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Tsz Him Lo
University of Nebraska-Lincoln, tszhimlo@huskers.unl.edu

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

Luciano Mateos
Instituto de Agricultura Sostenible

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

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

See next page for additional authors

Authors
Tsz Him Lo, Derek M. Heeren, Luciano Mateos, Joe D. Luck, Derrel L. Martin, and Dean E. Eisenhauer

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2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Potential Irrigation Reductions From Increasing Precipitation Utilization With Variable Rate Irrigation

Tsz Him Lo[1], Derek M. Heeren[1], Luciano Mateos[2], Joe D. Luck[1], Derrel L. Martin[1], and Dean E. Eisenhauer[1]

1 Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln, NE, USA

2 Instituto de Agricultura Sostenible, CSIC, Córdoba, Spain

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Abstract. *Much of the previous research quantifying the potential benefits of variable rate irrigation (VRI) consists of case studies with simulations using data from small numbers of intensely sampled fields. In this study, an indicator of the amount of root zone available water capacity that is unutilized by uniform rate irrigation was calculated for 49,224 center pivot irrigated fields in Nebraska using publicly available data exclusively. Based on the values of this indicator, potential seasonal irrigation reductions from increasing precipitation utilization with VRI were estimated to be high for a small fraction of analyzed center pivots but low on a regional scale. At current VRI and energy prices, pumping cost savings alone may fail to justify VRI adoption for most analyzed center pivots. Although the prevalence of center pivots with high indicator values differed among counties and among soil associations, ruling out with reasonable confidence the occurrence of either low or high indicator values in a county or soil association might be difficult. The study hopes to inform producers considering VRI and other entities interested in the potential impact of this particular application of VRI.*

Keywords. *center pivot, GIS, Nebraska, precision agriculture, site-specific, variable rate irrigation, water management.*

Introduction

Variable rate irrigation (VRI) is, in the words of Evans et al. (2013), “the ability to spatially vary water application depths across a field to address specific soil, crop, and/or other conditions”. For center pivots, VRI is currently achieved by varying the fraction of time that the outermost tower is moving (i.e., “speed control”) and/or the fraction of time that each sprinkler or bank of sprinklers is turned on (i.e., “zone control”). Like other precision agricultural technologies, VRI facilitates the adaptation of management to known field heterogeneity and offers

opportunities for improved profitability and environmental stewardship, such as:

- variable rate chemigation of fertilizers and pesticides;
- irrigation of crops grown concurrently in the same field but with diverse water requirements due to differences in planting dates, maturity lengths, or even species;
- reduction of application intensities over sectors with poor infiltration capacity when switching to sprinklers with larger wetted diameters is impractical or not preferred;
- avoidance of over-irrigation, which can damage yield due to promotion of plant diseases, decrease in nutrient availability, and limited root growth and function (Irmak, 2014); and
- transfer of excess irrigation water from fully irrigated soils to deficit irrigated soils for yield-increasing transpiration when water supply is inadequate for full irrigation throughout the field.

However, an appropriate way to predict the potential magnitude of VRI's proposed benefits on farmers' fields has not been developed. Previous research quantified some of VRI's benefits on several intensely studied fields by conducting simulations (Nijbroek et al., 2003; DeJonge et al., 2007; Hedley and Yule, 2009) or field experiments (King et al., 2006; Khalilian et al., 2008; Hillyer and Higgins, 2014). Despite the substantial and commendable efforts of our colleagues, these fields constitute a small sample even if they can be considered to be randomly selected from all irrigated fields in their respective regions. With the diversity among fields in their levels of spatial variability, it is unclear how those research results can be extrapolated to inform VRI investment decisions on other fields.

This paper presents a method to estimate on unsampled fields the magnitude of one of VRI's many possible benefits: irrigation reductions enabled by additional utilization of soil water captured from rainfall. This benefit exists for regions where precipitation causes irrigated soils to exceed their field capacities before or early in the irrigation season. In the Great Plains, average precipitation between April and June ranges from 175 mm (46% of annual normal) at Scottsbluff in the semi-arid west and 320 mm (38% of annual normal) at Falls City in the sub-humid east. Consequently, the managed root zone is generally refilled in the spring. The idea of scheduling irrigation to deplete the stored water by the end of the growing season and let it be naturally replenished was put forth by Woodruff et al. (1972), as cited in Lamm et al. (1994). In comparison to keeping the managed root zone full throughout the growing season, "planned soil moisture depletion" (Woodruff et al., 1972) reduces not only pumping expenses but also the leaching of nitrate, carried by water draining out of the root zone after rain infiltrates into an already wet soil. With uniform rate irrigation (URI), though, this strategy cannot be implemented to its maximum extent on fields with a variety of root zone available water capacity (R) values. As URI is typically managed to avoid water stress in most of the field, it treats the entire field as having a small R, thus leaving a small, uniform depletion but a variable amount of readily available water (Allen et al., 1998) across the field. In other words, the soils with larger R have unutilized capacity. VRI, in contrast, can capitalize on this unutilized capacity by applying less irrigation to these soils and allowing more stored rainwater to be extracted from them. Therefore, VRI empowers farmers to further increase energy savings and further decrease nitrogen loading into groundwater, which has become a problem for the drinking water supplies of some municipalities. It is worth noting that once the spatial distribution of R within a field is well-characterized, generating prescription maps to increase precipitation utilization with VRI planned soil moisture depletion is straightforward. So, this particular application of VRI is ready to be adopted by farmers to benefit both themselves and the public.

The method introduced by this study is applied to 49,224 center pivot irrigated fields in Nebraska to accomplish four objectives:

1. to describe the statistical distribution of field-average unutilized R under URI for Nebraska's center pivot irrigated fields;
2. to analyze the geographical distribution of the fields with large field-average unutilized R in relationship to counties and soil associations;
3. to assess the potential regional impact of the irrigation reductions from increasing precipitation utilization with VRI; and
4. to infer about the economics of adopting VRI solely for increasing precipitation utilization.

Methods

A main data source of this study was the gridded Soil Survey Geographic Database (gSSURGO; NRCS, 2014). Unlike its vector formatted counterpart, the raster formatted gSSURGO conveniently packages the spatial and tabular soil information for the whole state into one database. In gSSURGO, each contiguous area with similar soils is delineated as a map unit. Each distinct soil within a map unit is designated as a component that comprises a percentage of the map unit. In turn, the soil profile of each component is divided into horizons, each with a top depth, a bottom depth, and an available water capacity (AWC). For all soil properties (i.e., percent composition,

top depth, bottom depth, AWC), the “representative” value (NRCS, 2014) was exclusively taken in this study.

The core calculations were completed by running a Python script (Python, 2012) inside ArcGIS (ArcGIS, 2013). Horizons, components, and map units were excluded from the calculations if they met certain criteria (table 1). These criteria stipulated when to reject the data and assume that it can be well-represented by what was included.

Table 1. Exclusion criteria for horizons, components, and map units from gSSURGO.

	If AWC or *R* is… zero:	If AWC or *R* is… negative:	Also exclude if:
horizon	–	exclude, except assume zero for rock horizon	• missing top depth or bottom depth; • missing AWC, except assume zero for rock horizon; or • horizons depths are discontinuous
component	exclude	exclude	• managed root zone not entirely covered by included horizons; or • percent composition is negative or over 100%
map unit	exclude	exclude	• the sum of the percent compositions of excluded and missing/excess components is at least 10%

To begin, the *R* of every component was determined. Starting at the soil surface, each horizon’s AWC was multiplied by the horizon’s thickness and then summed. This computation ended at the bottom of the managed root zone—assumed to occur at a depth of 120 cm or at the top depth of the first “lithic bedrock” or “paralithic bedrock” restrictive layer (NRCS, 2014), whichever was shallower. Subsequently, the *R* of the components within each map unit could either be aggregated or remain separate. Each component’s *R* was weighted by the component’s percent composition and then averaged to obtain an average *R* for the map unit. Whenever the percent compositions of included components did not sum to 100% in an included map unit, they were normalized to 100%.

Another main data source of this study was the 2005 Nebraska center pivots data layer (CALMIT, 2007). It outlines the state’s “active” center pivots during the 2005 growing season that were identified from satellite and aerial imagery (CALMIT, 2007). The original 52,127 polygons underwent four filtering steps. First, the polygons were clipped by a data layer marking the borders of Nebraska (NRCS, 2009a). The twelve polygons that are entirely outside the state were removed. Second, the polygons were converted to a center pivot raster matching gSSURGO’s datum, grid size, and projection. This step paired each center pivot cell with a gSSURGO cell. Center pivot cells were not shared by polygons but were always assigned to the largest polygon that at least partially overlaps them. In the event of a tie between equally large polygons, the polygon with the larger feature identification number (FID) was given priority. Twenty-seven polygons were eliminated because no center pivot cells were assigned to them. Third, the 2728 remaining polygons with less than 2024 cells of 10 m × 10 m (50 ac) were discarded. The intent of this step was to exclude artifacts from the mapping process and fields that are less likely to consider VRI due to their small area. Fourth, the 136 remaining polygons were omitted because less than 90% of their cells corresponded to gSSURGO cells that belonged to included map units. The assumption that the area with excluded map units can be well-represented by the area with included map units was deemed to be unsuitable for those polygons. The 49,224 final polygons (94% of the original number) were analyzed in this study to represent all the center pivot irrigated fields in Nebraska. For each of these fields, the *R* values of the gSSURGO cells that corresponded to the field and that belonged to included map units were accepted as the *R* values for the field while preserving the field’s total cell area. From this point onward until the limitations section, excluded map units and excluded polygons will no longer be discussed.

Under URI planned soil moisture depletion, a certain *R* within the field is selected, and a constant fraction of this *R* is depleted throughout the field by the end of the growing season. The depletion fraction can be called the management allowed depletion (MAD) (Merriam, 1966), and the selected *R* can be called the URI management *R* (R_p). If an aggressive MAD is adopted, then the percentile of all *R* values that are less than R_p, which can be called the URI management percentile (p), may be underirrigated. To strike a balance between water stress and deep percolation, the target p was 10% for all fields. In this study, every field’s statistical distribution of *R* was discrete because every field was composed of discrete map units, each with one *R* value. So, whenever the actual p could not be equal to 10%, the calculations erred on the side of protecting yield. Hence, R_p was chosen as the largest *R* within the field that is greater than at most 10% of all the field’s *R* values. Under VRI planned soil moisture depletion, however, each map unit is depleted to the MAD of its *R*, and the amounts of *R* that exceed R_p can be utilized. U, defined as the field-average unutilized *R* under URI planned soil moisture depletion, is computed by equation 1 and has the dimension of depth.

$$U = \sum_{j=1}^{m}\left[\left(R_j - R_p\right)\left(\frac{A_j}{A_{inc}}\right)\right] = R_a - R_p \quad (1)$$

where j is the index for the map units within the field, m is the number of map units within the field, R_j is the R of map unit j, A_j is the field area that belongs to map unit j, A_{inc} is the total field area that belongs to included map units, and R_a is the area-weighted average R within the field.

As the value of U increases, the potential for irrigation reductions from increasing precipitation utilization with VRI also increases. To discover how the prevalence of large U values might differ between sub-regions of Nebraska, the fields were grouped by counties (NRCS, 2009b) and soil associations (Conservation and Survey Division, 2009) based on the centroids of the center pivot polygons. The number and fraction of fields within various ranges of U were then calculated for each county and soil association.

To increase precipitation utilization beyond URI planned soil moisture depletion, the seasonal net irrigation onto every map unit can be reduced by (R_j – R_p) × MAD. Consequently, Δd_g, the field-average potential depth of seasonal gross irrigation reductions from VRI planned soil water depletion, can be estimated by equation 2. In this study, URI was simplified as being perfectly uniform across every field, whereas VRI was simplified as being perfectly uniform within every management zone. Also, MAD and E_a were respectively assumed to be 0.5 (Kranz et al., 2008a) and 85% (Kranz et al., 2008b) for both URI and VRI. If a higher E_a is achieved with VRI, then VRI will provide greater gross irrigation reductions than what were estimated by this study. ΔV_g, the potential volume of seasonal gross irrigation reductions for the whole field, is, plainly, Δd_g multiplied by the field's total cell area.

$$\Delta d_g = \sum_{j=1}^{m}\left[\frac{\left(R_j - R_p\right)MAD}{E_a}\left(\frac{A_j}{A_{inc}}\right)\right] = \frac{U \times MAD}{E_a} \quad (2)$$

Yet where water supply is inadequate for full irrigation, producers will not be interested in reducing irrigation with VRI. On the contrary, current economics will drive them to apply as much irrigation as they can to maximize yield, whether with URI or VRI. Without knowledge of each field's water supply situation, irrigation reductions were simply not calculated for any fields whose center pivot polygon centroid fell within the four Natural Resources Districts (NRDs; Nebraska Department of Natural Resources, 2011) that enforce NRD-wide groundwater quantity allocations. As opposed to some of the sub-area allocations elsewhere in the state, the NRD-wide multi-year allocations in the South Platte, Upper Republican, Middle Republican, and Lower Republican NRDs are more severe and less likely to be sufficient for full irrigation throughout the allocation period.

Although potential irrigation reductions from increasing precipitation utilization with VRI is only one of VRI's many possible benefits, estimates of its magnitude can still contribute to informing farmers' VRI purchasing decisions. To break even on a VRI investment solely for this benefit, the total installed cost of VRI (C_v) has to equal the present worth of the irrigation reductions (simplified here as a uniform annual series) accumulated over an amortization period of n years (eq. 3). Both the variable cost of gross irrigation per unit of ΔV_g (C_w) and the annual discount rate (i; also called "interest rate") were assumed to be fixed and not to change in real (vs. nominal) terms during the amortization period.

$$C_v = \sum_{t=1}^{n}\left[\frac{C_w \times \Delta V_g}{\left(1+i\right)^t}\right] = C_w \times \Delta V_g \times \frac{\left(1+i\right)^n - 1}{i\left(1+i\right)^n} \quad (3)$$

where t is years since VRI system began operation.

Estimating the breakeven C_v for every field with confidence would be difficult. For instance, pumping cost alone can differ drastically between fields, depending on energy source and energy requirement. Nevertheless, by manipulating equation 3, C_v and C_w can be combined into a cost ratio, defined as C_v divided by the variable cost of 1,233 m^3 (1 ac-ft) of gross irrigation. The financial attractiveness of a VRI investment solely for increasing precipitation utilization can thus be expressed in terms of the breakeven cost ratio B (eq. 4).

$$B = \frac{C_v}{C_w\left(1{,}233\,\mathrm{m}^3\right)} = \frac{\Delta V_g}{\left(1{,}233\,\mathrm{m}^3\right)} \times \frac{\left(1+i\right)^n - 1}{i\left(1+i\right)^n} \quad (4)$$

Results and Discussion

Statistical Distribution of *U*

The distributions of the two variables from which *U* is calculated, R_a and R_p, are first presented (fig. 1). The distribution of R_a was left-skewed, and 61% of fields had an R_a value between 203 mm and 254 mm. Slightly bimodal but also left-skewed, the distribution of R_p loosely followed the shape of the R_a distribution with two noticeable exceptions. More R_p values than R_a values fell in the 76-102 mm range, whereas more R_a values than R_p values fell in the 229-254 mm range.

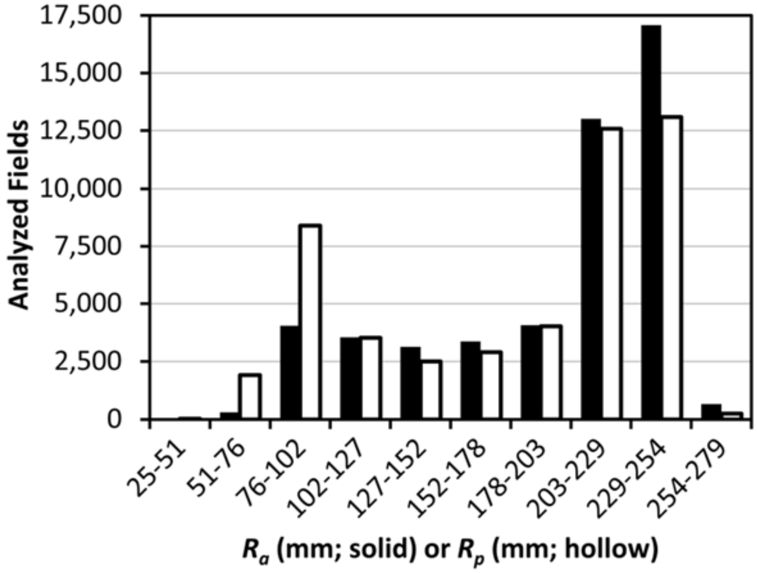

Figure 1. The distributions of R_a (solid) and R_p (hollow) for the analyzed fields.

In contrast, the distribution of *U* was right-skewed (fig. 2), with an observed range from -16 mm to 164 mm. Among the *U* values, 6% were negative, 83% were 0-51 mm, 10% were 51-102 mm, and 1% was greater than 102 mm. These results suggest that, in the majority of analyzed fields, URI only leaves a small total amount of unutilized *R* for VRI to exploit additionally.

A soil whose *R* is less than R_p can be said to have overutilized *R* or negative unutilized *R* under URI because its end-of-season depletion would be a larger fraction of its *R* than the specified *MAD*. Such a soil subtracts from the value of *U*. If a field's total amount of overutilized *R* exceeds its total amount of unutilized *R*, *U* becomes negative. Practically, a negative *U* indicates that switching from URI to VRI while maintaining *MAD* would call for an irrigation increase rather than an irrigation reduction.

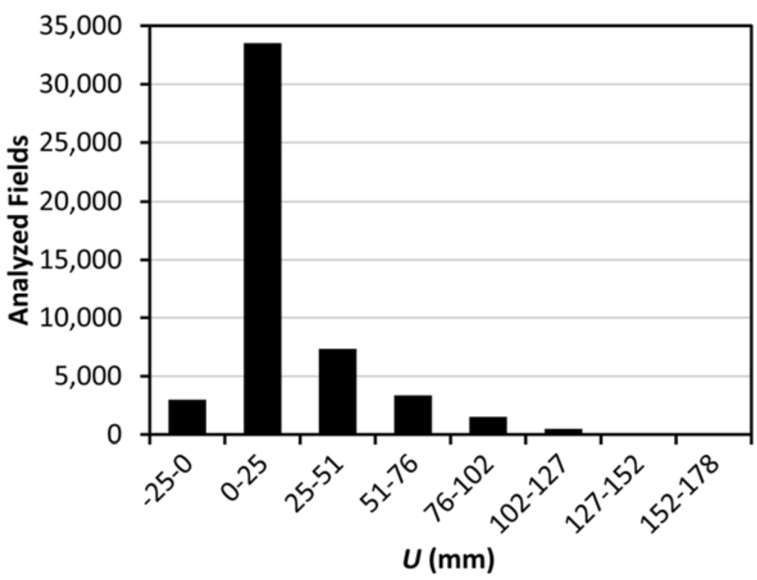

Figure 2. The distribution of *U* for the analyzed fields.

Geographical Distribution of Large *U* Values Among Counties

Figures 3a-d displays the locations of the analyzed fields in each of three ranges of *U*. It is evident that the fields are neither randomly nor regularly distributed across Nebraska in any of the three figures. Additionally, in some parts of Nebraska, fields with large *U*—the sparser dots on figure 3b and 3c—seem randomly scattered throughout fields with small *U*—the denser dots on figure 3a. Some other parts of the state appear to be densely covered in figure 3a but almost blank in figure 3b and 3c. These observations point to differences in the prevalence of large *U* values among subregions of Nebraska.

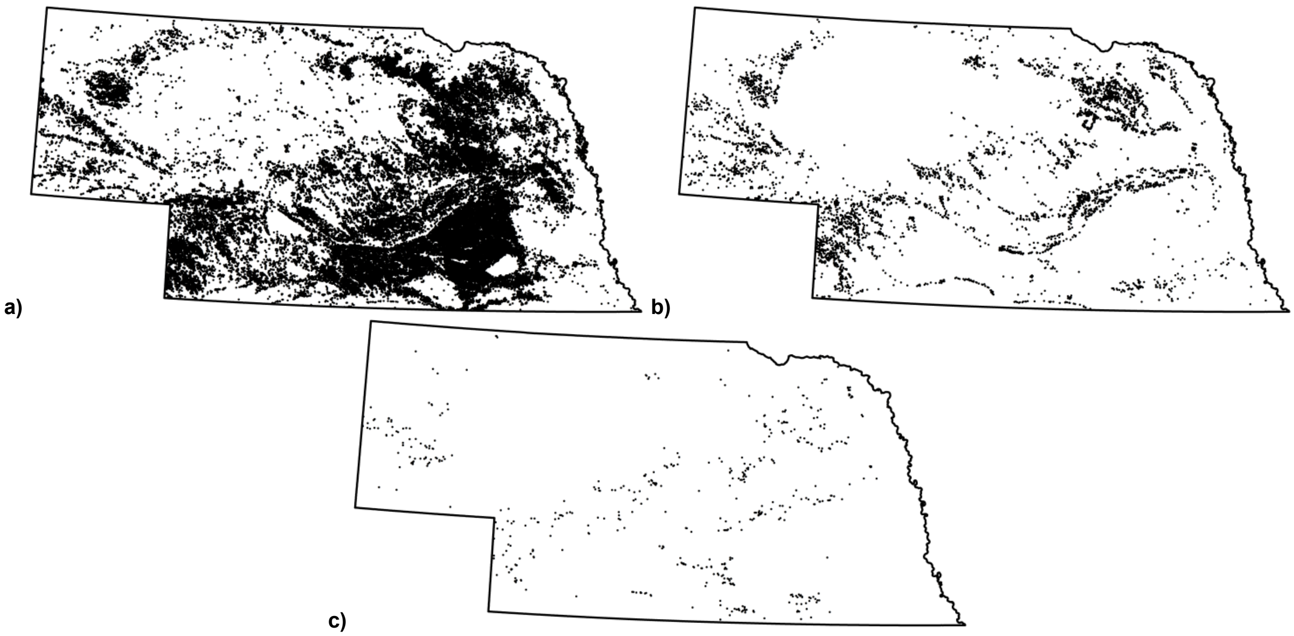

Figure 3. The centroids of the analyzed fields with *U* a) less than 51 mm, b) at least 51 mm but less than 102 mm, and c) at least 102 mm.

To further explore and to quantify these differences, the number of *U* values that were at least 51 mm and that were at least 102 mm, respectively, were counted in each of Nebraska's 93 counties. The counties with the most *U* values in these ranges were listed in tables 2 and 3.

Table 2. The 36 Nebraska counties with at least 40 *U* values of at least 51 mm, ranked in descending order by their number of *U* values in this range.

Rank	County	Number	Percentage	Rank	County	Number	Percentage	Rank	County	Number	Percentage
1	Antelope	472	24%	13	Cedar	122	20%	25	Knox	69	18%
2	Chase	313	23%	14	Dundy	108	12%	25	Phelps	69	6%
3	Perkins	277	27%	15	Greeley	103	18%	27	Brown	67	24%
4	Morrill	258	36%	16	Scotts Bluff	93	26%	28	Kearney	64	6%
5	Lincoln	255	17%	17	Sheridan	85	18%	29	Butler	57	8%
6	Pierce	240	24%	18	Keith	82	12%	30	Dixon	55	36%
7	Box Butte	230	20%	18	Thayer	82	8%	30	Stanton	55	26%
8	Custer	197	14%	20	Howard	80	17%	32	Logan	51	27%
9	Merrick	193	25%	21	Buffalo	78	6%	33	Dakota	47	43%
10	Holt	149	7%	21	Dodge	78	14%	34	Banner	45	23%
11	Cheyenne	143	31%	23	Hall	70	10%	35	Nance	43	12%
12	Madison	125	16%	23	Kimball	70	26%	35	Webster	43	11%

Table 3. The 35 Nebraska counties with at least 4 *U* values of at least 102 mm, ranked in descending order by their number of *U* values in this range.

Rank	County	Number	Percentage	Rank	County	Number	Percentage	Rank	County	Number	Percentage
1	Morrill	36	5%	13	Adams	15	1%	25	Brown	6	2%
2	Custer	34	2%	14	Dixon	14	9%	25	Dodge	6	1%
3	Lincoln	30	2%	15	Perkins	13	1%	25	Polk	6	0.7%
3	Thayer	30	3%	16	Furnas	10	3%	28	Cedar	5	0.8%
5	Chase	25	2%	16	Pierce	10	1%	28	Dakota	5	5%
5	Scotts Bluff	25	7%	18	Buffalo	9	0.7%	28	Dawson	5	0.6%
7	Greeley	24	4%	18	Stanton	9	4%	31	Franklin	4	0.7%
8	Kearney	23	2%	20	Butler	8	1%	31	Hall	4	0.6%
9	Antelope	22	1%	20	Howard	8	2%	31	Holt	4	0.2%

10	Merrick	20	3%	20	Phelps	8	0.7%	31	Keith	4	0.6%
10	Webster	20	5%	23	Boone	7	0.6%	31	Sheridan	4	0.9%
12	Madison	17	2%	23	Box Butte	7	0.6%				

Part of the clustered nature of large *U* values can be attributed to the clustered nature of the analyzed fields, over 50% of which were in nineteen counties (20%). Given equal spatial variability in *R*, a county with more analyzed fields will have a greater number of large U values than a county with fewer analyzed fields. As a result, the 22 counties (24%) with the most analyzed fields contained over 50% of all *U* values that were at least 51 mm, and the 24 counties (26%) with the most analyzed fields contained over 50% of all *U* values that were least 102 mm.

Nonetheless, some counties' number of large *U* values was vastly disproportionate to their number of analyzed fields. On one extreme, York and Fillmore Counties, with the third and the fifth most analyzed center pivots (1609 and 1472), respectively, both had no *U* values of at least 51 mm. On the opposite extreme, Stanton and Dixon Counties, with the 64th and the 70th most analyzed center pivots (215 and 154), both ranked 30th for *U* values of at least 51 mm and were both within the top twenty for *U* values of at least 102 mm.

In fact, large *U* values were more clustered than the analyzed fields. Eleven counties (12%) contained over 50% of all *U* values that were at least 51 mm, and ten counties (11%) contained over 50% of all *U* values that were at least 102 mm. Also, large *U* values were not concentrated in all of the same counties as the analyzed fields. Highlighted in figure 4, the nine counties that ranked in the top fifteen in both tables 2 and 3 were some of the subregions where the prevalence of fields with large *U* values was the highest.

Figure 4. The counties (light grey outlines) and Natural Resources Districts (medium grey outlines) of Nebraska; the nine counties that ranked in the top fifteen in both table 2 and table 3 were colored in light grey

Geographical Distribution of Large *U* Values Among Soil Associations

Fundamentally, however, the prevalence of large *U* values should be related to soil formation. A classification scheme based on soil formation was approximated by the division of Nebraska's soils into 80 soil associations (Conservation and Survey Division, 2009), each of which is a group of soil series that are generally found in proximity to each other. It was thought that fields with similar soil formation would have similar *U* values. By extension, the prevalence of large *U* values in a soil association would either be very high or very low. If this characteristic were true, then the extents of soil associations would be far more effective than county borders for demarcating subregions with especially high or especially low prevalence of large *U* values.

The analyzed center pivots were even more clustered with respect to soil associations than to counties. Over 50% of all analyzed center pivots were located in just 10 soil associations (13%). Because percentages convey prevalence without being confounded by the number of analyzed fields in each soil association, the percentage of *U* values that were at least 51 mm and that were at least 102 mm, respectively, were computed in every soil association. The soil associations with some of the highest percentages of *U* values in these ranges were listed in tables 4 and 5.

Table 4. Soil associations ranked in descending order by their percentage of U values that were at least 51 mm; only the 28 soil

associations with a minimum of 20% of *U* values in this range and with a minimum of 30 analyzed fields were listed.

Rank	Code	Soil Association	Percentage	Number	Rank	Code	Soil Association	Percentage	Number
1	54	Moody-Thurman	44%	102	15	66	Gibbon-Wann	26%	78
2	73	Brunswick-Paka-Simeon	38%	23	16	60	Gothenburg-Platte-Lawet	25%	51
3	69	Nuckolls-Holdrege-Campus	33%	12	17	42	Keith-Alliance-Rosebud	24%	166
4	12	Alliance-Rosebud-Kuma	33%	154	18	15	Hersh-Valentine	23%	407
5	46	Canyon-Alliance-Rosebud	32%	12	19	75	Jayem-Keith	23%	59
6	52	Valent-Sarben-Otero	31%	90	20	36	Jayem-Sarben-Valent	23%	134
7	27	Thurman-Boelus-Nora	30%	634	21	65	Dix-Altvan-Colby	21%	15
8	30	Hord-Cozad-Boel	30%	132	22	50	Gibbon-Zook	21%	93
9	38	Albaton-Haynie-Sarpy	29%	114	23	32	Kuma-Satanta-Rosebud	21%	203
10	61	Kennebec-Nodaway-Zook	28%	17	24	45	Hord-McCook-Inavale	21%	72
11	13	Tripp-Mitchell-Alice	27%	198	25	28	Shell-Muir-Hobbs	20%	109
12	51	Bazile-Thurman-Boelus	27%	155	26	47	Kenesaw-Hersh	20%	188
13	64	Canyon-Rosebud-Rock Outcrop	27%	8	27	49	Lawet-Gothenburg-Platte	20%	53
14	10	Rosebud-Alliance-Canyon	27%	193	28	31	Monona-Ida	20%	7

Table 5. Soil associations ranked in descending order by their percentage of U values that were at least 102 mm; only the 28 soil associations with a minimum of 1% of *U* values in this range and with a minimum of 30 analyzed fields were listed.

Rank	Code	Soil Association	Percentage	Number	Rank	Code	Soil Association	Percentage	Number
1	13	Tripp-Mitchell-Alice	6%	44	15	27	Thurman-Boelus-Nora	2%	46
2	54	Moody-Thurman	6%	14	16	66	Gibbon-Wann	2%	6
3	47	Kenesaw-Hersh	5%	51	17	20	Hobbs-Hord	2%	18
4	46	Canyon-Alliance-Rosebud	5%	2	18	23	Jansen-O'Neill-Meadin	2%	25
5	60	Gothenburg-Platte-Lawet	5%	10	19	35	Cozad-Hord	2%	16
6	30	Hord-Cozad-Boel	4%	16	20	39	Gibbon-Gothenburg-Platte	2%	7
7	45	Hord-McCook-Inavale	3%	11	21	73	Brunswick-Paka-Simeon	2%	1
8	15	Hersh-Valentine	3%	54	22	28	Shell-Muir-Hobbs	2%	8
9	16	Valentine-Els-Wildhorse	3%	2	23	18	Valent-Woodly-Jayem	1%	21
10	31	Monona-Ida	3%	1	24	37	Crofton-Alcester-Nora	1%	2
11	69	Nuckolls-Holdrege-Campus	3%	1	25	40	Satanta-Jayem-Canyon	1%	3
12	38	Albaton-Haynie-Sarpy	3%	10	26	32	Kuma-Satanta-Rosebud	1%	11
13	52	Valent-Sarben-Otero	2%	7	27	10	Rosebud-Alliance-Canyon	1%	8
14	48	Tassel-McKelvie-Rock Outcrop	2%	1	28	36	Jayem-Sarben-Valent	1%	6

Figure 5 highlights the eight soil associations that ranked in the top fifteen in both tables 4 and 5. All these soil associations were described as being formed from juxtapositions of coarser parent materials, such as eolian sand or sandstone, with finer parent materials, such as loess (Conservation and Survey Division, 2009). Also, three of these soil associations (codes 13, 30, and 38) appeared to have been affected by alluvial processes during their formation (Conservation and Survey Division, 2009), which may be why stretches of several major rivers in Nebraska can be roughly traced on the maps of the analyzed center pivots with high UR values (fig. 3b-c). These evidences support the claim that the greater prevalence of large *U* values in these soil associations may indeed be explained by soil formation.

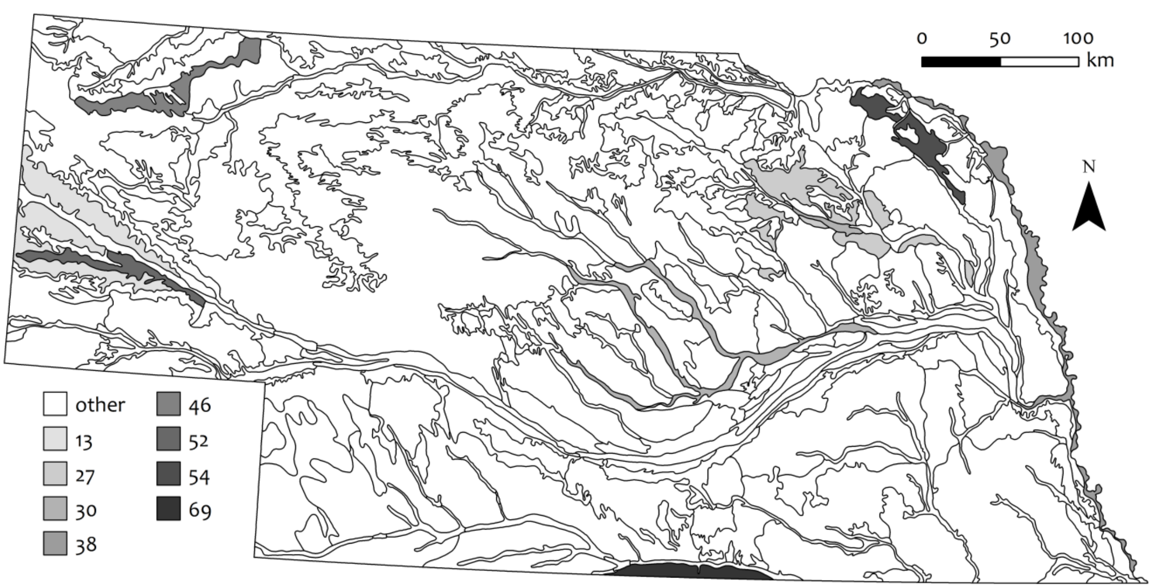

Figure 5. The soil associations of Nebraska (black outlines); the eight soil associations that ranked in the top fifteen in both table 4 and table 5 were colored in various shades of grey.

Yet contrary to expectations, the statistical distributions of the prevalence of large *U* values among soil

associations were not more bimodal than the statistical distributions of the prevalence of large *U* values among counties (fig. 6). For the prevalence of *U* values that were at least 102 mm, the two distributions were similar overall. For the prevalence of *U* values of at least 50.8 mm, the soil associations' distribution had a smaller lower tail and a larger upper tail than the counties' distribution; furthermore, intermediate prevalence percentages composed a substantial proportion of both distributions. In short, soil associations might not be better than counties as a predictor of the prevalence of large *U* values in a subregion.

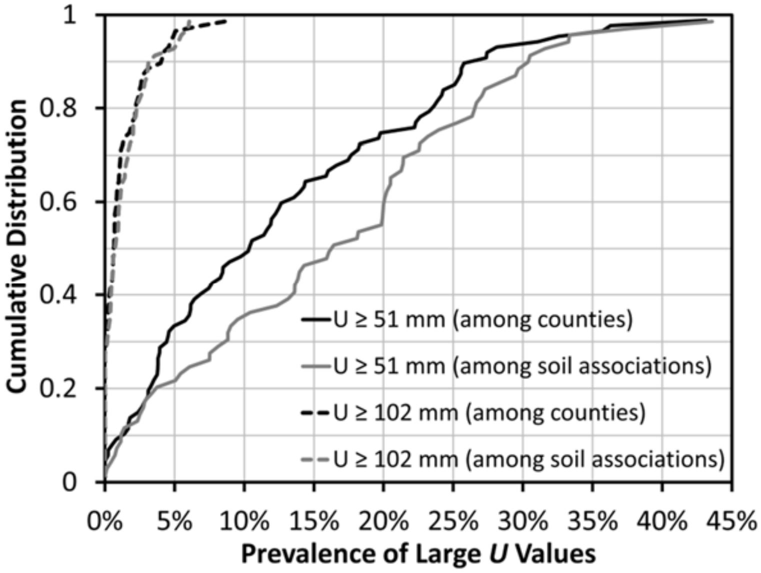

Figure 6. The cumulative distribution functions of the prevalence of large *U* values among Nebraska's counties and soil associations.

Potential Regional Impact

To quantify the potential regional impact of the irrigation reductions from increasing precipitation utilization with VRI, two hypothetical extents of VRI implementation were assumed. With the first, every analyzed field with Δd_g greater than 51 mm implements VRI. With the second, every analyzed field with Δd_g greater than 25 mm implements VRI. For both extents of VRI implementation, the percentage of implemented fields, the area-weighted average Δd_g among implemented fields, and the total ΔV_g were calculated in each of the nineteen NRDs without NRD-wide groundwater quantity allocations (table 6).

Readers should bear in mind that these irrigation reductions result from a shift in the source of evapotranspired water and not from a change in the quantity of evapotranspiration. Any reduction in groundwater withdrawal due to VRI planned soil moisture depletion is conditional upon a roughly equivalent reduction in groundwater recharge by water percolating past the root zone. Therefore, the water supply for other uses in the watershed would not be augmented by these irrigation reductions.

Table 6. Each NRD's percentage of implemented fields, area-weighted average Δd_g among implemented fields, and total ΔV_g for two hypothetical extents of VRI implementation; the Lower Republican, Middle Republican, South Platte, and Upper Republican NRDs were omitted due to their NRD-wide groundwater quantity allocations

		Δd_g > 51 mm			Δd_g > 25 mm		
NRD	Analyzed Fields	Implemented Fields	Avg. Δd_g (mm)	Total ΔV_g ($\times 10^6$ m^3)	Implemented Fields	Avg. Δd_g (mm)	Total ΔV_g ($\times 10^6$ m^3)
Central Platte	3666	3%	59	2.62	14%	40	9.81
Lewis & Clark	602	9%	58	1.48	34%	43	4.59
Little Blue	3348	2%	62	2.44	4%	51	3.47
Lower Big Blue	1079	0.09%	51	0.02	10%	30	1.52
Lower Elkhorn	3700	3%	60	3.93	19%	41	13.63
Lower Loup	6087	3%	61	5.25	11%	43	14.06
Lower Niobrara	1443	0.9%	57	0.34	12%	35	3.08
Lower Platte North	1989	1%	61	0.51	11%	37	3.83
Lower Platte South	104	0%	0	0	16%	34	0.27
Middle Niobrara	678	2%	59	0.33	20%	36	2.33
Nemaha	181	2%	65	0.24	25%	40	0.96
North Platte	1652	8%	61	3.76	33%	42	11.24
Papio-Missouri River	436	5%	59	0.64	25%	41	2.62
Tri-Basin	2563	2%	66	1.50	7%	43	3.81
Twin Platte	1826	4%	60	2.16	20%	40	7.76

Upper Big Blue	6841	0.04%	56	0.08	0.2%	34	0.23
Upper Elkhorn	3059	3%	57	2.13	25%	37	14.02
Upper Loup	380	2%	57	0.16	21%	38	1.48
Upper Niobrara-White	1763	3%	58	1.39	28%	37	9.39
Total	41397	2%	60	29.00	13%	40	108.07

Certain trends in table 6 were shared by all listed NRDs. As the extent of VRI implementation expanded, the total ΔV_g increased while the area-weighted average Δd_g decreased. Since VRI implementation was assumed to prioritize the fields with the largest potential irrigation reductions, the reductions achieved by implementing VRI on the next field could never surpass the reductions of any field already implementing VRI. At the same time, differences between NRDs can be observed too. For instance, for both extents of VRI implementation, the Lewis & Clark NRD had a much higher percentage of implemented fields than the Upper Big Blue NRD.

To illustrate the relative magnitude of these potential irrigation reductions for Nebraska as a whole, the results can be compared with total gross irrigation in the state. The NASS Farm and Ranch Irrigation Survey, which gathered farmers' mandatorily self-reported irrigation data, tallied 2,943,836 ha under center pivot irrigation in Nebraska for the 2013 growing season (NASS, 2014). If the analyzed center pivots (2,430,562 ha), which represent Nebraska's center pivots during the 2005 growing season, are also representative of Nebraska's center pivots installed after the 2005 growing season, then the total volume of ΔV_g in 2013 would be 35.13 million m^3 and 130.89 million m^3 for the two extents of implementation. These two volumes are 0.35% and 1.3% of the 9,953.12 million m^3 of gross irrigation in Nebraska during 2013 (NASS, 2014). Granted, this study estimated the irrigation reductions from increasing precipitation utilization with VRI from a baseline of well-managed URI. A smaller volume of gross irrigation would probably have been applied as compared to the NASS survey if well-managed URI was practiced on every irrigated field in Nebraska. The results, nevertheless, suggest that implementing VRI in the way described by this study will provide only a minor reduction of total gross irrigation statewide.

As a comparison, the Nebraska Agricultural Water Management Network (Irmak et al., 2010), which advocates for the use of the ETgage atmometer (ETgage Company, Loveland, Colo.) and Watermark granular matrix soil moisture sensors (Irrometer Company, Riverside, Cal.) to improve irrigation scheduling, was estimated to reduce seasonal gross irrigation by 56 mm for corn and 46 mm for soybeans (UNL Extension, 2009). These amounts are quite large considering that they are the average for 105 responding farmers managing over 70,000 ha (UNL Extension, 2009) and are likely to be achievable on many fields without groundwater quantity allocations. Also, the level of financial investment required for improving URI scheduling is presently far less than that for purchasing and implementing VRI.

In summary, in agreement with Evans et al. (2013), this study's results support the view that there are multiple tiers of irrigation management: poor URI management, good URI management, and good VRI management. Farmers who are interested in reducing their seasonal irrigation should first move from the first to the second tier because good irrigation scheduling is more broadly applicable and generally more cost-effective than VRI implementation. Afterwards, farmers can step up to the third tier by implementing VRI on their fields with large U values to achieve additional irrigation reductions.

Economics of Adopting VRI Solely for Increasing Precipitation Utilization

Although the expected regional impact is small, VRI investments may be justified for the fields with the largest ΔV_g. For an amortization period of ten years and three different discount rates, figure 7 shows the linear relationships between ΔV_g and B. In this study, the largest ΔV_g estimated for a field was 138 thousand m^3, which translated into B values of 1,122, 866, and 689 for the three i values of 0%, 5%, and 10%, respectively.

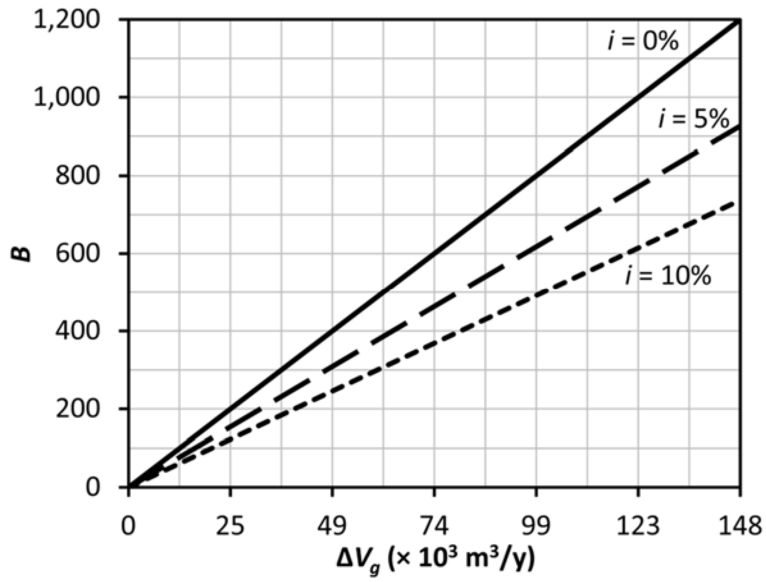

Figure 7. Breakeven cost ratio *B* (eq. 4) versus ΔV_g for an amortization period of ten years and three different discount rates *i*

Large irrigation savings and low discount rates (the latter reflecting the lack of highly profitable investment alternatives) led to the acceptance of high cost ratios. If C_v decreased relative to C_w, then VRI would become a justifiable option for fields with smaller irrigation reductions and higher discount rates.

The estimates of ΔV_g computed in the previous section were combined with the breakeven relationships in figure 7 to generate a cumulative distribution function of *B* for each of the three *i* values. VRI adoption percentages among all analyzed fields without NRD-wide allocations were assumed to be equal to probabilities of exceedance, as calculated using the Weibull formula P_e = *descending order rank of B* / (*number of analyzed center pivots without NRD-wide allocations* + 1) (fig. 8). The generally exponential increase in VRI adoption percentage with linearly decreasing cost ratios stemmed from the right-skewed distribution of *U* and, by extension, ΔV_g.

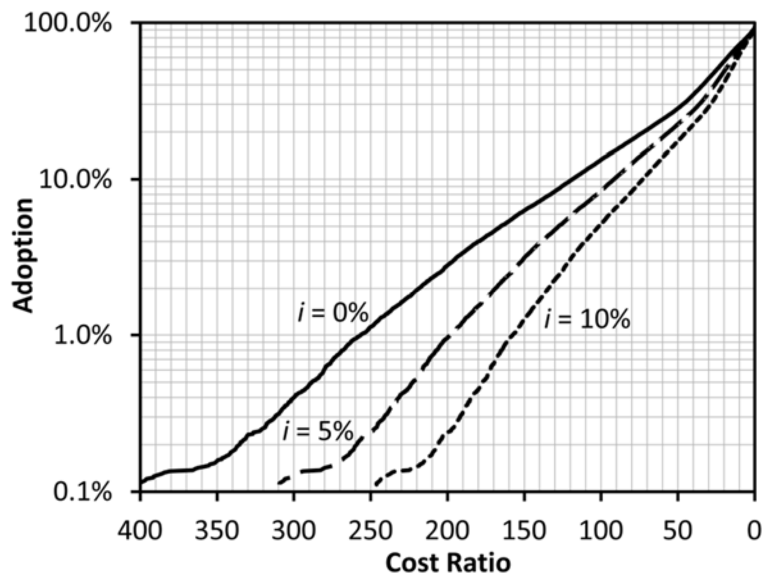

Figure 8. The cumulative distribution function of *B* given three different discount rates *i;* VRI adoption percentages among all analyzed fields without NRD-wide allocations were assumed to be equal to probabilities of exceedance

VRI adoption solely for increasing precipitation utilization is least favorable when C_w only includes the cost of pumping energy. According to the 2013 irrigation survey (NASS, 2014), a typical irrigation well in Nebraska might be connected to an electric pump (55% of all irrigation pumps in Nebraska) supplying 25 m of lift (average depth to water in Nebraska's irrigation wells is 20.7 m "at the start of the irrigation season") and 276 kPa of pressure (Nebraska's average operating pressure of pumped wells). If such a pump operates at 100% of the Nebraska Pumping Plant Performance Criteria (Kranz, 2010) and purchases anytime interruptible electricity service at

$0.106/kWh (NPPD, 2014), the variable cost of gross irrigation would be $28.65 per 1.23 ML. With a 5% discount rate, the price of VRI would have to be $9,086 for 0.1% adoption, $5,675 for 1% adoption, and $2,628 for 10% adoption. For the same adoption percentage, VRI prices can be higher with a lower discount rate but need to be lower with a higher discount rate. Regardless, unless prices for zone control VRI capability, "about $200-$550 ha^{-1}" (Evans et al., 2013), drop dramatically relative to pumping energy costs, VRI will not be prevalently adopted purely for reducing irrigation energy expenses. Speed control VRI capability is less expensive, but the effectiveness of management sectors at matching spatial variability in *R* and the consequent magnitude of the potential irrigation reductions are uncertain.

Nonetheless, increasing precipitation utilization and reducing seasonal irrigation may also lower the private cost of fertilizer (due to less nitrogen loss through denitrification and nitrate leaching), the public cost of drinking water with safe nitrate concentrations, and/or the environmental cost of pumping energy generation as well as fertilizer production and application. The magnitude of these neglected benefits is difficult to estimate, but their inclusion in C_w would improve the attractiveness of irrigation reductions with VRI as compared to what was portrayed in the example above.

Conclusion

The field-average amount of unutilized root zone available water capacity under good URI management, as represented by the value of *U*, was found to be small for most of the analyzed fields in Nebraska. Consequently, the ratio between VRI prices and gross irrigation variable costs may need to be quite low in order to induce substantial VRI adoption solely for reducing irrigation energy expenses. Statewide, a moderate extent of VRI implementation to deplete greater amounts of precipitation-derived soil water was estimated to enable potential irrigation reductions equivalent to less than 2% of total gross irrigation in 2013.

The results of this study also revealed considerable differences in the prevalence of large *U* values among Nebraska's counties as well as among its soil associations. Notably, some counties and some soil associations had many analyzed center pivots but few, if any, large *U* values. In spite of these observations, knowledge of neither counties nor soil associations generally guaranteed the presence of only large *U* values or only small *U* values. This finding underscores the importance of field-specific analyses for precision agricultural management.

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