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A Pivotal New Approach to Groundwater Quality Assessment

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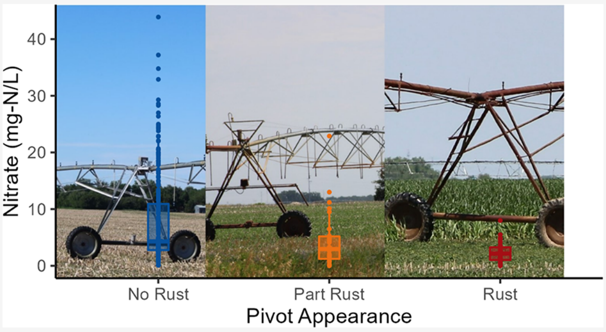

ABSTRACT: Areas of intensive agriculture and irrigation are prone to groundwater nitrate contamination, which can threaten drinking water supplies. Irrigation center pivots are a common feature in heavily irrigated regions and have the potential to provide insight into subsurface redox chemistry. In this study, we hypothesized that the same geochemical condition(s) that causes rust staining on center pivot systems will strongly influence groundwater nitrate concentrations. In south central Nebraska, 700 center pivot irrigation systems were classified by appearance of iron staining (full rust, part rust, or no rust) using Google Earth imagery and/or ground-based surveys. Ground-based observation of 270 center pivots yielded the same classifications as Google Earth imagery 83% of the time. Groundwater nitrate concentrations correlated with pivot classifications show lower nitrate concentrations in full rust and part rust pivots when compared with no rust pivots. The novelty of this work is to provide a framework for understanding groundwater quality using an inexpensive method applicable to both established and developing agricultural communities.

KEYWORDS: *groundwater quality, remote sensing, nitrate contamination, redox chemistry*

1. INTRODUCTION

Groundwater quality is essential for agricultural, municipal, and domestic use worldwide. Areas with intensive agriculture and irrigation are prone to groundwater nitrate contamination and other co-occurring agri-chemicals that are a threat to human health.[1−6] Traditional sampling programs to monitor and manage groundwater quality are time-intensive and expensive.[7] The ability to optimize groundwater sampling has the potential to minimize those costs for both established and developing agricultural areas.

Spatial patterns observed from aerial imagery may also be used to predict areas that are at a higher risk for nitrate contamination and/or be used as a predictor variable in machine learning models. One feature in many irrigated agricultural landscapes is the center pivot irrigation system. Center pivot irrigation is a system in which a crop is irrigated by a long arm with sprinklers that pivots in a circular motion around the field. The use of center pivot irrigation technology marks a shift from manual to more automatic irrigation practices and may lead to more water-conscious agricultural practices[8] compared to other irrigation methods.

Implementation of center pivot irrigation technology began in the United States Midwest in the 1940s and 1950s[9] and has continued to expand rapidly throughout the world since the 1980s.[10−12] The expansion of irrigation may increase the risk of groundwater nitrate contamination in previously undeveloped areas. Where center pivot irrigation is used, the use of aerial imagery and/or ground-based surveys to quickly determine underlying groundwater biogeochemical conditions has the potential to supplement current monitoring programs or act as a guide for new monitoring programs.

Because center pivot irrigation systems are often both connected to the groundwater below and visible above ground, their physical appearance and function may provide direct insights into groundwater quality, specifically redox chemistry. Iron is a common element found in groundwater due to the geology in the Midwest United States.[13] Low dissolved oxygen and/or high iron indicate anoxic conditions with the potential to reduce groundwater nitrate concentrations.[14] Under anoxic conditions, the dissolution of Fe(III)-bearing minerals in sediment occurs producing Fe(II).[14−16] These conditions can happen at any depth but tend to occur deeper in aquifers, where oxygen from recharge water has been used by microbes.[14] However, when groundwater is pumped through an irrigation system, iron can precipitate when the groundwater is exposed to oxygen in the atmosphere. Iron precipitation leads to a dark iron coating on irrigation center pivots. This is similar to biogeochemical conditions leading to iron staining on bathtubs or sinks.[17] The preservation or degradation of anthropogenic contaminants, such as nitrate, is impacted by the groundwater redox conditions.[14] Other

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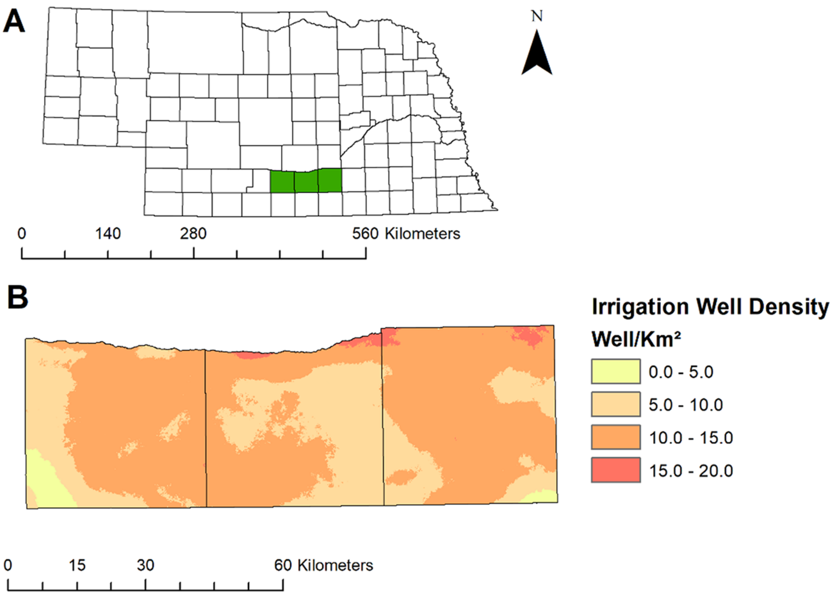

Figure 1. (A) Pivot analysis took place in Phelps, Kearney, and Adams counties, Nebraska, USA. The counties are shaded in green. (B) Irrigation well density in Phelps, Kearney, and Adams counties.

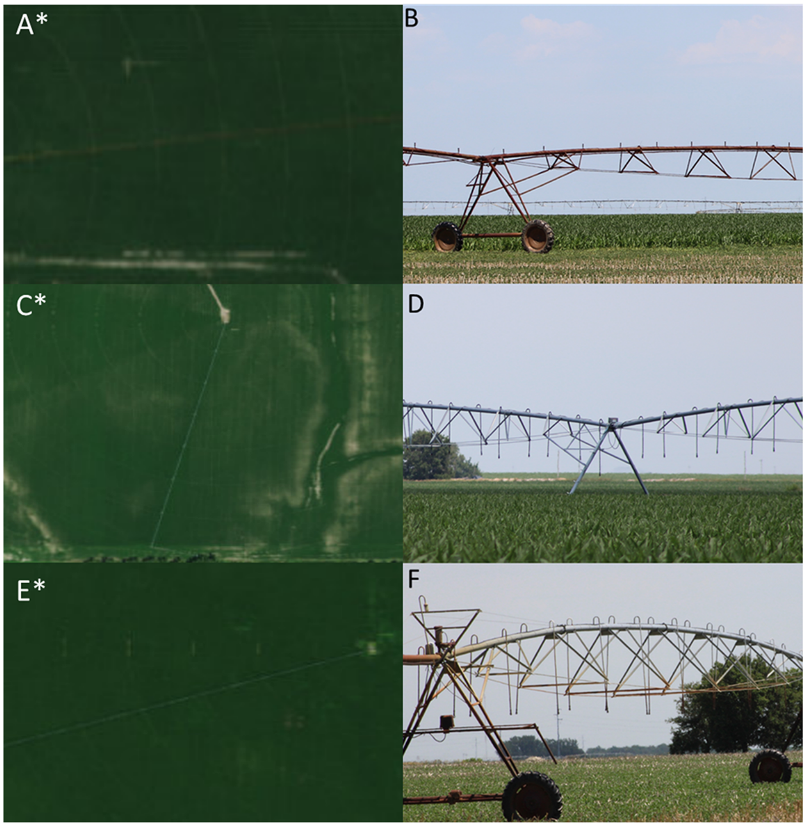

Figure 2. (A) Aerial view of full-rust pivot. (B) Ground view of full-rust pivot shown in panel (A). (C) Aerial view of the no-rust pivot. (D) Ground view of the no-rust pivot shown in panel (C). (E) Aerial view of the part-rust pivot. (F) Ground view of the part-rust pivot shown in panel (E). *Satellite images shown are from the National Map imagery (USGS).[22] Due to journal copyright restrictions, we are unable to show Google Earth imagery in this figure. See Cherry and Gilmore (2022) for example images actually used in the study.[23]

groundwater biogeochemical conditions can also lead to pivot corrosion of the metal itself and decrease the lifespan of a center pivot irrigation system, depending on pH and concentrations of chloride, sulfate, magnesium, bicarbonate, and calcium.[18−20]

The use of a visual method to assess groundwater quality has the potential to reduce groundwater sampling time and costs and provide insight into contamination risks in regions of intensive irrigation and fertilizer application. Therefore, we assessed the appearance of rust staining on 700 center pivot irrigation systems to determine if prediction of underlying groundwater quality conditions, particularly nitrate-N concentrations, may be possible as a bridge between remote sensing and field-based observations. The use of full-rust pivots as a predictor of low groundwater nitrate concentrations has the potential to reduce groundwater sampling time and costs.

2. METHODS

South Central Nebraska was chosen for this study due to the high density of center pivot irrigation systems and previous groundwater quality work in the region (Figure 1A). Approximately 50% of the land area in this region is irrigated by center pivots (Figure 1B). Pivots observed in this study were chosen from center pivot irrigation wells used previously for developing geologic cross-sections in the area and/or wells with long-term nitrate concentrations. A total of 700 wells were examined on Google Earth. Then, 277 wells were viewed in person (250 successfully classified) to ground-truth the Google Earth assessment. In-person classification of 27 center pivots was unsuccessful due to crop height, distance from accessible road, or because the pivot was no longer in use. There were two main types of center pivot sprinkler configurations observed in this study: top-mounted sprinkler systems, where the sprinkler was located above the water supply pipe (i.e., pivot span) and dropped sprinkler systems (equipped with drop nozzles, where the sprinkler was below the span) (Figure S1).

All pivots were viewed manually on Google Earth imagery[21] and classified as full-rust (>80% of pivot structure had a rust color), part-rust (10%−80%), no-rust (<10%), not found, and not identifiable. The percentage of rust was determined visually based on the amount of pivot and rust present and viewable on Google Earth. The term "rust" was used as a description of the color of the pivot, though the pivot may be rust-stained, coated in iron precipitation, or the metal itself corroded. Ground-based surveys focused on a subset of pivots (277 of the 700) were then conducted by the same research team using the same classification system. A photo was taken of each pivot that was viewed in person from the ground. Additional information such as the pivot nozzle configuration (e.g., drop nozzle) was recorded during ground surveys. Thirty pivots were classified as not identifiable on Google Earth, and four pivots were classified as not identifiable or not found during ground-based surveys. Full-rust pivots on Google Earth appeared as a dull, red/brown color (Figure 2A), while ground-based surveys revealed yellow, rust red, or even dark red/black (when wet) coloring (Figure 2D). Three pivots with a greenish color were observed but excluded from the study due to a lack of nitrate data. No-rust pivots appeared as a silver-blue color on ground-based and Google Earth classifications (Figure 2B,E). Part-rust pivots may appear the same as a no-rust pivot on Google Earth or as a mix of no-rust and full-rust pivot depending on where the coloring appears on the pivot (Figure 2C). From the ground-based view, part-rust pivots had partial areas of rust red, silver blue, and a yellow transition between the two (Figure 2F). On pivots with dropped sprinklers, the top of the pivot appeared free of rust while the wheel towers and other areas exposed to irrigation water appeared a yellow or rust red.

The two classification methods (Google Earth and ground-based) were compared, where differences between the two classifications were categorized as false positives (pivot appears full or part-rust on Google Earth classification but no-rust on ground-based classification) or false negatives (pivot appears no-rust on Google Earth but is full or part-rust on ground-based classification). Most false negatives were for center pivot systems equipped with dropped sprinklers. Information on the type of pivot sprinklers was not collected on the preliminary observations of 23 pivots examined in 2019 but was recorded for the subsequent 227 successful observations in 2020. Locations of all pivots examined on Google Earth and in person were mapped spatially in ArcMap (ERSI ArcGIS v10.8.1) to examine patterns in the occurrence of rust.

For pivots viewed on Google Earth, nitrate data was found where it existed using the Quality-Assessed Agrichemical Contaminant Database for Nebraska Ground Water.[24] The most recent nitrate data was used for each center pivot system, and only data from 2000 to the present was used. It is possible that more than one well supplied a single center pivot or that a single well supplied multiple center pivots. Retired center pivots are often left in the field, but no longer in use. However, in this study we did not find any center pivots with nitrate data that were currently supplied by multiple wells. In cases where more than one center pivot was associated with a single well, it was determined if all pivots were still operational and then all pivots associated with that well were classified. A total of 318 wells met these qualifications and were used in this study. A single factor ANOVA and Tukey test was completed in R using the ANOVA and Tukey test function to determine if there were differences between the categories of full-rust, no-rust, and part-rust.

3. RESULTS AND DISCUSSION

3.1. Pivot Classification.

Pivots had enough visible features for classification as full-rust, part-rust, or no-rust 88% of the time when using Google Earth imagery. Cases where pivot classification was not successful based on Google Earth were due to a combination of the time of year, time of day, or crop type when the image was taken. The classifications made using Google Earth matched ground-based classifications 83% of the time (Table 1, Table S1). Limitations to Google Earth-based classification include time lag between the acquisition date of Google Earth imagery and ground survey completion. Given substantial time lags (e.g., years), pivots appearing rusted in aerial imagery may have been replaced, or pivots that showed no rust in aerial imagery may have been stained or rusted. Additionally, pivots with dropped sprinklers were challenging to identify on Google Earth as the pivot's rusted parts were not visible from a vertical plane. Of the false negatives where pivots appeared as no-rust on Google Earth but was part-rust or full-rust in person, 52% were pivots with dropped sprinklers (Table S1).

Table 1. Comparison of Pivot Classification Classifications from Google Earth and Ground-Based Survey Approaches

	Google Earth	Ground View
full-rust	53	76
part-rust	25	48
no-rust	142	124
not identifiable	30	2
not found	0	0

While the classification method in Google Earth was not automated in this study, it takes significantly less time to observe a pivot in person and even less time to examine on Google Earth than to collect groundwater samples from individual wells. It is possible that pivot color classification could be automated using airborne or satellite imagery, but this would require much higher image resolution than currently available. Current machine learning techniques, which use aerial or satellite imagery to identify areas (i.e., the typical circular patterns created by the rotating pivots) irrigated by center-pivot irrigation, have been shown to have an accuracy of 88−93%.[25−27] Irrigation covers 53.8 hectares for a standard quarter section center pivot versus approximately 6×10^{-3} hectares for the viewable surface area of a single pivot span (here we define the span of a pivot is the length of the pivot arm that rotates through the field, or approximately 402 m). In addition, the most visible part of the pivot in Google Earth, the span, is a long and narrow feature that is often accompanied by a dark (also long and narrow) shadow that is likely to be a confounding factor for image processing algorithms.

Based on observations made in this study, classification using Google Earth imagery will be less effective in areas where irrigation center pivots mostly have dropped sprinklers. However, pivot appearance determined through ground surveys (and, perhaps, producer surveys) can still be used to supplement classification based on Google Earth imagery and/or to reduce sampling costs. In areas where there are top-mounted sprinklers or a mix of sprinkler types, then Google Earth may be a good starting place. If it is unknown what type of center pivot irrigation systems are in the area, ground surveys are especially important to ground-truth the Google Earth analysis.

3.2. Relationship between Pivot Appearance and Groundwater Nitrate Concentration. The mean groundwater nitrate concentrations for pivots classified as full-rust, part-rust, and no-rust were 2.4, 4.5, and 7.8 ppm, respectively. These mean concentrations for each classification of pivot appearance were below the current drinking water guidelines for nitrate.[28] However, while the groundwater nitrate concentrations for full-rust pivots range from 0.0 to 8.0 ppm, part-rust ranged from 0.0 to 22.9 ppm, and the no-rust ranged from 0.1 to 43.9 ppm, (Table S2). The presence of a no-rust pivot was not an accurate predictor of elevated underlying groundwater nitrate concentrations. However, based on observations in this study, full or part-rust pivot observations corresponded with lower groundwater nitrate concentrations at those locations (Figure 3). Using full-rust pivots as a predictor of low groundwater nitrate concentrations can guide existing or new water monitoring programs to reduce sampling time.

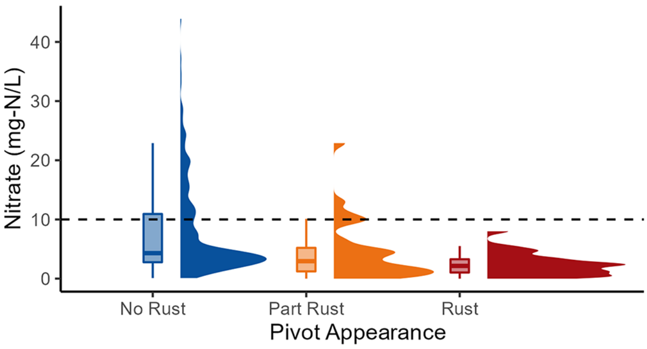

Figure 3. Groundwater nitrate-N concentration and pivot appearance for 250 wells in south central Nebraska. The black dashed line indicates the drinking water standard for nitrate.

In addition to aerial imagery and in-person surveys, based on these findings, water managers can work with producers to gather information regarding pivot appearance at individual farm operations, possibly through producer surveys. Producer engagement could have an additional benefit of educating the public about geoscience concepts (previous discussions with producers and water managers in Nebraska on this study and related topics such as rust stains on sinks/bathtubs, sulfur odor of groundwater, etc. have had strong engagement). The presence or absence of rust is also of interest to center pivot manufacturers, who could be an additional source of pivot classification information (though this information may be considered proprietary[29]). There is a statistically significant difference ($p = 0.0004$) in the nitrate concentrations observed at no-rust pivots versus the full-rust pivots. A significant difference ($p = 0.04$) was also observed when comparing no-rust pivots versus the part-rust pivots (Figure 2, Tables S3 and S4). There was no statistically significant difference ($p = 0.49$) observed in nitrate concentrations between part-rust pivots and full-rust pivots.

Wells included in this study ranged from 0 to 115 m below the water table (Figure S3). There is no trend in nitrate concentrations with depth, suggesting that the low nitrate concentrations are not due to vertical stratification of groundwater nitrate alone. There is no correlation between well depth and pivot classification in this area, but a better understanding of geology could help determine the prevalence of rust based on geologic conditions (Figure S4). The source of the irrigation water may have also impacted pivot appearance and areas using surface water with center pivot irrigation or a mix of surface and groundwater would need to be studied further to understand the validity of these relationships in those environments.

Since the number of no-rust pivots was greater than full-rust and part-rust pivots, it would be beneficial to obtain groundwater nitrate concentrations at more of the part-rust and full-rust pivots to strengthen the analysis. Ninety-six pivots were identified as full or part-rust on Google Earth or when ground viewed but had no nitrate data associated with the wells. Future work to obtain groundwater nitrate data would help refine the relationship between pivot appearance and groundwater nitrate concentrations for this area. Water managers in this region have observed the correlation between pivot appearance and groundwater nitrate concentrations, which might explain the lack of sampling in areas with a high density of ″rusty″ pivots.[30] There is generally less emphasis on sampling areas of low groundwater nitrate concentrations compared to areas of high groundwater nitrate concentrations.[7,11]

3.3. Spatial Patterns of Pivots with Rust. Pivots with rust tended to occur in patches instead of randomly throughout the study area, suggesting a potential relationship with underlying groundwater biogeochemical conditions (Figure 4A), although it could also relate to other factors such as temporal and spatial patterns of center pivot expansion through the region (e.g., older pivots may be more prone to corrosion). The presence of full-rust pivots is most prevalent in the northeast and south-central regions of the study area. Full- or part-rust pivots fell on the northeast-southwest diagonal between these two areas. Groundwater nitrate concentrations vary throughout the study area, with lower concentrations occurring in the mid-east to eastern portions of the study area (Figure 4B). Groundwater iron concentrations have been

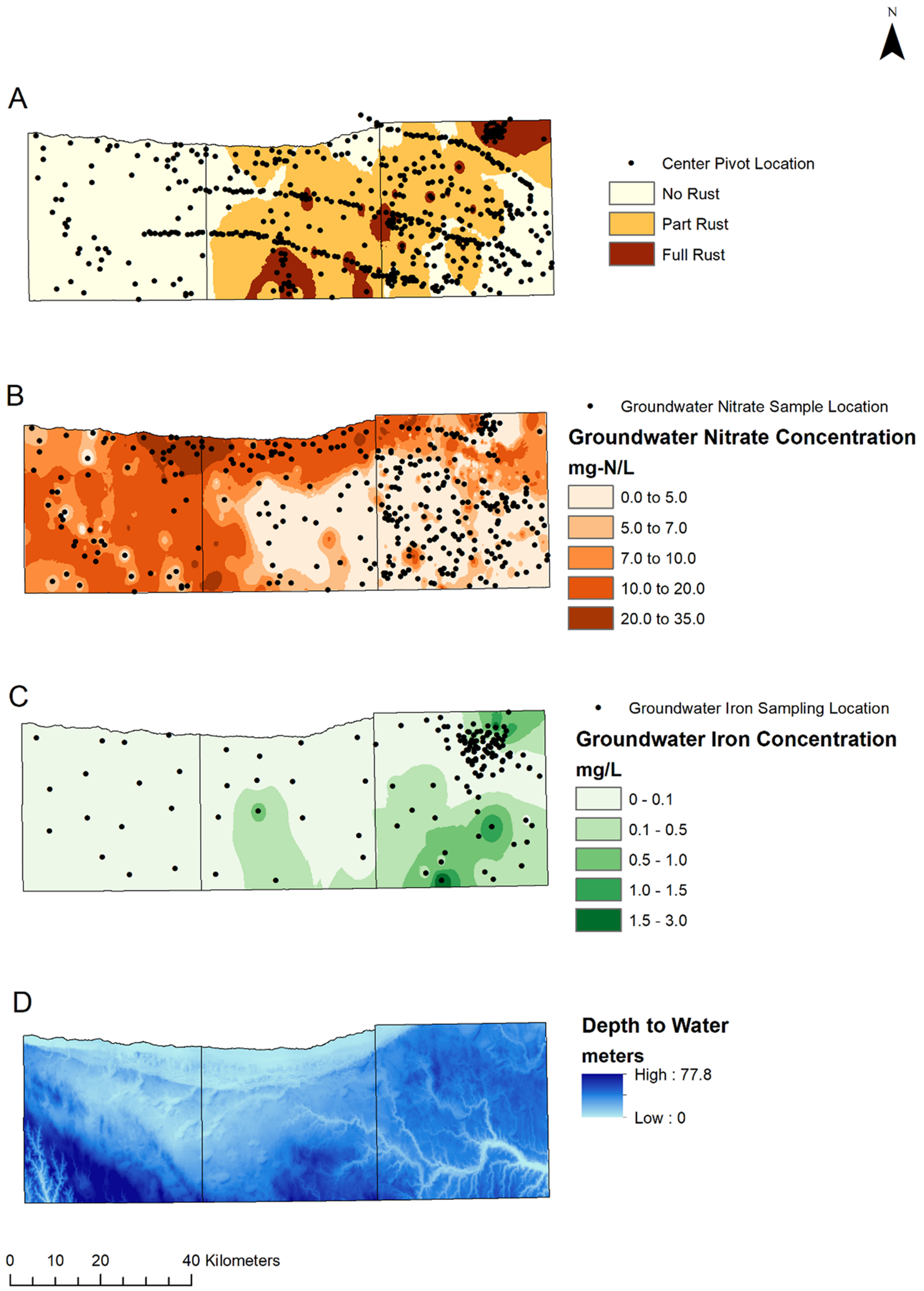

Figure 4. (A) Location of ground-viewed pivots with and IDW interpolations of rust classification, (B) groundwater nitrate concentrations throughout the study site from 2000 to present (data taken from the Ag contaminate database), (C) groundwater iron concentrations data taken from Little Blue NRD and Wortmann,[10,31] and (D) depth to water in m.

measured at a much lower sampling density compared to pivots and nitrate, but available data suggests the highest iron concentrations are in the south-central and eastern sections of the study area (Figure 4C).

The northern section of the study was dominated by surface water irrigation canals from the Platte River starting in the 1940s.[32] Depth to water varies throughout the study area with a shallow depth to water around the Platte River to the north and the Little Blue River in the east (Figure 4D). Flood irrigation supplied by canals has given way to center pivot irrigation with 50% of the land area irrigated by center pivots and a mix of surface water and groundwater used. The timespan of fertilizer application and approximate applied fertilizer amounts on a county level is equal throughout the study area. Nitrate management decisions in this area are made by two Natural Resources Districts (NRDs) based on groundwater nitrate concentrations at the township level. If the average groundwater nitrate concentration of a specific township reaches a predetermined concentration (average groundwater nitrate greater than 9.0 ppm), then fertilizer restrictions are put in place. These restrictions stay in place until groundwater nitrate concentrations decrease below that level or reach the next level of restrictions.[33]

Despite similar management strategies and historical land use, groundwater nitrate concentrations vary substantially throughout the region (Figure 4B). These concentrations indicate that denitrification is occurring. These areas also correspond with low groundwater nitrate and high groundwater iron concentrations (Figure 4B,C). In particular, the north-central section of the study area has some of the highest groundwater nitrate concentrations and highest irrigation well density (Figures 1B and 4B). There are some part-rust pivots in this area, but no full-rust pivots. While part-rust pivots are associated with a lower average groundwater nitrate concentration than no-rust pivots not all part rust pivots are associated with groundwater nitrate concentrations below 10 ppm. One exception is the northeast section of the study area, where there is high irrigation well density but low groundwater nitrate concentrations (Figures 1B and 4B)). This section of the study area corresponds to a large section of full-rust and part-rust pivots, indicating denitrification occurring in this location (Figure 4A). While nitrate and depth to groundwater vary throughout the study area, there is no clear pattern of nitrate concentrations corresponding with depth to groundwater. There are areas with high groundwater nitrate and a shallow depth to water as well as areas with high nitrate and a deep depth to groundwater (Figure 4D).

Groundwater iron concentrations above 0.1 mg/L indicate anoxic conditions conducive to denitrification.[15] Dissolved oxygen (DO) is often the most common indicator of anoxic conditions. However, this indicator requires groundwater sampling to determine DO conditions throughout an area. Dissolved oxygen data is routinely collected in many groundwater quality studies but is often missing in state and local groundwater monitoring in Nebraska.[11,14,33] The ability to visually assess potential anoxic conditions through pivot appearance can cut down on time and funds to conduct groundwater sampling campaigns. Currently, the NRD in this region spends up to 1 month and \$8000−\$10,000 dollars annually on groundwater nitrate sampling.[34] Areas of denitrification could be sampled less frequently resulting in an overall reduction of costs or sampling costs could be directed into areas of high groundwater nitrate concentrations for a more targeted approach. Since regular sampling campaigns are needed to determine nitrate regulations, a combination of visual assessment and directed sampling could provide more insight into groundwater nitrate contamination at a very minimal cost.[35]

Understanding the role that underlying geology and geochemical conditions are playing in redox conditions and denitrification is essential for producers to make more informed management decisions about equipment use and water managers to make more informed management decisions and regulation.[19,20,36] Previous studies have also found that iron or iron as pyrite can be used as an electron donor in denitrification.[37−39] Further research of this study area is needed to understand if iron plays a role in the denitrification progress or is merely an indicator of redox conditions conducive to denitrification. It is also possible that there are denitrifying geochemical conditions throughout this region and elevated iron at some of these locations. Further study is needed to understand the exact relationship between the geochemical conditions in the area and denitrification. Whether or not the iron plays a role in the denitrification process, it is still an indication of low groundwater nitrate concentrations.

Pivot corrosion is also a possible mechanism for pivot rust. Though advances in pivot technology have been made to reduce corrosion, certain water quality conditions can make the corrosion of center pivot systems more likely. Industry research has indicated that low pH (<6.2), high chloride (>500 mg/L) and sulfate (>250 mg/L) concentrations, and “soft” water (lacking dissolved minerals) can cause corrosion.[29] Hard water can also cause damage to pivots with calcium and magnesium build up on the inside of pipes.[29] Figure S4 shows the chloride, sulfur, hardness, and pH of the groundwater throughout the study area. The western portion of the study area has elevated chloride and sulfur that may indicate corrosion but also has higher water hardness, which is not an indicator of corrosion. None of the center pivots viewed meet the industry definition of being likely to experience corrosion and it is unlikely that any corrosion is occurring anywhere in the study area.

The appearances of pivot rust, low nitrate, and elevated iron all occur in the same general locations spatially (in map view), but the situation is more complicated when considering the vertical dimension (Figures S5−S7). There is the greatest spatial overlap between groundwater nitrate below 10 mg-N/L and the appearance of pivot rust (Figures, S5−S7). This may be due to the high number of nitrate and pivot samples compared to iron. It cannot be assumed that a new well placed in the center of a patch of rusty pivots would also have similar iron concentrations and denitrification because these values could be dependent on the depth and length of the wells screen. As irrigation wells often have long well screen, they might cross through multiple redox conditions making the placement of a new well difficult. Though this study did not find a correlation between rust and well depth this may not be universal. We also note a grouping of part-rust pivots in the north central portion of the study area that does not correspond to low nitrate or high iron. These wells are close to the Platte River and may be using Platte River water from a canal or a mix of surface water and groundwater. In this case, iron staining may not be related to anoxic groundwater conditions that cause denitrification. This area has been under irrigated production longer than the rest of the study area,[12,17,32] and the rust in this area may be due to natural corrosion of the center pivot system rather than iron staining from iron in groundwater.[29] Further research is needed to understand the vertical extent of iron and its relationship to geology. Detailed test holes (exploratory boreholes to determine geology) and well logs could provide insight into potential geologic layers associated with the presence of elevated groundwater iron concentrations. Similarly, there are few geochemical data available for the vadose zone in this area. Studies have been done examining the fate of nitrate in the vadose zone, with iron as an indication of redox conditions in the vadose zone and shallow groundwater.[40−42]

3.4. Conclusions. Groundwater nitrate contamination can negatively impact drinking water in agriculturally dominated areas. With irrigated agriculture expanding throughout the world, there is potential for more groundwater contamination in underlying aquifers. Classification of center pivot system color to determine underlying groundwater geochemistry, as demonstrated in this study, can help guide new sampling programs in emerging agricultural areas without extensive groundwater sampling. New and existing groundwater management agencies can also use center pivot classification to focus sampling locations and cut down on sampling costs. Water management agencies can quickly assess areas for denitrification potential as part of management decision-making processes (while acknowledging that nitrate leaching must be less than denitrification potential to avoid aquifer contamination).

While the automated detection of pivot appearance using analysis of airborne or satellite imagery (machine vision) would require much higher image resolution, spatially mapped observations of pivot rust may be well suited as a predictor variable in machine learning models that predict groundwater quality conditions.[43−45] This study demonstrates a statistically significant difference in groundwater nitrate concentrations when comparing full-rust center pivots to no-rust center pivots, but key limitations should be addressed to advance the method. More work is needed to understand the denitrification mechanisms and products, potentially including study of microbial communities and mineralogy of rust stains on pivots. Studies should be conducted over larger spatial areas, across diverse geological settings, and with different ambient groundwater quality conditions. In all cases, the highly visual and practical aspects of linking pivot appearance with groundwater quality will make such studies an engaging topic for agricultural producers and water managers, with the side benefit of introducing redox concepts to important water decision makers.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestwater.2c00121.

> Additional photographs of center pivot irrigation systems, tables with details of statistical tests, maps showing groundwater geochemistry related to irrigation suitability, and maps showing overlap in groundwater quality parameters (PDF)

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