

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

3 **ABSTRACT**

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

21
22 **INTRODUCTION**

23 The typical sloping landscapes of Oklahoma are characterized by the widespread use
24 of agricultural terraces, built with the purpose of increasing water infiltration and decreasing

25 water losses via runoff (Daniel, 1951; Harper, 1941; Finnell, 1934, Harper, 1934; Finnell,
26 1930). Agricultural lands that have a sloping landscape are prone to more soil erosion and
27 runoff, reflecting soil spatial variability in crop growth and grain yield (Miller and Shrader,
28 1988). Topographic attributes such as elevation, slope, and upslope length, also partially
29 ascribe spatial crop yield variability in sloping landscapes (Kaspar et al., 2004; Si and Farrel,
30 2004). Winter wheat (*Triticum aestivum* L.) represents more than 75% of Oklahoma's
31 cropland (NASS 2012); therefore, understanding the effects of agricultural terraces in soil
32 physical properties, and the effects of topographic attributes of a terraced land on winter
33 wheat growth and by-plant variability can be a valuable tool in the management of precision
34 agriculture practices, improving the efficiency in the use of resources such as water and
35 nitrogen fertilizer.

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

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

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

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

74 Another way to increase NUE use is to apply variable rates based on wheat population
75 density variability, represented by the coefficient of variation (CV) derived from the
76 normalized difference vegetative index (NDVI) readings (Arnall et al., 2006; Morris et al.,
77 2006). The NDVI is an index developed from the red and the near infra-red wavebands
78 (Martin et al., 2007), that present direct relationship with crop canopy and biomass (Ashcroft
79 et al., 1990; Anderson and Hanson, 1992) . The NDVI CV is an indicator of plant population
80 density (Martin et al., 2007), as CV's greater than 17-20% indicate plant populations lower
81 than 100 plants m⁻², and the response to applied N should be low. Nonetheless, CV's lower
82 than 17% can result in maximum grain yields and increased nitrogen use efficiency (Arnall et
83 al., 2006; Morris et al., 2006). Thus, the understanding of the by-plant variability as affected
84 by terracing can aid in improving the efficiency in the use of nitrogen fertilizer.

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

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

97

98

MATERIALS AND METHODS

99

Site and experimental description

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

110 The design of the study consisted of one 212 m long transect established across
111 terraced landscape, encompassing four full terraces. Terraces are wide base and were built in
112 1989 using moldboard plow to move the soil from the channel to the knoll. Two
113 maintenance operations were performed since then. A full terrace had a knoll (points on
114 convex positions in elevation), followed by a channel (points on concave positions in
115 elevation), foot (points accounting for the bottom-half of the upslope length from one
116 terrace's channel until the next terrace's knoll), and a back (points accounting for the upper-
117 half of the upslope length from one terrace's channel until the next terrace's knoll),
118 modifying the methodology used by Miller et al. (1988) when studying complex hills (Figure
119 1). Sixty one points were sampled along the transect with distances between points of 4.5 m.
120 To better represent the knoll, points on that position were sampled 1.5 m apart.

121 A rotating laser level (Leica Geosystems, Norcross, GA) was used to calculate the
122 elevation of each individual point in relation to the first point of the transect. From this
123 information, topographic attributes such as slope of the landscape, slope between each pair of

124 points, change in elevation, and true horizontal distance were calculated, similarly to Bao-
125 Liang et al. (2009). Upslope length was calculated as the distance from a given point in the
126 landscape to the highest elevation point within the local slope, and for points characterized by
127 concave angle the distance until the highest point at both sides slope was considered.

128 **Soil Sampling and analysis**

129 Soil samples were collected on Oct 2nd, 2012, using the tractor-mounted Giddings
130 hydraulic soil probe (Soil Exploration Equipment, Windsor, CO) at each point along the
131 transect to a depth of 60 cm, as 0 - 60 cm represents the main profile explored by crop roots
132 (Zhang and Raun, 2006). Soil cores were 3.97 cm in diameter and samples were separated by
133 depth at the intervals 0-15, 15-30, and 30-60 cm, following the methodology suggested by
134 Bao-Liang et al. (2009), to a total of 183 samples. Samples were weighed and oven dried at
135 105°C for 36 hours for determination of volumetric soil water content (θ), then soil water
136 storage was calculated from depth 0 - 60 cm. Samples were then ground using a Dyna-Crush
137 soil grinder (Custom Laboratory Inc., Orange City, FL) and passed through a 2 mm sieve for
138 particle size analysis, which was performed via hydrometer method (Bouyoucos, 1927). Bulk
139 density was determined by the core method (Blake, 1965).

140 **Soil water content at field capacity and wilting point**

141 Volumetric soil water content at field capacity and wilting point were estimated for
142 each depth according to the van Genuchten (1980) water retention curve. Soil water content
143 at field capacity (θ_{fc}) was calculated using a matric potential (ψ_m) of -33 kPa, whereas a ψ_m of
144 -1500 kPa was used to estimate θ_{wp} (Veihmeyer and Hendrickson, 1931). The van Genuchten
145 parameters including residual and saturated water contents (θ_r and θ_s , $m^3 m^{-3}$) and the
146 empirical constants α (kPa^{-1}) and n (unitless) were estimated for the 0 - 15, 15 - 30, and 30 -
147 60 cm soil depths using the Rosetta pedotransfer function, model H3 (Schaap et al., 2001).

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

150 **Soil nitrate and ammonium nitrogen contents**

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

156 **Wheat canopy cover and NDVI assessment**

157 Winter wheat was sown on 17 Sept. 2012 at 134 kg ha^{-1} , initial growing season soil
158 pH was 5.4, and fertility levels were 23 ppm of N, 34 ppm of P, and 187 ppm of K.
159 Vegetative development was assessed in November 9th, at approximately Feekes GS 4
160 (Large, 1954). No topdress fertilization occurred prior to vegetative development assessment.
161 A method similar to the one described by Purcell (2000) was used to measure canopy closure,
162 where digital photographs are taken with the camera lens pointing down and encompassing
163 approximately 1m^2 of each individual point. The camera is mounted on a monopod attached
164 to a piece of polyvinyl chloride (PVC) pipe, the mount remains 1m above the soil surface,
165 and the camera is inclined to avoid the PVC pipe from being included in the picture. Digital
166 photographs were analyzed using a macro program for Sigma Scan Pro (v. 5.0, systat
167 software, Point Richmond, CA) (Karcher and Richardson, 2005). The software has selectable
168 options defining hue and saturation values. According to Purcell (2000), setting hue and
169 saturation values selectively include the green pixels in the digital image. For this study hue
170 was set for the range of 30 to 150, and saturation was set for the range of 0 to 115. The output
171 of the program is fractional canopy coverage, defined as the number pixels within the

172 selected range divided by the total number of pixels per image (Purcell, 2000). Normalized-
173 difference vegetative index (NDVI) measurements were taken using GreenSeeker™ sensor
174 (model 505, NTech Industries, Ukiah, CA) by measuring approximately 15 m across each
175 individual elevation. The coefficient of variation (CV) obtained from the NDVI readings
176 were also analyzed, as it can be used as an indicator of plant population and homogeneity
177 (Arnall et al., 2006).

178 **Statistical approach**

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

189

190 **RESULTS AND DISCUSSION**

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

194 **Transect properties**

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

201 **Soil water storage and plant available water**

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

215 A detailed assessment of soil water storage by depth as a function of position on the
216 landscape can be observed in Fig. 3. Water storage in the channel was significantly higher
217 than in the back and in the knoll at the 0-15, 15-30, and 30-60 cm layers, and was higher than
218 the one the at foot in the upper 0-15 cm and the bottom 30-60 cm layers. The greater average
219 upslope length in the channel may have induced greater soil water storage and plant available

220 water, as the upslope length can be considered the contributing area for a given point (Bao-
221 Liang, 2009). Finnell (1930) indicated more soil moisture was saved with level terraces,
222 increasing the annual supply of soil water saved in rainfed semi-arid systems. Likewise,
223 Harper (1941) indicated greater soil moisture in the terrace channel than in the knoll in
224 Oklahoma terraces.

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

232 **Particle size distribution and soil bulk density**

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

242 It is known that bulk density is an indicator of soil compaction. According to USDA
243 NRCS (2008) the ideal bulk density in sand-, silt-, and clay-based soils is 1.6, 1.4, and 1.1 g
244 cm^{-3} , respectively. The soil in our research was a silty clay loam, thus, bulk density values

245 varying among 1.51 to 1.68 g cm⁻³ indicates soil compaction (Table 3). This is most likely a
246 result of long term grazing on this field, which has been conducted for at least 20 years
247 (Greenwood and McKenzie, 2001). In the 0-15 cm layer, bulk density higher in the knoll than
248 it was in the channel; however, at the 15-30 and 30-60 cm depth, the channel presented
249 higher bulk density than any other position studied.

250 **Soil Nitrate- and Ammonium-Nitrogen**

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

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

265 As nitrogen is a mineral nutrient added as fertilizer, it is a property expected to be
266 more uniformly distributed than other soil properties such as organic matter (Brubaker et al.,
267 1993). However, nitrogen uptake by plants can be decreased if soil water availability is
268 restricted (Clarke et al., 1990). Therefore, the lower water availability in the knoll probably
269 led to lower nitrogen uptake on that position, and also leads us assume that the lower nitrogen

270 content in the channels is mainly a function of greater plant uptake resulting from greater
271 water availability. Furthermore, Wood et al. (1991) reported greater inorganic nitrogen in the
272 summit than in the back- or footslopes of a loamy soil in Sterling, Colorado. Brubaker et al.
273 (1993) also reported that nitrate-N content tended to decrease downslope.

274 **Crop growth and variability**

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

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

289 On the other hand, NDVI CV had exactly the opposite behavior. Knoll presented the
290 greatest NDVI CV, with a mean 17.1 and values reaching a maximum of 29.7%. The NDVI
291 CV decreased as the analysis switched to the back, foot, finally reaching a mean of 4.7% in
292 the channel (Table 1). A greater NDVI CV means that the wheat plant population is poor, and
293 therefore the response to applied N is lower (Arnall et. al, 2006). The threshold for the NDVI
294 CV above which low wheat populations can be expected is 17-20%, and wheat populations

295 with this characteristic NDVI CV may not reach maximum yields even with late season N
296 application (Arnall et al., 2006; Morris et al., 2006). Otherwise, wheat with low NDVI CV
297 can achieve maximum yields and increased NUE (Morris et al., 2006).

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

309 **Correlation between topographic attributes, soil, and crop properties**

310 Upslope length presented correlation coefficients (r) positive and greater than 0.6 with
311 soil water storage, plant available water, and NDVI (Table 4). Alternatively, upslope length
312 was negatively correlated to inorganic nitrogen in the 0-15cm layer (-0.60) and NDVI CV (-
313 0.67). By definition the upslope length is higher the lower the point is placed along the
314 terrace; thus, points placed in the channel presented greater upslope length as they were
315 further away from the higher point within that terrace (Table 1). The results regarding soil
316 water storage, plant available water, NDVI, NDVI CV, and inorganic nitrogen described in
317 the previous sections explain the correlation coefficients obtained between these variables
318 and upslope length.

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

326 **Conclusions**

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

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

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REFERENCES

347 Anderson, G.L. and J.D. Hanson. 1992. Evaluating handheld radiometer derived vegetation

348 indices for estimating aboveground biomass. *Gercarto Int.* 1:71-78.

349 Arnall, D. B., W. R. Raun, J. B. Solie, M. L. Stone, G. V. Johnson, K. Girma, K. W.

350 Freeman, R. K. Teal, and K. L. Martin. 2006. Relationship between coefficient of

351 variation measured by spectral reflectance and plant density at early growth stages in

352 winter wheat. *Journal of Plant Nutrition* 29:1983–1997.

353 Ashcroft, P.M., J.A. Catt, P.J. Curran, J. Mundem, and R. Webster. 1990. The relation

354 between reflected radiation and yield on the broad baik winter wheat experiment. *Int.*

355 *J. Remote Sens.* 11:1821-1836.

356 Bao-Liang, C., Cheng-Si, B., Walley, and F., Yates, T. 2009. Topographic Indices and Yield

357 Variability in a Rolling Landscape of Western Canada. *Pedospere.* 19:362-370.

358 Blake, G.R. 1965. In: C.A. Black (ed.) *Methods of Soil Analysis, Part 1. Physical and*

359 *Mineralogical Properties, Including statistics of Measurement and Sampling.* ASA-

360 *SSSA, Agronomy Monograph 9: 374-390.*

361 Bouyoucos, G. J. 1927. The hydrometer as a new method for the mechanical analysis of soil.

362 *Soil Sci.* 23:343-352.

363 Ballantyne, C. R., P. Jacobson, H. Howell, and F. W. Schaller. 1965. Improved terrace

364 systems for western Iowa. Iowa State University Cooperative Extension Service

365 Publication AG-14.

366 Bapna J.S. and Khuspe V.S. 1980. Effect of different soil moisture regimes and N levels on

367 moisture use by dwarf wheat. *Mysore J. Agric. Sci.* 14:211-214.

368 Brubaker, K.L., Entehkabi, D., and Eagleson, P.S. 1993. Estimation of continental
369 precipitation recycling. *Jornal Clim.* 6:1077-1089.

370 Butchee, J.D. Effect of simulated grazing intensity on dual purpose winter wheat (*Triticum*
371 *aestivum* L.) grain yield in Oklahoma. M.S. Thesis. Oklahoma State Univ., Stillwater.

372 Clarke, J.M., C.A. Campbell, H.W. Cutforth, R.M. DePauw, and G.E. Winkleman. 1990.
373 Nitrogen and phosphorus uptake, translocation, and utilization efficiency of wheat in
374 relation to environment and cultivar yield and protein levels. *Can. J. Plant Sci.*
375 70:965-977.

376 Crusciol, C.A., O. Arf, R.P. Soratto, and J.R. MACHADO. 2003. Influência de lâminas de
377 água e adubação mineral na nutrição e produtividade de arroz de terras altas. *Rev.*
378 *Bras. Ciênc. Solo* 27:647-654.

379 Daniel, H.A. 1951. Water conservation for wheat production in Oklahoma. *Soil Sci. Soc. Of*
380 *Am. J.* 15:408-412.

381 Edwards, J.T., B.F. Carver, G.W. Horn, and M.E. Payton. Impact of dual-purpose
382 management on wheat grain yield. *Crop Sci.* 51:2181-2185.

383 Finnell, H.H., 1930. The moisture-saving efficiency of level terraces under semi-arid
384 conditions. *Journal of The American Society of Agronomy.* 6:522-529

385 Finnell, H.H. 1934. Results of level terracing on heavy silt loam soil. Penhandle (Okla.) *Agr.*
386 *Exp. Sta. Bul.* 53.

387 Greenwood, K.L. and McKenzie, B.M. 2001. Grazing effects on soil physical properties and
388 the consequence for pastures: a review. *Australian J of Experimental Agriculture.*
389 41:1231-1250.

390 Harper, H.J. 1941. The effect of terrace ridges on the production of winter wheat. *Soil Sci.*
391 *Soc. Proc.*, 474-479.

392 Harper, H.J. 1934. Studies on moisture movements in terraced soils. Okla. Agr. Exp. Sta.
393 Bienn. Rpt., 1932-34:28-30.

394 Horneck, D.A., Hart J.M., Topper, K., and Koespell, B. 1989. Methods of soil analysis used
395 in the soil testing laboratory at Oregon State University. SM 89:4. Agric. Exp. Stn.,
396 Oregon State Univ., Corvallis.

397 Karcher, D.K., and M.D. Richardson. 2005. Batch analysis of digital images to evaluate
398 turfgrass characteristics. Crop Sci. 45:1536-1539.

399 Kaspar, T.C., D.J. Pulido, T.E. Fenton, T.S. Colvin, D.S. Karlen, D.B. Jaynes, and D.W.
400 Meek. 2004. Relationship of corn and soybean yield to soil and terrain properties.
401 Agron. J. 96:700-709.

402 Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

403 Liu, X., B. He, Z. Li, J. Zhang, L. Wang, and Z. Wang. 2011. Influence of land terracing on
404 agricultural and ecological environment in the loess plateau regions on China.
405 Environ. Earth Sci. 62:797-807.

406 Lu, H.; Y. Zhu; T.H. Skaggs, Z. Yu. 2009. Comparison of measured and simulated water
407 storage in dryland terraces of the Loess Plateau, China. Agric. Water Manag. 96:299-
408 306.

409 Marschner H. 1995. Mineral Nutrition of Higher Plants, 2nd edn. Academic Press, New
410 York.

411 Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubana, D.B. Arnall, B. Chung, O.
412 Walsh, J.B. Solie, M.L. Stone, and W.R. Raun. 2007. Expression of variability in corn
413 as influenced by growth stage using optical sensor measurements. Agron J. 99:384-
414 389.

415 Meisinger, J.J., Schepers, J.S., and Raun W.R. 2008. Crop nitrogen requirement and
416 fertilization. P. 563-612. In J.S. Schepers et al. (ed.) Nitrogen in agricultural systems.
417 Agron. Monogr. 49. ASA, CSSA, and SSSA, Madison, WI.

418 Miller, E. L. and W.D. Shrader. 1973. Effect of Level Terraces on Soil Moisture Content and
419 Utilization by CornAgron. J. 65: 600–603.

420 Miller, E. L., Shrader, W. D., and Nielsen, D. R. 1988. Spatial Variability of Wheat Yield
421 and Soil Properties on Complex Hills. Soil Sci. Soc. Am. J. 52:1133-1141.

422 Morris, K.D., K.L. Martin, K.W. Freeman, R.K. Teal, K. Girma, D.B. Arnall, P.J. Hodgen, J.
423 Mosali, W.R. Raun, and J.B. Solie. 2005. Mid-season recovery from nitrogen stress in
424 winter wheat. J. Plan Nutr. 29:727-745.

425 NASS. 2012a. National Agricultural Statistics Service. Oklahoma wheat county estimates.
426 Available at [http://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/
427 County_Estimates/2012/ok_wheat_county_estimates_2011.pdf](http://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/County_Estimates/2012/ok_wheat_county_estimates_2011.pdf) (accessed 11 July
428 2012; verified 27 July 2012).

429 Phillips, R. L. and Beauchamp, K. H. 1966.Parallel terraces. Soil Conservation Service
430 Manual.

431 Purcell, L.C. 2000. Soybean canopy coverage and light interception measurements using
432 digital imagery. Crop Sci. 40:834-837.

433 Raun, W.R., and G.V. Johnson. 1999. Improving nitrogen use efficiency for cereal
434 production. Agron. J. 91:357-363.

435 Refsgaard, J.C., M. Thorsen, J.B. Jensen, S. Kleeschulte, S. Hansen. 1999. Large scale
436 modeling of ground water contamination from nitrate leaching. J. Hydrol. 221:117-
437 140.

438 SAS Institute. 2004. SAS/STAT: Procedures. SAS Proprietary Software Release 9.2. SAS
439 Inst., Cary, NC.

440 Saxton, K. E., and R. G. Spomer. 1968. Effects of conservation on the hydrology of loessal
441 watersheds. *Transactions of the American Society of Agricultural Engineers* 11(2):
442 848-849, 853.

443 Schaap, M.G., F.J. Leij, M.T. van Genuchten. 2001. ROSETTA: a computer program for
444 estimating soil hydraulic parameters with hierarchical pedotransfer functions. *J.*
445 *Hydrol.* 251:163-176.

446 Si, B.C. and R.E. Farrel. 2004. Scale-dependent relationship between wheat yield and
447 topographic indices: a wavelet approach. *Soil Sci. Soc. Am. J.* 68:577-587.

448 Taiz, L., and E. Zeiger. *Plant physiology*. 5th ed. ISBN 978—87893-866-7. Sunderland, MA.

449 Wheaton, R.Z. and Monke, E.J., 2001. Terracing as a 'Best Management Practice' for
450 controlling erosion and protecting water quality. *Agricultural Engineering* 114,
451 Purdue University. [online] URL: [http://www.agcom.purdue.edu/AgCom/Pubs/AE/AE-](http://www.agcom.purdue.edu/AgCom/Pubs/AE/AE-114.html)
452 [114.html](http://www.agcom.purdue.edu/AgCom/Pubs/AE/AE-114.html)

453 van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductivity
454 of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892-898.

455 Veihmeyer, F.J., and A.H. Hendrickson. 1931. The moisture equivalent as a measure of the
456 field capacity of soils. *Soil Sci.* 32:181-193.

457 Wood, C.W., G.A. Peterson, D.G. Westfall, C.V. Cole, and W.O Willis. 1991. Nitrogen
458 balance and bioamass production of newly established no-till dryland agroecosystem.
459 *Agron. J.* 83:519-526.

460 Wortmann, C.S., D.D. Tarkalson, C.A. Shapiro, A.R. Dobermann, R.B. Ferguson, G.W.
461 Hergert, and D. Walters. 2011. Nitrogen use efficiency of irrigated corn for three
462 cropping systems in Nebraska. *Agron. J.* 103:76-84.

463 Zhang, H., and B. Raun. 2006. *Oklahoma soil fertility handbook*. 6th ed. Dep. of Plant and
464 Soil Sci., Oklahoma State Univ., Stillwater

465 **Tables**

466

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

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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 $\alpha = 0.05$

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483 Table 2. Soil particle size distribution and bulk density as a function of position on the
 484 landscape and depth on the soil profile for the studied Kirkland Silty Clay Loam at Marshall,
 485 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

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

497

Position on Landscape	Depth cm	Soil Water Content		Plant Available Water mm
		Field capacity [†] cm ³ cm ⁻³	Wilting point [‡] cm ³ cm ⁻³	
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.

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

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Index	Elevation	Upslope length	Percent Slope	Soil Water Storage	Plant Available Water	NH ₄ ⁺ -N and NO ₃		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	-

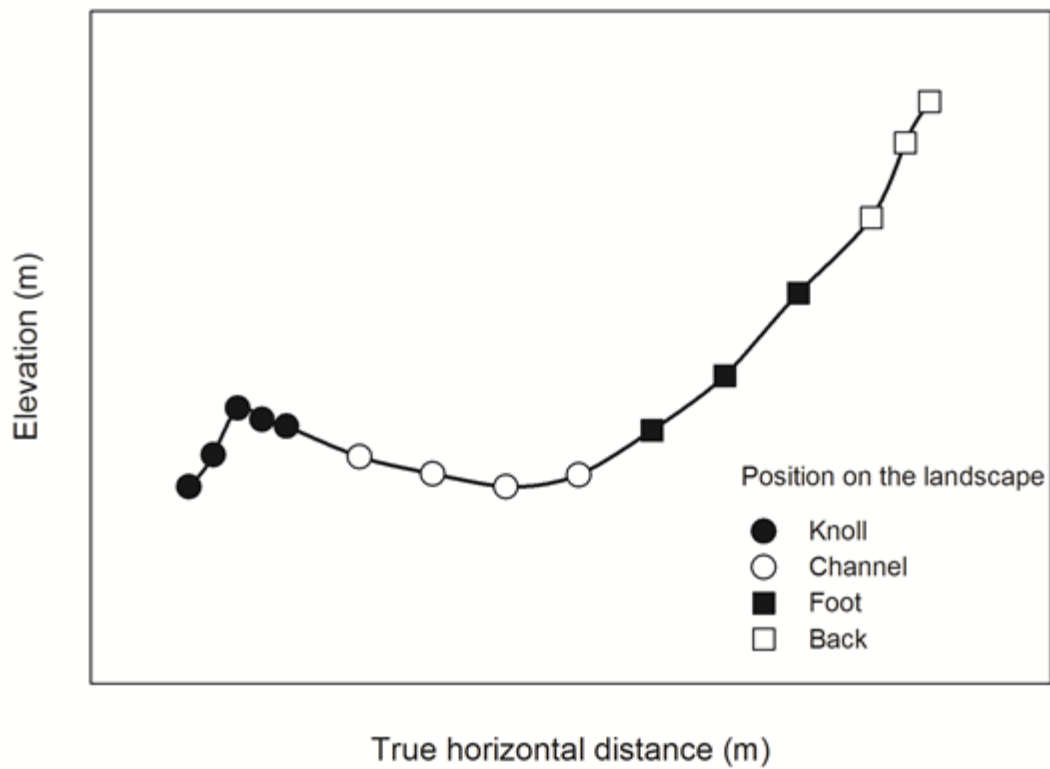
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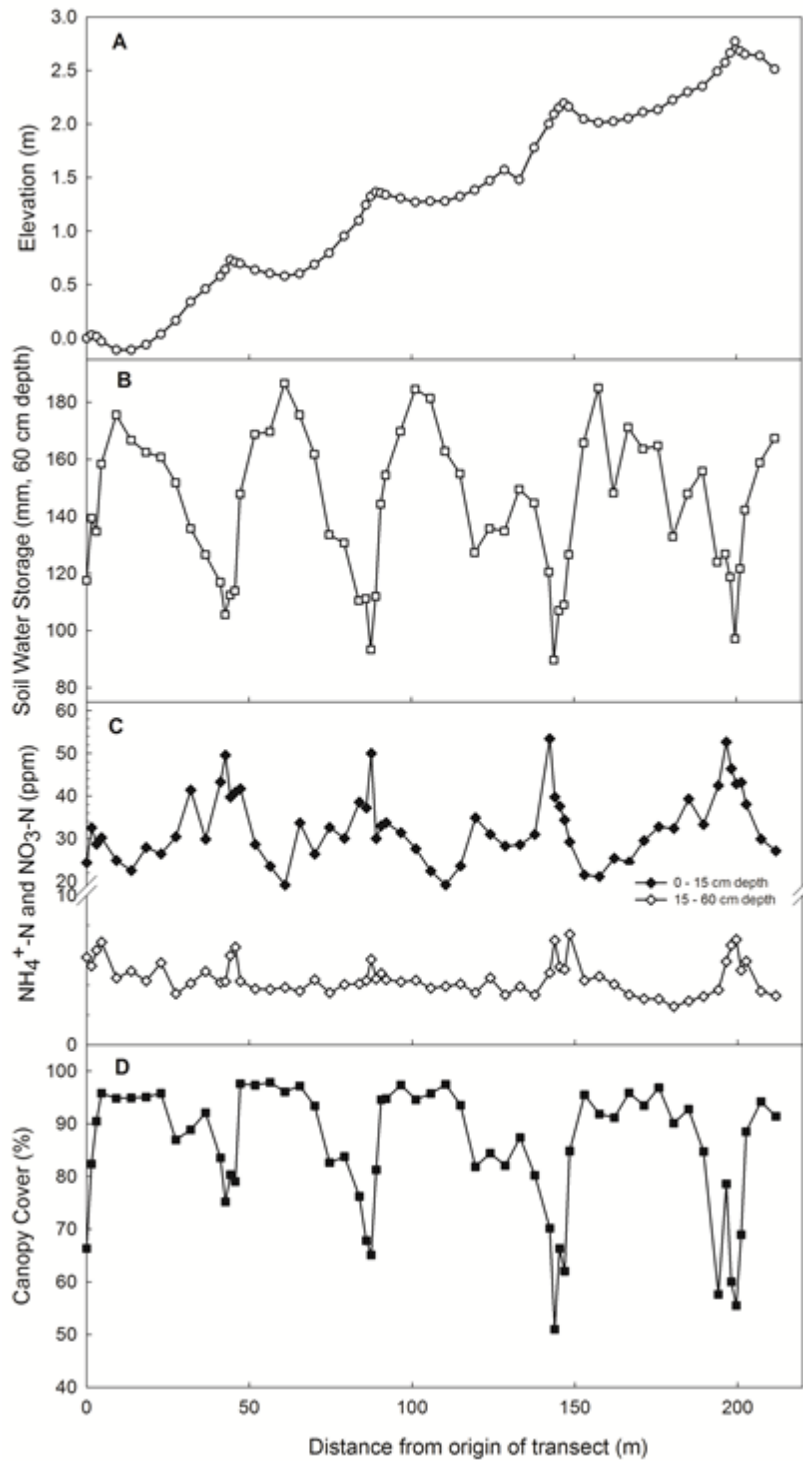
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513 **Figures**
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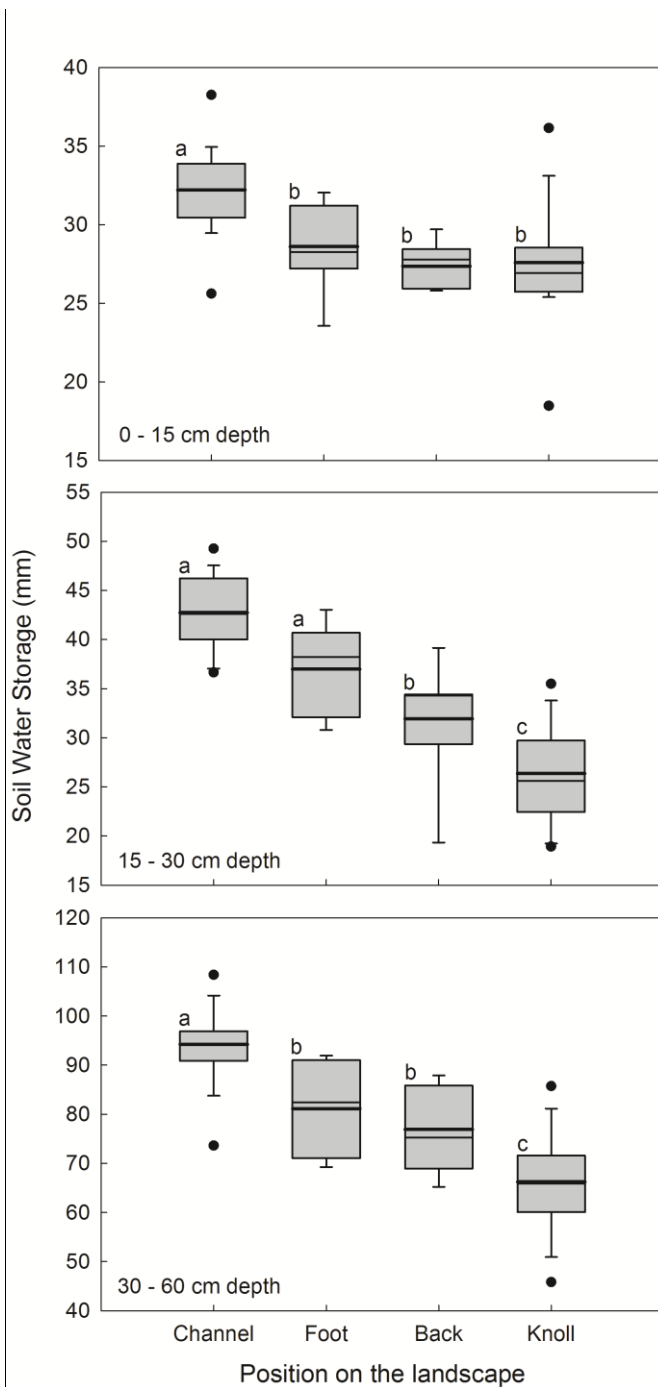


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518 Figure 1. Description of the positions on the landscape within a single terrace.
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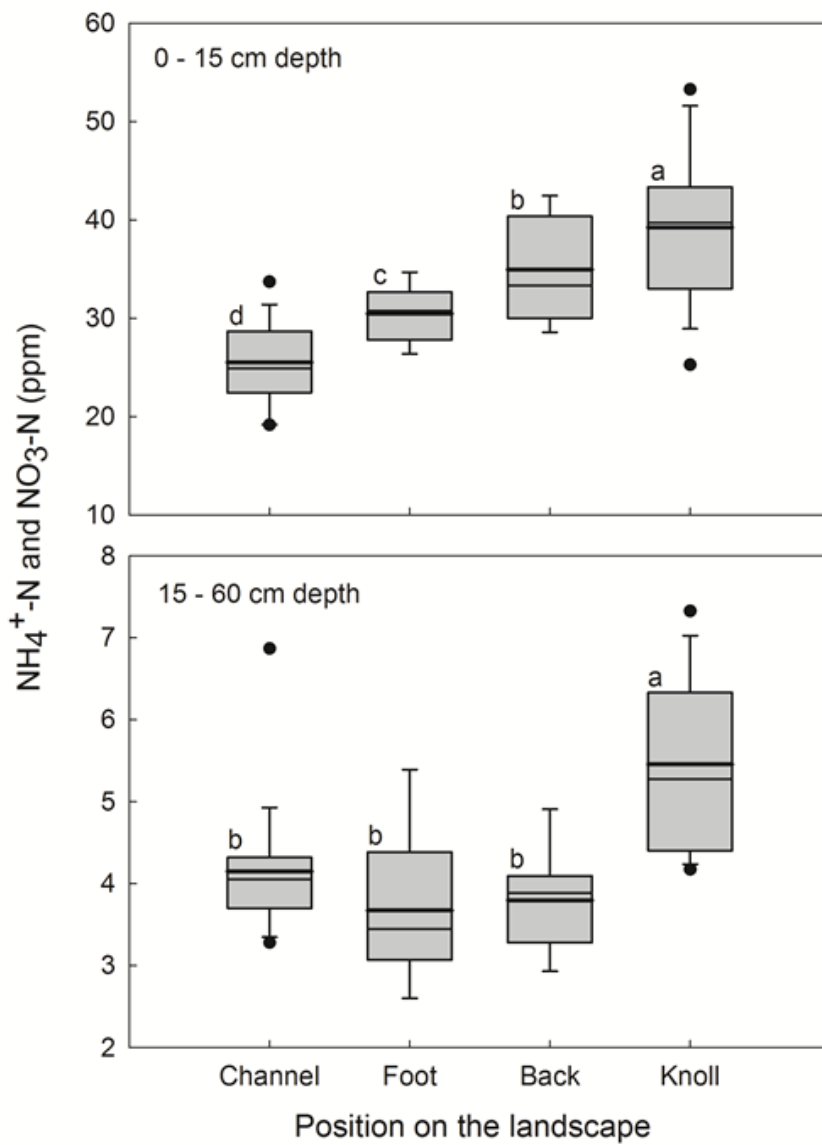
Figure 2. Measured elevation (A), soil water storage (B), soil mineral nitrogen content (C), and winter wheat canopy cover (D) as a function of distance from origin of the transect.



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

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

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

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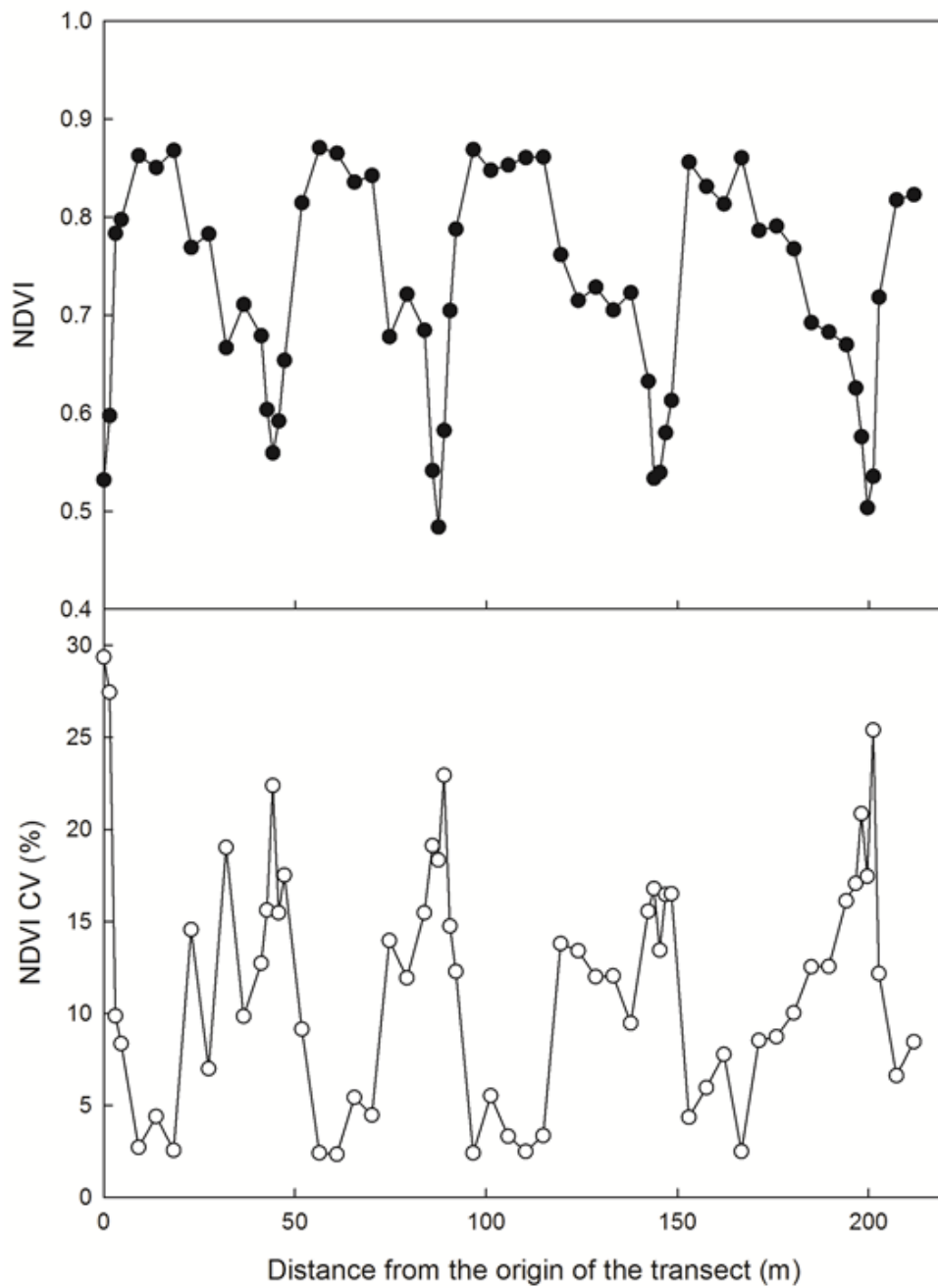
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563 Figure 6. Mean normalized difference vegetative index (NDVI) and coefficient of variation
564 from NDVI readings (NDVI CV) obtained via GreenSeeker sensor as a function of distance
565 from the origin of the transect in a terraced Kirkland Silty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