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Demonstration of Center Pivot Uniformity Evaluation and Retrofit to Improve Water Use Efficiency

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Abstract

Agricultural irrigation is a primary user for freshwater withdrawal. Irrigation plays an important role in crop production, as it provides the benefit of reducing the effects of prolonged dryness and erratic precipitation. Center pivot irrigation system is the most common irrigation system in agriculture. As the center pivot irrigation system ages, the system could develop a leaking joint, clogged sprinklers, and physical damage. This can cause areas of non-uniformity that can lead to under- or over-irrigated in some areas of the land, resulting in excess energy use and cost, wasting resources, and environmental impacts. Thus, it is important to evaluate the performance of a center pivot irrigation system regularly to maximize return on investments and minimize wasting resources. This study focuses on evaluating the impacts and benefits of improved center pivot irrigation distribution uniformity by performing distribution uniformity evaluations pre- and post-retrofit. This study also focused on demonstrating an unmanned aerial vehicle (UAV) to assess the performance of the center pivot irrigation system in two irrigated farmlands. The Coefficient of Uniformity (CU), Distribution Uniformity (DU), and Scheduling Coefficient (SC) were calculated based on the catch can test data. The values were utilized to evaluate water and energy savings from the improved coefficients. The team has found that replacing sprinkler packages increased the CU from 78 to 89 and the DU from 77 to 82, and reduced the SC from 1.3 to 1.2 in Field A. In Field B, replacing sprinkler packages increased the CU from 73 to 91 and the DU from 62 to 84 and reduced the SC from 1.6 to 1.2. The estimated water savings in Field A due to the reduced scheduling coefficient was approximately 151,000 liters/hectare/year, with consideration of the corn and soybean rotation field in Michigan. The estimated water savings in Field B was 608,000 liters/hectare/year. The data from this demonstration study showed the value of distribution uniformity evaluation and retrofit of irrigation systems. This information will encourage farmers and agricultural industries to consider performing more distribution uniformity evaluations, ultimately improving irrigation water use efficiency and supporting sustainable water management in agriculture.

Keywords

Center Pivot, Irrigation, Uniformity, Sprinkler System Evaluation, Water Saving, UAV

1. Introduction

Agricultural irrigation contributes 65% of the world's freshwater withdrawals, excluding thermoelectric power. As the world experiences climate change, agricultural irrigation plays a significant role in crop production. Irrigation can reduce the effect of erratic precipitation and prolonged soil dryness, which will increase the resilience of crop production to climate change. However, improper or unnecessary irrigation can waste resources. Freshwater is a valuable and limited resource. Thus, efficient water use in agriculture is important for sustainable water management in agriculture, as well as crop production.

A center pivot is a pipe-sprinkler irrigation system that rotates around a central pivot and moves in a circular area. The center pivot irrigation system is the most popular sprinkler system in the world [1]. Center pivot irrigation systems have been used in corn, soybean, potato, alfalfa, wheat, cotton, vegetables, and sugar beet fields [2]-[9]. As center pivot irrigation systems age, several issues can be found, such as leaking joints, clogged sprinklers, missing sprinkler heads, and rusted equipment [10]. These can cause areas of non-uniformity that can make locations under- or over-irrigated and increase the potential for nitrogen leaching into groundwater [11]. Poor uniformity in irrigation can lead to excess energy use and cost and potentially affect yield negatively due to poor soil aeration and increased disease incidence [12]. Some research observed good uniformity can positively affect crop yield. The increase in the coefficient of uniformity resulted in a 4% increase in corn yield for a common irrigation strategy and an 11% increase for 17% additional irrigation application [13] [14]. In addition to corn, previous research found that increasing the uniformity of irrigation systems direct correlates with the growth of alfalfa and hay yield. The study discussed that the highest alfalfa yield was found in the highest uniformity condition [15]. Therefore, it is important to maintain good uniformity to maximize yield and growth, save water, and reduce nutrient loss to percolation [16] [17].

A common method to evaluate the irrigation system uniformity is a catch can method. The catch can method requires setting catch cans every 3 m (10 ft) from the center of the irrigation system. The cans should be at least 12 cm above ground level. The test should be conducted when the wind is less than 3.6 km/h

(2.25 mph) and during the late evening through early morning hours to minimize evaporation [18]. Once the uniformity evaluation is completed, distribution uniformity can be calculated to determine whether the center pivot system is applying the water evenly or not. Irrigation distribution uniformity evaluation provides useful information, however, estimation of the values regarding water, energy, and cost savings should be conducted to encourage more farmers and agricultural industries to perform the evaluation. This study focuses on assessing the benefits and impacts of improved center pivot irrigation uniformity by conducting center pivot uniformity evaluations pre- and post-retrofit. In addition, the study evaluates an Unmanned Aerial Vehicle (UAV) to observe its capability to assess irrigation system water distribution.

2. Materials and Methods

2.1. Demonstration Sites

Two center pivot irrigated fields were selected for demonstration. Field A has a 6-tower center pivot irrigation system, located in Three Rivers, MI, USA. The center pivot irrigation system in Field A is equipped with a cornering arm and an end gun. Field B has a 4-tower center pivot irrigation system with an end gun and is located in Constantine, MI, USA. Both farmlands rotate corn and soybean.

2.2. Catch Can Setup

Uniformity was conducted following the ANSI/ASAE S436.1 standard, which is a Testing Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles. The procedure includes placing 946 ml (32 oz) catch can at 3 m (10 ft) distance apart in a straight line outward from the pivot elbow. Once the catch cans were installed in the field, irrigation was started. The water level in each of the cans was measured using a graduated cylinder and recorded. **Figure 1** and **Figure 2** show the catch can setup in Field A and Field B, respectively.

Figure 1. Catch can setup in demonstration field A (Three Rivers, MI, USA).

Figure 2. Catch can setup in demonstration field B (Constantine, MI, USA).

2.3. Unmanned Aerial Vehicle (UAV) Flight

UAV or unmanned aerial systems (UAS), commonly referred to as drones, have been used in many agricultural applications such as monitoring water management, nutrient management, crop health, topography evaluation, etc. [19] [20] [21] [22] [23]. Typical height of a center pivot pipeline is located at 3 m (10 ft) and some sprinkler packages are mounted on the top of the pipeline which makes hard to observe the condition of the sprinkler packages. Aerial photos and videos provide valuable information, especially with the ability to capture images at the top of the pipeline. Thus, a UAV was used to determine how much information could be gathered about the uniformity of a center pivot irrigation system. An Autel EVO II Pro V2 (Autel Robotics, Bothel, WA, USA) with stock optical hardware (6 K video, 2.54 cm CMOS 20 MP sensor) was used to capture all aerial imagery. The Autel remote controller was connected to either a smartphone (iPhone 13) or a small tablet (iPad Mini) and the Autel Explorer app was used during flight. The UAV was flown over irrigation systems in operation to detect differences in water distribution patterns from individual sprinkler heads. No software was needed to view aerial imagery aside from standard photo or video players as orthomosaics were not created and only RGB imagery (red-green-blue, *i.e.*, standard optics) was collected. The goal was to determine whether qualitative information, quantitative information, or both could be gathered about the systems.

The UAV was flown at various altitudes and angles relative to the center pivot and the direction of flight. Altitudes included: 3.0 m (10 ft) above ground level (AGL), roughly equal to the height of the sprinkler heads; 7.6 m (25 ft) AGL; 10.7 m (35 ft) AGL; and 15.2 m (50 ft) AGL. The angle of video capture in relation to the ground included: 0 degrees (when at sprinkler head height); 90 degrees (when flying directly over the pivot); and roughly 20 to 30 degrees (at 7.6 and 10.7 m AGL) when flying roughly 9 m (30 ft) to the side of the pivot. The UAV was also flown at various angles to the direction of travel from 90 degrees (*I.e.*, directly facing the irrigation span traveling sideways) to roughly 45 degrees in the direction of travel.

2.4. Coefficient of Uniformity

Once the catch can data were collected, the Coefficient of Uniformity (CU), also known as the Christiansen coefficient, was calculated. This is the most common method to determine the system's uniformity. This method accounts for the increased area coverage of each sprinkler head as one moves away from the center. It is defined as shown in Equation (1) [24].

$$\text{CU} = \left[1 - \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)}{n\bar{X}}\right] * 100\% \quad (1)$$

where,

X_i is the water depth collected from the *i*th catch can (mm/h).

$\bar{X}$ is the average of water depth collected in all catch cans (mm/h).

n is the total number of catch cans.

2.5. Distribution Uniformity

Distribution Uniformity (DU), an indication of how uniform the spray of the system is, compares the lowest one-quarter of depth in the catch cans to the overall depth of the catch cans. It is defined as shown in Equation (2) [8].

$$\text{DU} = \frac{D_{lq}}{\bar{D}} * 100 \quad (2)$$

where,

D_{lq} is the average of the lowest one-quarter of measure depth.

$\bar{D}$ is the average of water depth collected in all catch cans.

2.6. Scheduling Coefficient

Scheduling Coefficient (SC) is a run time multiplier that shows the amount of extra water that needs to be applied to get the dry areas of the field wet. It is defined as shown in Equation (3) [24].

$$\text{SC} = \frac{1}{\text{DU}} * 100\% \quad (3)$$

where,

DU is distribution uniformity.

2.7. Uniformity Evaluation Criteria

The CU, DU, and SC were calculated using the collected data. In these calculations, data from the first 15 m from the center and the end gun areas were eliminated for the calculations. The acceptable ranges for CU, DU, and SC from other studies are shown in **Table 1**. In this study, the criteria to evaluate the satisfaction of retrofit were using CU > 85%, DU > 80%, and SC < 1.3.

3. Results and Discussion

3.1. Catch Can Results

Figure 3 and **Figure 4** show the catch can test results pre- and post-retrofit of

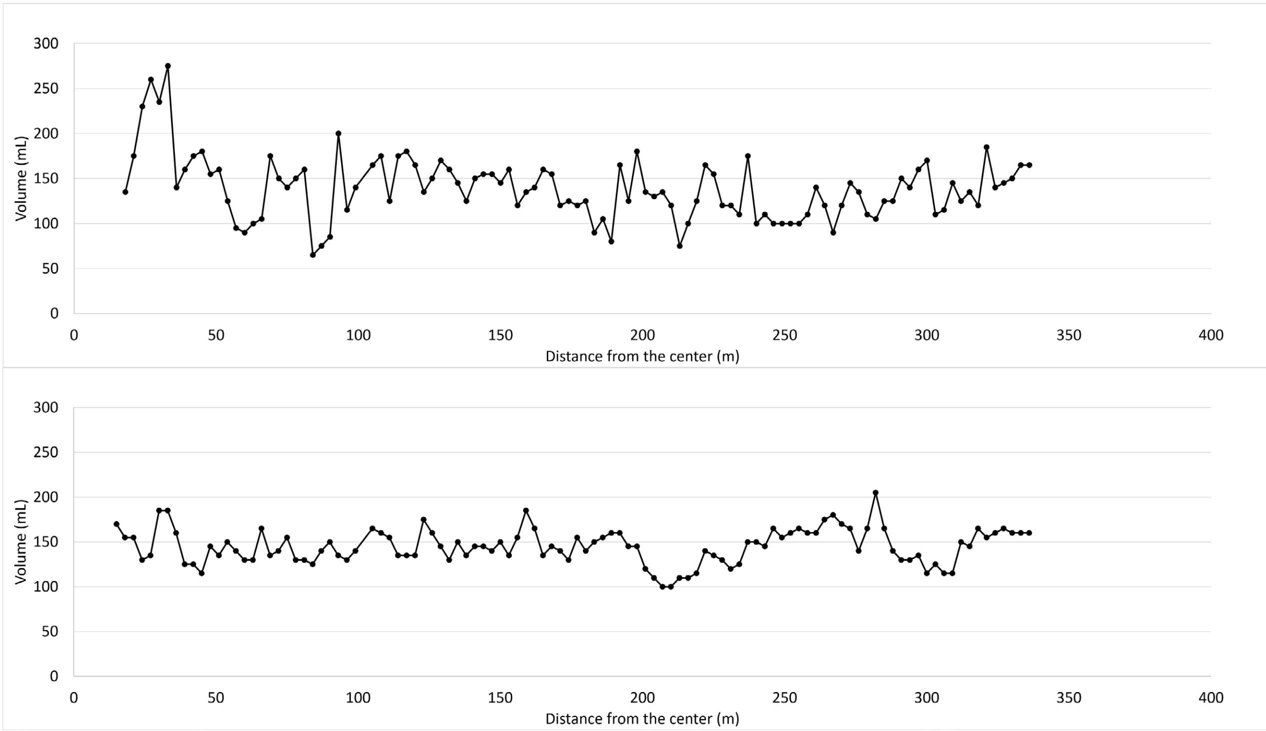

Figure 3. Uniformity data of pre- (top) and post- (bottom) sprinkler package upgrade in Field A using the catch can method.

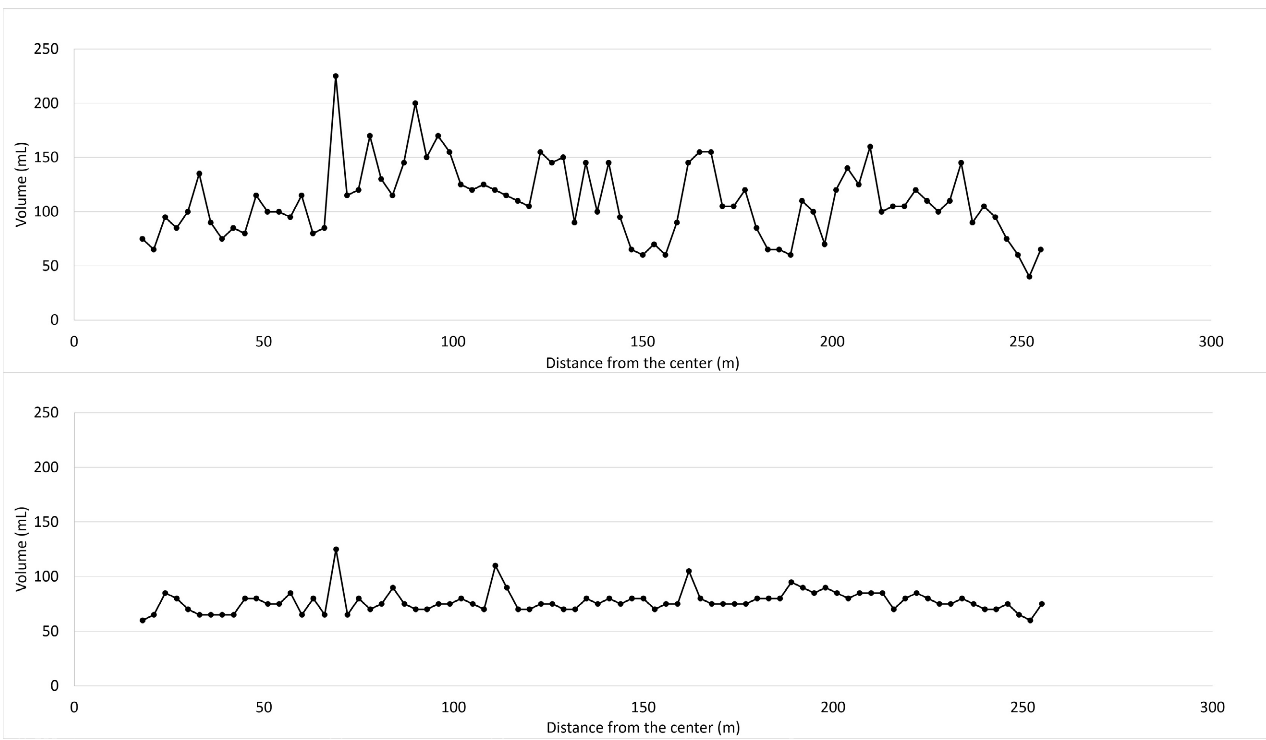

Figure 4. Uniformity data of pre- (top) and post- (bottom) sprinkler package upgrade in Field B using the catch can method.

the sprinkler packages replacement. The catch can test was effective in determining the problematic locations of the center pivot and measuring the actual water application to the soil. In Field A, the areas between 18 and 36 meters from the center were significantly higher than the average. Several areas at 57 - 66, 84 - 90, 183 - 189, and 213 meters from the center were lower than the average. At Field B, the areas at 69, 78, and 90 meters from the center were markedly higher than the average and the areas at 150 - 156, 183 - 189, 198, 249 - 255 meters, were considerably lower than the average. Under-irrigated areas could have plant water stress, resulting in reduced crop yield and quality. Over-irrigated areas can waste water and leach nutrients below the root zone [11].

CU, DU, and SC can be calculated using the data collected by the catch can test. These coefficient values can be used as an evaluation of the improvements after repairing or upgrading or retrofitting the irrigation system. At both demonstration farms, the farmers and the project team have replaced the sprinkler package which was the major contributor for poor uniformity (see **Table 2**). The CU, DU, and SC of the pre-sprinkler package upgrade from Fields A and B did not meet the criteria. Post sprinkler upgrades for both CU and DU were increased by approximately 11% and 5%, respectively. The CU, DU, and SC met the criteria after replacing sprinkler packages. These data show that upgrading sprinkler packages when the uniformity is poor improved the CU, DU, and SC. In addition to the sprinkler package upgrade, other potential issues, such as leakage at the pipe joint and pressure differences within a system caused by the elevation changes and pipeline friction losses should also be inspected and considered.

Table 1. Uniformity acceptance ranges.

Analysis	Recommended Range (%)	References
Coefficient of Uniformity	>85	[25] [26] [27] [28]
	>84	[29]
Distribution of Uniformity	90 - 95	[30]
	>75	[31] [32]
Scheduling Coefficient	<1.3	[29]

Table 2. Result of coefficient of uniformity, distribution uniformity, and scheduling coefficient for Field A and Field B.

Analysis	Field A		Field B	
	Pre-Sprinkler Upgrade	Post-Sprinkler Upgrade	Pre-Sprinkler Upgrade	Post-Sprinkler Upgrade
Coefficient of Uniformity	78	89	73	91
Distribution Uniformity	77	82	62	84
Scheduling Coefficient	1.3	1.2	1.6	1.2

3.2. UAV Results

A UAV was used to capture aerial pictures and videos of center pivot irrigation systems with known problems, primarily with faulty sprinkler heads, to determine what kind of information could be obtained with the UAV and how best to capture the imagery. It was apparent that video was helpful and necessary in some cases, as photos were difficult to observe the obvious differences in water distribution patterns among sprinkler heads. **Figure 5** is a clear UAV photo that shows three sprinklers with the middle having a very distinct throw pattern. Therefore, while video is the preferred way for identifying problematic sprinklers, photos can also be used if it is clear and high-resolution.

The second lesson learned was that the height of the UAV relative to the irrigation equipment was important, particularly with a light-colored backdrop like the cloudy sky seen in **Figure 6(a)**. Being able to position the UAV at some height above the pivot allowed for a greater contrast between the lighter water spray and the darker crop canopy or trees as background (**Figure 6(b)**) making it easier to detect differences in throw patterns. Positioning the UAV directly above the pivot had some advantages, especially when using a gimbal angle of roughly 45 degrees and a greater altitude to see a larger section of the irrigation system to look for obvious water distribution pattern anomalies (**Figure 7**). The altitude could then be decreased to further investigate any differences detected.

For most situations, it was found that flying approximately 9 m away from the irrigation span, 10.7 m AGL and approximately 45 degrees in the direction of travel resulted in an efficient method of examining an entire pivot for sprinkler head anomalies (**Figure 8**). This method allows the pilot to effectively maneuver

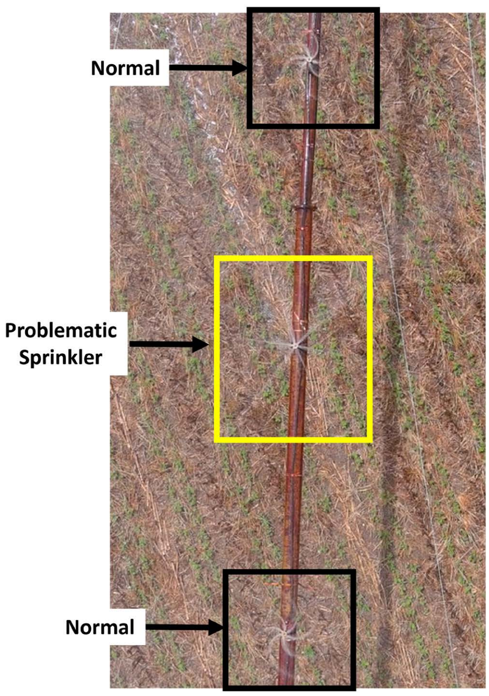

Figure 5. A worn sprinkler head in the middle of this UAV image.

Figure 6. (a) Positioning the UAV at the same height as the pivot span is not useful when there is not sufficient contrast between the water throw and the backdrop. (b) With trees as a backdrop allows to see the water spray patterns.

Figure 7. Positioning the UAV directly above the pivot at a higher altitude (*I.e.* 15 m AGL) and capturing video at a gimbal angle of roughly 45 degrees is an efficient way to detect obvious differences in sprinkler throw patterns.

the UAV, see water distribution differences, and safely fly while keeping the UAV away from the water spray. An exception to this protocol would be when examining the end gun for coverage and any equipment failures. Care should be taken to begin flying at a greater altitude over the end gun to enable the pilot to see the full extent of coverage while keeping the UAV away from the water spray before decreasing altitude for a closer inspection if necessary (**Figure 9**).

Figure 8. Flying above the pivot and approximately 45 degrees in the direction of the flight path is an efficient protocol for viewing sprinkler anomalies in most situations.

Figure 9. Begin flying the UAV well above the height of the pivot when capturing video of the end gun to capture the full extent of coverage and to keep the UAV away from the water spray.

3.3. Potential Water and Energy Cost Savings

Potential water and energy savings of the two demonstration sites were estimated based on available data and assumptions, including annual average irrigation application in corn and soybean production in Michigan and an average irrigation power cost in Michigan. The scheduling coefficient for Field A was reduced from 1.3 to 1.2 after replacing the sprinkler packages. The scheduling coefficient is a run time multiplier to ensure dry areas of the field are wet. The annual average irrigation application in corn and soybean production in Michigan is 15.24 cm. This means the annual irrigation application for corn and soybean production was reduced from 19.81 cm to 18.29 cm. Therefore, 1.52 cm per year of irrigation application can be conserved from the retrofit. This translates into savings of 4.9 million liters per year, given the size of 32.4 hectares of field A. The scheduling coefficient for Field B was reduced from 1.6 to 1.2 after the retrofit. This equates to saving 19.7 million liters per year, given the size of 32.4 hectares of field B. Michigan has over 8000 center pivot irrigation systems, and one-third of them are more than 20 years old. Therefore, evaluation and retrofit of the existing center pivot irrigation have the potential to significantly impact and support sustainable water management in agriculture. Irrigation water saving directly relates to energy saving. An average irrigation power cost in Michigan is $5.24/hectare/cm. The potential energy savings for Field A and Field B are $258/year and $1023/year, respectively. This energy cost saving could potentially motivate more farmers and agricultural professionals to conduct the irrigation system evaluation and retrofit.

4. Conclusions

Performance evaluation of water distribution uniformity of the center pivot irrigation system was helpful in determining whether the system needs a repair or replacement of parts. Retrofit on two demonstrated center pivot irrigation systems increased the coefficient of uniformity to above 85, which is recommended threshold. Improved uniformity shows the potential water saving of 4.9 and 19.7 million liters/year for Field A and B, respectively. In addition, the potential energy savings were $258/year and $1023/year for Field A and B, respectively. Efforts to evaluate and retrofit the existing irrigation systems and outreach activities should be continued to support sustainable water management in agriculture. The collaboration between University Extension agents, local USDA NRCS staff, Soil and Water Conservation Districts, and irrigation dealers is critical to accelerating the number of evaluations and their impacts. In addition, a study on the effect of the newer sprinkler packages on distribution uniformity is needed for the retrofit recommendation.

In this study, identifying problematic sprinklers of a center pivot irrigation system can be achieved using a UAV. However, it was not possible to quantitatively estimate the volume of water distribution of a sprinkler head or compare distribution among sprinklers using only RGB video. Therefore, UAVs should only be relied upon to detect qualitative differences among sprinklers and other equipment anomalies or failures. More evaluation and potential use of Artificial Intelligence (AI) techniques may allow UAV to determine quantitative analysis.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Waller, P. and Yitayew, M. (2016) Center Pivot Irrigation Systems. In: *Irrigation and Drainage Engineering*, Springer, Cham, 209-228. https://doi.org/10.1007/978-3-319-05699-9_12

[2] Arens, C. (2018) A Closer Look at Managing Wheat under Irrigation. Nebraska Farmer. https://www.farmprogress.com/irrigation-systems/closer-look-managing-wheat-under-irrigation

[3] Evans, R.G. (2001) Center Pivot Irrigation. https://www.ars.usda.gov/ARSUserFiles/21563/center%20pivot%20design%202.pdf

[4] Hines, S. and Neilbling, H. (2013) Center Pivot Irrigation for Corn Water Management and System Design Considerations in Southern Idaho. http://www.extension.uidaho.edu/publishing/pdf/bul/bul0881.pdf

[5] Neilbling, H., Shewmaker, G. and Falen, C. (2009) Center Pivot Management for Forage Production. UC Davis. https://alfalfa.ucdavis.edu/+symposium/proceedings/2009/09-87.pdf

[6] Nuñez, J., *et al.* (2019) Agriculture: Potato Pest Management Guidelines: Irrigation. UC IPM. https://www2.ipm.ucanr.edu/agriculture/potato/Irrigation/

[7] TRAXCO (2017) Cotton Crop in the Mississippi Delta. http://www.traxco.com/cotton-crop-in-the-mississippi-delta

[8] USGS (2013) Center Pivot Irrigation in the Midwest Corn Belt. https://www.usgs.gov/media/images/center-pivot-irrigation-midwest-corn-belt

[9] Vegetable Growers (2011) California Growers Turning to Center-Pivot. Vegetable Growers News. https://vegetablegrowersnews.com/article/california-growers-turning-to-center-pivot/

[10] Ortiz, B., McClendon, P., Marata, G., Bondesan, L. and Duzy, L. (2021) Operation & Maintenance Problems of Center Pivot Irrigation. https://www.aces.edu/blog/topics/crop-production/operation-maintenance-problems-of-center-pivot-irrigation/

[11] Almasraf, S., Jury, J. and Miller, S. (2011) Field Evaluation of Center Pivot Sprinkler Irrigation Systems in Michigan. Michigan State University, East Lansing. https://www.egr.msu.edu/bae/water/irrigation/sites/default/files/content/Evaluating_CPUniformity.pdf

[12] University of Minnesota (2019) Application Uniformity Testing for Center Pivot Irrigation Systems. University of Minnesota Extension. https://extension.umn.edu/irrigation/application-uniformity-center-pivot-irrigation-systems#:~:text=Uniformity%20testing%20can%20be%20done,sprinkler%20package%20on%20the%20machine

[13] López-Mata, E., Tarjuelo, J.M., de Juan, J.A., Ballesteros, R. and Domínguez, A. (2010) Effect of Irrigation Uniformity on the Profitability of Crops. *Agricultural Water Management*, **98**, 190-198. https://doi.org/10.1016/j.agwat.2010.08.006

[14] Nascimento, A.K., *et al.* (2019) Effects of Irrigation Uniformity on Yield Response and Production Economics of Maize in a Semiarid Zone. *Agricultural Water Management*, **211**, 178-189. https://doi.org/10.1016/j.agwat.2018.09.051

[15] Camp, C.R., Sadler, E.J. and Busscher, W.J. (1997) A Comparison of Uniformity Measures for Drip Irrigation Systems. *Transactions of the American Society of Agricultural Engineers*, **40**, 1013-1020. https://doi.org/10.13031/2013.21353

[16] Center Pivot Irrigation Test Program. Clemson University. https://www.clemson.edu/extension/water/programs/center-pivot-irrigation-test.html

[17] Montazar, A. and Sadeghi, M. (2008) Effects of Applied Water and Sprinkler Irrigation Uniformity on Alfalfa Growth and Hay Yield. *Agricultural Water Management*, **95**, 1279-1287. https://doi.org/10.1016/j.agwat.2008.05.005

[18] Henggeler, J.C. and Vories, E.D. (2009) Evaluating Center Pivot Distribution Uniformity from Catch Can Tests. *American Society of Agricultural and Biological Engineers Annual International Meeting* 2009, Reno, 21-24 June 2009. https://doi.org/10.13031/2013.27346

[19] Li, B., Xu, X., Han, J., *et al.* (2019) The Estimation of Crop Emergence in Potatoes by UAV RGB Imagery. *Plant Methods*, **15**, Article No. 15. https://doi.org/10.1186/s13007-019-0399-7

[20] Meinen, B.U. and Robinson, D.T. (2020) Mapping Erosion and Deposition in an Agricultural Landscape: Optimization of UAV Image Acquisition Schemes for SfM-MVS. *Remote Sensing of Environment*, **239**, Article ID: 111666. https://doi.org/10.1016/j.rse.2020.111666

[21] Radoglou-Grammatikis, P., Sarigiannidis, P., Lagkas, T. and Moscholios, I. (2020) A Compilation of UAV Applications for Precision Agriculture. *Computer Networks*, **172**, Article ID: 107148. https://doi.org/10.1016/j.comnet.2020.107148

[22] Santesteban, L.G., di Gennaro, S.F., Herrero-Langreo, A., Miranda, C., Royo, J.B. and Matese, A. (2017) High-Resolution UAV-Based Thermal Imaging to Estimate the Instantaneous and Seasonal Variability of Plant Water Status within a Vineyard. *Agricultural Water Management*, **183**, 49-59. https://doi.org/10.1016/j.agwat.2016.08.026

[23] Uddin, M.A., Mansour, A., le Jeune, D., Ayaz, M. and Aggoune, E.H.M. (2018) UAV-Assisted Dynamic Clustering of Wireless Sensor Networks for Crop Health Monitoring. *Sensors*, **18**, Article No. 555. https://doi.org/10.3390/s18020555

[24] Shouqi, Y., Darko, R. O., Xingye, Z., Junping, L. and Kun, T. (2017) Optimization of Movable Irrigation System and Performance Assessment of Distribution Uniformity under Varying Conditions. *International Journal of Agricultural and Biological Engineering*, **10**, 72-79.

[25] Dong, Y., Kelley, L. and Miller, S. (2020) Efficient Irrigation Management with Center Pivot Systems. Michigan State University, East Lansing. https://www.canr.msu.edu/resources/efficient-irrigation-management-with-center-pivot-systems

[26] Islam, Z., Mangrio, A.G., Ahmad, M.M., Akber, G., Muhammad, S. and Umair, M. (2017) Application and Distribution of Irrigation Water under Various Sizes of Center Pivot Sprinkler Systems. *Pakistan Journal of Agricultural Research*, **30**, 415-425.

[27] Porter, W., Harrison, K. and Perry, C. (2013) Evaluating and Interpreting Application Uniformity of Center Pivot Irrigation Systems. University of Georgia, Athens. https://extension.uga.edu/publications/detail.html?number=c911

[28] Darimani, H.S., Kpoda, N., Suleman, S.M. and Luut, A. (2021) Field Performance Evaluation of a Small-Scale Drip Irrigation System Installed in the Upper West Region of Ghana. *Computational Water, Energy, and Environmental Engineering*, **10**, 82-94. https://doi.org/10.4236/cweee.2021.102006

[29] Connellan, G. (2002) Efficient Irrigation: A Reference Manual for Turf and Landscape. University of Melbourne, Melbourne.

[30] Islam, Z., Mangrio, A. G., Ahmad, M. M., Akber, G., Muhammad, S. and Umair, M.

(2017) Application and Distribution of Irrigation Water under Various Sizes of Center Pivot Sprinkler Systems. *Pakistan Journal of Agricultural Research*, **30**, 415-424.

[31] Mecham, B. (2004) Using Distribution Uniformity to Evaluate the Quality of a Sprinkler System. *Irrigation Association's 2004 International Irrigation Show*, Tampa, 14-16 November 2004, 379-386.

[32] Dong, Y., Kelley, L. and Miller, S. (2020) Efficient Irrigation Management with Center Pivot Systems. Michigan State University, East Lansing.