Considerations on Improving Nitrogen Use Efficiency in Wheat by Assessing Terraced-Induced Spatial Variability

ABSTRACT

Considering the widespread use of agricultural terraces in Oklahoma and the inherent soil spatial variability importance to nitrogen use efficiency, the objectives of this study were: assess spatial variability of soil physical and chemical properties as a function of distance from agricultural terraces; determine how soil properties spatial variability reflects on wheat growth; and make inferences on possible strategies for increasing NUE based on results. A transect 212 m long was established across four terraces on a wheat field in a Kirkland Silty Clay Loam near Marshall, OK. Soil physical and chemical parameters and wheat growth were assessed in sixty one points along the transect. Soil physical properties were influenced by the position on the landscape and depth. Soil water storage and plant available water in the terrace channel was higher than in other positions on the landscape, whereas inorganic nitrogen concentration was higher in the terrace knoll. Soil spatial variability was reflected on wheat growth and population uniformity, with reduced canopy cover and normalized difference vegetative index (NDVI), and higher coefficient of variation (CV) of the NDVI on the terrace knoll. Higher inorganic nitrogen concentration and NDVI CV in the knoll could lead to lower nitrogen use efficiency (NUE) if a fixed N rate were to be applied in the field. Thus, position on the landscape should be considered for N variable rate applications in terraced land to increase NUE.

INTRODUCTION

The typical sloping landscapes of Oklahoma are characterized by the widespread use of agricultural terraces, built with the purpose of increasing water infiltration and decreasing water losses via runoff (Daniel, 1951; Harper, 1941; Finnell, 1934, Harper, 1934; Finnell, 1930). Agricultural lands that have a sloping landscape are prone to more soil erosion and runoff, reflecting soil spatial variability in crop growth and grain yield (Miller and Shrader, 1988). Topographic attributes such as elevation, slope, and upslope length, also partially ascribe spatial crop yield variability in sloping landscapes (Kaspar et al., 2004; Si and Farrel, 2004). Winter wheat (*Triticum aestivum* L.) represents more than 75% of Oklahoma's cropland (NASS 2012); therefore, understanding the effects of agricultural terraces in soil physical properties, and the effects of topographic attributes of a terraced land on winter wheat growth and by-plant variability can be a valuable tool in the management of precision agriculture practices, improving the efficiency in the use of resources such as water and nitrogen fertilizer.

The effectiveness of level terraces in preventing surface runoff, increasing soil water infiltration, and plant available water, have been widely discussed (Saxton and Spomer, 1968; Miller and Shrader, 1973; Phillips and Beauchamp, 1966; Ballantyne et al., 1965). Although it has been shown that soil moisture content is greater in contour terrace channels than in terrace intervals (Miller and Shrader, 1973), the gradient of change in soil moisture as a function of distance from the channel has been poorly explored in this type of terrace. Indications of moisture gradients and topographic indices such as wetness index have been proposed for rolling landscapes (Bao-Liang et al., 2009; Si and Farrell, 2004); however, work performed for terraced land has mainly been focused in dryland terraces in the Loess Plateau of China (Liu et al., 2011; Lu et al., 2009). Although these studies assessed winter wheat and potato, the region where these were conducted is characterized by steeper slopes (~47% of the area with slopes between 15° and 25°) and different agricultural terraces from those in the Southern Great Plains of the United States. Thus, results derived from these research studies have little application in Oklahoma conditions, where terraces are often wide-based.

The distribution of soil particles can also vary as function of the position on the landscape (Brubaker et al., 1993; Miller et al., 1988). Furthermore, soil particle distribution can vary as a function of depth in the profile, and the interaction between depth and position on the landscape may be significant for percent sand and clay (Brubaker et al., 1993). Spatial variability of soil properties can be reflected in crop growth and yield (Si and Farrell, 2004). Thus, refinement of the understanding of water and soil properties distribution as a function of distance from terraces is crucial for farming systems in Oklahoma, characterized by the widespread use of terraces.

Soil moisture content influences nitrogen uptake by plants (Crusciol et al. 2003; Marschner, 1995). Therefore, readily available water could increase the nitrogen use efficiency (NUE) which is considered to be 33% (Raun and Johnson, 1999). Nitrogen is the nutrient uptaken in greatest amount by plants, and the main pathway for N uptake is mass flow, transport primarily driven by plant transpiration and highly influenced by soil available water (Marschner, 1995; Taiz and Zieger, 2010).

Additionally, soil testing to within-field variability of nitrogen is an approach to refine in-field NUE (Raun and Johnson, 1999). Generally nitrogen fertilization is performed at a single-rate throughout a field, based on average needs of the field as a whole (Raun and Johnson, 1999). However, knowledge of the effect of terraces on soil nitrogen content can allow for more precise application of N fertilizer, avoiding over-fertilization of areas where N is abundant and focusing resources where the crop response will be greater. Few studies have been conducted relating soil nitrogen status to landscape position in the Southern Great Plains. Wood et al. (1991) indicated that landscape position on the slope had little effect on plant N uptake or soil N dynamics, and the observed greater crop productivity downslope was related to greater soil water content instead of N availability.

Another way to increase NUE use is to apply variable rates based on wheat population density variability, represented by the coefficient of variation (CV) derived from the normalized difference vegetative index (NDVI) readings (Arnall et al., 2006; Morris et al., 2006). The NDVI is an index developed from the red and the near infra-red wavebands (Martin et al., 2007), that present direct relationship with crop canopy and biomass (Ashcroft et al., 1990; Anderson and Hanson, 1992) . The NDVI CV is an indicator of plant population density (Martin et al., 2007), as CV's greater than 17-20% indicate plant populations lower than 100 plants m^{-2}, and the response to applied N should be low. Nonetheless, CV's lower than 17% can result in maximum grain yields and increased nitrogen use efficiency (Arnall et al., 2006; Morris et al., 2006). Thus, the understanding of the by-plant variability as affected by terracing can aid in improving the efficiency in the use of nitrogen fertilizer.

The excess use of agricultural fertilizers can lead to leaching of nitrates, contribute to soil acidification, and contamination of ground water deposits (Refsgaard et al., 1999). Furthermore, excess applied N combined with low NUE results in major economic losses, approximately $15.9 billion dollars worldwide annually (Raun and Johnson, 1999).

Given the importance of wheat to the Oklahoma agricultural economy and the typical sloping landscape of the state, reevaluation of the effects of terraces on soil properties and how this spatial variability affects wheat growth is warranted.The objectives of this study were (i) to assess spatial variability of soil physical and chemical properties as a function of distance from agricultural terraces, elevation, upslope lenght, and percent slope; (ii) determine how soil properties spatial variability reflects on wheat growth and by-plant variability; and (iii) make inferences on possible strategies for increasing NUE based on results.

MATERIALS AND METHODS

Site and experimental description

The study was conducted at a the Oklahoma State University Wheat Pasture Unit (WPRU) near Marshall, north central Oklahoma (36°26'N, 97°29'W) in a Kirkland Silty Clay Loam, deep, well drained soil (USDA soil series). The site has a gently rolling landscape with slopes ranging between 1 and 3%, and is characterized by the presence of contoured terraces to limit runoff. The 30-year average precipitation and temperature in the experimental site is approximately 825 mm and 11.1°C (www.mesonet.org). The site has been used for continuous dual-purpose wheat – summer fallow production for more than 20 years (Edwards et al., 2011). Cattle grazing starts late in the fall and continues until the emergence of first hollow stem, then calfs are removed and the wheat continues its cycle until reaching maturity (Butchee, 2011).

The design of the study consisted of one 212 m long transect established across terraced landscape, encompassing four full terraces. Terraces are wide base and were built in 1989 using moldboard plow to move the soil from the channel to the knoll. Two maintainance operations were performed since then. A full terrace had a knoll (points on convex positions in elevation), followed by a channel (points on concave positions in elevation), foot (points accounting for the bottom-half of the upslope length from one terrace's channel until the next terrace's knoll), and a back (points accounting for the upper-half of the upslope length from one terrace's channel until the next terrace's knoll), modifying the methodology used by Miller et al. (1988) when studying complex hills (Figure 1). Sixty one points were sampled along the transect with distances between points of 4.5 m. To better represent the knoll, points on that position were sampled 1.5 m apart.

A rotating laser level (Leica Geosystems, Norcross, GA) was used to calculate the elevation of each individual point in relation to the first point of the transect. From this information, topographic attributes such as slope of the landscape, slope between each pair of points, change in elevation, and true horizontal distance were calculated, similarly to Bao-Liang et al. (2009). Upslope length was calculated as the distance from a given point in the landscape to the highest elevation point within the local slope, and for points characterized by concave angle the distance until the highest point at both sides slope was considered.

Soil Sampling and analysis

Soil samples were collected on Oct 2nd, 2012, using the tractor-mounted Giddings hydraulic soil probe (Soil Exploration Equipment, Windsor, CO) at each point along the transect to a depth of 60 cm, as 0 - 60 cm represents the main profile explored by crop roots (Zhang and Raun, 2006). Soil cores were 3.97 cm in diameter and samples were separated by depth at the intervals 0-15, 15-30, and 30-60 cm, following the methodology suggested by Bao-Liang et al. (2009), to a total of 183 samples. Samples were weighed and oven dried at 105°C for 36 hours for determination of volumetric soil water content (θ), then soil water storage was calculated from depth 0 - 60 cm. Samples were then ground using a Dyna-Crush soil grinder (Custom Laboratory Inc., Orange City, FL) and passed through a 2 mm sieve for particle size analysis, which was performed via hydrometer method (Bouyoucos, 1927). Bulk density was determined by the core method (Blake, 1965).

Soil water content at field capacity and wilting point

Volumetric soil water content at field capacity and wilting point were estimated for each depth according to the van Genuchten (1980) water retention curve. Soil water content at field capacity (θ_{fc}) was calculated using a matric potential (ψ_m) of -33 kPa, whereas a ψ_m of -1500 kPa was used to estimate θ_{wp} (Veihmeyer and Hendrickson, 1931). The van Genuchten parameters including residual and saturated water contents (θ_r and θ_s, $m^3 m^{-3}$) and the empirical constants α (kPa^{-1}) and n (unitless) were estimated for the 0 - 15, 15 - 30, and 30 - 60 cm soil depths using the Rosetta pedotransfer function, model H3 (Schaap et al., 2001).

This model estimates the van Genuchten parameters based on percent sand, silt, and clay and bulk density, which were collected for each depth.

Soil nitrate and ammonium nitrogen contents

Samples were submitted to soil ammonium- (NH_4^+-N) and nitrate - nitrogen (NO_3-N) analysis via potassium chloride and calcium phosphate extraction, respectively (Horneck et al., 1989). These analyses were performed for every 0 - 15 cm sample representing the surface soil, and samples corresponding to 15 - 30 and 30 - 60 cm depth of each point were mixed together representing the subsoil, as suggested by Zhang and Raun (2006).

Wheat canopy cover and NDVI assessment

Winter wheat was sown on 17 Sept. 2012 at 134 kg ha^{-1}, initial growing season soil pH was 5.4, and fertility levels were 23 ppm of N, 34 ppm of P, and 187 ppm of K. Vegetative development was assessed in November 9th, at approximately Feekes GS 4 (Large, 1954). No topdress fertilization occurred prior to vegetative development assessment. A method similar to the one described by Purcell (2000) was used to measure canopy closure, where digital photographs are taken with the camera lens pointing down and encompassing approximately 1m^2 of each individual point. The camera is mounted on a monopod attached to a piece of polyvinyl chloride (PVC) pipe, the mount remains 1m above the soil surface, and the camera is inclined to avoid the PVC pipe from being included in the picture. Digital photographs were analyzed using a macro program for Sigma Scan Pro (v. 5.0, systat software, Point Richmond, CA) (Karcher and Richardson, 2005). The software has selectable options defining hue and saturation values. According to Purcell (2000), setting hue and saturation values selectively include the green pixels in the digital image. For this study hue was set for the range of 30 to 150, and saturation was set for the range of 0 to115. The output of the program is fractional canopy coverage, defined as the number pixels within the selected range divided by the total number of pixels per image (Purcell, 2000). Normalized-difference vegetative index (NDVI) measurements were taken using GreenSeekerTM sensor (model 505, NTech Industries, Ukiah, CA) by measuring approximately 15 m across each individual elevation. The coefficient of variation (CV) obtained from the NDVI readings were also analyzed, as it can be used as an indicator of plant population and homogeneity (Arnall et al., 2006).

Statistical approach

Data collected were first subjected to classical statistical analyses to obtain descriptive statistics such as mean, standard deviation, maximum and minimum values. Afterwards, a factorial analysis was performed in SAS Version 9.2 (SAS Institute, Cary, NC, 2001) using the PROC GLM. The four terraces were treated as four repetitions, position on the landscape (knoll, channel, foot, and back) and depth (0 - 15, 15 - 30, and 30 - 60 cm) were treated as main factors, and the interactions between main effects were assessed. Variables such as average upslope length, canopy cover, or NDVI, were differentiated using ANOVA procedures with PROC GLM and a LSD option to separate means in the MEANS statement. All the analyses were performed at $\alpha = 0.05$. Additionally, Pearson correlation coefficients (r) were calculated from topographic attributes and soil properties.

RESULTS AND DISCUSSION

Differences in soil water storage, plant available water, particle size distribution, bulk density, inorganic nitrogen, and crop development, were found among positions on the landscape along the transect.

Transect properties

Average distance between the terraces knoll (Fig. 2A) was 49.9 m (± SD 7.64), and total elevation increased from zero in the reference point at the origin of the transect to 2.77 m at the highest elevation. Upslope length varied significantly among positions and channels presented the highest mean (30.1 m), followed by foot, back, and lastly by knoll (1.9 m) (Table 1). Percent slope was also significantly different among positions on the landscape, and ranged from -0.6 % in the channel to 2.69 % in the back.

Soil water storage and plant available water

Within the same terrace, soil water storage varied significantly according to the position on landscape (Fig. 2B). The channel presented highest soil water storage reaching values as high as 186 mm in the 60 cm soil profile. Channel was followed by the foot, back, and the knoll, which presented soil water storage values as low as 89 mm. Total precipitation amount in Marshall in the nine-month period prior to sample collection was 560 mm, and the three-month cumulative rainfall before sampling was 123.2 mm. As water storage in the channel was higher than the 90-day cumulative rainfall, the soil in the channel behaved as a water reservoir for the scarce rainfall. Soil moisture content at contour terrace channels has been shown to be greater than in terrace intervals (Miller and Shrader, 1973), on the other hand, the gradient of change in soil water storage in these terraces was yet unexplored. Our results indicate a clear decrease in soil water storage with the increase in the distance from the channel, which is similar to what Bao-Liang (2009) observed studying rolling landscapes in Canada.

A detailed assessment of soil water storage by depth as a function of position on the landscape can be observed in Fig. 3. Water storage in the channel was significantly higher than in the back and in the knoll at the 0-15, 15-30, and 30-60 cm layers, and was higher than the one the at foot in the upper 0-15 cm and the bottom 30-60 cm layers. The greater average upslope length in the channel may have induced greater soil water storage and plant available water, as the upslope length can be considered the contributing area for a given point (Bao-Liang, 2009). Finnell (1930) indicated more soil moisture was saved with level terraces, increasing the annual supply of soil water saved in rainfed semi-arid systems. Likewise, Harper (1941) indicated greater soil moisture in the terrace channel than in the knoll in Oklahoma terraces.

Differences in plant available water (PAW) among the studied positions on the landscape were significant and followed the same trend then did soil water storage (Table 2). Interestingly, the channel presented highest volumetric water content at wilting point, and lowest volumetric water content at field capacity for the 15-30 and 30-60 cm depth. Thus, available water holding capacity was slightly lower in the channel when compared to other positions on the landscape. However, due to substantially higher storage water in the channel, plant available water was also greater on this position.

Particle size distribution and soil bulk density

Particle size distribution varied significantly among position on the landscape and depth, and also with the interaction position on the landscape versus depth. Percent clay was higher in the channel than in the knoll for all three depths studied, while the knoll presented highest percent silt at all three depths assessed. Sand content was not different between channel and the knoll in the 0-15 cm layer, but the knoll presented greater sand content values at the 15-30 and 30-60 cm depths. Brubaker et al. (1993) and Miller et al. (1988) also found that particle size varied significantly with position on the landscape and depth, Brubaker et al. (1993) further stated that and clay and sand contents were affected by the interaction between position on the landscape versus depth.

It is known that bulk density is an indicator of soil compaction. According to USDA NRCS (2008) the ideal bulk density in sand-, silt-, and clay-based soils is 1.6, 1.4, and 1.1 g cm^{-3}, respectively. The soil in our research was a silty clay loam, thus, bulk density values varying among 1.51 to 1.68 g cm^{-3} indicates soil compaction (Table 3). This is most likely a result of long term grazing on this field, which has been conducted for at least 20 years (Greenwood and McKenzie, 2001). In the 0-15 cm layer, bulk density higher in the knoll than it was in the channel; however, at the 15-30 and 30-60 cm depth, the channel presented higher bulk density than any other position studied.

Soil Nitrate- and Ammonium-Nitrogen

Total soil inorganic nitrogen presented opposite behavior than did soil water storage, and greater soil nitrate- and ammonium-nitrogen was observed in the knoll as contrasted to the channel or other positions on the landscape (Figure 2C). Inorganic soil nitrogen was greater in the top 0-15cm layer, with values ranging among as low as 19.2 ppm in the channel and as high as 53.4 ppm in the knoll, whereas the 15-60 cm layer ranged from as low as 2.6 ppm in the channel to as high as 7.4 ppm in the knoll. Greater soil nitrogen content in the topsoil as compared to the subsoil has been previously reported (Wortmann et al., 2011).

Statistical differences of soil inorganic nitrogen as a function of position on the landscape and depth are presented on Figure 4. Nitrate- and ammonium-nitrogen were significantly greater in the knoll for both the top 0-15 cm layer and the 15-60cm layer than the other positions on the landscape. For the 0-15cm layer, the mean inorganic-N in the knoll was 39.2 ppm, and it was followed by the back, foot, and channel, with significant differences among positions. There were no significant differences among channel, foot, or back inorganic nitrogen content in the 15-60 cm layer.

As nitrogen is a mineral nutrient added as fertilizer, it is a property expected to be more uniformly distributed than other soil properties such as organic matter (Brubaker et al., 1993). However, nitrogen uptake by plants can be decreased if soil water availability is restricted (Clarke et al., 1990). Therefore, the lower water availability in the knoll probably led to lower nitrogen uptake on that position, and also leads us assume that the lower nitrogen content in the channels is mainly a function of greater plant uptake resulting from greater water availability. Furthermore, Wood et al. (1991) reported greater inorganic nitrogen in the summit than in the back- or footslopes of a loamy soil in Sterling, Colorado. Brubaker et al. (1993) also reported that nitrate-N content tended to decrease downslope.

Crop growth and variability

Plant growth, assessed as fractional canopy cover (Fig. 2D), was affected by the position on the landscape within each terrace. Mean canopy cover at the channel was 95.3%, compared to a mean of 75.3% in the knoll (Table 1). Differences in soil water content most likely led to the overall decrease of canopy cover on the knoll, as this position presented the lowest soil water storage. Moreover, the knoll presented the highest mineral nitrogen content, indicating that N was not a limiting factor to canopy development. A representation of the canopy cover as a function of position on the landscape can be seen in Figure 5.

Differences in plant growth were also observed in the NDVI and NDVI CV readings (Fig. 6). NDVI, as would be expected, followed the patterns of canopy cover and was higher in the channel and lower on the knoll (Channel > Foot > Back > Knoll, Table 1). High NDVI values indicate that the area was well covered by vegetation, and/or, the plants have sufficient nitrogen available. Martin et al. (2007) indicated that NDVI and vegetation coverage should follow the same pattern, and Butchee (2011) also reported that NDVI and fractional canopy cover were highly related.

On the other hand, NDVI CV had exactly the opposite behavior. Knoll presented the greatest NDVI CV, with a mean 17.1 and values reaching a maximum of 29.7%. The NDVI CV decreased as the analysis switched to the back, foot, finally reaching a mean of 4.7% in the channel (Table 1). A greater NDVI CV means that the wheat plant population is poor, and therefore the response to applied N is lower (Arnall et. al, 2006). The threshold for the NDVI CV above which low wheat populations can be expected is 17-20%, and wheat populations with this characteristic NDVI CV may not reach maximum yields even with late season N application (Arnall et al., 2006; Morris et al., 2006). Otherwise, wheat with low NDVI CV can achieve maximum yields and increased NUE (Morris et al., 2006).

The application of nitrogen in excessive rates is one of the main causes of reduced NUE in agricultural systems (Meisinger et al., 2008). Thus, the use of a single rate N application in a field characterized by high N spatial variability can cause localized excessive N and lead to lower NUE. Spectral reflectance sensors are a tool in variable rate N application, aiding on the increase of NUE by applying higher rates where there is a greater need and responses are expected (Scharf and Lory, 2009; Barker and Sawyer, 2010; Roberts et al., 2010). Our results indicate that NUE can be improved in terraced lands by the use of variable rate N application by decreasing rates at the knoll, where inorganic N and NDVI CV are greater, and thus a lower response is expected. Additionally, the high NDVI, low NDVI CV, and low soil inorganic N content in the channel, suggests the possibility of yield increase by greater N fertilizer rates.

Correlation between topographic attributes, soil, and crop properties

Upslope length presented correlation coefficients (r) positive and greater than 0.6 with soil water storage, plant available water, and NDVI (Table 4). Alternatively, upslope length was negatively correlated to inorganic nitrogen in the 0-15cm layer (-0.60) and NDVI CV (-0.67). By definition the upslope length is higher the lower the point is placed along the terrace; thus, points placed in the channel presented greater upslope length as they were further away from the higher point within that terrace (Table 1). The results regarding soil water storage, plant available water, NDVI, NDVI CV, and inorganic nitrogen described in the previous sections explain the correlation coefficients obtained between these variables and upslope length.

Correlation between percent slope of each individual sampled point and other studied variables had the opposite trend (Table 4). Negative correlation was obtained between percent slope and soil water storage, plant available water, and NDVI; and positive correlation with inorganic nitrogen at 0-15cm depth and canopy cover. Points located in the knoll and back had the largest percent slope, and channel presented the lowest (Table 1). Similarly to upslope length, results previously discussed explain the resulting correlation between variables. Relative elevation was not strongly correlated to any variable assessed.

Conclusions

Soil physical parameters such as water storage, plant available water, bulk density, and particle size distribution varied according to the position on landscape in the terraced area, presenting a gradient of change among positions. Greater soil water storage and plant available water were observed in the channel. Inorganic nitrogen concentration varied significantly among position on the landscape, being greater in the knoll. Wheat growth was influenced by soil spatial variability and reflected the pattern observed in soil water storage. Wheat plant population was more heterogeneous in the knoll than in the other positions on the landscape.

Under the conditions studied, nitrogen use efficiency could be increased by variable rate N application. This would be achieved by decreasing N rates applied in knoll as result of already high inorganic nitrogen concentration and low expected response to applied nitrogen, reflecting the population heterogeneity. Furthermore, lower levels of indigenous N and the low NDVI CV observed in the channels indicate that N rates could be increased in that position. Thus, position on the landscape should be considered for nitrogen variable rate application in terraced lands.

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Tables

Table 1. Upslope length, percent slope, normalized difference vegetative index (NDVI), coefficient of variation of the NDVI, and canopy cover as a function of position on the landscape in the studied Kirkland Silty Clay Loam at Marshall, Oklahoma.

Position on Landscape	Upslope length	Percent slope	NDVI	NDVI CV	Canopy Cover
	m	%		%	%
Channel	30.1 a[†]	-0.60 c	0.84 a	4.7 d	95.3 a
Foot	15.9 b	1.90 b	0.76 b	10.5 c	88.9 ab
Back	10.3 bc	2.69 a	0.69 c	13.1 b	83.2 b
Knoll	1.9 c	2.36 ab	0.60 d	17.1 a	75.3 c
Significance					
Position on Landscape	***	***	***	***	**
Terrace	NS	NS	NS	NS	NS
LSD	9.03	0.72	0.03	2.60	7.69
CV (%)	38.7	28.54	2.51	14.10	5.61

, *, NS Significant at $P = 0.01, 0.001$, and non-significant, respectively

[†] Identical letters in the same column indicate no significant difference at $\alpha = 0.05$

Table 2. Soil particle size distribution and bulk density as a function of position on the landscape and depth on the soil profile for the studied Kirkland Silty Clay Loam at Marshall, Oklahoma.

Position on Landscape	Depth	Clay	Silt	Sand	Bulk density
	cm		%		g cm^{-3}
Channel	0 - 15	32.6	54.2	13.2	1.51
	15 - 30	41.9	48.8	9.4	1.66
	30 - 60	45.6	46.5	7.9	1.68
Foot	0 - 15	25.9	57.9	16.2	1.55
	15 - 30	38.8	51.1	10.1	1.63
	30 - 60	44.6	47.7	7.7	1.66
Back	0 - 15	25.5	59.1	15.4	1.51
	15 - 30	33.7	53.9	12.4	1.60
	30 - 60	46.3	46.2	7.5	1.65
Knoll	0 - 15	29.6	56.8	13.6	1.52
	15 - 30	27.2	57.5	15.3	1.59
	30 - 60	39.0	51.2	9.8	1.59
Significance					
Terrace		NS	**	NS	*
Position on Landscape		***	***	**	**
Depth		***	***	***	***
Position x Depth		***	**	**	*
LSD position		2.04	1.83	1.43	0.02
LSD depth		1.76	1.57	1.24	0.02
CV (%)		6.83	4.17	14.96	1.92

*, **, ***, NS Significant at P = 0.05,0.001, and non-significant, respectively

Table 3. Soil water content at field capacity and at wilting point and measured plant available water in October 2nd according to depth and position on landscape in the studied Kirkland Silty Clay Loam at Marshall, Oklahoma.

Position on Landscape	Depth	Soil Water Content Field capacity†	 Wilting point‡	Plant Available Water
	cm	$cm^3\ cm^{-3}$		mm
Channel	0 - 15	0.27	0.11	15.10
	15 - 30	0.27	0.14	22.20
	30 - 60	0.28	0.15	51.20
Foot	0 - 15	0.26	0.10	13.90
	15 - 30	0.27	0.13	17.90
	30 - 60	0.28	0.14	38.30
Back	0 - 15	0.26	0.10	12.40
	15 - 30	0.26	0.12	14.10
	30 - 60	0.28	0.15	31.90
Knoll	0 - 15	0.27	0.11	11.40
	15 - 30	0.26	0.10	11.10
	30 - 60	0.28	0.13	26.90
Significance				
Terrace		NS	NS	NS
Position on Landscape		**	***	***
Depth		***	***	***
Position x Depth		**	***	***
LSD position		0.005	0.005	2.9
LSD depth		0.004	0.004	2.51
CV (%)		2.01	4.94	15.74

, *, NS Significant at $P = 0.01, 0.001$, and non-significant, respectively

† Soil at field capacity was considered to have a matric potential of -33kPa.

‡ Soil at wilting point was considered to have a matric potential of -1500kPa.

Table 4. Correlation coefficients (r) among topographic indices, soil physical and chemical properties, and biomass indicators for the Marshall site at Oklahoma, United States.

Index	Elevation	Upslope length	Percent Slope	Soil Water Storage	Plant Available Water	NH4+-N and NO3		NDVI	NDVI CV	Canopy Cover
						0 - 15 cm	15 - 60 cm			
Elevation	-									
Upslope length	-0.07	-								
Percent Slope	0.26	-0.49	-							
Soil Water Storage	-0.18	0.67	-0.68	-						
Plant Available Water	-0.19	0.64	-0.66	0.98	-					
Inorg. N (0 - 15 cm)	0.28	-0.60	0.63	-0.70	-0.66	-				
Inorg. N (15 - 60 cm)	-0.06	-0.40	0.37	-0.47	-0.44	0.29	-			
NDVI	-0.22	0.68	-0.69	0.9	0.87	-0.71	-0.51	-		
NDVI CV	0.1	-0.67	0.52	-0.76	-0.75	0.61	0.44	-0.89	-	
Canopy Cover	-0.35	0.53	-0.73	0.84	0.85	-0.62	-0.45	0.84	-0.68	-

Figures

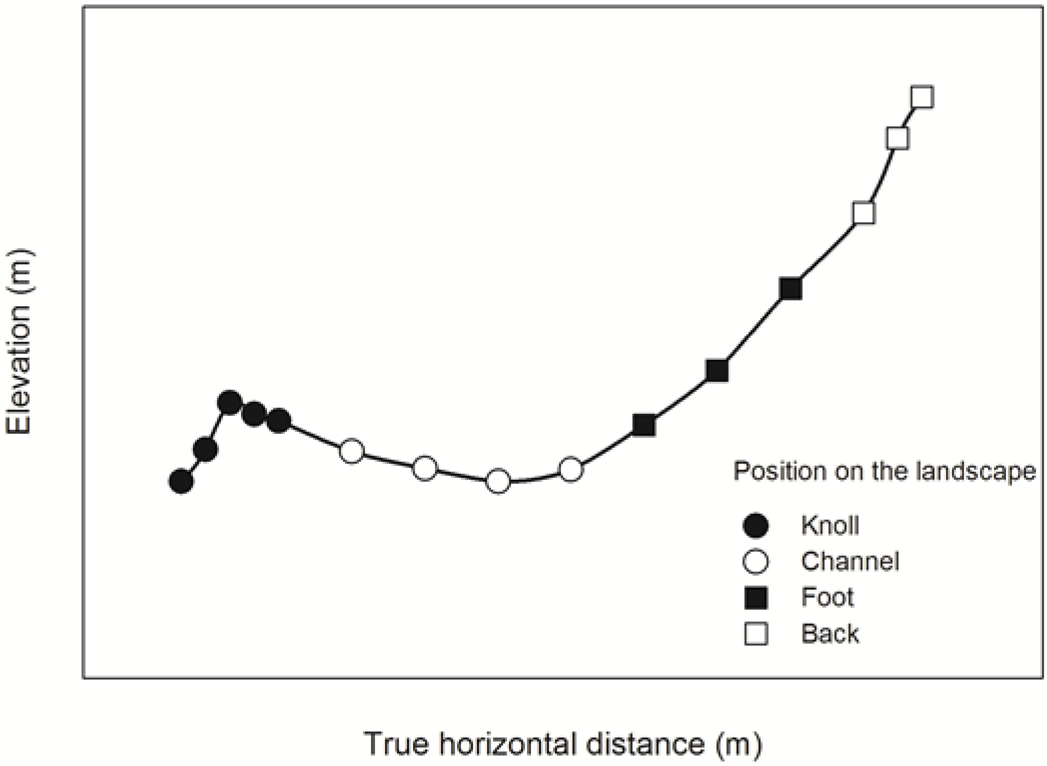

Figure 1. Description of the positions on the landscape within a single terrace.

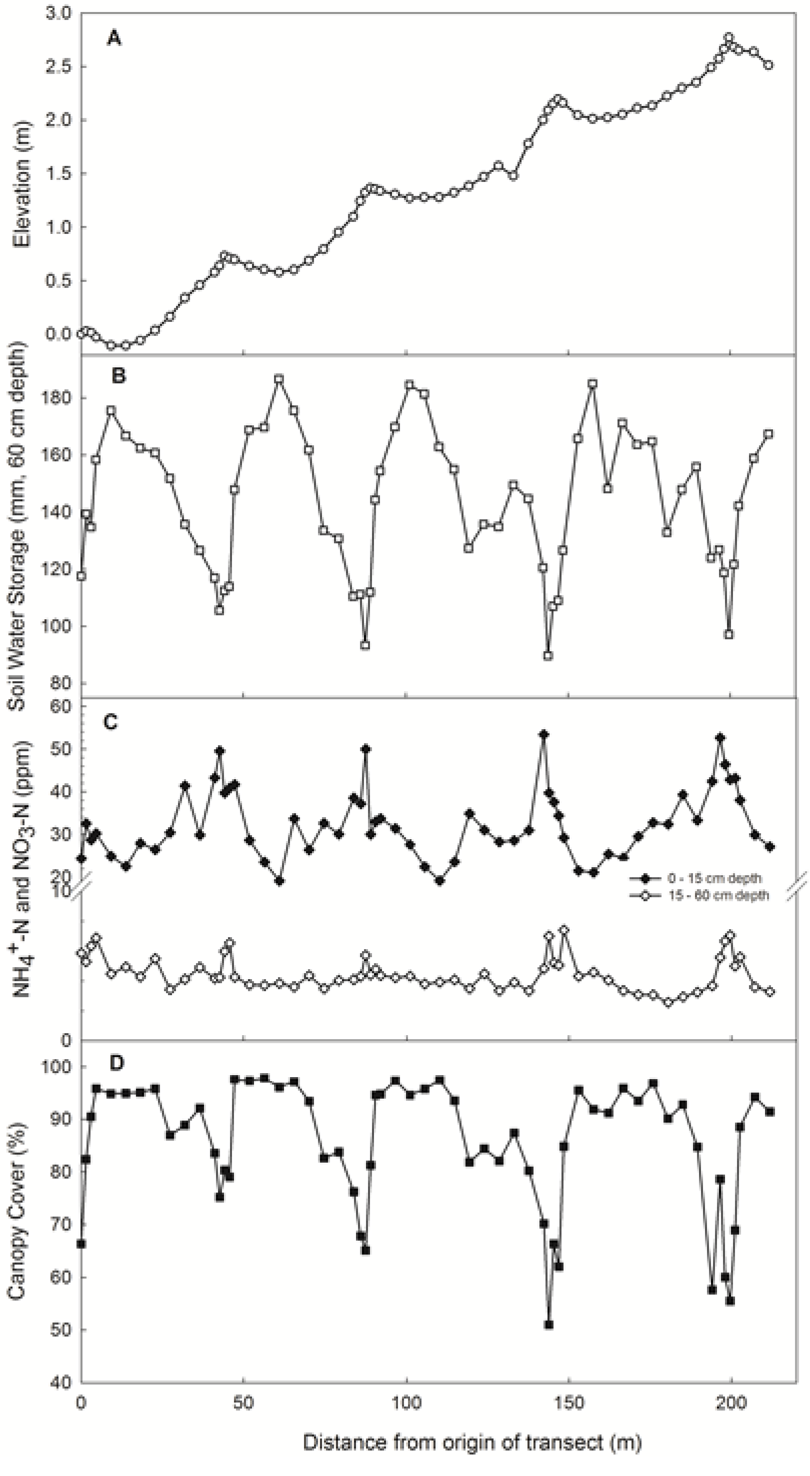

Figure 2. Measured elevation (A), soil water storage (B), soil mineral nitrogen content (C), and winter wheat canopy cover (D) as a function of distance from origin of the transect.

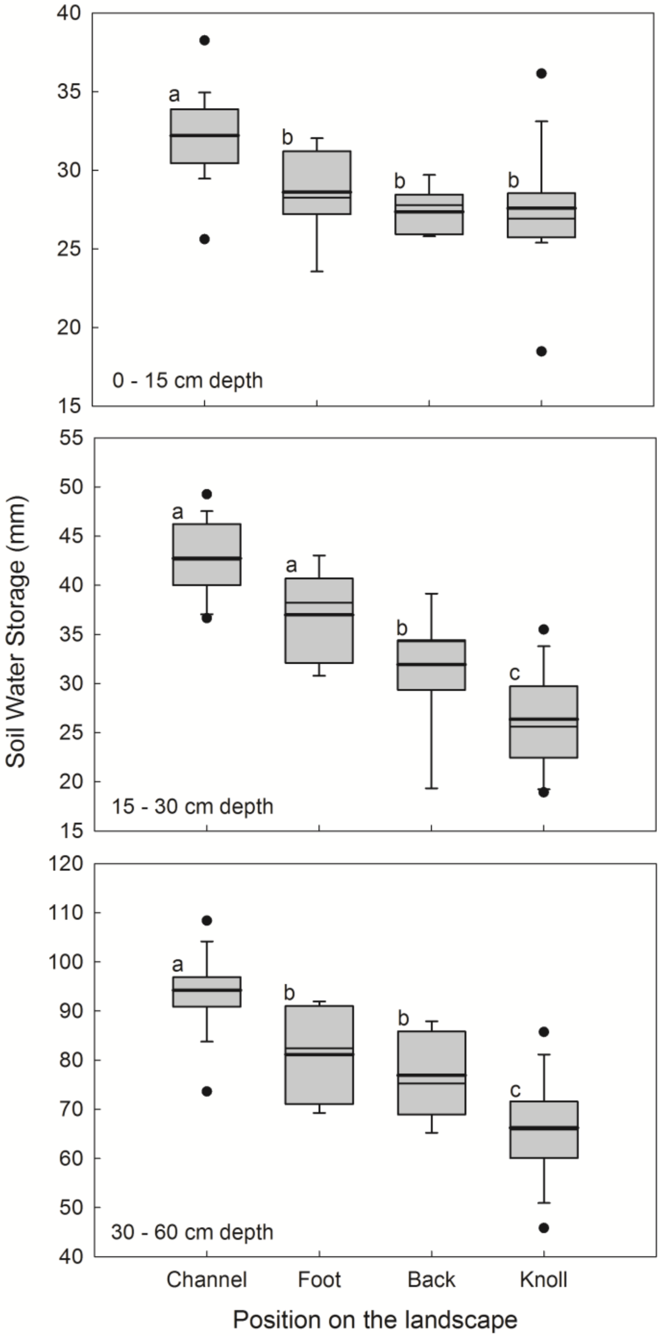

Figure 3. Soil water storage according to depth and position on the landscape. Whiskers indicate the 10th and 90th percentiles, black dots are 5th and 95th percentiles. From bottom to top, the three lines in each box represent the first quartile, median, and third quartile. The heavy black lines represent the mean, and similar letters indicate no statistically significant differences.

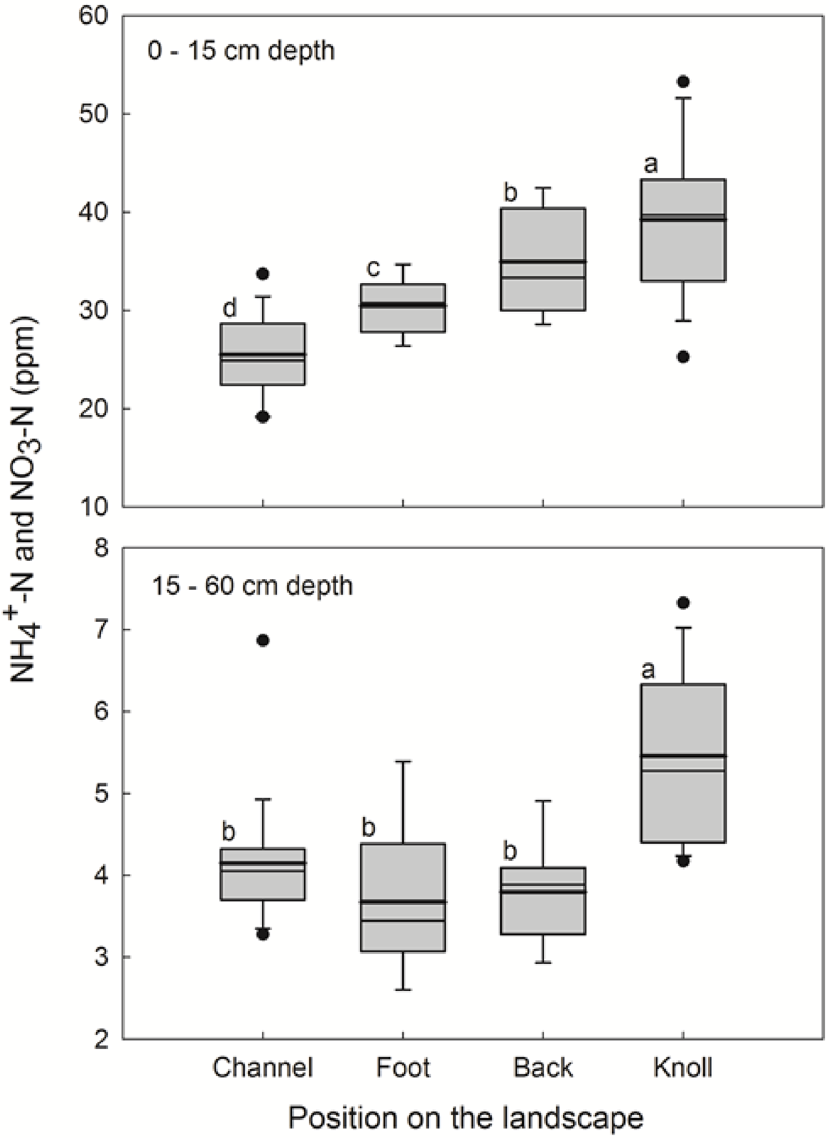

Figure 4. Mineral nitrogen content according to depth and landscape position. Whiskers indicate the 10th and 90th percentiles, black dots are 5th and 95th percentiles. From bottom to top, the three lines in each box represent the first quartile, median, and third quartile. The heavy black lines represent the mean, and similar letters indicate no statistically significant differences.

[redacted] [redacted]

[redacted] [redacted]

Figure 5. Digital imagery used for wheat canopy cover estimation at each position on landscape.

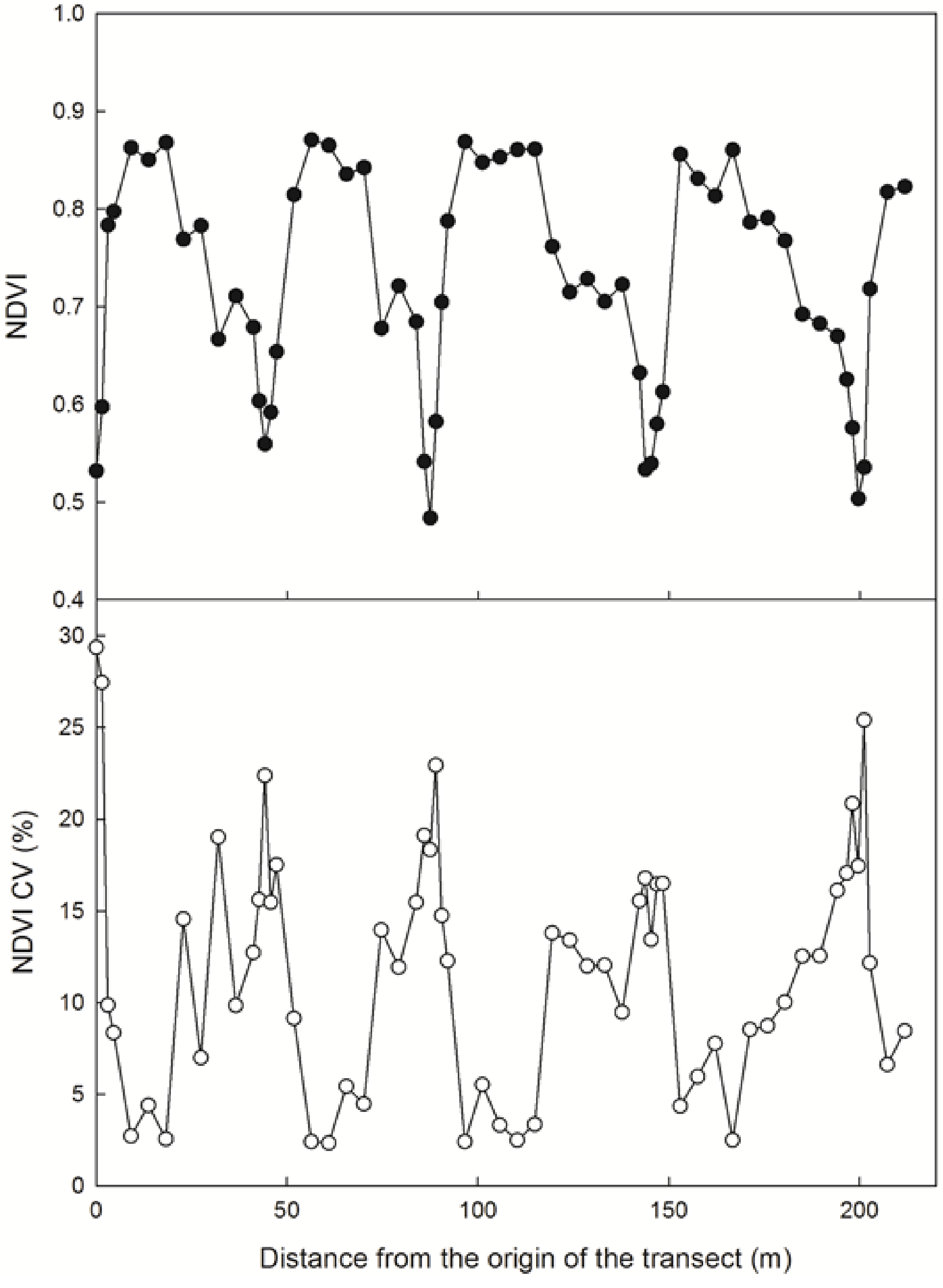

Figure 6. Mean normalized difference vegetative index (NDVI) and coefficient of variation from NDVI readings (NDVI CV) obtained via GreenSeeker sensor as a function of distance from the origin of the transect in a terraced Kirkland Silty Clay Loam, during winter wheat growth stages Feekes GS 4, in the 2012-2013 growing season at Marshall, Oklahoma.