Relationships between Soil–Landscape and Dryland Cotton Lint Yield

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ABSTRACT

Topographical land features shape the spatial variability of soils and crop yields, especially in dryland cotton (*Gossypium hirsutum* L.). The objectives of this study were to (i) quantify the relationships between cotton lint yields vs. derived topographical attributes in combination with measured soil physical properties, and (ii) quantify the relationships between measured soil physical properties and derived topographical attributes. The dominant soil of the study area was classified as Vaiden soil series (very-fine, smectitic, thermic Aquic Dystruderts). More than 4500 elevation point data were recorded in a 42-ha field using a real-time kinematic-global positioning system (RTK-GPS) used in a geographic information system (GIS) to derive topographic (slope, curvature and aspect) and hydrologic attributes (wetness index, flow direction, flow length, flow accumulation, and sediment transport index). Surface (0–17 cm) sand, clay, saturated hydraulic conductivity (K_s), bulk density (ρ_b), water content at seven equilibrium pressure levels ranging from -0.01 to -1.5 MPa, and 2-yr cotton lint yield data were measured from sites selected based on classified normalized difference vegetation index (NDVI). Stepwise linear regression indicated that cotton lint yield variability was explained by soil properties (65% in 2001 and 58% in 2002), and topographic and hydrologic attributes (40 and 21%), as well as their combined effects (82 and 72%). Elevation, flow direction, sediment transport index, percentage sand content, and volumetric water content (θ_v) at -0.001 MPa pressure explained most of the lint yield variation. Overall, statistical analysis indicated that higher elevation areas generally yielded lower ($r = -0.50$, $P < 0.01$) and may experience water stress earlier in the season, as compared with lower elevation areas. We expect that once these features are derived and interpreted, they will have a long-lasting impact on cotton management under dryland conditions.

Topography plays an important role in agricultural fields in terms of shaping the spatial variability of soils, surface and subsurface hydrology, and crop yields. Landscape topography affects soil physical and chemical properties by erosion and deposition processes (Delin et al., 2000; Norton and Smith, 1930; Ebeid et al., 1995; and Agbenin and Tiessen, 1995). Li and Lindstrom (2001) reported water erosion as the primary cause for the overall decline in soil quality on a steep cultivated hillslope, while tillage erosion had a similar contribution to the overall level of soil quality on a terraced hillslope. Soil movement by tillage controlled the spatial patterns in OM, N, and P on both terraced and steep cultivated hillslopes. Selective removal of finer particles by water erosion caused a linear decrease in clay content of 0.02% m^{-1}, and a corresponding increase in silt content of 0.04% m^{-1} downslope on the steep cultivated hillslope.

Kravchenko et al. (2000) reported higher crop yield at lower slope locations, and a wide range of yield values on moderate and higher slopes during moderate to dry weather conditions; however, low yield values were measured on lower slope locations during the wet season. Kravchenko et al. (2000) also examined the effects of derived topographic and hydrologic derived indices on variability in soil properties and crop yield. They reported crop yield had a significant negative correlation with elevation, slope and curvature. Sinai et al. (1981) calculated a soil surface curvature factor from the elevation of neighboring points in a grid-sampled field. The factor was positive in concave positions in the landscape, negative in convex positions, and highly correlated with soil water content. The redistribution of soil water downslope, both at the surface and subsurface (throughflow), gave soil properties downslope indicative of soil water conditions and moved solute laterally. This process could be beneficial in terms of higher yield at lower positions in dry years. Stone et al. (1985) reported that differences in corn (*Zea mays* L.) yield between landscape positions were much more consistent than yield differences between erosion classes. Higher grain yield values were recorded on landscape positions that received water from higher elevations. Terrain elevation (Bakhsh et al., 2000; Kravchenko et al., 2000; Timlin et al., 1998), slope, curvature (Kravchenko and Bullock, 2002a; Changere and Lal, 1997; Sinai et al., 1981), aspect (Kravchenko and Bullock, 2002b; Yang et al., 1998), wetness index, sediment transport index, stream power index, flow direction, and flow length (Jenson and Domingue, 1988; Moore et al., 1993) have been considered as important topographical and hydrological attributes in crop production systems.

Soil properties vary with topographic settings. One reason for this is the orientation of the hillslopes on which soils develop; this affects the microclimate, such as north- vs. south-facing slopes, and hence the soils. Krause et al. (1959) reported the influence of a slope's aspect on soil development in Alaska. They reported ice-rich permafrost occurrence at shallow depths on N-facing slopes, but its absence on S-facing slopes. In addition, soils on the S-facing slopes were well drained and relatively deep; whereas, those on the N-facing slopes were poorly drained and shallow. Another factor

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Abbreviations: ρ_b, bulk density; DEM, digital elevation model; GIS, geographic information system; GPS, global positioning system; K_s, saturated hydraulic conductivity; NDVI, normalized difference vegetation index; PAWC, plant available water content; OM, organic matter; RTK, real-time kinematic.

is the shape of the slope, which influences the redistribution of soil water content along the slope. This also affects soil properties, because the rate of surface water runoff influences erosion and soil water content. In a rolling terrain, higher parts of the landscape could experience greater evaporation, so higher-located soils would have lower soil water content (Finney et al., 1962).

Sampling for soil properties on a narrow grid is both labor intensive and costly. An alternative approach could be to use the NDVI-based target sampling in conjunction with a digital elevation model (DEM). A DEM is considered by many (Jenson and Domingue, 1988; Mark, 1984; Moore et al., 1991; Martz and Garbrecht, 1992) as a source of easily obtained data that is useful information to soil survey maps for enhancement of soil characterizations of an agricultural landscape. Grid-based hydrological processes are commonly investigated using a watershed algorithm imbedded in a GIS. The automation of terrain-based analysis and the use of a DEM have made it possible to quantify various topographic and hydrologic variables including slope, aspect, curvature, stream network, flow direction, flow accumulation, flow length, sediment transport index, wetness index, and stream power index. Previously these variables and indices were derived from maps or field surveys. But, in the last two decades they have been directly derived from a DEM, as this data source has various advantages. The advantages include faster derivation, less subjectivity, and more reproducible measurements than manual techniques (Tribe, 1992). Another major advantage is that these derived grid-based variables can be exported as an ASCII text file for further analysis. Moore et al. (1993) used DEM-based derived terrain slope, wetness index, stream power index, aspect, and curvature to calculate variation in A horizon depth, organic matter (OM), pH, and percentage sand and silt. They reported significant correlation between terrain attributes and the measured soil properties.

The multifaceted complexity of topographic and hydrologic variables and their relationships with soil properties and crop yield has been determined using both traditional statistical and geostatistical techniques. Spatial variability of measured soil properties has been characterized by many using crossvariance, state-space analysis, co-spectral analysis, and geostatistical techniques for pattern analysis and for relating topography to yield (Nielson and Wendroth, 2003; Li et al., 2001, 2002; Trangmar et al., 1985; Journel and Huijbregts, 1978; Burgess and Webster, 1980; Matheron, 1963). These studies mainly concentrated on pattern characterization, but not pattern to process as emphasized by Moore et al. (1993). For instance, many soil properties are related to the gradient of the slope as well as to the particular position of the soil on a slope. This lateral variability on hillslopes means that each soil along a slope bears a distinctive relationship to the soils above and below it, which is a catena process. Several models have been proposed (Conacher and Dalrymple, 1977; and Ruhe and Walker, 1968) to describe how landscape is related to soil catena. Ruhe and Walker (1968) proposed a five-unit model based on slope form. These units include flat summit, shoulder, backslope, and base (footslope and toeslope) positions. Most studies dealing with landscape topography have used these qualitative units to explain the catena process rather than to quantify topographical variables and explain the extent of variability in a mapping unit. Aside from the nonquantitative nature of these units, it is hard to draw a distinctive unit boundary line, and in most of the studies, the boundary lines are arbitrary.

The hypothesis of this study was that landscape topographical attributes and soil hydrological variables are among the major determinants of crop water availability, especially in nonirrigated systems, and are thus useful for explaining crop yield variability on a field scale. The objectives of this study were to (i) quantify the relationships between cotton lint yields vs. derived topographical landscape attributes in combination with measured soil physical properties, and (ii) quantify the relationships between measured soil physical properties and derived topographical attributes.

MATERIALS AND METHODS

Study Site

A 2-yr study was conducted during 2001 and 2002 (33°07′52′′ N, 88°29′25′′ W) located in east-central Mississippi. A 42-ha field, Field-104, was chosen as a long-term site for studying soil and crop management practices in dryland agroecosystems where variability in landscape topography is a major determinant of soil water availability. The land in Field-104 has been cultivated for at least 80 yr, and has been in a soybean [*Glycine max* (L.) Merr.]–cotton–corn rotation. The field has a complex rolling topography with local relief of 10 m. On the basis of 29 yr of climatic data of Noxubee County, average yearly precipitation in this region is about 1422 mm (56 inches), with rainfall evenly distributed throughout the year (USDA-SCS, 1983). Daily weather parameters were collected from a weather station located at the Farm. Figure 1 shows monthly total precipitation and monthly average air temperature for the years 2001 and 2002. The cotton cultivar DP 555 was planted on rows running across the elevation contours. The planting dates were 1 May 2001 and 5 May 2002. Fertilizer N, applied as urea-ammonium nitrate solution (32–0–0 N–P–K) at the rate of 134 kg N ha^{-1}, was knife-injected 2.5 cm below the seed. The cotton lint was picked on 5 Oct. 2001 and 17 Sept. 2002.

The dominant soil series of the field is Vaiden, which consists of very deep, somewhat poorly drained, very slowly permeable soils that formed in clayey sediments overlying chalk or calcareous clays (USDA-SCS, 1983). Years of water erosion, especially on steeper slopes, have created deep rills across the crop rows in some areas and carried suspended materials and deposited them in lower landscape positions.

Sites Selection for Soil Sampling

Target Soil Sampling

A digital image of a soybean crop was obtained in July 2000 from an airborne digital camera system that acquired three bands (840, 695, 540 ± 5 nm) with a 2-m spatial resolution. Values for NDVI were calculated from the raw digital numbers from each pixel location using the equation of Rouse et al. (1973). The NDVI is a measure of the relative greenness of an area, and its values range between 0 and 1 (Rouse et

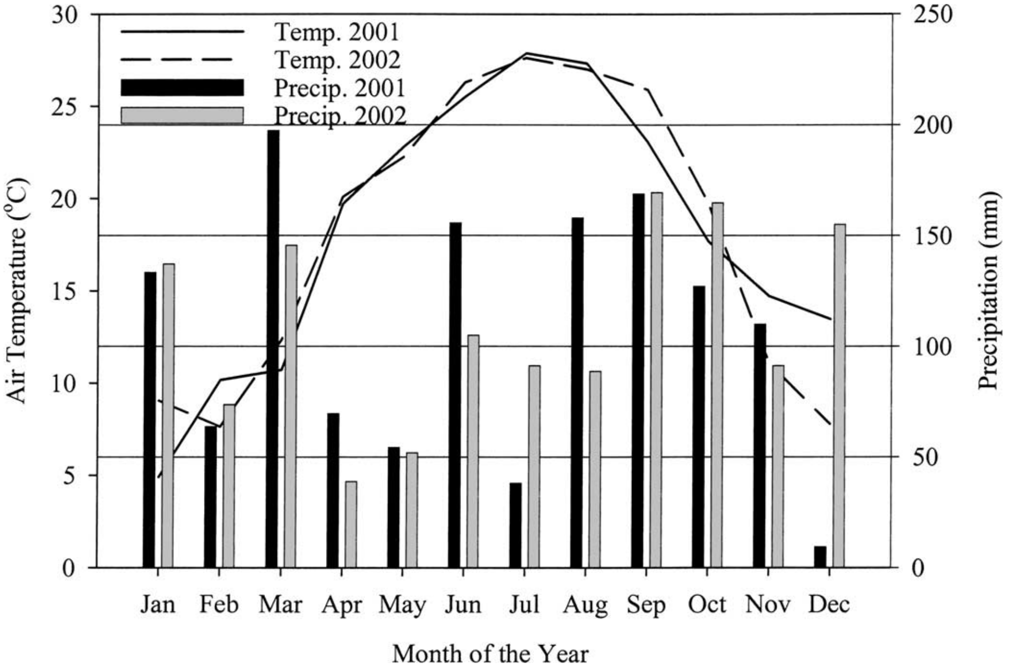

Fig. 1. Average minimum and maximum temperatures and total monthly precipitation at the farm for 2001 and 2002.

al., 1973). High NDVI values usually indicate the presence of dense green vegetation, whereas low values generally indicate areas having more bare ground. The image was classified using an unsupervised (isodata) classification approach into three NDVI classes, that is, low, medium, and high, with image analysis software (Earth Resources Data Analysis System, 2001).

Twenty-four sites were selected from the classified map, eight sites per NDVI class and positioned on a previously established 0.75-ha grid. Undisturbed soil cores were taken at each site using a Giddings soil hydraulic probe mounted on the back of a tractor. First, a 1-m long stainless steel probe was used to take a soil profile, which was described using National Cooperative Soil Survey procedures (Soil Survey Staff, 1984). Taxonomic classification of soils was based on field descriptions and laboratory analyses of soil physical properties. The depths for $A_{p,}$ Bt_1, and Bt_2 horizons ranged from 10 to 26 cm (average 17.3 cm), 30 to 73 cm (average 53.0 cm), and 73 to 100 cm, respectively. Soil samples were then taken from each horizon in each profile and analyzed for soil particle analysis (Day, 1965) and OM using modified Walkley–Black method (Schnitzer, 1982). Additional undisturbed soil cores were taken from each horizon of each profile for measurement of K_s with 7.62- by 7.62-cm cylinders; volumetric soil water content (θ_v) was measured at seven equilibrium pressure levels (−0.001, −0.01, −0.033, −0.067, −0.1, −0.5, −1.5 MPa) with 7.62- by 2.54-cm rings (Klute, 1986); and ρ_b was measured with 7.62- by 7.62-cm cylinders.

Cotton Lint Yield

Cotton lint yield data in 2001 and 2002 were collected with a yield monitor equipped with a differential GPS receiver. However, lint yield was only collected from every other four rows because only one of the two yield monitors used was equipped with a GPS. Because of complex rolling topography and picker speed variations, yield monitors are prone to errors in yield and position measurements, especially along steeper slopes. Cotton lint yield data were also obtained by hand picking from the predefined NDVI category sites (2.0- by 6.1-m area). On the basis of comparisons with handpicked yield data, any extreme outliers in yield monitor data were excluded. An inverse distance weighting interpolation (Environmental Systems Research Institute, 1998) method was used to smooth the effects and possible errors in individual data points, and to calculate lint yield at unsampled locations with a 4.7-m grid size. Specifically, the measured data was interpolated by selecting 12 nearest neighbors with a distance power of two.

Deriving Topographic and Hydrologic Attributes

Landscape elevation data were measured with Trimble AgGPS 214 RTK receiver, which had a relative accuracy of 1 cm in *x*, *y* directions and 2 cm in *z* direction. Measurements were taken on an irregular grid. Measurements on steep slopes were intensely measured compared with level surface. Elevation data was converted to 4.71-m grid-based map. Before deriving hydrologic and topographic attributes from the grid-based elevation data, preprocessing was required to fill depressions known as *sinks* in the data. The process of filling increases the values of cells in each depression to the value of the cell with the lowest values on the depression boundary (Jenson and Domingue, 1988). This type of processing can greatly increase the measurement accuracy of hydrologic flow directions. Several topographic and hydrologic attributes (Table 1) were derived using ArcView, Spatial analyst (Environmental Systems Research Institute, 1998) from elevation data (Fig. 2), and include slope, curvature, aspect, flow direction, flow length, wetness index, and sediment transport index. Numerous sources give more complete descriptions of theory and derivation of topographic and hydrologic attributes (Jenson and Domingue, 1988; Moore et al., 1991, 1993). Inverse distance weighting with 12 neighbors and with a distance power of two was used for creating maps. All map grid sizes were obtained on the same cell-size basis as the yield map. ArcView was used to extract the surface soil physical and chemical properties with corresponding yield, topographical data, and hydrological data for statistical analysis.

Table 1. Definitions and descriptions of digital elevation model (DEM)-based derived topographic and hydrologic attributes.

Attribute	Definition and Description
Elevation, m	Elevation above sea level at a given point on the land surface.
Slope, °	Describes the rate of elevation change, and is defined as the first order derivative of the terrain.
Aspect, °	Measured in degrees clockwise from north.
Plan curvature, m^{-1}	Describes the acceleration or deceleration of water flow over a surface, negative curvature corresponds to concave surface, while positive curvature corresponds to convex surfaces or hills.
Flow direction	Corresponds to steepest decent in elevation and is determined based on elevation difference between neighboring cells.
Flow accumulation, Σ cells	It is defined as the total numbers of cells contributing to water inflow into a given cell.
Flow length, m^{-1}	Describes the path of the longest flow path within a drainage basin.
Wetness index	Indicator of soil water variability over a surface. It is derived using the slope of a cell measured in degrees and the contributing catchment area in m^{-2}.
Sediment transport index	Characterizes the process of soil erosion and deposition. It presents the effects of topography on soil loss and can vary along the length of a stream.

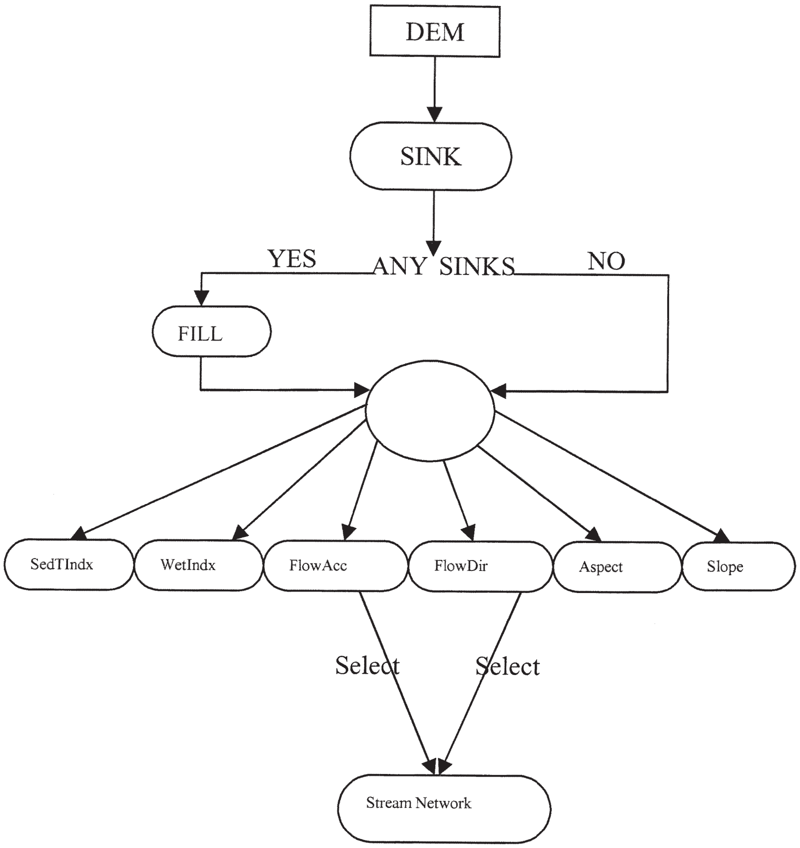

Fig. 2. Functional flow of topographic and hydrologic features extraction process in a geographic information system. First, the real-time kinematic-global positioning system elevation data was converted to a 4.71-m grid then depressions known as *sinks* were filled, and subsequently slope, aspect, flow direction (FlowDir), flow accumulation (FlowAcc), wetness index (WetIndx), and sediment transport index (SedTInd) maps were derived. While the combination of flow direction and flow accumulation maps were used to derive stream network map. DEM = digital elevation model.

Statistical Analysis

Descriptive statistics of soil physical properties from the 24 sites were calculated for each variable at each horizon (Table 2). Pearson's correlation coefficients (r) were calculated between the lint yield monitor data; measured surface soil properties and topographic and hydrologic attributes. Surface soil properties included OM, nitrate N (NO_3), sand, clay, ρ_b, K_s, and θ_v at time of sampling (fresh wt.), at saturation, and at seven different pressures of -0.001, -0.01, -0.033, -0.067, -0.1, -0.5, -1.5 MPa. The difference between -0.033 MPa (field capacity) and -1.5 MPa (wilting point) was taken as assumed to be plant available water content (PAWC). Topographic and hydrologic attributes included elevation, slope, curvature, aspect, flow accumulation, flow length, flow direction, sedimentation transport index, and wetness index.

Stepwise multiple linear regressions (backward and forward) were performed using SAS (SAS Institute, Cary, NC, 2001) to determine the individual and combined effects of soil properties, topographical attributes, and hydrological attributes on cotton lint yield. A variable was retained in the model if the probability at $P > 0$ was 95%.

RESULTS AND DISCUSSION

Soil Physical Properties

The 3-D field elevation contours (Fig. 3) depicts a complex rolling topography with a range of 10 m. The low-lying areas are located along the southern and northern borders of the field and in the middle along the main drainage area.

Table 2. Descriptive statistic of measured field soil physical properties.

Variable	Horizon	Mean	SD	Variance	Skewness	Normality†
				%		
Thickness, cm	A_p	17.29a‡	3.7	13.69	−0.19	0.06
	Bt_1	53.33b	10.38	107.71	−0.54	0.1
	Bt_2	–	–	–	–	–
Bulk Density, g cm^{-3}	A_p	1.18b	0.12	0.01	−0.29	0.51
	Bt_1	1.25a	0.09	0.01	0.27	0.92
	Bt_2	1.21ab	0.07	0	0.55	0.16
Ks, cm d^{-1}	A_p	7.03ns§	14.68	215.58	3.27	0.001
	Bt_1	3.62ns	6.81	46.32	4.33	0.001
	Bt_2	2.04ns	1.99	3.95	3.59	0.001
Sand, %	A_p	9.06a	2.14	4.58	−0.28	0.79
	Bt_1	5.95b	2.9	8.43	1.39	0.001
	Bt_2	5.63b	4.3	18.53	3.49	0.001
Clay, %	A_p	39.20c	8.12	66.01	0.37	0.52
	Bt_1	50.66b	7.39	54.54	0.78	0.09
	Bt_2	56.37a	7.81	60.98	−0.51	0.07
Soil water potential, MPa		—— cm^3 cm^{-3} (%) ——				
−0.01	A_p	34.70b	4.68	21.88	−0.74	0.03
	Bt_1	41.76a	3.9	15.22	−0.19	0.67
	Bt_2	40.34a	4.19	17.52	0.53	0.42
−0.033	A_p	30.08b	4.32	18.67	−0.76	0.21
	Bt_1	39.43a	4.06	16.51	−0.17	0.46
	Bt_2	37.47a	4.51	20.37	0.24	0.47
−1.5	A_p	23.80c	3.94	15.49	0.31	0.97
	Bt_1	34.23a	3.82	14.61	−0.08	0.81
	Bt_2	31.71b	4.7	22.13	0.48	0.19
PAWC¶	A_p	10.89a	1.62	2.62	−0.19	0.84
	Bt_1	7.53b	1.08	1.17	−0.63	0.16
	Bt_2	8.56b	1.4	1.96	−0.1	0.67

† The Shapiro Wilks test was used to test for the presence of a normal distribution; a variable is not normally distributed if $P < 0.05$.
‡ Variable means with the same letter across the horizons are not significantly different at $P = 0.05$, according to Waller–Duncan K ratio *t* test.
§ ns = not significant.
¶ PAWC = plant available water content = difference between water content at −0.033 and −1.5 MPa.

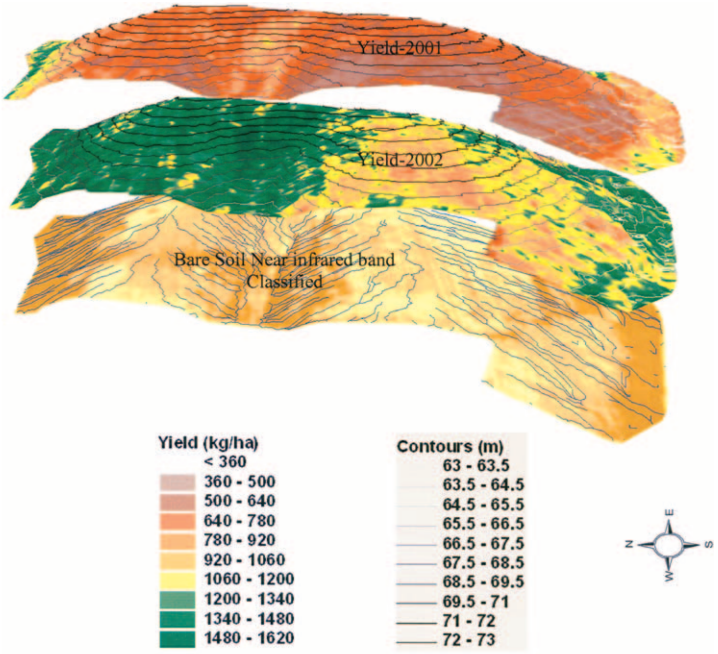

Fig. 3. Cotton lint yield monitor data for 2001 and 2002 draped over a three-dimensional field elevation (real-time kinematic-global positioning system) map along with elevation contours and classified bare soil near-infrared band (wavelength of 950 nm with 100-nm bandwidth) with 0.5-m spatial resolution. Stream Networks are superimposed on a bare soil imagery map to depict landscape hydrology–soil catena process–yield interaction on a field scale.

The Shapiro-Wilk test (Shapiro and Wilk, 1965) was used to test the significance level of normality of each variable at each horizon. A variable was considered to be nonnormally distributed if the probability of the Shapiro and Wilk test statistic was <0.05 (Table 2). The measured soil properties sampled from Field-104 were normally distributed except for K_s on all three horizons, percentage sand content in Bt_1 and Bt_2 horizons, and percentage θ_v at −0.01 MPa in the Ap horizon (Table 2). Mean values for K_s were low and generally had a decreasing trend with increase in depth. This could be due to the increase in the clay content with depth. The mean percentage θ_v at -0.033 MPa (field capacity) was higher at subsurface horizons than at surface horizons. A similar trend was measured at -1.5 MPa (wilting point) percentage θ_v values. Mean PAWC (% θ_v) was higher at surface horizons than subsurface horizons. Soil hydraulic properties on a field scale have been reported to have high spatial variability (Albrecht et al., 1985; Ciollaro and Comegna, 1988; Mallants et al., 1996; Peck et al., 1977; Rhoton et al., 1998).

Jury (1985) summarized coefficients of variation (CVs) for various soil physical properties, which reached well in excess of 100% for K_s (48–320%), θ_v at -0.01 MPa, θ_v at -1.5 MPa (4–45%), and percentage sand and clay (3–55%). He argued that large CV values were due to skewed distributions. Iqbal (2000) studied the spatial variability of soil physical properties in a 164-ha diverse field located along the Mississippi River, reporting CVs of K_s (57–62%), θ_v at -0.01 MPa, and θ_v at -1.5 MPa (253–283%).

Measured Soil Properties vs. Derived Topographic and Hydrologic Attributes

Larger Ap horizon depths were generally measured at high elevations (elevation vs. depth; $r = 0.16$, not significant), while shallower Ap depths were found at steeper slopes (slope vs. depth; $r = -0.19$, not significant). The higher ρ_b values were measured along the northwestern border of the field, while lower values were found along the southwestern part. However, ρ_b was low on steeper slopes (slope vs. ρ_b; $r = -0.50$, $P < 0.01$). The K_s at the summit (elevation vs. K_s; $r = 0.27$ ns) was similar to that on steeper slopes (slope vs. K_s; $r = -0.16$, not significant), but this pattern was not consistent across the field. Higher percentage sand content was measured along the western border extending toward the center on the summit and steeper slopes, where the percentage clay content ranged from moderate to low. A significant negative correlation was obtained between percentage clay content and elevation ($r = -0.59$, $P < 0.001$), and there was a nonsignificant relationship with slope ($r = 0.35$, not significant) and a significant relationship with aspect ($r = 0.47$, $P < 0.05$). These relationships indicated that percentage clay content tends to be low on summit positions and high on steeper slopes and the toeslope, which is a strong indication of downslope colloidal movement. Malo et al. (1974) found a similar spatial distribution of percentage clay within a glacial till toposequence field in North Dakota. Li and Lindstrom (2001) reported selective removal of finer particles by water erosion caused a linear decrease in clay content of 0.02% m^{-1} and a corresponding increase in silt content of 0.04% m^{-1} downslope on steep cultivated hillslope. Pierson and Mulla (1990) found the highest clay content at the summit and the lowest in footslope positions. They argued that the soil erosion removes the topsoil and OM from the ridge tops, thus exposing the subsoil horizons, which were higher in clay content and lower in aggregate stability. Mapa and Pathmarajah (1995) reported significant increases in clay content downslope were responsible for a decrease in infiltration rate and K_s, and an increase in PAWC.

Volumetric water content at -0.03 MPa, -0.067 MPa, and -1.5 MPa and PAWC were greater at landscape positions where the percentage clay content was high; an indication of the greater water holding capacity of clay-sized particles. The observed correlation between derived terrain attributes and measured soil variables supports the development of the soil catena; that is, it develops in response to the way water flows through and across the landscape (Mapa and Pathmarajah, 1995).

When the best combination of terrain variables for explaining variations in soil properties of the Ap horizon was explored, the resulting multiple regression equations explained 10 to 62% of the variability in measured soil attributes (Table 3). Slope, flow length, flow direction, and aspect explained 45 to 56% of the variation in soil water retention at different pressures. Usually soil scientists do not incorporate information about local processes in attempting to develop soil pedotransfer functions. The listed regression equations could be used to calculate surface-horizon soil physical properties. Kravchenko et al. (2000) showed that topography explained about 30% of the observed variability in OM, P, and K content of the soils. However, soil properties are highly variable in an agricultural environment due to interactions between environmental and man-induced factors.

In summary, a high-resolution elevation data for an agriculture landscape could be used in a GIS to derive topographic (slope, curvature, and aspect) and hydrologic attributes (wetness index, flow direction, flow length, flow accumulation, and sediment transport index) and these variables could be used in site-specific farming on a rolling topography to calculate the soil physical properties, especially soil water content in a dryland farming condition.

Cotton Lint Yield vs. Soil Physical Properties and Topographic Attributes

Various stacked maps, including contours of elevation, lint yield monitor for 2001 and 2002, stream networks, and bare soil imagery, were draped over a three-dimensional elevation map (Fig. 3). In 2001 and 2002, the field had an average cotton lint yield of 510 and 1014 kg ha^{-1}, with SD of 202 and 213 kg ha^{-1}, respectively. The average total monthly precipitation during both growing seasons was similar, but in 2002, during first bloom, the crop received 53 mm more precipitation. This emphasizes the effects of the distribution of precipitation rather than the total amount of precipitation during the growing season in dryland cotton production, especially during the critical phenological growth stage like first bloom. Increased precipitation during the growing season and the associated changes in soil water availability would induce and shape the spatial growth structures of plant communities especially if a field is variable in terms of topography and soils.

However, in 2002, cotton lint yield was significantly

Table 3. Stepwise multiple linear regression equations relating measured soil properties in the Ap horizon (0–17 cm) to significant landscape derived attributes. A variable is added if its addition contributes a positive increase in the R^2 value of the model.

Soil attributes	Intercept	Elevation	Slope	Aspect	Curvature	Flow direction	Flow accumulation	Flow length	Wetness index	Sediment transport index	R^2
Depth, cm	18.40	–	–	–	–	–	–	–	–	−1.573	0.27*
Organic matter, %	6.70	−0.068	–	–	−0.523	−0.013	–	–	–	–	0.31*
K_s, cm d^{-1}†	–	–	–	–	–	–	–	–	–	–	ns‡
Sand, %	9.75	–	–	–	–	−0.038	–	–	–	–	0.10ns
Clay, %	55.11	–	–	−0.153	–	0.398	−0.117	−0.032	2.421		0.62***
Fresh wt., cm^3 cm^{-3}, %§	12.53	–	1.696	0.030	–		–	0.019	–	−1.484	0.45**
Pressure head, MPa¶											
−0.01 MPa	26.24	–	1.115		–	0.136	–	0.031	–	–	0.56***
−0.03 MPa	16.62	–	1.664	0.028	–		–	0.025	–	–	0.49**
−0.067 MPa	21.03	–	1.390		–	0.086	–	0.025	–	–	0.48**
−0.1 MPa	13.88	–	1.663	0.028	–	–	–	0.024	–	–	0.48**
−0.5 MPa	12.85	–	1.701	0.024	–	–	–	0.023	–	–	0.48**
−1.5 MPa	13.11	–	1.763	0.018	–	–	–	0.020	–	–	0.48**
PAWC#	2.79	–	–	–	–	0.032	–	0.007	0.250	–	0.34*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† K_s = saturated hydraulic conductivity.
‡ ns = not significant.
§ Percentage volumetric water content at sampling.
¶ Volumetric water content cm^3 cm^{-3} expressed in percentage at specified pressure head (−0.01, −0.03, −0.067, −0.1, −0.5, −1.5 MPa).
# PAWC = plant available water content.

($P < 0.05$) positively correlated ($r = 0.49$–0.51, $P < 0.01$) with percentage θ_v at −0.001, −0.01, −0.033, −0.067, −0.1, −0.5, and −1.5 MPa; nonsignificantly ($P > 0.05$) correlated ($r = 0.33$) at saturation; and significantly correlated ($r = -0.76$, $P < 0.001$) to percentage sand. In 2001, cotton lint yield was nonsignificantly ($P > 0.05$) positively correlated ($r = 0.05$–0.29) with percentage θ_v at −0.001, −0.01, −0.033, −0.067, −0.1, −0.5, and −1.5 MPa, and significantly correlated ($r = 0.50$, $P < 0.01$) at saturation and percentage sand ($r = -0.58$, $P < 0.01$). Areas in the field with medium to low yield had higher percentage sand content, retained less percentage θ_v, and had higher ρ_b as compared with high lint yield areas.

In 2002, high yielding areas had slopes < 2%. About 80% of the landscape elevation ranged from 4 to 9 m. Higher lint yields were recorded at lower landscape positions ($r = -0.52$, $P < 0.01$), areas that should receive runoff and throughflow from the higher landscape positions. Throughflow may occur in the Vaiden soils because, as percentage clay increased with depth, the soil K_s tended to decrease from 2.7 to 1.7 cm d^{-1} (Table 1). As a result, water may accumulate above the Bt_1 horizon during periods of high infiltration and flow laterally downslope. Results in this study are consistent with those reported by Kravchenko et al. (2000). The relationship between cotton lint yield and landscape elevation was low ($r = -0.23$, not significant) in 2002. However, McConkey et al. (1997) argued that yield and topography relationships could be masked by previous weather conditions, due to accumulation of water and different rates of water consumption by plants located uphill or downhill.

Figures 4 and 5 show the derived topographic and hydrologic attribute maps including elevation, slope, aspect, curvature, sedimentation transport index, wetness index, flow accumulation, flow length, and flow direction. These attributes have the potential for not only predicting the catena processes, but also delineating the spatial distribution of lint yield in a complex rolling topographic landscape. For instance, aspect plays a significant role when the soil water content is limiting (Krause et al., 1959). Slopes or landscape positions that face directly toward solar irradiance for longer periods during the day may experience soil water stress earlier in the season as compared with positions facing away. On the basis of the analysis of field aspect data, landscape orientation was mostly in the order of 30% SW facing, 29% W facing, and 21% NW facing.

In agricultural fields with complex rolling topography, the pattern of water movement across the landscape is more complicated in the presence of crop rows. To minimize the erosive power of water, crop rows were laid out approximately across the contour lines, running southwest to northeast. Field observations showed that runoff water carried sediments along the crop rows due to the convex shape of contours, filling the furrows with sediment as it moved between rows and converging in the case of a concave contour, allowing runoff downslope normal to contours. In the above scenario, depending on the intensity and duration of precipitation, prolonged runoff has created some deep channels normal to the crop rows.

The majority of flow directions in the field were in the order of 23, 23, 20, and 18% flowing in the direction of S = SW > NW > W, respectively. The field-based pixel analysis of the flow direction data indicated that ≈41% of the water flows along the tillage direction. Souchere et al. (1998) studied the effects of tillage on runoff directions and reported runoff flows > 50% of the surface along the directions imposed by tillage. In a similar study, Takken et al. (2001) predicted the runoff flow directions on tilled fields and reported runoff flows > 75% of the mapped areas on hillslopes along the directions of tillage. The aspect and flow direction attributes explain why most of the high-yielding areas

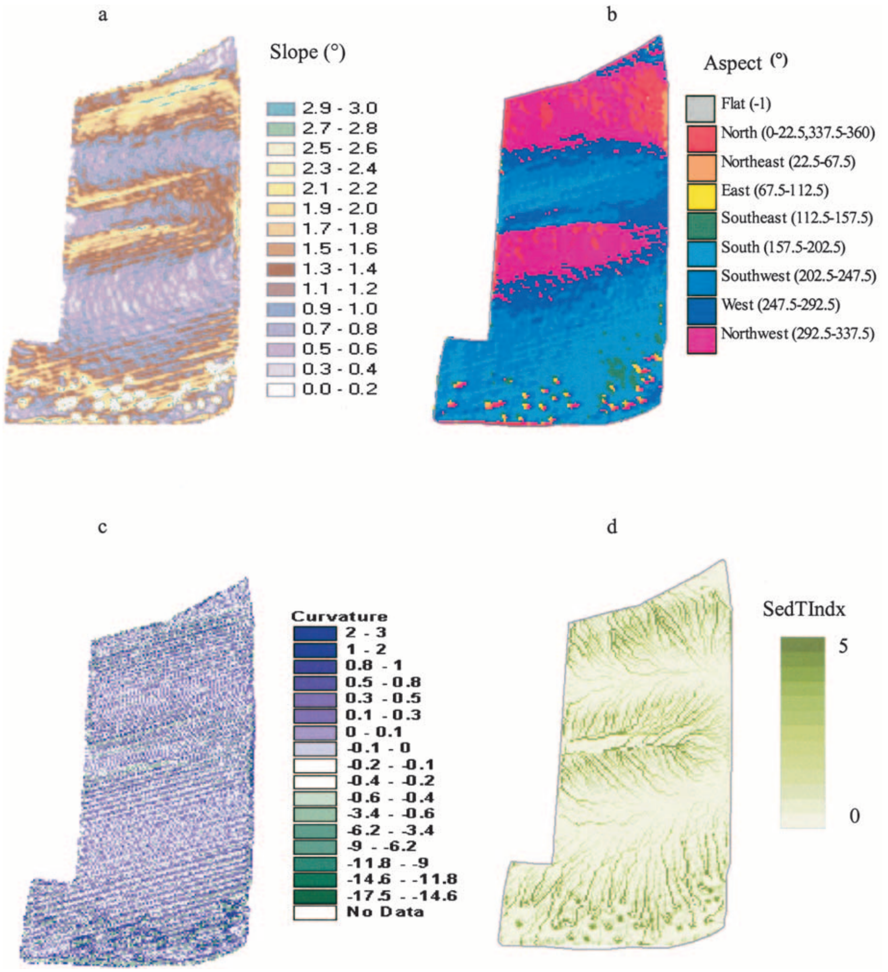

Fig. 4. Grid-based topographic and hydrologic attributes maps of (a) slope, (b) aspect, (c) curvature, and (d) sedimentation transport index (SedTInd) of the field derived from real-time kinematic-global positioning system elevation data using ArcView (Environmental Systems Research Institute, 1998).

in the field were located along the southwestern and northwestern borders, as well as in the fluvial areas of the drainage basin in the middle of the field where water flows downslope converges. Indeed, in both years lint yield was positively correlated with flow accumulation ($r = 0.22$, not significant; and 0.26, not significant) and flow direction ($r = 0.30$, not significant; and $r = 0.44$, $P < 0.05$). Aspect was significantly correlated with PAWC ($r = 0.44$, $P < 0.05$), and percentage θ_v at −0.01 MPa ($r = 0.43$, $P < 0.05$), indicating the relationship of landscape orientation on the availability of soil water to the crop.

Monthly weather conditions had considerable effects on the topography–yield relationship. The negative correlation observed between curvature and lint yield was likely due to extremely low total precipitation during the months of April, May, and July 2001 (on average, <50 mm per month). Hence, during periods of water stress, areas with concave shapes may provide more soil water due to its accumulation in depressions, as compared with areas with convex shapes. The landscape curvature effect on lint yield was more evident in 2002 than 2001 with higher correlation that was enhanced due to more rain.

Wetness index, which characterizes zones of surface saturation and soil water content in the landscape, was positively correlated with lint yield in both years. The sediment transport index, which is equivalent to the length–slope factor in the universal soil loss equation (Moore and Burch, 1986), characterizes erosion and depositions processes, particularly the effects of topography on soil loss, and was negatively correlated with lint yield.

Stepwise linear regression was performed between lint yield and soil variables, landscape topographic and hydrologic attributes, and their overall combined effects (Table 4). The best combination of soil physical properties, including percentage θ_v at saturation and at −0.001 MPa and percentage sand content, explained 65% of variation in lint yield during 2001. While in 2002, percentage sand content was the only variable that improved the regression at the 0.05 level and explained 58% of the variability in yield (Table 4). The landscape topographic and hydrologic attributes explained 40% ($P = 0.038$) of lint yield variability in 2001, while in 2002 only flow direction explained 21% ($P = 0.073$) of lint yield variability (Table 4).

When lint yield vs. soil variables, and topographic

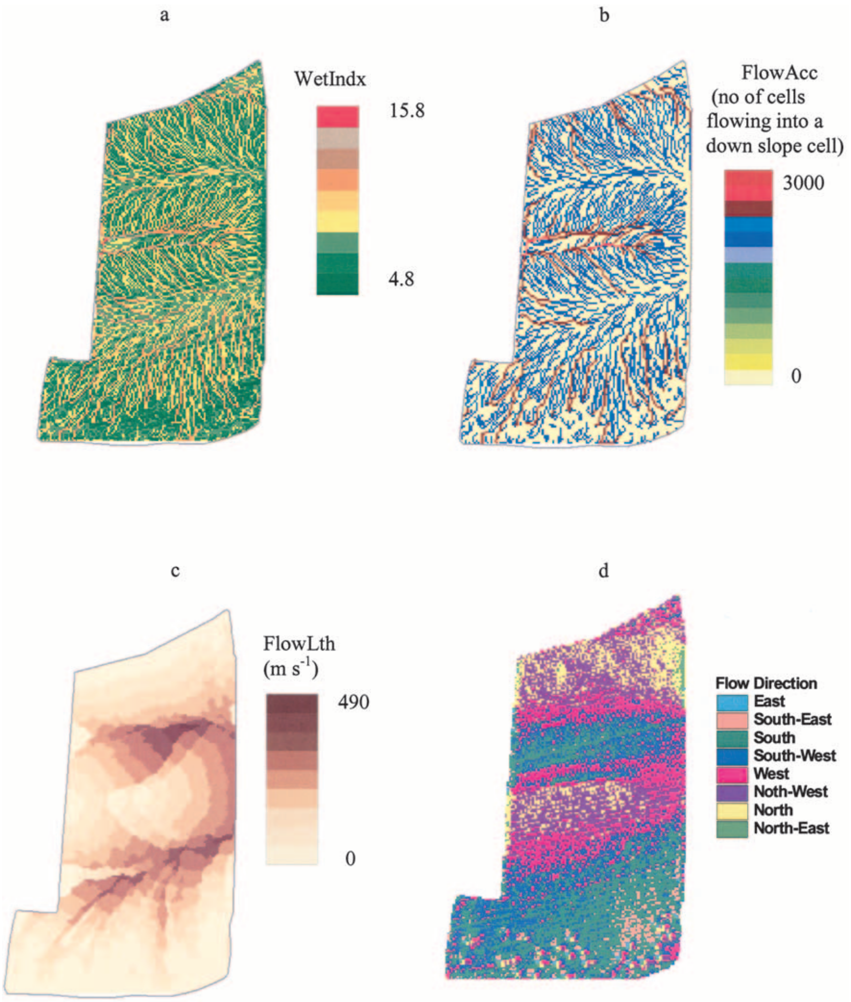

Fig. 5. Grid-based derived hydrologic attributes maps of (a) wetness index (WetIndx), (b) flow accumulation (FlowAcc), (c) flow length (FlowLth), and (d) flow direction (Flow Dir) of the field derived from real-time kinematic-global positioning system elevation data using ArcView (Environmental Systems Research Institute, 1998).

Table 4. Stepwise multiple linear regression equations relating cotton lint yield (kg ha^{-1}) (2001 and 2002) to measured soil variables, derived topographical and hydrological attributes, and their combined effects. A variable is added if its addition contributes a positive increase in the R^2 value of the model.

Year	Intercept						R^2	P value
				Lint Yield Soil Variables				
		θ_v sat.		θ_v (0.001 MPa)		Sand		
		cm³ cm^{-3} (%)		cm³ cm^{-3} (%)		%		
2001	−494.2	9.3		18.9		−61.5	0.65	0.026
2002	1729.7	–		–		−74.2	0.58	0.001
				Topographic and Hydrologic Attributes				
		Elevation			Flow direction			
		m						
2001	3365.6	−4246.0			3.6°		0.40	0.038
2002	983.2	–			4.1°		0.21	0.073
				Soil Variables and Topographic and Hydrologic Attributes				
		θ_v (0.001 MPa)	Sand	Elevation	Aspect	SedTIndx†		
		cm³ cm^{-3} (%)	%	m				
2001	3141.2	15.4	−62.4	−44.0	0.77°	–	0.82	0.014
2002	3291.6	–	−73.8	−23.2	–	41.7	0.72	0.050

† SedTIndx = sediment transport index, which characterizes the process of soil erosion and deposition and presents the effects of topography on soil loss.

and hydrologic attributes were subjected to stepwise linear regression, percentage sand content, elevation, and aspect explained 82% ($P = 0.014$) of the variation in lint yield in 2001, while percentage sand content, elevation, and sediment transport index explained 72% ($P = 0.05$) of variability in yield in 2002 (Table 4). In summary, topographical attributes in combination with soil variables played an imperative role in explaining cotton lint yield variability on field scale. However, the importance of these variables varies at the same location from year to year due to the uniqueness of each year's weather condition, and varies from one location to another due to relative elevation range of the landscape topography and other factors like soil fertility, insect and pest pressure, and so forth.

CONCLUSIONS

Cotton lint yield was related to soil physical properties and topographic and hydrologic attributes in a dryland cotton production system. These variables largely determine the ability of soil to retain and supply plant available water. Cotton lint yield variability was explained by soil properties (65% in 2001 and 58% in 2002), and topographic and hydrologic attributes (40 and 21%) as well as their combined effects (82 and 72%). Elevation, flow direction, sediment transport index, percentage sand content, and θ_v at -0.001 MPa pressure explained most of the lint yield variation. Overall, statistical analysis indicated that higher elevation areas generally yielded lower ($r = -0.50$, $P < 0.01$) and may experience water stress earlier in the season as compared with lower elevation areas. Our results support other results that suggest that knowledge of soil properties and landscape features together are important for aiding the implementation of site-specific crop management. While soil and elevation measurements are somewhat costly, once obtained they may have a long-lasting influence on crop management. For example, seed and fertilizer application rates can be manipulated by field locations (landscape topography); that is, low-yield areas in the field located on the summit and steeper slopes where crops are sensitive to low rain (dry weather) due to lower soil water retention would receive lower seed and fertilizer rates. In addition, topographical attributes explained from 10 to 62% of variation in measured soil physical properties and may be considered in studying the landscape catena process to explain the variability in a soil mapping unit.

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