Spatial and Temporal Variability of Soil Water Content in Leveled Fields

Water scarcity threatens the sustainability of crop production and environmental stewardship in several regions of the globe. Precision irrigation appears as a promising way to sustain productivity while using lower amounts of water. While precision irrigation is at its infancy stage, farmers and crop practitioners often doubt the existence of spatial variability of soil water content in leveled fields (slope of 1% or lower in a single plane gradient). The objectives of this study were to quantify the spatial and temporal variability of soil water content in leveled fields. Neutron probe readings were acquired at five depths over a whole crop growing season at two sites. A total of 41 and 31 locations from north eastern Colorado were monitored. Moran’s I and semivariograms were used to study the data. Results showed that up to 87% of measured soil water content locations across leveled fields can be mis-represented by the field’s mean soil water content. In general, the spatial range of dependency was shorter for soil water content near the surface than with depth, indicating that more sample points may be required to characterize near-surface soil water contents than at deeper depths. Temporal dependency of soil water content was 50 d or more at or greater than depths of 45 cm. In general, the spatial and temporal variability of soil water content observed in this study was conducive to the implementation of water management zones because it was variable in space with long spatial range, yet with long temporal dependency.

Abbreviations: AIC, Akaike information criterion; AWC, available water content; CV, coefficient of variation; FC, field capacity; MAD, maximum allowed depletion; VRI, variable rate irrigation.
et al., 2000). Instead of a pre-programmed time-based schedule, irrigation is triggered based on indirect measure of soil water content. Sensors that measure soil water content can be installed in the soil for the entire cropping season and when connected to a radio emitter, such sensors transmit soil water data in real-time (e.g., every 30 min). The purpose of such a system is to monitor soil water content and maintain it between the maximum allowable depletion (MAD) and the field capacity (FC) to minimize plant drought stress and water loss through drainage and/or deep percolation (Zotarelli et al., 2010). The advantage of this approach over prescheduled irrigation timing is that it can take into account the actual soil water content which is influenced by soil texture, soil structure, soil organic matter content, air temperature, wind speed, past and present precipitations, crop growth stage, etc. However, as per the industry definition of “precision irrigation” it does not take into account the spatial variability of the soil water content in the field. Sadler et al. (2005) have included in their definition of “precision irrigation” a spatial component and this is the definition that prevails for the scope of the present paper.

While it may be easier to justify the application of variable rate irrigation (VRI) for fields showing a high level of spatial heterogeneity such as a field with topographic features (e.g., non-leveled fields), evidence of the usefulness of VRI in leveled fields can be questionable. Soil particle size and organic matter content influence soil water content (Tisdall and Oades, 1982; Hawley et al., 1983). Micro-topography is another important aspect of the spatial variability of soil water content at field scale (Western et al., 1999). On the basis of simulation models Merz and Plate (1997) reported that spatial variability of soil water content is a complex behavior that includes aspects of organization and randomness and is the result of spatial distribution of soil properties, topography, and evapotranspiration. Although several studies have reported spatial heterogeneity of soil water content at the field and at regional scale, few studies have addressed spatial heterogeneity of soil water to answer important questions related to VRI.

The first question of interest is whether or not there is a significant spatial variability of soil water content in leveled fields. Answers to this question could help address the feasibility of using VRI by farmers who have leveled their fields. It is expected that profitability of VRI depends in part on field spatial variability (Almas et al., 2003). Indeed, if soil water holding capacity is uniform throughout the field, there would be no economic gain in using VRI irrigation equipment. However, Hedley and Yule (2009) have observed mean annual water savings of 26.3% using VRI in a 53–ha maize field showing little variability (161–164 mm m−1) in available water content (AWC). Sadler et al. (2002) reported strong variation in crop response to irrigation rates within soil map units and pointed out the need for further investigation based on spatial analysis rather than soil survey units.

The second question of interest is to determine the spatial range of soil AWC. Answers to this question could guide the industry in the appropriate level of control (e.g., probe every 20 m or every 100 m) required to address the spatial variations in soil water content with VRI systems. Western and Blöschl (1999) studied the spatial range of surface (0–30 cm depth) soil water using time domain reflectometry (TDR). They found that geostatistics could be used to model soil water and observed a spatial range of about 65 m. Iqbal et al. (2005) reported a spatial range of AWC from 78 to 99 m depending on the depth of measurement and suggested sampling at spacing <100 m for soil hydraulic properties.

The third question of interest is the dynamics of the soil water content in time. Answers to this question could guide farmers and agronomists as to whether or not irrigation maps can be delineated and used across the crop growing season. It is logical to think that at FC, spatial variability would be low and would increase with decreasing soil water content due to spatial heterogeneity in soil water holding capacity (Famiglietti et al., 1999; Hupet and Vanloose, 2002). However, other studies have reported diverging observation (i.e., inverse trend or no trend) on that matter (Charpentier and Groffman, 1992; Western et al., 1998; Famiglietti et al., 1998). Ambiguity may be related to the effect of average soil water content in a field and the resulting spatial variability of soil water content. Baroni et al. (2013) explained that “starting from a very wet soil state, the standard deviation of the soil water increases with decreasing mean soil water, it reaches a maximum value at a critical mean moisture content and then decreases during further drying.” Thus, the relationship between the variability and the soil water content depends on when, in the range of soil water content, the readings are acquired.

The specific objectives of this project were (i) to quantify the spatial variability of soil water content in leveled fields, and (ii) to describe the temporal variability of soil water content in leveled fields. For the purpose of this study, a leveled field is defined as a crop field with a slope of 1% or less that has either been precision leveled by heavy machinery or that is classified as having a slope of 1% or less by a NRCS soil survey.

Materials and Methods

Study Sites

This study was conducted on two sites located in north-eastern Colorado from April to September 2012. The climate of north-eastern Colorado is considered semiarid as it receives less precipitation than potential evapotranspiration. The first site (Site 1) is located at Colorado State University’s Agricultural Research Development and Education Center, located in Fort Collins, CO (40° 40′ N, 104° 58′ W). The soil at this site is a Kim loam (1–3% slopes) classified as a fine, loamy, mesic, Aridic Haplustalf (Soil Survey Staff, 1980). Based on soil samples acquired from Site 1, texture was classified as a sandy clay loam. This field was precision leveled (FieldLevel II, Trimble Navigation, Sunnyvale, CA) in 2012 and the slope is 0.9% in a single plane gradient (Fig. 1). This site has a history of continuous maize (Zea mays L.) production for the past 10 yr under conventional tillage (i.e., 20–cm deep disk tillage in the fall and 20–cm deep disk tillage, 30–cm deep plowing and 10–cm deep roller arrow in the spring). In 2012, the entire field was planted to maize. The second site (Site 2) is a farm field located...
in Iliff, CO (40° 46' N, 103° 2' W). Soil at this site is a Loveland clay loam (0–1% slopes) classified as a fine—loamy over sandy or sandy—skeletal, mixed (calcareous), superactive Fluvaquentic Haplaquolls (Soil Survey Staff, 1980). Based on soil samples acquired from Site 2, texture was classified as a clay loam. The slope is 1.0% in a single plane gradient (Fig. 1). This farm field has been used as a research site since 2007 and has a history of various crop rotations including wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), canola (*Brassica rapa* var. Maverick), maize, triticale (*×Triticeoscale* Wittmack) and fallow. In 2012, the field was strip tilled in the spring and was entirely planted to maize.

**Data Collection**

Soil water data were acquired at five soil depths (15, 45, 75, 105, and 135 cm) using a neutron probe (Model 503 DR Hydroprobe, CPN International, Martinez, CA). For Site 1, data were acquired 13 times during the growing season, on a weekly basis, from 1 June to 24 Sept. 2012 and for Site 2, data were acquired 9 times during the growing season, on a weekly basis, from 14 June to 17 Aug. 2012. At both sites, location of neutron probe access tubes were distributed in a systematic unaligned (both axes) pattern except for certain tubes at Site 2 that were aligned in a systematic pattern (Fig. 1, Site 2). A total of 41 and 31 neutron probe access tubes were installed at Site 1 and Site 2, respectively (Fig. 1). The location of each access tube was recorded using Universal Transverse Mercator (UTM) coordinates. The neutron probe was calibrated against measured gravimetric soil water and bulk density so that counts from the probe can be converted to volumetric soil water content. The neutron probe was calibrated in situ for soil water content ranging from 0.08 to 0.42 m$^3$ m$^{-3}$. The resulting calibration curve for Site 1 was:

\[ q_C = -0.1655 + 0.2994 \times C_R \]

and for Site 2 was:

\[ q_C = -1.9863 + 3.5927 \times C_R \]

where \( C_R \) is the ratio of neutron counts (\( x \)) to the standard count (\( x_s \)) acquired at the surface of an access tube with the probe still in the instrument. The value of the linear regression coefficients varies according to the probe and the site.

**Statistical Analysis**

**Statistical Description and Spatial Variability of Soil Water Content**

Moran’s *I* (Moran, 1948) was measured for each set of measurement (e.g., site, date, and depth) as a descriptor of spatial structure. Average volumetric soil water content and coefficient of variation (CV) were also measured for each set of measurement. A custom R (R Development Core Team, 2013) code was used to generate the Moran’s *I*. Correlation analysis (Pearson’s Correlation with \( \alpha = 0.05 \)) was used to detect trend in the interactions between depth, average soil water content, CV, and Moran’s *I*. The function “cotest” from the “stats” package of the R statistical software was used (R Development Core Team, 2013).

Soil water data were analyzed and compared with the field average to determine the proportion of the field that was represented by the field average. In a first step, data were classified into three classes using volumetric soil water content. The FC and the MAD, which is the volumetric soil water content value half-way between FC (suction pressure at 33 kPa (0.33 bar)) and the permanent wilting point (suction pressure at 1500 kPa [15 bar]), were determined independently for each site. The FC and MAD estimated for Site 1 (sandy clay loam) were 0.263 and 0.207 m$^3$ m$^{-3}$ respectively and for Site 2 (clay loam) were 0.330 and 0.261 m$^3$ m$^{-3}$, respectively (Ratliff et al., 1983). A single FC and a single MAD value was defined for each site with the intent of measuring the proportion of error embedded in the conventional approach, which consists of managing irrigation based on field average values. Volumetric soil water content data for each depth, date, site, and probe were classified as either above FC, between FC and MAD, or below MAD. Subsequently, data from all access tubes were averaged by site, depth, and date to determine the field average. In each context (site, depth, and date), data classification for each probe was compared with the field average and was considered as above, the same, or below field average. This data set thus allowed measuring the percentage of monitored field locations (access tubes) requiring a similar...
management decision as the field average and the percentage of access tubes where different management decisions than the field average were required.

**Spatial Range of Soil Water Content**

Soil water data were analyzed to detect the spatial range of autocorrelation using semivariograms. The semivariance was calculated using:

\[ \gamma(h) = \frac{1}{2m(h)} \sum_{i=1}^{m(h)} [Z(x_i) - Z(x_i + h)]^2 \]

where \( \gamma \) is the semivariance of \( m \) data pairs separated by a distance of \( h \) and \( Z \) is the soil water value at Positions \( x_i \) and \( x_i + h \) (Webster, 1985). The theoretical semivariogram model best fitting the semivariograms was chosen based on average Akaike information criterion (AIC; the lowest AIC characterized the best fitting model) and was either Gaussian, spherical, or exponential. The same theoretical semivariogram model was used for all semivariograms. The ranges of the semivariograms were used for studying soil water content acquired at different dates and depths. A custom R (R Development Core Team, 2013) code was used to generate semivariograms and AIC values. A model (linear or curvilinear) was tested (with \( \alpha = 0.05 \)) to verify if there was a trend between the spatial range and depth or date. The function “lm” from the “stats” package of the R statistical software was used (R Development Core Team, 2013).

**Variability of Soil Water Content across Time and Depth**

The temporal variability of soil water content was assessed using temporal semivariograms. This technique is similar to the use of semivariance to study the range of spatial dependency of a transect because there is only one dimension, which is time. For each depth and each site, semivariance of soil water content was measured against time. Semivariance was modeled using an exponential function and weighting the values by the number of observations. There were more observations for short—time range than for long—time range. The range and sill were derived from the semivariograms thus created. The same approach was used to measure the variability across depths. Semivariance was measured across depth lags to create semivariograms of soil water content in depth. Instead of creating a semivariogram for each date in each site, the average soil water content of each date was measured and only dates with the seasonal minimum, average (nearest value), and maximum soil water content were retained. Again, exponential models were used and models were weighted by number of observation per bin. The R statistical software (R Development Core Team, 2013) was used to develop the semivariograms.

**RESULTS AND DISCUSSION**

Moran’s \( I \), average soil water and CV were increasing (statistically significant correlation) with decreasing depths (from 45 to 15 cm) at both sites with the exception of average soil water at Site 2, which was not significantly correlated with depth (Table 1). Average soil water at Site 2 showed an inverse relationship with depth up to −45 cm followed by a positive relationship from −75 to −135 cm. Despite the significant linear correlation between depth and CV, for both sites, the surface readings (−15 cm) had a CV higher than the readings just below (−45 cm) where the lowest average (over dates) CV was observed. Stronger spatial autocorrelation and heterogeneity in depth (−75 to −135 cm) indicates that there was spatially structured variability in depth where soil properties are less impacted by surface fluctuations and reflect more the landscape underground features (e.g., ancient river bed, spatial pattern of parent material, slope). Stronger spatial autocorrelation of soil properties (e.g., silt, clay, and cation exchange capacity) in depth as compared with surface was observed by Jung et al. (2006) and may explain the same behavior in volumetric soil water content observed in this study (Table 1). Netto et al. (1999) measured volumetric soil water content at nine depths from 0 to −105 cm and observed a higher CV at the surface layer than at the layer just below the surface and they have observed the highest CV values at deeper layers. This is consistent with our observations and may be explained by a higher susceptibility for the top layer (−15 cm) to have heterogeneous patterns of volumetric soil water content, engendered by heterogeneous rain patterns, weed patches, crop growth and/or soil cracks, among others. At shallow layers below the surface, low CV could be attributed to soil properties such as texture or organic matter content that are homogenized by tillage while not being directly affected by surface vagaries. Going deeper in the soil profile, CV increased, revealing larger variations happening at the scale of the landscape.

Another trend observed in the data was the inverse relationship between average soil water content and CV. The same observation was made by Choi and Jacobs (2007) who monitored the first 30 cm of soil depth. It is expected that at extreme soil water content (e.g., dry and saturated), CV would be minimal while it would be maximum at intermediate values of soil water content. The range of moisture observed was 0.18 to 0.38 m\(^3\) m\(^{-3}\) and 0.14 to 0.31 m\(^3\) m\(^{-3}\) for Sites 1 and 2, respectively. Soil water content below permanent wilting point (PWP) was observed only 3% of the observed time (i.e., at −15 cm at Site 2) and soil water content above FC was observed 14% of the time (i.e., from −45 to −135 cm at Site 1). Majority of times, observations at both sites were in between FC and MAD, which may explain the relationship between CV and average soil water that decreases except for readings at −15 cm at Site 2 that had a lower CV despite having a low average for soil water content. In that matter, both sites were behaving differently as for Site 1, CV was decreasing with increasing average soil water values while for Site 2, it was true only for readings from −45 to −135 cm. Moreover, for Site 2, soil water content values appeared to be strongly clustered by depth (e.g., gap in soil water content from one depth to the other), which was not observed in Site 1. This corroborates that sites behave differently and that in some cases, soil depth (and possi-
Soil horizon may have a stronger effect on CV than average soil water itself. Moreover, it appears that studying soil water content when the field is at intermediate soil water content values (i.e., neither completely dry nor saturated) may bring more insights to the complexity of its spatial pattern than when the soil water content is at extreme values. It should be noted that during the crop growing season, when soil water content is at intermediate values, both soil properties and plants may have an effect on the local soil water content.

Comparing individual data to Field average

Volatilizable soil water content values were converted into three management classes: above FC, between FC and MAD, and below MAD. Classified data were then compared with the field average to verify if they fell in the same management class. The proportions of the field falling in the same class as the field average and being over- or underestimated were variable across sites, time, and depths (Fig. 2). For both sites, the shallow readings (−15 cm) were, most of the time (>80%), in the same management class as the field average. As per Table 1, average soil water was low near the surface (−15 cm) and majority of the sample locations fell in the same management class (i.e., field average below MAD). It is logical to think that in the opposite situation (i.e., field average above FC), a large proportion of the field would fall in the same management class as field average. Comagna and Basile (1994) observed the lowest CV when average soil water content was the highest with neutron probe data acquired from 20 locations on a 12-m grid. This situation could be intensified (e.g., even larger proportion of the samples in the same category as field average) by extreme values below MAD or above FC. Therefore, the use of spatial water management may not always lead to spatially variable irrigation prescription after prolonged drought or precipitation events. For example, the FC and MAD of Site 2 were 0.290 and 0.235 m^3 m^−3, respectively, and at 75 cm deep, the field average volumetric content was 0.253 m^3 m^−3. This value is located about half-way between FC and MAD. Thus, it is possible that an irrigation scheduling that aims at maintaining soil water content around half-way between FC and MAD would be an appropriate approach, especially during the crop growing season, when soil water content values, both field and management class average, may bring more insights to the complexity of its spatial pattern than when the soil water content is at extreme values.
ing soil water content between MAD and FC will emphasize spatial variability as opposed to an irrigation schedule allowing soil water content to reach either low or high extreme values. It has been demonstrated that crop yield decreases with irrigation schedules allowing soil water content to reach low values (Panda et al., 2004). In counterpart, excess water can also impact crop yield (T orbert et al., 1993). Consequently, most farmers try to maintain soil water content at intermediate values.

Spatial Range

The relationship between semivariance of volumetric soil water content and distance was best described (lowest AIC on average) by a Gaussian model. For all data (i.e., dates and depths) of Site 1 pooled together, there was no interaction between date and depth and there was a significant linear trend ($p < 0.05, r^2 = 0.11$ and RMSE = 17.17) between depth and spatial range, with the highest spatial range occurring at $-75$ cm (Table 1). The spatial range varied from 60 to 334 m among sampled depths and dates for Site 2. Divergent results between the two sites indicate that although surface soil water content shows a shorter spatial range in both cases, the highest spatial range values are not always at the deeper depths. Site 2 has a shallow soil and is partly located on an ancient river bed, which can potentially explain the phenomenon observed at intermediate depths. Green and Erskine (2004) studied the spatial and temporal variability of soil water content up to a scale of 500 m and reported a lack of spatial structure (i.e., randomness) and thus a low potential for predictability of soil water content in space and time at shallow soil depths (<30 cm). Following root growth, this may translate into a uniform management at early growth stages when roots are shallow, and into spatially variable irrigation management at later growth stages when roots reach deeper soil depths. Based on generally admitted procedure for spatial soil survey that recommends the sampling interval to be shorter than half the range of the semivariogram (Kerry and Oliver, 2003), more samples would be required at the surface than at deeper depths for characterizing the spatial dependency of volumetric soil water content of crop fields.

Variability in Time and Depth

For both sites, the temporal dependency was about 20 d at the surface and was longer at deeper depths, except for depth $-135$ cm of Site 2 where temporal range was shorter (Fig. 4). Large rain events ($>25$ mm precipitation) happened with 20– and 50–d intervals at both sites, which may potentially explain the temporal dependency of about 20 d. Both sites showed the highest temporal range at the $-45$ cm depth (greater than 80 d in Fig. 4). In general (i.e., 7 times out of 10) across all depths, time, and sample locations, the temporal dependency of soil water content was above 50 d. This was consistent with results of Martínez–Fernández and Ceballos (2003), who studied temporal stability of soil water content at a larger spatial (e.g., kilometers) and temporal (e.g., years) scale and observed a strong temporal correlation ($r_S$ of Spearman > 0.75) of average soil water content between one date and the previous reading date across 3 yr. This indicates that with land management and tilling system implemented in this study, the pattern of soil water content is stable in time. Temporal stability across the crop growing season is conducive to the development of water management zones as opposed to high temporal variability across time lags. Temporal stability allows the development of irrigation management zones that will be useful throughout the season. In that perspective, $-45$ cm deep seems to be an appro-

Fig. 2. Cumulative bar graphs of the average (across all reading dates) percentage of access tubes (y axis) representative of the field average (gray), below field average (white) and above field average (black), by depth (x axis). Standard deviation across all reading dates is indicated in parentheses.
proper depth to gather data and develop irrigation management zones that will be stable in time. In contrast, soil water data gathered at -15 cm deep seemed to be more dynamic in time. This higher temporal variability may potentially be explained by meteorological conditions affecting the soil surface and by higher crop root activity near the soil surface (Biswas and Si, 2011). For this reason, developing irrigation management zones from data gathered at or near the soil surface may result in zones that are not optimal throughout the crop growing season.

For both sites, there was a strong spatial dependency in soil water content within the measured depths (from -15 to -135 cm; Fig. 5). For Site 1, three types of semivariograms were observed depending on the date: pure nugget effect (2 out of 13), linear relationship (2 out of 13) and exponential (9 out of 13). No link was established between the shape of the semivariogram or the range and the average soil water. However, the range of spatial dependency in depth significantly (Pearson’s $r = 0.84$, $p$-value < 0.05) increased along the crop growing season. For Site 2, all semivariograms but one had an exponential shape with

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Fig. 3. Spatial range values per depth (primary y axis) for selected dates (every other reading) at Site 1. Average volumetric soil water content across depths and observations for each date is illustrated with horizontal blue lines and secondary y axis.

Fig. 4. Temporal semivariograms for each site and each reading depth. Bins are separated by time with lag indicated in the X axis label. Exponential models were used. The temporal range for each depth is indicated with arrows on the x axis. The $R^2$ and RMSE for each curve is indicated in the box.
one having a linear shape. Similarly to Site 1, no link was established between the shape of the semivariogram or the range and the average soil water. Contrary to Site 1 where a clear trend was observed between the date of data acquisition and the range of spatial dependency in depth, no such trend was observed for Site 2. These results indicate that at the depths where majority of the maize roots normally grow, there is a strong spatial dependency in depth for soil water content. These results indicate that there is a strong relationship between values sensed at a specific depth and values sensed above and below this depth. Although no study specifically reports spatial dependency of soil water content across depths, reported values of soil water content measured by neutron probes across depths appear to be spatially dependent (Evett and Steiner, 1995; Evett et al., 2009). A strong spatial dependency in depth indicates that for these sites, a limited number of sensed depths could provide enough information to interpolate soil water content for the whole profile from 0 to −135 cm. The factors explaining an increase in spatial dependency across depths along the crop growing season for Site 1 were not identified. However, the main change happening along the crop growing season is the increased presence of roots in the soil profile. The presence of crop roots may potentially explain a stronger spatial dependency of soil water content in depth later in the crop growing season.

CONCLUSIONS

The tools for variable rate irrigation are commercially available, but little documentation and scientifically validated information exists on how to utilize this technology. Conditions conducive to variable rate irrigation were observed in this study, notably: the existence of spatial variability in soil water content in precision leveled fields and the temporal stability of the spatial pattern of soil water content. This study also provided new insights in the way to approach variable rate irrigation, notably suggesting the use of variable rate irrigation only when crop roots reach deeper depth (below 45 cm) and spatial patterns are more stable (Moran’s I significantly increasing with depth) than when roots are at the surface, where more randomness (Moran’s I not statistically significant) in soil water content occurs. This study provided new and valuable information about the spatial and temporal variability of soil water content. However, more work is needed to learn how to delineate irrigation management zones and how to estimate soil water content by means that are more practical for farmers such as proximal soil sensing, than using neutron probes.

ACKNOWLEDGMENTS

We acknowledge the assistance received from a number of individuals towards completion of this study notably, Neil Hansen, Allan Andales, J.R. Hermann, Jessica Gerk, Chris Fryrear, and Mark Collins. This project was partly funded by USDA—Natural Resource Conservation Services—Conservation Innovation Grant, Colorado State University Agricultural Experiment Station, Colorado Corn Growers Administrative Committee, the 21st Century Equipment Inc., John Deere—Water, Inc., and the Fluid Fertilizer Foundation.

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