State-Space Description of Field Heterogeneity: Water and Nitrogen Use in Cotton

Hong Li, Robert J. Lascano,* Jill Booker, L. Ted Wilson, Kevin F. Bronson, and Eduardo Segarra

ABSTRACT
Field heterogeneity in soil texture and site elevation (SE) may affect crop water and N use. A 2-yr (1998–1999) study was conducted on the Texas High Plains to determine the interdependence between management (irrigation and N fertilization), soil heterogeneity (texture, soil water, and NO$_3$-N) and topography, and their impact on cotton (Gossypium hirsutum L.) lint yield and N uptake. Treatments were irrigation at 50 and 75% estimated cotton evapotranspiration (ET) and N rates at 0, 90, and 135 kg ha$^{-1}$. Soil water content (SWC), lint yield, N uptake, and N fertilizer recovery, measured as a function of management and space, were higher on low positions. Mixed model analysis showed that irrigation was significant on SWC, lint yield, and N uptake ($P < 0.05$) each year. The N treatment had no effect on lint yield or N uptake in 1998 because of high soil residual NO$_3$-N, and the model residual was significant for all measured variables ($P < 0.0001$). Sand, SWC, lint yield, and N uptake were negatively correlated with SE ($r = -0.64$). In 1998, lint yield, SWC, clay, sand, and SE were cross correlated within 60 to 80 m. Multivariate state-space analysis showed that lint yield at position $i$ was weighted on lint yield, SWC, clay, sand, and SE at previous position $i-1$. It is concluded that 75% ET and N rate at 90 kg ha$^{-1}$ would be the basis to consider variable water and N rates related to field conditions, and the state-space model quantified spatial interdependence between irrigation, fertilization, and field heterogeneity.

Two important factors affecting cotton production on the Southern High Plains of Texas are water supply (Lyle and Bordovsky, 1981; Bordovsky et al., 1992; Lascano, 2000), and N fertility (Segarra et al., 1989; Morrow and Krieg, 1990). At present, Low Energy Precision Application (LEPA) irrigation is recognized as one of the most efficient irrigation methods for cotton grown in this area (Bordovsky et al., 1992), and information for calculating the daily water use is available (Lascano, 2000). However, there is no consensus on managing N applications for cotton and high rates (135–168 kg ha$^{-1}$) are currently recommended to growers. Also, in this area functional relations between cotton (lint yield and N uptake), management (irrigation and N rates), and soil factors are not well established. Information on the effects of irrigation and N rates on cotton lint yield (Morrow and Krieg, 1990; Bronson et al., 2001), and N uptake by cotton are limited (Li et al., 2001c). In other cotton growing areas, upland lint yields varied for soils containing different amounts of total plant-available water (Steger et al., 1998), and N rates for maximizing lint yield varied between 60 and 165 kg ha$^{-1}$, depending on tillage, soil type, pH, N application method, and residual N (Soileau et al., 1994; McConnell et al., 1996; Harris 1998; Moore, 1998; Varco et al., 1999; Plant et al., 2000).

While soil water was associated with cotton lint yield (Bordovsky et al., 1992; Moore, 1998; Lascano and Li, 2001), few studies have attempted to quantify the effects of N runoff on cotton yield and N uptake because of tillage (Soileau et al., 1994), and slope and SE (Li et al., 2001a, 2001b). Soil texture and topographic features affected spatial distribution patterns of soil water (Stone et al., 1985; Halvorson and Doll, 1991; Lascano and Hatfield, 1992; Brubaker et al., 1994; Li et al., 2001a), organic C, particle-size (Kabrick et al., 1997; Merrill et al., 2001), N and P distribution and use (Brubaker et al., 1994; Soileau et al., 1994), and grain yields of wheat (Triticum L.), corn (zea maize L.) and soybean (Glycine max L. Merr.) (Halvorson and Doll, 1991; Timlin et al., 1998; Kravchenko and Bullock, 2000; Stevenson et al., 2001). Li et al. (2001a) reported that cotton lint yield, measured on the semiarid High Plains of Texas, increased by 34% on low positions, where soil in the rooting zone contained 9% more water compared with upslope areas. However, that study focused on spatial soil water, lint yield and landscape relations, and N fertilizer management was not considered.

Since spatial soil heterogeneity poses problems on field experiments, Van Es et al. (1989) suggested to use an incomplete block (ICB) of size two design, based on the principles of regionalized variable theory, to minimize the influence of field heterogeneity on the outcome of experiments in large fields. Van Es et al. (1989) also showed that the use of incomplete blocks with constrained randomization estimates treatment effects by means of equal average-distance comparison, reduces the average error mean square by 44% compared with using complete blocks. Given that many soil properties do not vary randomly, multiple linear regression models (Brubaker et al., 1994), topographic parameters such as surface elevation and curvature (Timlin et al., 1998), and a topographic factor determined from neighboring sites slopes (Halvorson and Doll, 1991; Li et al., 2001b) have been used to explain soil and crop variability. However, these methods were limited for site-specific water and N management purposes.

Crop response varies within a field because the reciprocal relationships between crop growth and underlying soil processes are variable in both space and time (Cassel et al., 2000; Wendroth et al., 2001). Spatial or temporal domain methods based on state-space models have been used to estimate parameters, test hypotheses, and describe spatial correlations among soil water, nutrient

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Abbreviations: ET, evapotranspiration; ICB, incomplete block design; LEPA, Low Energy Precision Application; RE, relative elevation; SD, standard deviation; SE, site elevation; SWC, soil water content.

and crop variables (Morkoc et al., 1985; Shumway et al., 1988; Wendroth et al., 1992, 2001; Nielsen et al., 1994; Cassel et al., 2000; Li et al., 2001a; Stevenson et al., 2001). Spatial correlation between soil temperature and moisture (Morkoc et al., 1985), alfalfa (Medicago sativa L.) and ryegrass (Lolium L.) yield, effective soil N and N fixation (Wendroth et al., 1992), wheat-grain yield, soil-base saturation, and water-storage capacity (Cassel et al., 2000), and cotton lint yield, soil water, NO₃-N, and SE varying along transects (Li et al., 2001a) were described using multivariate autoregressive state-space analysis. However, none of these state-space models included landscape position or soil texture variables.

Recent developments on new approaches for cotton site-specific water and N management indicate the need for application of water and N based on site-specific soil and field conditions. There is also a need for information on variability in soil properties, yield, lint uptake, and fertilizer N recovery with different irrigation and N rates. Although variability in soil water, lint yield, and N uptake across the landscape (Li et al., 2001a), effects of irrigation and N rates on lint yield (Bronson et al., 2001), soil water ET patterns (Lascano and Li, 2001), and in-season cotton N uptake and plant growth have been analyzed (Li et al., 2001c), the effects of different N rates, interaction between irrigation and N treatment, and influence of soil texture and topographic features on water and N use requires further study. The interdependence between cotton growth, soil properties, irrigation, fertilization, and field heterogeneity must be both understood and quantified to develop a variable water and N application framework.

We hypothesized that SE and soil texture are factors controlling water and N effects on cotton growth, lint uptake, and thus lint yield. Our objectives were to (i) determine the effects and interaction of irrigation and N treatments on cotton N uptake and lint yield using a mixed model analysis, (ii) identify the major soil and site parameters that control water and N effects on lint yield, and N uptake using simple, cross and canonical correlation, (iii) use a state-space approach to analyze the major factors and underlying processes that affect lint yield, and (iv) compare the state-space forecasted lint yield with that measured the following year.

**MATERIALS AND METHODS**

**Site Characteristics and Experimental Setup**

This study was conducted at the Lamesa Agricultural Research Farm (32°46′N long., 101°56′W lat.) of Texas A&M University on the Southern High Plains of Texas. In May 1998, the USDA-NRCS surveyed the altitude across the center-pivot irrigated field (45 ha) using a Trimble Survey Grade GPS Model 4700 Dual Channel RTK system (Trimble, Sunnyvale, CA). Altitude at the site declines from west to east, and downward from south toward the center, then gently rolling upward to the north. The soil, classified as an Amarillo sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs), is well drained, highly erodible, and characterized by low electrical conductivity (1.3 dS m⁻¹), moderate available water-holding capacity (84 mm m⁻¹), mildly alkaline pH (7.6), and low organic matter content (2.0 g kg⁻¹). The surface soil (0–0.3 m) contained, on average, 256, 8, 860, 618, and 86 mg kg⁻¹ as NH₄, acetate extracted exchangeable K, P, Ca, Mg, and S accounting, respectively. The previous crop was rye (Secale cereale L.) grown for winter cover and chemically terminated in the spring.

The study began in May 1998 on an area 32 m wide by 700 m long within the center pivot (45 ha). Treatments consisted of irrigation at 50 and 75% of estimated cotton ET, and N fertilizer at rates of 0, 90, and 135 kg ha⁻¹. The applied ET was estimated as 50 or 75% multiplied by (cotton ET − rain), where cotton ET was calculated by multiplying the reference ET by a cotton coefficient (Lascano, 2000). The N treatments were in the range of N rates applied for cotton (Soileau et al., 1994; Moore, 1998; Varco et al., 1999). Treatments were arranged in an ICB design with blocks of size two, as designed by Van Es et al. (1989), to equalize the average comparison distance of N treatments for reducing any influences of field heterogeneity on outcome of field experiments (Van Es et al., 1989; Van Es and Van Es, 1993). For each ET level, there were four replicates for the control and N treatment rate of 135 kg ha⁻¹, and five replicates for the N rate of 90 kg ha⁻¹. Plot size was sixteen 1-m rows wide and 50 m long. Cotton (’Paymaster Roundup Ready 2326’) was seeded at a rate of 16.8 kg ha⁻¹ on 8 May 1998 and 10 May 1999. Fertilizer N (urea, 32-0-0) was fractionally chiseled into the soil at a rate of 45 kg ha⁻¹ at emergence, bloom, and first square stage, respectively, based on local recommendations given by the Texas Agricultural Extension Service. Other requirements of fertilizers and weed and insect control were done according to regional recommendations. Irrigation (5.1–15.2 mm d⁻¹) was applied using the LEPA system (Lyle and Bordovsky, 1981). In-season rain was below (91 mm) the 30-yr average (320 mm) in 1998, and was unusually wet (130 mm) in June, but dry thereafter, in 1999. Total irrigation water was 242 and 323 mm in 1998, and 190 and 286 mm in 1999 for the 50 and 75% ET, respectively.

**Soil Water Monitoring, and Plant and Soil Analysis**

Soil water distribution in space and time was monitored along transects in the south-north direction across the field. There were four neutron access tubes (5-cm diam. and 2 m long each), installed on row 7 and 14 of each plot, for a total of 52 soil-water monitoring points for each ET level. The average distance was 12 m between tubes along irrigation circles. Monthly SWC was measured in 0.3-m increments to a 1.8-m depth at each tube using a neutron probe (Model 503 Hydroprobe, CPN Corporation, Martinez, CA) calibrated for this field (Li et al., 2001a). Surface (0–0.06 m) SWC was measured using a ThetaProbe (Delta-T Devices Ltd., Cambridge, England) in 1999, and site altitude measurement and calibration are also given by Li et al. (2001c).

Cotton rooting depth was measured at plant maturity (late August) in soil profiles excavated at three locations (south, center, and north) for each ET level. Since cotton roots were only observed within the 0- to 0.9-m depth, we evaluated soil tests in two zones: (i) the rooting zone (0–0.9 m), and (ii) below the root zone (0.9–1.8 m). Soil water was sampled on the row, within 0.5 m from each neutron access tube, to a depth of 1.8 m in 0.3-m increments at emergence, bloom, and harvest. Soil samples were air-dried and sieved to 2 mm. Soil texture was measured using the hydrometer method (Gee and Bauder, 1986). The 0.1 M KCl extractable NO₃-N was measured using a Technicon Auto-Analyzer II C (Technicon Instruments Corp., Tarrytown, NY) (Li et al., 2001a).

Total N uptake by the crop was determined on 10-d intervals beginning at an early vegetative stage (2 wk after emergence).
until harvest. At the vegetative stage, 32 plants per plot were taken from four 5 by 25 m sampling regions around each neutron access tube, and 16 plants per plot were taken from the same areas during bloom and boll growth stages. Root length and fresh and dry weights of roots, leaves, stems, bolls, and seeds were measured. Plant samples were dried at 70°C to a constant weight and ground to pass through a 0.5-mm sieve. Plant N was determined using a LECO FP-528 Analyzer (LECO Corp., St. Joseph, MI) (Li et al., 2001a). Cotton lint was hand harvested on 5 October in 1998 and on 12 October in 1999. Lint yield was determined at each plot within four 1 by 4 m areas, 10 m apart on rows 10 and 11, which had not been sampled.

Total N uptake was calculated by multiplying N content by total plant dry weight. The amount of fertilizer N used by the cotton was calculated as the difference between total N uptake in fertilized plots and the control (zero fertilizer N) plots. Fertilizer N recovery was defined as the ratio of the amount of fertilizer N used to N applied. We assumed that (i) cotton use of residual soil N and N from other sources (ryegrass mineralization, atmospheric deposition, and irrigation water) was the same in control and N treatments, (ii) there was no enhancement of mineralization caused by adding N fertilizer, and (iii) there was no significant immobilization of applied fertilizer N. Thompson et al. (2000) made similar assumptions for estimating N balance.

### Mixed Model, Cross Correlation, and State-Space Analysis

Mixed model analysis (Little et al., 1996) was used to determine effects of irrigation and N fertilization on response variables. Regression relationships and linear correlation among the soil and cotton crop variables was determined using PROC GLM and PROC CORR procedures (SAS Institute, 1990). The spatial correlation between two variables x and y (lint yield, SWC, sand, clay, and SE) was determined with the cross-covariance function ($C_{xy}(h)$) and the cross-correlation function ($\gamma_{xy}(h)$), as described by Cassel et al. (2000) as follows:

\[
C_{xy}(h) = \frac{1}{n(h)} \sum_{i=1}^{n-h} (x_{i+h} - \bar{x})(y_i - \bar{y}) \tag{1}
\]

\[
\gamma_{xy}(h) = \frac{C_{xy}(h)}{\sigma_x \sigma_y} \tag{2}
\]

where in Eq. [1] $n(h)$ is the number of pairs of sample points a distance h apart, $x_{i+h}$ is measurement x at location $i + h$, $y_i$ is measurement y at location i, h is the lag or the distance between measurements, and are the mean of measurement x and y respectively, and $i$ and $h$ are vectors (Cassel et al., 2000).

In Eq. [2], $\sigma_x$ and $\sigma_y$ are the standard deviations of x and y, respectively. The ARIMA procedure (SAS Institute, 1993) was used to estimate the cross correlation function $\gamma_{xy}(h)$ between lint yield, soil water, clay, sand and SE.

Cotton lint yield, SWC, texture, and SE were identified in state-space analyses as quadrivariate first-order autoregressive processes. We described how the state vector $x_i$ of cotton yield at a location $i$ was related to the system state vector $x_{i-1}$ of all measured variables at location $i - 1$ as described by Cassel et al. (2000) as follows:

\[
x_i = \Phi x_{i-1} + \epsilon_i \tag{3}
\]

where $\Phi$ is a $p \times p$ matrix of state coefficients, and $\epsilon_i$ is the model error vector. The state-space model (Eq. [3]) assumes errors to be zero-mean, uncorrelated, and included in the model error vector $\epsilon_i$ with common $r \times r$ covariance matrix $Q$. The error vector $\epsilon_i$ is assumed to be independent. The elements of the state vector $x_i$ are determined via a sequence of canonical correlation analyses of the sample autocovariance matrix (state-space coefficient matrix) $\Phi$ by approximate maximum likelihood (SAS Institute, 1993). The Proc StateSpace...
Table 1. Mean and standard deviation (SD) of soil properties, cotton lint yield, total plant dry matter, total N uptake, N repartitions in different parts, and fertilizer N recovery in 1998 and 1999.

<table>
<thead>
<tr>
<th>Site and crop variables</th>
<th>1998</th>
<th>1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation, m</td>
<td>892.1</td>
<td>891.6</td>
</tr>
<tr>
<td>Clay content, g kg⁻¹</td>
<td>194</td>
<td>176</td>
</tr>
<tr>
<td>Sand content, g kg⁻¹</td>
<td>760</td>
<td>797</td>
</tr>
<tr>
<td>Soil water content, m³ m⁻³</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Soil NO₃-N in 0-0.9 m, kg ha⁻¹</td>
<td>179</td>
<td>174</td>
</tr>
<tr>
<td>Cotton lint yield, kg ha⁻¹</td>
<td>704</td>
<td>962</td>
</tr>
<tr>
<td>Total dry matter, Mg ha⁻¹</td>
<td>171</td>
<td>220</td>
</tr>
<tr>
<td>N in leaves, kg ha⁻¹</td>
<td>56</td>
<td>68</td>
</tr>
<tr>
<td>N in stems, kg ha⁻¹</td>
<td>42</td>
<td>50</td>
</tr>
<tr>
<td>N in boll, kg ha⁻¹</td>
<td>76</td>
<td>97</td>
</tr>
<tr>
<td>N in roots, kg ha⁻¹</td>
<td>4.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Fertilizer N recovery, %</td>
<td>19.9</td>
<td>20.2</td>
</tr>
</tbody>
</table>

† Mean and standard deviation (SD) of all N treatments at the same irrigation level.  
‡ Soil water content in 0 to 0.9 m on 23 July 1998, and in 0 to 0.06 m on 22 Aug. 1999.  
§ Soil NO₃-N measured on 1 July 1998, and on 6 May 1999.  
¶ Sum of dry matter or N uptake in leaves, stems, lint, seeds, boll, and roots, measured on mid September each year.  
# Sum of N in lint, seeds, and bolls of burrs.

The state-space forecasts were calculated using the Kalman filtering technique (SAS Institute, 1993), and the forecasted lint yield obtained with the lint yield measured in 1998, was then compared with the lint yield measured the following year (1999). This was an attempt to show how and where future lint yields could be forecasted under local field conditions.

RESULTS

Spatial and Temporal Patterns of Soil Water

Soil water distribution at different soil depths (Fig. 1a,b) varied with irrigation level, SE, and slope length across the field (Fig. 1c,d). Site elevation declines from the south toward the center (0.1–1.4% slope), and then gently rolls upward to the north (1.2–4.2% slope). Slopes extend longer on the northern 50% ET transect (Fig. 1c), and lower positions extend toward the middle on the 75% ET (Fig. 1d). The means and standard deviations (SD) of SE and the SWC on the two irrigation areas are given in Table 1. As shown in Fig. 1a and 1b, the SWC (n = 52 per ET) at different layers, measured on 24 June 1998, varied between 0.036 and 0.189 m³ m⁻³ across the field. The SD range was larger (0.007–0.018 m³ m⁻³) on the high-positioned 50% ET transect than on the low-positioned 75% ET (Table 1). Total SWC in the rooting zone (0–0.9 m) was significantly different (P < 0.0162) between the 50 and 75% ET levels in 1998 (Table 2).

The SWC was lower on upslope areas 400 to 500 m from the south along the transects (Fig. 1). The SWC in the rooting zone (0–0.9 m) was on average 0.14 m³ m⁻³ on south-center low position areas, an increase of 15% compared with the northern upslope areas (0.12 m³ m⁻³). The surface SWC (0–0.06 m) patterns, measured using the Theta Probe, also showed similar distribution trends (means and SD, Table 1). The surface SWC (0–0.06 m) ranged between 0.060 to 0.247 and 0.065 to 0.360 m³ m⁻³.

Table 2. Mixed model analysis of fix effects and interaction of treatments, and Z-statistics on the random variance components (block, and black × treatments) of the mixed model for the variables of soil water content (SWC), cotton lint yield, and total N uptake.

<table>
<thead>
<tr>
<th>Sources</th>
<th>SWC†</th>
<th>Lint Yield‡</th>
<th>N Uptake‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation (1)</td>
<td>6.02*</td>
<td>5.43*</td>
<td>66.1**</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>0.10ns</td>
<td>0.14ns</td>
<td>0.72ns</td>
</tr>
<tr>
<td>I × N</td>
<td>2.21ns</td>
<td>2.24ns</td>
<td>0.39ns</td>
</tr>
<tr>
<td>Block × I</td>
<td>0.23ns</td>
<td>0.33ns</td>
<td>0.54ns</td>
</tr>
<tr>
<td>Block × N</td>
<td>0.13ns</td>
<td>0.28ns</td>
<td>0.40ns</td>
</tr>
<tr>
<td>Residual</td>
<td>6.78**</td>
<td>6.48**</td>
<td>6.51**</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.  
** Significant at the 0.01 probability level.  
† Soil water content (SWC) in m³ m⁻³ measured in 0 to 0.9 m on 23 July 1998, and in 0 to 0.06 m on 22 Aug. 1999.  
‡ Lint yield (Mg ha⁻¹) at harvest in Oct., and N uptake (kg ha⁻¹) measured in mid September each year.  
§ Not significant.
0.273 m$^3$ m$^{-3}$ at the 50 and 75% ET, respectively. There was a significant difference ($P < 0.0364$) in the SWC (0–0.06 m) between the 50 and 75% ET levels, measured on 3 Aug. 1999 (Table 1).

In 1998, temporal SWC profiles decreased from the vegetative (June) to boll growth stage (August) and increased again towards harvest (October) (Fig. 2). The top 0- to 0.3-m soil was dry throughout the growing season. The SWC in the rooting zone (0–0.9 m) was on average 42% (or 85 mm m$^{-3}$) of the total soil water measured within 0- to 1.8-m depth. As expected, analysis of variance indicated that temporal SWC between
Fig. 4. Regression of lint yield as a function of (a and b) soil water content (SWC), (c) clay and (d) sand contents, and (e and f) site relative elevation (RE).

Lint Yield, Nitrogen Uptake, Clay, Sand, and NO₃⁻N Relations

Cotton lint yield, total plant dry matter, N uptake, and N repartitions in different plant parts also varied with irrigation level, and SE, as shown by their means and SD in Table 1. Cotton lint yields ranged between 441 to 995 and 570 to 1488 kg ha⁻¹ in 1998, and between 507 to 1230 and 578 to 1326 kg ha⁻¹ in 1999 for the 50 and 75% ET, respectively. As compared with the 50% ET, lint yield increased 37% in 1998 and 33% in 1999 at the 75% ET. Cotton lint yield increased significantly ($P < 0.004$) with irrigation level (Table 2). The spatial pattern of lint yield decreased from the south-center to the north on the 50% ET transect where the slope length was extended (Fig. 3a). High lint yields (greater than the mean) were measured in the center field (footslope areas) on the 75% ET (Fig. 3b). There is a 3.4-m elevation drop from the northern plateau to the footslope areas, where lint yields increased (Fig. 3a,b) with greater SWC in the root zone (Fig. 1).

Total N uptake by cotton (including N in roots, leaves, stems, bolls, and seeds) ranged between 124 to 243 and 142 to 266 kg ha⁻¹ in 1998, and 113 to 202 and 126 to 248 kg ha⁻¹ in 1999 at the 50 and 75% ET, respectively, which significantly increased ($P < 0.05$) with irrigation (Table 2). Total N uptake in the control plot was 156 and 204 kg ha⁻¹ in 1998, but decreased to 137 and 150 kg ha⁻¹ in 1999 at the 50 and 75% ET, respectively. The spatial N uptake pattern tended to decrease on the northern upslope areas (Fig. 3c,d). The N accumulation in leaves was similar to that in stems while roots contained small amounts of N (Table 1). In bolls 80% of N was attributed to seeds, and only 2 to 4 kg N ha⁻¹ was in the lint. Fertilizer N recovery was similar for the two irrigation levels in 1998 but varied (31 versus 19%) in 1999 (Table 1), when the maximum fertilizer N recovery value (36%) was measured in the center field, a low position area, with an N rate of 90 kg ha⁻¹ and 75% ET irrigation.

There were larger SD in clay and sand contents (0–0.3 m) in the 50% ET areas than the 75% areas (Table 1). Unlike the SWC patterns, soils on the northern up-
slope areas contained more clay (194–275 g kg\(^{-1}\)) compared with the footslope areas (140–235 g kg\(^{-1}\)) between 300 and 400 m in the center field as measured in July 1998 (Fig. 3e). It appeared that sand content varied with position because of deposition in low lying areas, in the order: center areas > southern area > northern upslope (Fig. 3e,f). As a result, soils (0–0.3 m) contained more sand (785–816 g kg\(^{-1}\)) in low position areas (south-center field), compared with the northern upslope areas (740–785 g kg\(^{-1}\)). Soil NO\(_3\)-N in the root zone (0–0.9 m) declined in 1999 compared with 1998 (Table 1). Soil NO\(_3\)-N (0–0.9 m) patterns showed trends similar to clay content distribution on the northern upslope areas (Fig. 3e), where the soil NO\(_3\)-N (measured on 10 July 1998) was similarly high, but with different rates of N fertilizers applied (Fig. 3e). For example, in this area the control plot (zero N fertilizer) contained a NO\(_3\)-N level (148 kg ha\(^{-1}\) in 0–0.9 m) as much as its neighbor plots, where soils were fertilized at 90 or 135 kg ha\(^{-1}\) (Fig. 3e,f).

**Mixed Effects of Treatments**

The main effects of irrigation, determined with the mixed model procedure, were significant on cotton lint yield, followed by N uptake, and SWC during the 2 yr (Table 2). There was no interaction between irrigation and N treatment on response variables. The fixed effect of N was significant only on lint yield in 1999 (Table 2), where the lint yields averaged 824, 911, and 847 kg ha\(^{-1}\) for the N treatments at rates of 0, 90, and 135 kg ha\(^{-1}\), an increase of 10.6% (vs. control) and 7.6% (vs. 135 kg N ha\(^{-1}\)) for the N treatment at 90 kg ha\(^{-1}\).

Random effects of the mixed model variance components (block, and block × treatments) were not significant (Table 2). However, Z-statistics showed that the residual of the mixed model was significant on all measured parameters (Table 2). The Z-statistics for the model variance components was based on asymptotic normality (Little et al., 1996). The mixed model residual effects consisted of the covariance of other independent variables such as SE, SWC, texture, or other nutrients rather than N.

**Linear Regression and Correlation Between Variables**

Cotton lint yield was linearly correlated (Fig. 4a,b) with SWC in the rooting zone (0–0.9 m), which explained as much as 56% of the lint yield variation for the 50% ET irrigation level (Fig. 4a). A large portion (80%) of the lint yield greater than mean was produced with a SWC >0.10 m\(^{3}\) m\(^{-2}\). Cotton lint yield was negatively correlated with clay (Fig. 4c), and positively correlated with sand (Fig. 4d). There was smaller correlation coefficient between lint yield and soil NO\(_3\)-N \((r = 0.21)\). Cotton lint yield was quadratically related to soil NO\(_3\)-N with yields decreasing at NO\(_3\)-N content >140 kg ha\(^{-1}\) in the rooting zone (0–0.9 m). The N uptake was less influenced (11–16% of the variations) by the SWC.

Site elevation was correlated with soil water \((r = 0.58)\), sand \((r = 0.54)\), clay \((r = 0.33)\), soil NO\(_3\)-N \((r = 0.24)\), cotton lint yield \((r = 0.64)\), and N uptake \((r = 0.42)\). All soil properties and cotton response variables were negatively correlated with elevation, except for NO\(_3\)-N and clay content. As related to the
lowest position (890.8 m) of the two transects, SWC, lint yield, and N uptake decreased quadratically with the relative elevation (RE). The RE explained the largest portion (40–51%) of lint yield variation (Fig. 4e,f). Higher lint yields were produced on lower RE, which was within 2 m higher than the lowest position; and, lower yields were measured on upslope and shoulder areas, which had a plus RE of 3 to 4 m from the lowest position (Fig. 4e,f).

Cross Correlation Between Lint Yield, Soil Texture, and Site Elevation

Site elevation and soil texture were identified as the important factors contributing to variability in SWC, cotton lint yield, and N uptake. There was a cyclic, positive or negative, feedback relationship between lint yield, SWC, and elevation as measured in 1998. As illustrated in the scatter diagram (Fig. 5), the cross-correlation functions ($\gamma_i$), calculated with Eq. [1] and [2], of cotton lint yield, SWC, clay, sand, and SE ranged between −0.72 and 0.64. Considering the 95% confidence level as described by Cassel et al. (2000), the lint yield was positively cross correlated with SWC (Fig. 5a) but negatively cross correlated with SE (Fig. 5b) across a lag distance of 60 m (±30 m); cross correlation between lint yield and clay was negative across a distance of 80 m on the 50% ET transect (Fig. 5b). On the 75% ET transect, lint yield was negatively cross correlated with elevation (Fig. 5e) and positively with sand content (Fig. 5f) across a lag distance of 80 m (±40 m). Clay was also positively cross correlated with elevation across a lag distance of 80 m on the 50% ET transect (Fig. 5d), where clay content increased with elevation. As the lag distance increased, these cross-correlation functions became positive at a lag distance of ±180 m (Fig. 5). However, there was no cross correlation between N uptake and SWC (results not shown). As a result of larger variation of SE on the 50% ET, the cross correlation distance between SWC, lint yield and elevation was 20 m shorter on the 50% ET than on the 75% ET transect (Fig. 5e,f).

State-Space Cotton Lint Yield Model

The state-space analysis quantified how strongly lint yield (measured in 1998) at position $i$ was spatially based transect (Eq. [7]), but positively weighted on the sand content $S_i$ along the 50% ET transect (Eq. [7]), but positively weighted on the sand content $S_i$ along the 75% ET transect (Eq. [8]). Differently, 50% ET lint yield at position $i$ is much more influenced by the previous SE (Eq. [7]) compared with the 75% ET lint yield at position $i$ (Eq. [8]).

The above estimated 4 × 4 transition matrix showed that the weight relations between these state-space variables become alternatively negative or positive as the position $i$ changed. The estimated transition matrix leads to a multivariate state-space cotton lint yield model shown in Fig. 6. Via the state coefficient $\Phi$, both multivariate state-space equations (Eq. [7] and [8], Fig. 6) demonstrated that cotton lint yield $y_i$, was positively weighted on soil water and negatively weighted on elevation at previous position $i - 1$ on both transects (Eq. [7] to [8]). However, lint yield, $y_i$, was negatively weighted on the clay content $C_i$ along the 50% ET transect (Eq. [7]), but positively weighted on the sand content $S_i$ along the 75% ET transect (Eq. [8]).

Standard errors and t-statistics values of the parameter estimates for the transition matrix $\Phi$ are shown in Table 3 for the two state-space cotton lint yield equations given in Fig. 6. The standard error for the yield, SWC and elevation are comparable. The t-statistics showed that all parameter estimates were significant ($t > |2|$) for both models (Table 3).

As illustrated in Fig. 6, the 95% confidence limits (shaded area) of estimates for lint yields at position $i$
Table 3. Standard error and t-value of parameter estimates at position $i - 1$ of the state vector $x_{i-1}$ for the state-space equations, given with data measured in 1998.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50% ET Standard Error</th>
<th>t Value†</th>
<th>75% ET Standard Error</th>
<th>t Value†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lint Yield (Y)</td>
<td>0.1375</td>
<td>2.033*</td>
<td>0.1171</td>
<td>2.281*</td>
</tr>
<tr>
<td>Soil Water (SWC)</td>
<td>0.6858</td>
<td>2.882*</td>
<td>0.7286</td>
<td>2.230*</td>
</tr>
<tr>
<td>Clay (C) or Sand (S)‡</td>
<td>0.4498</td>
<td>2.012*</td>
<td>0.6686</td>
<td>2.343*</td>
</tr>
<tr>
<td>Site Elevation (E)</td>
<td>4.1006</td>
<td>-10.19*</td>
<td>4.4246</td>
<td>-8.322*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 probability level.
† Significance determination by value $>|2|$.
‡ Clay and Sand for 50 and 75% ET, respectively.

Field Heterogeneity and Treatments

It has been shown that water supply is a more limiting factor to cotton production when compared with N rates applied in the Southern High Plains of Texas (Morrow and Krieg, 1990; Bronson et al., 2001; Li et al., 2001c). Our study shows that field heterogeneity in SE and soil texture interacted with irrigation and N rates to influence cotton responses to the treatments. Although irrigation was uniformly and regularly applied across the field, SWC was not evenly distributed in all areas. The significance of the mixed model residual ($P < 0.001$) qualified the covariance of independent variables such as SE and texture on cotton responses to the treatments (Table 2). As the regression of SE versus all measured variables yielded higher $R^2$ values compared with soil texture versus all variables (Fig. 4), SE had the greatest impact on soil, water, and crop variables. Also based on the regression analysis, lint yield versus soil texture gave higher $R^2$ values than versus NO$_3$-N; therefore, soil texture appeared to be a secondary factor that contributed to modify the spatial patterns of soil water, NO$_3$-N, and lint yield variability. Li et al. (2000) also showed that patterns in soil water were more consistent than soil NO$_3$-N, and largely affected by SE across the landscape.

Because of sand deposition in lower areas, summit areas had more clay. Therefore correlation between sand and elevation was negative. Since the impact of SE on SWC was greater than soil texture, soils in lower position areas contained more water (Fig. 1) through run-on water from upslope areas (Li et al., 2001b). As a result, higher cotton lint yield and N uptake were measured on lower positions (Fig. 3). Because of possible water runoff, described using a topographic factor calculated using slopes and distance from neighboring site points (Li et al., 2001b), lower cotton lint yield and N uptake were measured on northern upslope and summit areas (Fig. 3). Other studies have also shown the impacts of elevation and slope length on crop yield. For example, soil water was not evenly distributed and spring wheat yield and water use were linked to elevation and slope length (Halvorson and Doll, 1991), and surface elevation and curvature, and soil organic matter, P, and K contents strongly contributed to the spatial and temporal variability of maize yield on a hillslope (Timlin et al., 1998). Topography influences hydrologic and agronomic processes complicating water and N application decisions.

Soil NO$_3$-N and Nitrogen Treatments

In the study site, N fertilizer has been applied to the soil at a rate of 190 kg ha$^{-1}$ yr$^{-1}$ for the last 5 yr, explaining the lack of cotton response to N treatments. Large amounts of soil NO$_3$-N (including residual and fertilizer N) were measured in July 1998 (Table 1). The preseason soil residual NO$_3$-N in the effective root zone (0–0.9 m) remained moderately high before seeding in May 1999 (Table 1). However, assuming N from other sources (rye residue mineralization, atmospheric deposition, and irrigation water) was the same for control and N treatments, total N inputs at 90 kg ha$^{-1}$ for 1999 year were reasonable, based on N uptake in 1998 (Table 1) and preplant NO$_3$-N assessment (Table 1). Larger amount of residual NO$_3$-N caused the lack of N treatment effect on lint yield and N uptake in 1998. Also, rain variability could have influenced cotton responses to the treatments within years. Rain at the vegetative growth stage in 1999 favored plant growth. Therefore there was an increase of 14% on lint yield with 50% ET in 1999 compared with 1998, and the irrigation level became more important on lint yield in 1998 than in 1999 as compared by the $P$ values (Table 2).

As expected, significant effects of N treatments and interaction between irrigation and fertilizer N on lint yield occurred in 1999, a wet year, when residual soil NO$_3$-N was at moderate levels (Table 1). In other areas, cotton lint yield increased significantly with N rates between 90 and 135 kg ha$^{-1}$ in a deep sandy soil in Georgia (Harris, 1998). Higher amounts of N (112–134 kg ha$^{-1}$) were needed for cotton production on a high pH alluvial soil of Louisiana (Moore, 1998). Profitable N rates ranged between 60 and 105 kg ha$^{-1}$ for no-tillage cotton grown in a loamy soil in Mississippi (Varco et al., 1999), and between 110 and 165 kg ha$^{-1}$ for cotton production in a clay loam in California (Plant et al., 2000). These conclusions were based on the relationship between lint yield and N rates. Our results showed that N rate of 90 kg ha$^{-1}$ could be a basis rate for farmers. While one in two years there was significantly higher lint yield with the N rate at 90 kg ha$^{-1}$ as mentioned above, the mean fertilizer N recovery was consistently higher with this N rate compared with the rate of 135 kg ha$^{-1}$ (25.9
versus 14.3% in 1998, and 25.8 versus 19.0% in 1999). Higher fertilizer N recovery means less residual fertilizer N left in the soil. Further, low input of N is agronomically, economically, and environmentally beneficial in this semiarid area (Segarra et al., 1989; Morrow and Krieg, 1990; Bronson et al., 2001), which has also been shown in other areas (McConnell et al., 1996; Varco et al., 1999; Thompson et al., 2000).

State-Space Description of Cotton Lint Yield Variability

The measured lint yield (1998) decreased toward the upslope area on the 50% ET transect, (Fig. 6a), so that lint yield at position \( i \) was negatively weighted on yield at the previous position \( i - 1 \) (Eq. [7]), and therefore the negative weight of SE was significant (Table 3). Conversely, on the 75% ET transect, lint yield at position \( i \) was positively weighted on the yield at the previous position \( i - 1 \) (Eq. [8]), since the measured lint yield tended to increase on lower areas (Fig. 6b). As a result, the influence of SE at position \( i - 1 \) on the lint yield at position \( i \) was more significant on the 50% ET than the 75% ET (Table 3), where site positions are on average 0.5 m lower than on the 50% ET (Table 1).

The positive weight on SWC and negative weight on elevation (Eq. [7] to [8]) indicated that lint yield increased at position \( i \) were weighted based on an increase of SWC and decrease of elevation. Clay (50% ET) and sand (75% ET) at the previous position \( i - 1 \) also had significant weight on lint yield at position \( i \) (Table 3). The linear regression analysis showed the dispersion of lint yield versus SWC, clay, sand (Fig. 4). However, all measured lint yield values were within the 95% confidence limits of lint yield forecasts given by the state-space model (Fig. 6). Future cotton yields in such an undulating field, given by the autoregressive state-space analysis, are weighted on soil water, texture, and topography variability. Higher lint yields would be expected on lower positions (Fig. 6), where water and nutrient run-on is expected (Li et al., 2001b). Conversely, lower lint yields are predicted on upslope areas (Fig. 6), where water and nutrient runoff should be high (Li et al., 2001b).

The forecasted yield values \( Y_i \), given by the state-space models with data measured in 1998, were related to cotton lint yield measured in 1999. The forecasted values \( Y_i \) ranged from 528 to 942 and 696 to 1144 kg ha\(^{-1}\), and the measured lint yield values varied between 507 to 1097 and 578 to 1326 kg ha\(^{-1}\) on the 50 and 75% ET transects, respectively. The correlation coefficients between these forecasted and measured lint yield values were 0.71 and 0.74 for the 50 and 75% ET, respectively. This result is important as it further shows the validity and applicability of state-space models to predict crop yield from 1 yr to the next. In this case, the soil NO\(_3\)-N amounts and weather conditions were different in 1999 compared with 1998. Because cotton lint yield had greater correlations with soil water, sand, clay, and SE, and a much smaller coefficient with soil NO\(_3\)-N, our state-space lint yield model, including lint yield, soil water, sand, clay, and SE as model parameters, gave a reliable lint yield prediction (\( r > 0.70 \)) from 1 yr to the next.

The autoregressive state-space model appears to be a useful forecast tool to predict future yields related to soil properties and field conditions. Many studies have used linear and multiple regression models to describe and estimate soil, water, and crop variables. For example, Halvorson and Doll (1991) and Brubaker et al. (1994) used such regression models to describe and predict crop yields and soil properties by landscape position. However, the state-space model is a result of a multivariate autoregressive analysis. A difference in estimate of crop yield or soil properties between the state-space model and linear model analysis is that the locations of forecasted values are given by the state-space model. In our state-space cotton lint yield models (Fig. 6), the spatial association of lint yield, soil water, clay, sand, and SE are described, and the future lint yields are quantified and located. Our results suggest that variability of field measurements could be combined with state-space models to describe the association of crop yields with soil properties and site topography in space, and to understand the interdependency between irrigation and fertilization in heterogeneous soils.

CONCLUSIONS

Field heterogeneity in SE, soil texture, water, and residual soil NO\(_3\)-N was attributed to their influence on cotton response to irrigation and N treatments. Site elevation was the important control factor creating differences in soil water, lint yield, N uptake, and fertilizer N recovery in this heterogeneous field. The mixed effects of irrigation, and residual covariance of the mixed model were significant on SWC, lint yield, and N uptake. Soil residual NO\(_3\)-N amounts affected N treatment efficiency. The cross-correlation functions between lint yield, soil water, clay, sand and SE varied between −0.72 and 0.63, and their cross-correlation distances suggested that cotton crop and soil physical properties were correlated within 60 to 80 m across the field. The state-space analysis successfully described underlying processes of field heterogeneity on cotton yield, and the forecasted lint yield data given by the state-space model were correlated (\( r = 0.74 \)) with the lint yield measured the following year. State-space descriptions of crop yield variability helped explain the complex relationship between crop yield, soil properties, topography, and treatments. We recommend applying 75% ET and 90 kg N ha\(^{-1}\) as basis rates and considering local SE and soil texture conditions for their adjustment. A variable irrigation and N fertilization adopted to local soil properties and field conditions may improve water and N use efficiencies and crop yields in heterogeneous soils.

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REFERENCES


