{10th\text{-}PCTL,i}$ assigned to each IMZ ranged from 210 to 229 mm for the zone control scenarios, resulting in a one-time use of the prescription map during the season (N = 1). For sector control, however, the $R_{10th\text{-}PCTL,i}$ was 210 mm for all sectors, indicating that sector control did not enable the producer to mine any undepleted *R* (N = 0, Eq. 1). The $I_{net,p}$ for the prescription maps ranged from zero to 10 mm (Fig. 10). Due to the lack of range in $R_{10th\text{-}PCTL,i}$, the sector control prescription map resulted in no irrigation depth changes (i.e., no undepleted *R* could be mined using sector control or (Eq. 2) had no solution), thus indicating that prescription map was non-applicable for this scenario.

The VRI seasonal irrigation was compared with CI seasonal irrigation, which allowed for calculation of $\Delta I_{net,i}$ for each IMZ for Field A (Figs. 11, 12). For Field A (Fig. 11), each control scenario contained regions throughout the field that required less water than the CI applied. The figures visually offer further understanding on how increased control offers more precise water application. The easiest and largest difference to notice was between the sector control map compared with the tower-zone control. The increase in IMZ definition from the

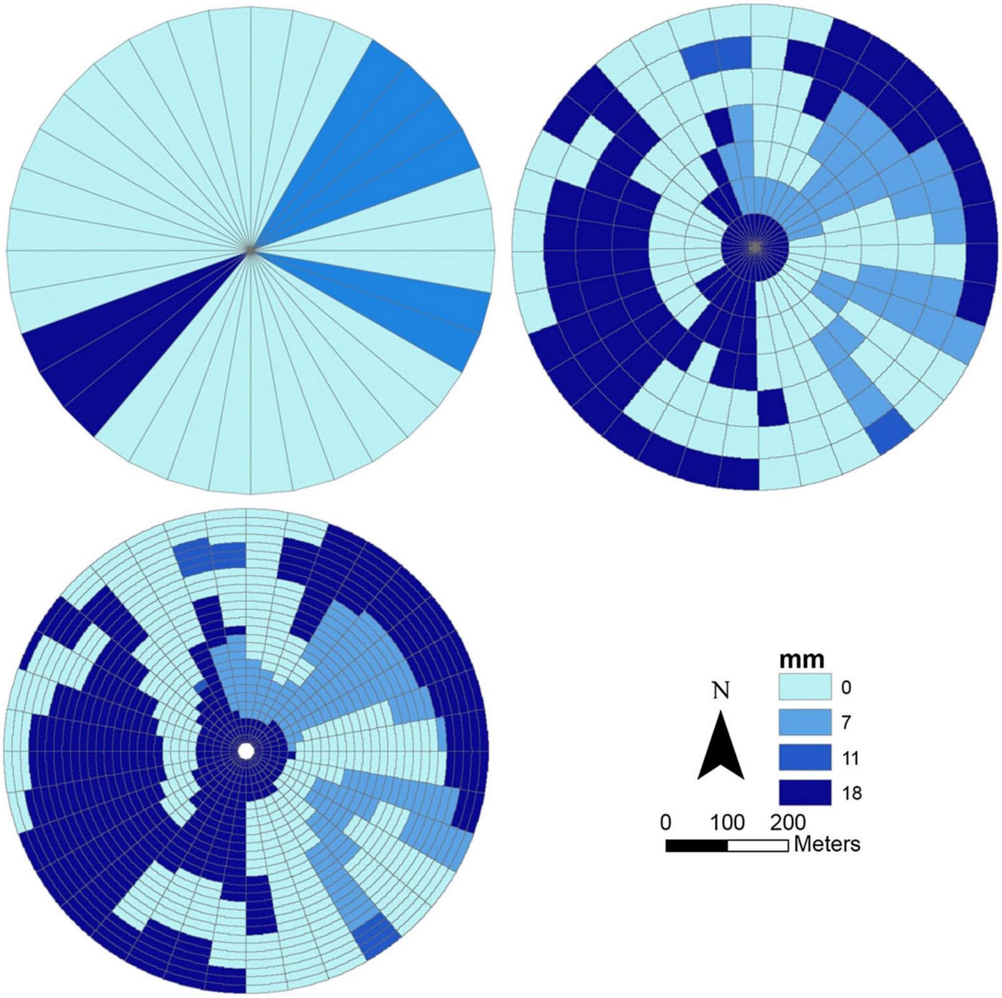


Fig. 11. Depth of reduction in irrigation (ΔInet,i) for Field A for 10° control scenarios: sector (top left), tower-zone (top right), and 12.5 m lateral zone (bottom left)

sector control to zone control further defines the target areas within soil map units. For zone control, decreasing the angle of resolution allowed for more precise on/off control of irrigation sprinklers in order to water the edges of different soil map units more effectively and efficiently (not shown). The increase in zone control resolution from a pivot span to 12.6 m has smaller gains than stepping from sector control to zone control.

Similar geospatial data files for irrigation depth reductions were generated for Field B (Fig. 12) which show that smaller depths could be applied strategically across this field. Decreasing the application

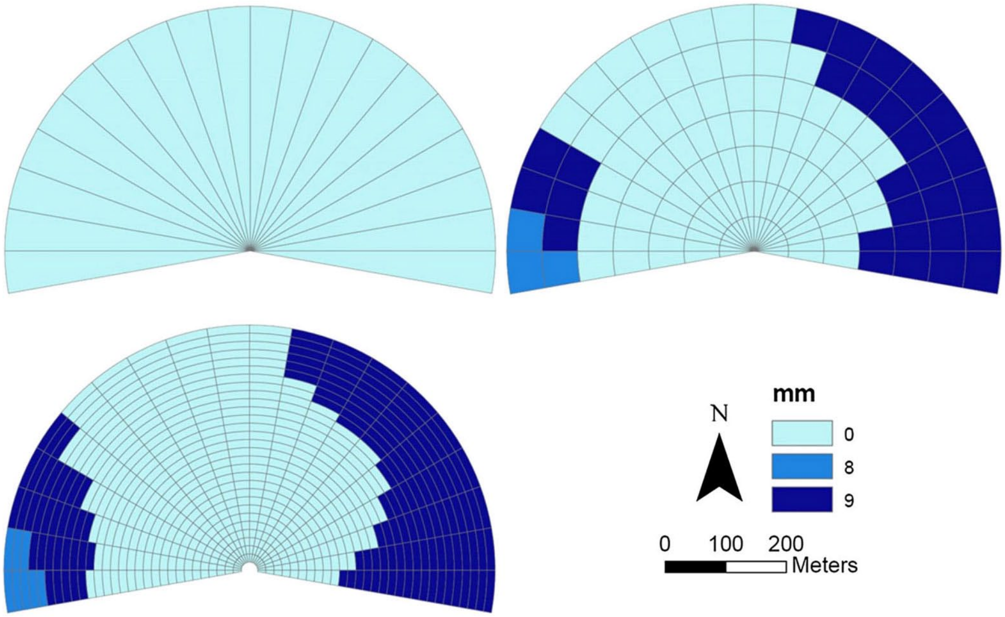


Fig. 12. Depth of reduction in irrigation ($\Delta I\text{net,i}$) for Field B for 10° control scenarios: sector (top left), tower-zone (top right), and 12.5 m lateral zone (bottom left)

depth in some areas allowed for increased management in water application, which might result in more efficient water use. Sector control did not result in any pumpage reduction since the $R_{\text{10th-PCTL,field}}$ was 210 mm and the $R_{\text{10th-}PCTL,\text{i}}$ was 210 mm for all IMZs (Eq. 5). Similar to what was discovered with Field A, the increased water savings from sector control to zone control allows for additional management options and decisions for water application practices. The highest $\Delta I_{\text{net,i}}$ occurred in portions of the field with the highest R, which had the most undepleted soil water to be mined with VRI.

Energy analysis

To estimate energy savings, the $\Delta I_{\text{g,field}}$ was calculated for each control scenario. Results for Field A indicated that the prescription maps based on gSSURGO data resulted in reductions in pumping compared with CI (Table 1). The greatest energy savings were around 1100 kWh per year, which resulted from the finest level of irrigation control tested (2° by 12.5 m lateral zone control). Increasing the angle of resolution from 10° to 2° only resulted in a small increase in $\Delta I_{\text{g,field}}$, but

Table 1. Field A annual energy and economic impacts of reduced pumpage with VRI.

Pivot control scenario	Pumpage reduction ($\Delta I_{\mathrm{g,field}}$, mm)	Pumpage reduction (m^3)	Energy savings (kWh)	Cost difference ($)
2° Sector	3.3	1400	320	32
2° × Span	9.8	4100	970	97
2° × 12.5 m Lateral	12	4900	1100	120
5° Sector	3.4	1400	340	34
5° × Span	9.4	4000	940	93
5° × 12.5 m Lateral	11	4700	1100	110
10° Sector	3.1	1300	310	31
10° × Span	9.3	3900	920	92
10° × 12.5 m Lateral	10	4300	1000	100

increasing the lateral resolution from sector control to span control tripled the $\Delta I_{\mathrm{g,field}}$. Sector control was only able to achieve 28–31% of the pumpage reduction achieved by 12.5 m lateral zone control, although equipment costs are much lower for sector control than zone control. Sector control costs less than $5000 and is free on some new pivot panels; zone control VRI systems have been estimated to be in the range of $200–$550 ha$_{-1}$ (Evans et al. 2013).

For Field B, reductions in pumping were expected for zone control but not for sector control (Table 2). Energy savings generally increased with improved VRI resolution. For this application, results indicated the 2° by 12.5 m lateral zones again resulted in the highest energy savings, at 310 kWh. Moderate improvements were observed for increasing zone control from span to 12.5 m lateral, but the largest improvements were from investing in zone control technology compared to sector control. Increasing the angular resolution only had a minimal impact.

The economic impact from energy savings for these two field sites is not likely enough to justify implementing a zone control VRI system. For comparison, the seasonal energy cost for 230 mm of gross irrigation would be approximately $2300 for Field A and $1500 for Field B. Pumpage reductions would be greater if the soil profile is refilled by precipitation in the middle of the irrigation season. Costs savings are likely to be the highest in fields with a large degree of spatial soil variability, large pumping lift (depth to the water source), and high energy costs (Lo et al. 2016). An economic analysis of the amount of pumping reduction (and energy cost savings) required to pay for a VRI system was presented in Lo et al. (2016). If water limitations that could

Table 2. Field B annual energy and economic impacts of reduced pumpage with VRI.

Pivot control scenario	Pumpage reduction ($\Delta I_{g,field}$, mm)	Pumpage reduction (m³)	Energy savings (kWh)	Cost difference ($)
2° Sector	0.0	0	0	0
2° × Span	4.1	1000	270	27
2° × 12.5 m Lateral	4.5	1200	310	31
5° Sector	0.0	0	0	0
5° × Span	4.0	1000	270	27
5° ×12.5 m Lateral	4.5	1100	300	30
10° Sector	0.0	0	0	0
10° ×Span	3.9	1000	270	27
10° ×12.5 m Lateral	4.3	1100	290	29

reduce yield are put into practice, water application strategies might become more significant. Even though this analysis did not support implementing VRI at these field sites, the methodology developed for the simulations could be applied to other fields as a preliminary analysis. This analysis did not account for the impact of VRI on yield (e.g. minimize yield losses due to over irrigation), which could have a more significant economic impact than pumping reductions.

Further work is needed to test the methods produced in this paper by utilizing VRI systems in the field. The authors recognize that gSSURGO data may not generate *R* maps of the highest resolution. Additional studies are planned to address the potential for more intensely sampled data (e.g., EC_a, terrain, and soil moisture measurements) for generating *R* maps, and determine how these maps might further inform the methodology presented here for VRI control resolution planning.

Conclusions

Data from NRCS gSSURGO maps were used to develop *R* maps. A total of nine irrigation control scenarios were analyzed (2°, 5°, and 10° radial sectors combined with sector control and zone control with lateral zones at the span length and 12.5 m). The IMZ irrigation requirements determined from the polygon files were compared by simulating CI where the 10th-PCTL *R* of the field was used to determine irrigation MAD. Minimal water savings were quantified for the fields, but the study demonstrated the ability of VRI to spatially distribute applied water depth throughout the field to better manage the different zones. Therefore, IMZs received the same or less water than was applied with the CI treatment. The highest reductions in irrigation depth were 18 and 9 mm for Fields A and B, respectively, in locations where higher values of *R* were estimated. The greatest improvements in pumpage reduction resulted from converting from sector control to zone control, while increasing the angular resolution only had a minor impact.

Acknowledgments — This research was supported by the Water, Energy and Agriculture Initiative, which was made possible with funding from the Nebraska Corn Board, the Nebraska Soybean Board, the Agricultural Research Division at the University of Nebraska–Lincoln (UNL) and Nebraska Public Power District through the Nebraska Center for Energy Sciences Research at UNL.

The authors declare they have no conflicts of interest.

References

Barker, J. B., Franz, T. E., Heeren, D. M., Neale, C. M. U., & Luck, J. D. (2017). Soil water content monitoring for irrigation management: A geostatistical analysis. *Agricultural Water Management, 188,* 36–49. https://doi.org/10.1016/j.agwat.2017.03.024

Barker, J. B., Heeren, D. M., & Neale, C. M. U. (2016). Perspectives on VRI prescription map development with satellite imagery. In Proceedings of the 28th Annual Central Plains Irrigation Conference (pp. 59–67). Colby, KS, USA: Central Plains Irrigation Association.

Beven, K. J., & Kirkby, M. J. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Journal, 24*(1), 43–69.

Boluwade, A., Madramootoo, C. & Yari, A. (2016). Application of unsupervised clustering techniques for management zone delineation: Case study of variable rate irrigation in Southern Alberta, Canada. *Journal of Irrigation and Drainage Engineering, 142*(1). http://ascelibrary.org/doi/10.1061/%28ASCE%29IR.1943-4774.0000936

Daccache, A., Knox, J. W., Weatherhead, E. K., Daneshkhah, A., & Hess, T. M. (2015). Implementing precision irrigation in a humid climate—Recent experiences and on-going challenges. *Agricultural Water Management, 147,* 135–143. https://doi.org/10.1016/j.agwat.2014.05.018

Evans, R., Han, S., & Kroeger, M. (1996). Precision center pivot irrigation for efficient use of water and nitrogen. In P. C. Robert, R. H. Rust, & W. E. Larson (Eds.), *Precision agriculture* (pp. 75–84). Madison, WI, USA: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Evans, R. G., LaRue, J., Stone, K. C., & King, B. A. (2013). Adoption of site-specific variable rate sprinkler irrigation systems. *Irrigation Science, 31,* 871–887.

Feinerman, E., & Voet, H. (2000). Site-specific management of agricultural inputs: An illustration for variable-rate irrigation. *European Review of Agricultural Economics, 27*(1), 17–37.

Godwin, R. J., & Miller, P. C. (2003). A review of the technologies for mapping within-field variability. *Biosystems Engineering, 84*(4), 393–407.

Haghverdi, A., Leib, B. G., Washington-Allen, R. A., Ayers, P. D., & Buschermohle, M. J. (2015). Perspectives on delineating management zones for variable rate irrigation. *Computers and Electronics in Agriculture, 117,* 154–167. https://doi.org/10.1061/j.compag.2015.06.019

Hedley, C. (2015). The role of precision agriculture for improved nutrient management farms. *Journal of the Science of Food and Agriculture, 95*(1), 12–19. https://doi.org/10.1002/jsfa.6734

Hedley, C. B., & Yule, I. J. (2009). Soil water status mapping and two variable-rate irrigation scenarios. *Precision Agriculture, 10,* 342–355.

Hezarjaribi, A., & Sourell, H. (2007). Feasibility study of monitoring the total available water content using non-invasive electromagnetic induction-based and electrode-based soil electrical conductivity measurements. *Irrigation and Drainage, 56*(1), 53–65.

Hillyer, C. C., & Higgins, C. W. (2014). A demonstration of energy and water savings potential of variable-rate irrigation. Paper No. 141914755. St. Joseph, MI, USA: ASABE.

Huang, H. H., Adamchuk, V. I., Madramootoo, C., & Yari, A. (2015). Economic optimization of the levels of control in variable rate irrigation (VRI). Paper No. 12147596 in 2015 ASABE/IA Irrigation Symposium: Emerging Technologies for Sustainable Irrigation—A Tribute to the Career of Terry Howell, Sr. Conference Proceedings. St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/irrig.20152147596

Kitchen, N. R., Drummond, S. T., Lund, E. D., Sudduth, K. A., & Buchleiter, G. W. (2003). Soil electrical conductivity and topography related to yield for three contrasting soil-crop systems. *Agronomy Journal, 95,* 483–495.

Kranz, W. L., Evans, R. G., Lamm, F. R., O'Shaughnessy, S. A., & Peters, R. T. (2012). A review of mechanical move sprinkler irrigation control and automation technologies. *Applied Engineering in Agriculture, 28*(3), 389–397.

Lo, T., Heeren, D. M., Martin, D. L., Mateos, L., Luck, J. D., & Eisenhauer, D. E. (2016). Pumpage reduction by using variable rate irrigation to mine undepleted soil water. *Transactions of the ASABE, 59*(5), 1285–1298. https://doi.org/10.13031/trans.59.11773

Lo, T., Heeren, D. M., Mateos, L., Luck, J. D., Martin, D. L., Miller, K. A., et al. (2017). Field characterization of field capacity and root zone available water capacity for variable rate irrigation. *Applied Engineering in Agriculture, 33*(4), 559–572. https://doi.org/10.13031/aea.11963

Martin, D., Kranz, W., Dorn, T., Melvin, S., & Corr, A. (2010). Reducing the cost of pumping irrigation water. In Proceedings of the 22nd Annual Central Plains Irrigation Conference (pp. 41–50). Colby, KS, USA: Central Plains Irrigation Association.

Martin, D. L., Stegman, E. C., & Freres, E. (1990). Irrigation scheduling principles. In G. L. Hoffman, T. A. Howell, & K. H. Solomon (Eds.), *Management of farm irrigation systems* (pp. 155–372). St. Joseph, MI, USA: American Society of Agricultural and Biological Engineers.

Maupin, M. A., Kenny, J. F., Hutson, S. S., Lovelace, J. K., Barber, N. L., & Linsey, K. S. (2014). Estimated use of water in the United States in 2010. Circular 1405. Reston, VA: U.S. Department of the Interior, U.S. Geological Survey. Retrieved 13 July, 2015, from http://pubs.usgs.gov/circ/1405/pdf/circ1405.pdf

Nebraska Department of Natural Resources. (2015). Registered Groundwater Wells Data Retrieval. Retrieved 23 October 2017 from http://nednr.nebraska.gov/dynamic/wells/Menu.aspx

NRCS. (2014). Gridded Soil Survey Geographic (gSSURGO) Database by state. Washington, DC: Natural Resources Conservation Service. Retrieved 13 July 2015 from: https://gdg.sc.egov.usda.gov/GDGOrder.aspx

Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal, 70*(5), 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Scherer, T. F., Kranz, W., Pfost, D., Werner, H., Wright, J. A., & Yonts, C. D. (1999). *Sprinkler irrigation systems*. Ames, IA, USA: MidWest Plan Service.

Sharma, V., & Irmak, S. (2012). Mapping spatially interpolated precipitation, reference evapotranspiration, actual crop evapotranspiration, and net irrigation requirements in Nebraska: Part II. Actual crop evapotranspiration and net irrigation requirements. *Transactions of the ASABE, 55*(3), 923–936. https://doi.org/10.13031/2013.41524

Stone, K. E., Bauer, P. J., & Sigua, G. C. (2016). Irrigation management using an expert system, soil water potentials, and vegetative indices for spatial applications. *Transactions of the ASABE, 59*(3), 941–948. https://doi.org/10.13031/trans.59.11550

Sudduth, K. A., Drummond, S. T., Birrell, S. J., & Kitchen, N. R. (1996). Analysis of spatial factors influencing crop yield. In P. C. Robert, R. H. Rust, & W. E. Larson (Eds.), Proceedings of the 3rd International Conference on Precision Agriculture (pp. 129–140). Madison, WI, USA: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

Sudduth, K. A., Drummond, S. T., & Kitchen, N. R. (2001). Accuracy issues in electromagnetic induction sensing of soil electrical conductivity for precision agriculture. *Computers and Electronics in Agriculture, 31,* 239–264.