Impacts of center pivot irrigation system uniformity on growth of potato crop and residual soil nitrogen

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Abstract: Maintaining the homogeneity of soil nitrogen (N) and plant vigor across agricultural fields is a major concern for farmers and agricultural scheme planners, particularly fields that are irrigated through pressurized systems, such as center pivots. Therefore, this study was carried out on a 30 hm^2 potato field located 650 km south of Riyadh, the capital city of the Kingdom of Saudi Arabia, to investigate the impacts of the center pivot irrigation distribution uniformity on the crop development and the spatial distribution of residual soil N. Irrigation performance test was designed to investigate water application rate and distribution uniformities. The overall water application uniformity coefficients (Cu), determined through Christiansen (Cud) and Heerman (CuH) methods, were determined at 81.29% and 80.64%, respectively. However, the overall water distribution uniformity (Du) was determined at 70%. A considerable variability in the distribution uniformity of irrigation water was observed across the experimental field (a Du value of 67% over the medium spans compared to a Du value of 88% over the inner spans). Results of this study showed a linear correlation between the irrigation water distribution uniformity and the soil N (R^2=0.88). On the other hand, the vegetation cover distribution, indicated by the Cumulative Normalized Difference Vegetation Index (CNDVI), was not found to be much responsive to the irrigation distribution uniformity (R^2=0.11). A time series of successive NDVI maps extracted throughout the potato crop growth stages showed a consistent trend in the distribution of NDVI across the field, with R^2 values that ranged between 0.25-0.73.

Keywords: irrigation performance, uniformity, center pivot, potato, soil nitrogen, NDVI
DOI: 10.25165/j.ijabe.20191201.3684

Citation: Al-Gaadi K A, Hassaballa A A, Tola E, Kayad A G, Madugundu R, Assiri F, et al. Impacts of center pivot irrigation system uniformity on growth of potato crop and residual soil nitrogen. Int J Agric & Biol Eng, 2019; 12(1): 126–131.

1 Introduction

An excellent irrigation system is that which uniformly and consistently discharges an appropriate amount of water. Compared with conventional surface irrigation methods, sprinkler irrigation systems contribute significantly to an effective and consistent application of irrigation water with less labor costs[1], and the result is more yields per unit volume of water[2]. The functionality of an irrigation system is affected by various activities, including layout, construction and setting up, operation, maintenance and optimal use of irrigation water. Therefore, the effective implementation of these activities requires appropriate monitoring of the functional methods of irrigation[3]. According to Raine et al.[4], the capability of the field irrigation system to uniformly and effectively provide irrigation water is a significant component affecting the agronomic and economic stabilities of the agricultural systems. In addition, Solomon[5] stated that due to the fact that irrigation uniformity guaranteed optimum crop yield and productive use of resources, engineers considered it as a key point in the design, selection and management of irrigation systems.

Enhancing irrigation functionality is an important aspect in irrigating agricultural fields, especially in the arid zones, and depends mainly on climatic and economic measures. Enhanced water distribution uniformity assists farmers optimize the use of limited water to obtain higher yields and benefit the ecosystem, thus enhance livelihood in the region[6]. The advantages of more efficient systems include less pressure on water resources, reduced leaches of agro-chemicals to groundwater and surface water and enhanced productivities and total profits[7], in addition to the possibility of irrigating more areas using the available amount of water. Because of the ever increasing water demand and the accelerated decline in the finite water resources, useful and uniform distribution of water are keys for the optimum functionality of any

Received Date: 2017-12-20 **Accepted Date:** 2018-10-31

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irrigation system. This can be attained only through the optimal design, good preparation, effective maintenance and continuous monitoring of the irrigation system. The application uniformity of irrigation water influences the soil moisture content and the available water for plant use, as well as, surface water runoff and drainage. Although the uniform application of irrigation water is essential for optimum crop yields, it minimizes the losses of water and crop nutrients due to leaching and deep percolation underneath the root zone[8].

With improper irrigation uniformity, portions of the field are likely to be either over- or under-irrigated. Therefore, irrigation system efficiency and uniformity play a crucial role in determining the total amount and the distribution pattern of irrigation water. The irrigation uniformity for a system is a measure of its capability to apply the same depth of water over the whole surface of the irrigated area; therefore, it is viewed as an essential management aspect for attaining high irrigation efficiency[9]. The uniformity of a sprinkler irrigation system is usually assessed based on uniformity coefficients. The Christiansen uniformity coefficient (CuC) is one of the common measures that is usually used to define the uniformity of sprinkler irrigation systems[10].

Three uniformity measures are commonly used for the assessment of an irrigation system, namely, the coefficient of uniformity (Cu), the distribution uniformity (Du) and the potential application efficiency of the low quarter (PELQ). The uniformity of irrigation water application through sprinkler systems can be affected by numerous factors, including inappropriate sprinkler nozzles, nozzles spacing, type and size of pipes, pressure distribution across the laterals and wind speed and direction throughout the irrigation time[11]. In addition, the assessment of an irrigation uniformity involves the pressure, the system and nozzles flow rates and the travel speed.

Irrigation system analysis that includes performance characteristics, such as the rate and uniformity of the applied irrigation water, can help identify issues related to system design and management, which may result in reduced energy costs and increased crop yield, or both[12]. This study was designed to investigate the effect of irrigation water application uniformity of a center pivot system on potato crop's vigor (represented by the Normalized Difference Vegetation Index – NDVI) and soil residual nitrogen (N) distribution.

2 Materials and methods

2.1 Study area

The study was conducted on a 30 hm^2 center pivot irrigated potato field in a commercial farm owned by the Saudi Agricultural Development Company (INMA). The study field was located in Wadi Al-Dawasir area in the southern sector of the Riyadh Province in the middle of the Kingdom of Saudi Arabia between the latitudes of 19°45′ and 20°30′N and the longitudes of 44°15′ and 45°15′E (Figure 1). This area was one of the prominent agricultural areas in the Kingdom, where the temperatures varied between 6℃ and 43℃ with mostly stable relative humidity of about 24%. Solar radiation of typical sunshine duration was 11 h/day and the typical wind speed was about 13 km/h with a maximum of 46 km/h in thunderstorm occurrences. Many farms were located in the area with large number of agricultural fields irrigated by center pivot irrigation systems, drawing water from Wajid aquifer in the southern part of the Kingdom. This aquifer supplied Wadi Al-Dawasir city and vicinity areas with freshwater for civil and agricultural purposes[13].

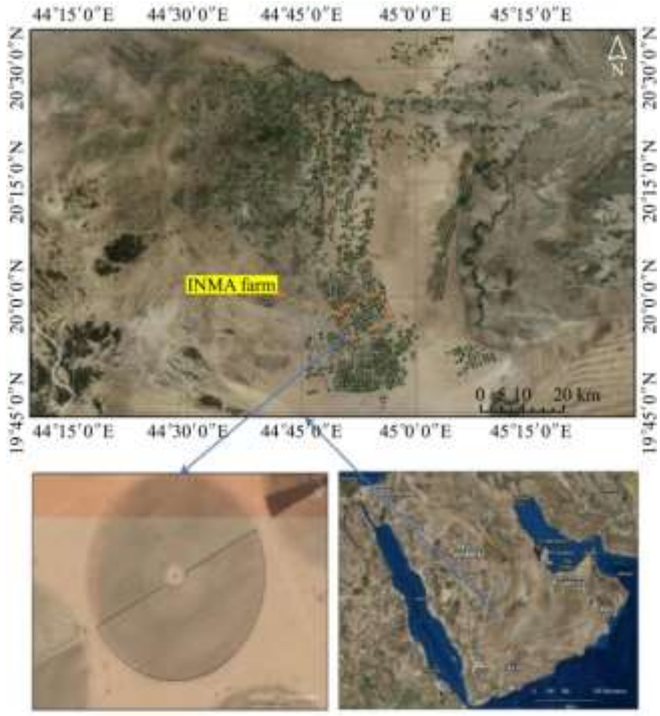


Figure 1 The study area: Field 63S (INMA Farm)

2.2 Irrigation performance

The most frequently used term for placing a numerical value on the uniformity of application for agricultural irrigation systems is Christiansen's uniformity coefficient (CuC) stated as a percentage[14]. It is based on the absolute deviation of individual water quantities from the mean water quantity. Another parameter which is commonly used is the distribution uniformity (Du), described as the ratio of the mean depth of the applied water on the quarter of the field that receives the least water amount divided by the overall mean depth caught on the whole field. The value of the CuC is often higher than that of Du; however, this is not the case for all data sets[15].

The study field conditions were observed to be optimum and ideal for test conductance considering the values of wind speed, air temperature and relative humidity collected from a stationary micro weather station (model: MKIIIRTN-RaiWise III System), which were found to be 4.45 m/s, 20.5℃ and 37%, respectively. A total of 202 catch cans, of 90 mm diameter and 130 mm height, were used for irrigation water collection. The catch cans were fixed with wire bearers placed at a height of 150 mm above the ground and positioned 2000 mm apart from each other in a straight line parallel to the pivot lateral and perpendicular to the pivot travel direction (Figure 2a). A dual application of irrigation performance check was achieved in terms of an overall check for the whole pivot as well as a performance check for the individual spans along the pivot lateral. This was done in order to examine the irrigation performance of each span and its effects on the NDVI and N distribution. Subsequently, the area covered by three spans, selected based on their noticeable variation in the application and distribution uniformity, was used as a pilot area for this study. The selected spans were number 2, 5 and 8, representing the high, low and moderate irrigation performances, respectively. Ground sampling locations (60 sampling locations) were then distributed across the three given spans, and soil samples were collected accordingly (Figures 2b and 2c).

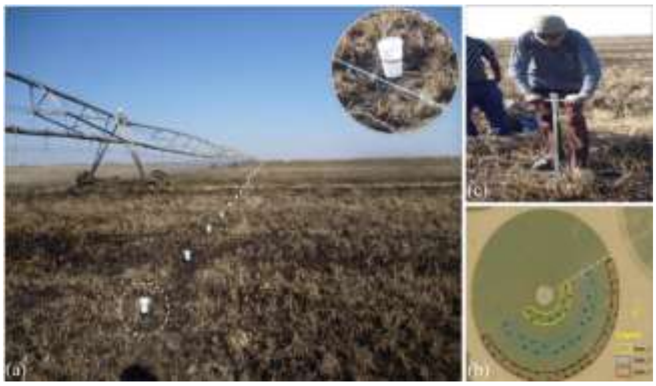


Figure 2 Field data collection: (a) setup of irrigation performance test, (b) soil samples allocation and (c) soil samples collection

The system was adjusted to deliver irrigation water to the field at the rate of 0.07 m^3/s, so that the lateral speed provided a depth of irrigation of 2.4 cm. The two algorithms used to assess the Cu of the irrigation water were: (i) the modified formula of Heermann and Hein[16] and (ii) Christiansen formula[14], expressed in Equations (1) and (3), respectively.

$$Cu_H = 100\left[1 - \frac{\sum_{i=1}^{n}|V_i - \bar{V}_p|}{\sum_{i=1}^{n}V_i S_i}\right] \quad (1)$$

where, Cu_H: Heermann and Hein uniformity coefficient; n: Number of catch cans used in the data analysis; i: Number assigned to identify a particular can beginning with $i=1$ for the can closest to the pivot point and ending with $i=n$ for the most remote can from the pivot point; V_i: Volume (or alternately the mass or depth) of water collected in the i^{th} can; S_i: Distance of the i^{th} can from the pivot point; V_p: Weighted average of the volume of water caught and computed using Equation (2).

$$\bar{V}_p = \frac{\sum_{i=1}^{n}V_i S_i}{\sum_{i=1}^{n}S_i} \quad (2)$$

$$Cu_C = 100\left[1 - \frac{\sum_{i=1}^{n}|V_i - \bar{V}|}{\sum_{i=1}^{n}V_i}\right] \quad (3)$$

where, Cu_C is Christiansen uniformity coefficient; i is number of cans used in data analysis; V_i is volume (or alternatively the mass or depth) of water collected in the i^{th} can; $\bar{V}$ is arithmetic average volume caught by all cans.

In order to determine whether the system is operating at an acceptable efficiency, the *Du* of the low water depth quarter was calculated using Equation (4).

$$Du = \frac{\text{Aveg.Wgt Low }\frac{1}{4}\text{ depth Catch}}{\text{Aveg.Wgt System Catch}} \times 100 \quad (4)$$

where, *Du* is the distribution uniformity (%) of the low water depth quarter.

2.3 Residual soil nitrogen and NDVI

The main core of the study was to investigate the performance of the irrigation system based on the development of potato crop, represented by the NDVI values, and residual soil N. Figure 3 shows the flow diagram of the applied satellite image acquisition and analysis processes, in addition to field irrigation performance and soil sample collection. The land preparations and crop cultivation processes were achieved on November, 2016.

The experimental field was divided into 120 sampling 50 m × 50 m plots/grids. Soil samples were collected from each location (center of the sampling grid) and geo-referenced using a hand-held GPS receiver (Trimble GeoXH). The collected samples were analyzed for the residual soil N content in the laboratory adopting the Kjeldhal method[17]. The method consisted of three steps. The first step involved digestion of the sample in sulphuric acid with a catalyst, where the nitrogen contained in the sample was converted into ammonia and ammonium sulphate was formed. In the second step, distillation of ammonia released from ammonium sulphate was conducted by adding sodium hydroxide, where ammonia was trapped in a trapping solution (sulphuric acid). In the final step, back-titration of the excess of the trapping solution was performed.

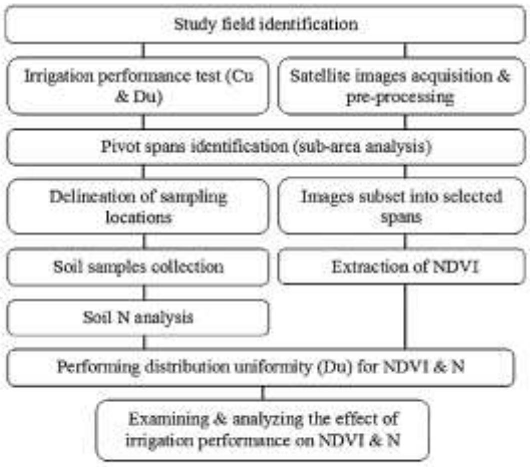


Figure 3 Flow diagram of data collection and analysis procedure

The auto-lift digestion system (Tecator™ Line Digestor 2540, FOSS, Denmark) was used for digesting collected soil samples. One gram of soil sample was transferred to the digestion tube, then concentrated H_2SO_4 was added followed by catalysts (potassium sulphate and selenium) and followed the procedure as described in the user manual. After successful digestion of soil samples, the digestion tubes were transferred to the fully automated Kjeldhal analyzer (Kjeltech™ 8400, FOSS, Denmark) for nitrogen analysis. During the process, the digested soil samples were subjected to distillation and titration. The automated system calculated the amount of N present in the sample and reported the value.

ArcGIS software program was used for mapping soil N distribution across the experimental field using the Kriging method. This method relies on the interpolation of collected soil N sampling points to create a surface covering the whole study area.

A spatial variability assessment was carried out for NDVI using satellite images of 10 m resolution acquired from Sentinel-2A satellite (European optical imaging satellite). A total of five images corresponding to the potato growth period (December, 2016 to March, 2017) were downloaded from the USGS portal (https://earthexplorer.usgs.gov/). The acquired images were subjected to a series of image processing stages and the NDVI, which is widely used as crop health indicator[18,19], was extracted from the optical bands, which included the red (ρRED) and the near-infrared (ρNIR) spectral bands of each image (Equation (5)), using the ArcGIS software program. The cumulative NDVI (CNDVI) was then computed accordingly[20].

$$NDVI = \frac{(\rho_{NIR} - \rho_{RED})}{(\rho_{NIR} + \rho_{RED})} \times 100 \quad (5)$$

Specific points in the NDVI maps that matched the sampling locations, used for soil N analysis, were also used to extract the point-based NDVI values. To investigate the temporal and spatial variability in the development of potato crop, the NDVI values of each image were plotted against the NDVI values of the subsequent acquisition dates.

2.4 Statistics of the acquired/ collected data

Descriptive statistics of the extracted satellite NDVI throughout the growth season, in addition to the analyzed soil N, is given in Table 1. Values of the calculated coefficient of variation (CV) revealed the effects of irrigation performance on the soil N distribution and NDVI values. .

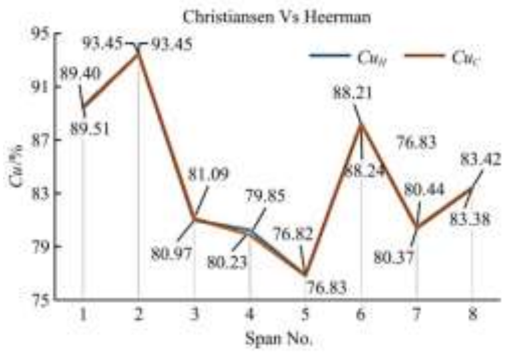
Table 1 Descriptive statistics of the NDVI and soil N data

Data type	Data size/N	Acquisition date	Min.	Max.	Mean	Standard deviation	CV
NDVI	60	December 27, 2016	0.32	0.70	0.52	0.06	0.12
		January 6, 2017	0.55	0.89	0.79	0.06	0.08
		January 16, 2017	0.71	0.92	0.87	0.03	0.04
		January 26, 2017	0.73	0.90	0.84	0.04	0.04
		February 5, 2017	0.62	0.88	0.81	0.05	0.06
CNDVI			3.22	4.18	3.83	0.19	0.05
Soil N/mg kg^{-1}			119.73	2075.23	1050.92	312.00	0.30

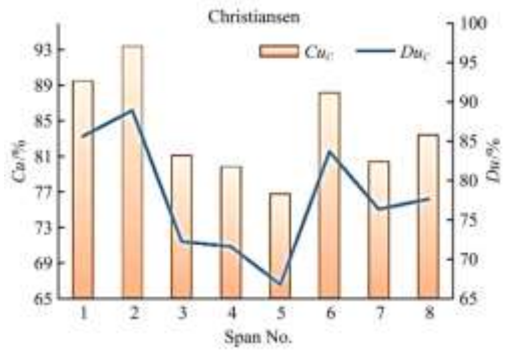
3 Results and discussion

3.1 Pivot irrigation

Investigation of the total pivot application uniformity has resulted in values of CuC and CuH of 81.29% and 80.64%, respectively. A noticeable rapprochement can be observed between CuC and CuH assuring the validity of both approaches in assessing the performance of the irrigation system. However, the Christiansen low-quarter distribution uniformity coefficient (Du) was determined at 70%. The sub-area irrigation uniformity check (Figure 4a) showed a high water application uniformity (89%-93%) throughout the inner spans (spans number 1 and 2) with moderate values (80%-83%) at the outer spans (spans number 7 and 8). However, the middle spans (spans number 4 and 5) were found to receive the least irrigation uniformity (76%-79%). On the other hand, the Du was also applied to the sub-area observations in order to address the status of irrigation water variability at the field (Figure 4b). The noticeable similarity between the two approaches assured the susceptibility of the NDVI and soil N distributions to the distribution uniformity of the irrigation water.



a. Application uniformities

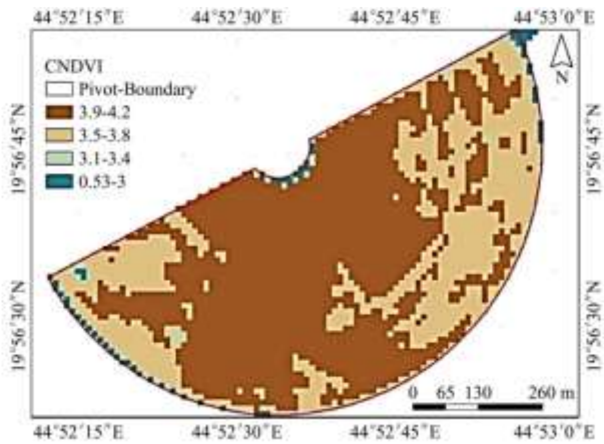


b. Distribution uniformities

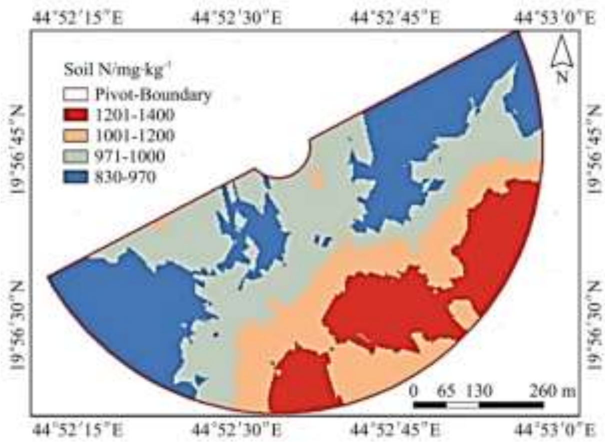
Figure 4 Irrigation performance tests

3.2 NDVI and soil N maps

For each satellite image, the NDVI values were extracted from the red and the near infrared bands of the Sentinel-2A satellite, and accumulated in order to reveal the resultant crop variations throughout the growth stages (Figure 5a). Soil N, however, was mapped through interpolating of N values (Figure 5b). It can be observed that the soil N varied drastically across the field with a range of 570 mg/kg and a coefficient of variation (CV) of 0.3. The CNDVI, however, was found to be slightly variant across the field, with differences expressed by a CV of 0.05, reflecting a uniform nature of vegetation cover.



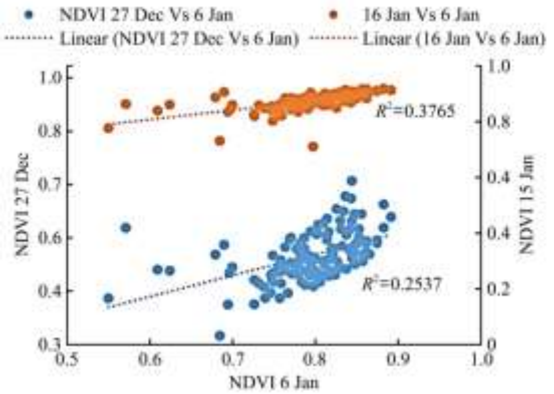
a. CNDVI



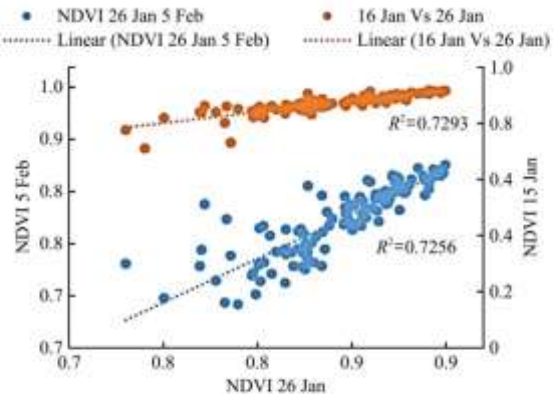
b. Soil N

Figure 5 CNDVI and soil N maps

Figure 6 shows the spatial correlation of the seasonal NDVI generated from the successive images and highlights the development pattern of the potato crop. Since the early stages of the crop encountered noised reflections caused by the soil-background, NDVI scatter plots did not show a consistent correlation, with R^2 values of 0.25 and 0.37 for the correlated images captured on December 27, 2016 against January 6, 2017 and January 6, 2017 against January 16, 2017, respectively. However, the crop status extended from mid-January up to early February produced relatively high correlations due to the complete shading of the ground after more than 60 d since sowing. Hence, these spatial correlations assured a harmony between the extracted points across the growth stages.



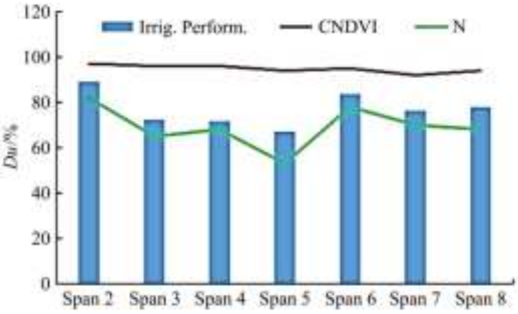
a. December 2016 to January 2017



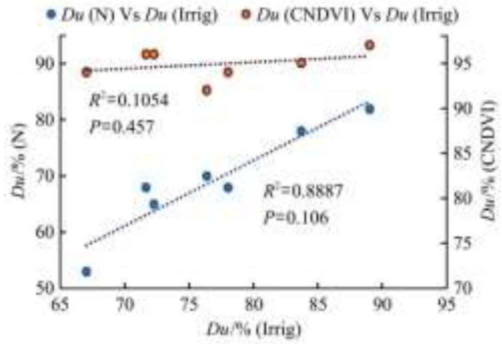
b. January 2017 to February 2017

Figure 6 Spatial correlation of seasonal NDVI for December 2016 to January 2017 and January 2017 to February 2017 images

Finally, the study also examined the crop vigor uniformity as well as soil N (residual) by applying the Christiansen Du for the three selected span areas (Figure 7a). Similar relationship between the Du of soil residual N and irrigation water was observed over all pivot spans, revealing that the spatial variability in the soil residual N positively correlated with the uniformity of the irrigation system. However, the spatial variability in CNDVI was observed to be less affected by the irrigation performance compared to the soil N (residual). The spatial correlation of the Du between the irrigation water uniformity and both the CNDVI and the soil N, applied to the whole field spans, produced R^2 values of 0.88 (p = 0.106) and 0.11 (p = 0.457) for the soil N and CNDVI, respectively (Figure 7b). These results exhibited that the irrigation performance influenced the soil N distribution in a much higher degree compared to that for the CNDVI. This can be attributed to the fact that the absolute crop maturity depends on many factors other than available water[21]. Mateos et al.[22] reported that sprinkler irrigation uniformity has less influence on crop performance than speculated by models. This low influence was also confirmed by Li and Rao[23], who justified that irrigation water from sprinklers tended to transform into uniform while penetrating through the canopy. Possible reason for soil N variability is that the soil has probably been affected by nitrification and denitrification processes caused by the non-uniformly of applied water.



a



b

Figure 7 CNDVI and soil N plots for (a) distribution uniformity and (b) spatial correlation

In another attempt to examine the vegetation uniformity, a statistical range of NDVI values ($NDVI_{max}$-$NDVI_{min}$) for each image, as well as the CNDVI, was calculated and plotted for the three selected spans (Figure 8). It can be seen in Figure 8 that the area of span 5, which had the least irrigation Du, showed the maximum range of NDVI values as an indicator of maximum vegetation variability (e.g. $CNDVI_{max}$=4.18 & $CNDVI_{min}$=3.53) over all images through the growth stages. On the other hand, span 2, which had the highest irrigation Du, produced the least NDVI range (e.g. $CNDVI_{max}$ = 4.16 & $CNDVI_{min}$ = 3.90). The qualitative uniformity of the vegetation canopy, which has been applied in many studies[24-26], was confirmed to be a possible potential indicator for crop yield assessment.

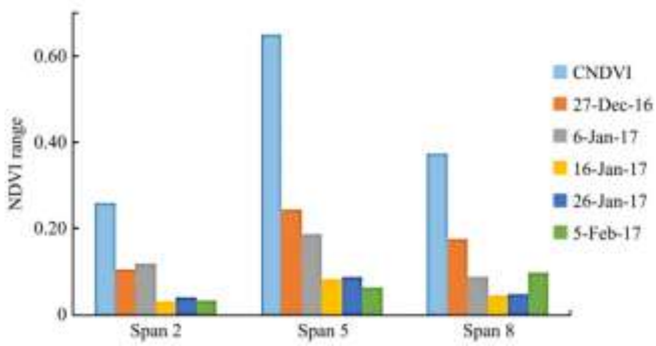


Figure 8 Statistical range NDVI and CNDVI data

4 Conclusions

The study conducted an investigation on a center pivot irrigated field to examine its performance in terms of water application and distribution uniformities. The overall coefficient of uniformity (Cu) of the applied irrigation water, determined through Christiansen and Heerman methods, were found to be 81.29% and 80.64%, respectively, while the overall water distribution uniformity (Du) was 70%. The study also examined the effects of the irrigation distribution uniformity on the spatial distribution of potato crop NDVI and soil residual N. Specific conclusions could be summarized in the following points:

A noticeable variability in the water distribution uniformity was observed across the experimental field with a lowest Du of 67% in the medium spans and a highest Du of 88% in the inner spans.

A time series maps of NDVI extracted throughout the potato crop growth stages showed a consistent trend in the distribution of NDVI values across the experimental field, with R^2 values ranged from 0.25 to 0.73.

The distribution uniformity comparison of the three variables assured that the irrigation Du significantly affected the soil residual N distribution, with a slight effect on the NDVI, producing R^2 values of 0.88 (p = 0.106) and 0.11 (p = 0.457), respectively.

Acknowledgments

The authors are grateful to the Deanship of Scientific Research, King Saud University for funding this study through the Vice Deanship of Scientific Research Chairs. The extensive cooperation and support extended by Saudi Agricultural Development Company (INMA) farm in carrying out the field research work are gratefully acknowledged.

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