Antecedent soil moisture affecting surface cracking of a Vertisol in field conditions
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A B S T R A C T
Cracking of shrink–swell soils influences landscape hydrology. Watershed models that address soil cracking phenomena generally use a relationship between shrinkage and current soil water content to estimate the extent of cracking. Although antecedent soil moisture prior to soil shrinkage is found to affect the shrinking of expansive soils in laboratory measurements, field observations are limited. In a previous study, a series of in situ surface crack measurements over 10 years indicated the effect of soil moisture just prior to the start of cracking (antecedent soil moisture) on cracking extent, but this relationship was not specifically analyzed. The objectives of this study were (i) to estimate the antecedent soil water content prior to cracking, (ii) to analyze the effect of antecedent moisture on crack area density in microhighs and microlows, and (iii) to assess the temporal distribution of antecedent soil moisture in relation to an estimated water availability index. Soil cracking was measured on a 10-m×10-m plot of Laewest clay (fine, smectitic, hyperthermic Typic Hapludert) covered with native tallgrass vegetation on 42 dates during 1989–1998. Gravimetric soil water content was measured on 50 dates; 18 dates corresponded to crack measurements. Gilgai microtopography was mapped, and surface crack area density was calculated. For days when soil water content was not measured, it was estimated from precipitation and evapotranspiration. Antecedent soil water content prior to cracking was estimated for depth at 10 cm using daily estimates of soil water content and field notes on cracking. Results indicated that the temporal variation in surface crack area density of the study area during 10 years was related to dynamics of current and antecedent soil water content on microhighs and microlows (R2 = 0.68 and 0.59, respectively). Prediction accuracies improved with classifying drying–wetting conditions during cracking. Dynamic temporal changes in the surface crack area density exhibited dependence on a long-term (multi-year) cycle of antecedent soil water content superimposed by short-term (within a year) cycles of current soil water content.

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1. Introduction

Soil cracking, driven by drying of shrink–swell soils, alters infiltration, runoff, evapotranspiration and redistribution of water and chemicals. This phenomenon contributes to complex spatial and temporal variability of water redistribution in the landscape, and creates challenges to modeling of surface hydrology. Present models that simulate water flow in shrink–swell soils use shrinkage characteristics based on current soil water content (e.g. Hendrickx and Flury, 2001; Greco, 2002; Deliberty and Legates, 2003; Arnold et al., 2005; Cao et al., 2006; Bradley et al., 2007; Bedient et al., 2008; Lepore et al., 2009). Laboratory characterization of soils reinforces the idea that soil shrinkage, and therefore crack formation, is a function of current soil water content. Commonly used laboratory measurements are the coefficient of linear extensibility (COLE), which relates soil shrinkage potential to soil water loss (Grossman et al., 1968; Reeve et al., 1980; Yule and Ritchie, 1980a; Bronswijk, 1990b), and the soil shrinkage characteristic curve (e.g. Haines, 1923; McGarry and Danieis, 1987; Bronswijk, 1988, 1991; Mitchell, 1992; Coulombe et al., 1996; Olsen and Haugen, 1998; Braudeau et al., 1999; Boivin et al., 2006; Cornelis et al., 2006).

In most shrink–swell studies, soil water loss is calculated between the current soil water content and a constant, such as the soil water content at field capacity (associated with a matric water potential of −33 kPa or −10 kPa) or at saturation. However, a variable initial soil water content caused by soil water content history may affect the magnitude of shrinking and swelling of soils containing smectitic clay minerals (Yule and Ritchie, 1980a; Parker et al., 1982; Wilding and Tessier, 1988; Tessier, 1990, Santamarina et al., 2001; Wells et al., 2003, 2007; Saiyouri et al., 2004). In this paper, we use the terms antecedent and current soil water content to identify soil moisture prior to surface desiccation cracking, when the soil surface is still closed, and at the time of crack measurement, respectively. The term initial soil water content specifies any soil moisture condition at the beginning of a measurement, with or without the presence of desiccation cracks.
The complex processes of shrinking and swelling, and associated crack opening and closing in Vertisols and vertic intergrades depend on the microstructure and intra- and interparticle porosity of soils (Wilding and Tessier, 1988; Tessier, 1990; Quirk, 1994; Coulombe et al., 1996). Available water is one of the external factors driving the balance of attractive and repulsive interparticle forces. These attractive (capillary suction, London–van den Waals and ion–ion correlation) and repulsive (structural water and osmotic) forces depend internally on mineralogy, cations, electrolyte concentration, and organic matter, but also externally on varying climate, parent material, topography, land use, vegetation, and stress history (Quirk, 1994). The effect of stress history on soil cracking is most noticeable from extreme wetting and drying or compaction (Santamarina et al., 2001; Saiyouri et al., 2004). Considering the effect of the history of drying–wetting on soil shrink–swell, it was observed in electron microscopic and X-ray scattering studies that initial soil water content played a significant role in shrink–swell processes of smectitic clay samples (Tessier, 1984 reviewed by Wilding and Tessier, 1988; Tessier, 1990). On core samples taken from Vertisols, initial moisture prior to desiccation has been also shown to affect the final magnitude of shrinkage (Yule and Ritchie, 1980a).

In addition to high initial moisture, repeated dry–wet cycles have enhanced swelling in small soil samples (Parker et al., 1982; Peng et al., 2007). Additionally, in a large repacked sample of a smectitic Vertisol (76.5-cm × 80-cm × 30-cm), a sequence of simulated wetting and drying increased swelling and vertical crack depth during subsequent wetting and drying cycles (Wells et al., 2003, 2007; Römkens and Prasad, 2006). It was postulated that the spatial and temporal variability of antecedent soil moisture caused the increase in swelling and cracking during the repeated wetting–drying cycles (Wells, personal communication, 2008).

In a previous study conducted by Kishné et al. (2009) based on a 10-yr crack monitoring of Vertisols, findings indicated the effect of antecedent soil moisture on cracking to cause variation in shrinkage and retained soil water content due to hysteresis. Soil cracks were mapped in field conditions (Fig. 1) on a 100-m² site of smectitic Laewest clay with gilgai in native grassland in the Texas Gulf Coast Prairie on 42 dates during 1989–1998 (Miller et al., 2010). The greatest extent of cracking was measured in 1997 and 1998 (Fig. 2) preceded by months of above normal precipitation. These dates in 1997 and 1998 had about 10-fold greater crack area density than dates with similar soil water content but below normal precipitation in the prior months, i.e. 1995 and 1996. Temporal trends in the extent of cracking, expressed as crack area density, were similar on microlow and microhigh gilgai categories (Fig. 2). However, surface cracking occurred with a much smaller extent in microlows despite of greater shrinkage potential measured as Cole to 1 m depth (Kishné et al., 2009). Current gravimetric soil water content proved to have an overall weak, negative relationship with surface crack area density. The weak relationship measured gravimetric soil water content and crack area density was somewhat improved by separating microhighs and microlows and by grouping data according to drying, uniform and wet soil moisture conditions within 10–25 cm. A probable influence of antecedent soil moisture was hypothesized, but not tested because antecedent soil water content prior to cracking was not the objective of that study.

In the current investigation, we study the temporal dynamics in surface cracking at the previously investigated Vertisol site (i.e. Kishné et al., 2009; Miller et al., 2010). Particularly, we focus analysis on the relationship of antecedent soil moisture prior to cracking and long-term weather variations with cracking densities measured over 10 years, in this 10-m by 10-m area of a Vertisol. The specific...
objectives of this study were (i) to estimate the antecedent soil water content prior to cracking, (ii) to analyze the antecedent moisture effect on crack area density on microhighs and microlows, and (iii) to assess the temporal distribution of antecedent soil moisture in relation to an estimated water availability index.

2. Materials and methods

2.1. Field measurements

A detailed description of the site and data collection was presented in Kishné et al. 2009 and Miller et al., 2010; nevertheless, we give a brief summary of data regarding this study specifically. A 10-m by 10-m study plot in Victoria County, Texas (28° 39' 46" N, 96° 46' 20" W), was investigated in 1989–1998. The soil was Laewest clay (fine, smectitic, hyperthermic Typic Hapludert, Soil Survey Staff, 1999) with native tallgrass prairie vegetation, and circular gilgai microtopography (Miller et al., 2010). The study area contained distinct microrhig mounds and ridges (38%), microlows (19%), and the rest (43%) was considered microslopes (Kishné et al., 2009). The elevation ranged from 12.20 to 12.45 m with a mean and median of 12.29 m. Microlows were 2–3 m across and about 6 to 7 m apart. Wilding et al. (1990) reported on the original scope of the study, how the site was selected, characterized of the region, and the botanical survey of the native prairie vegetation. Soil morphology was described in detail for the microhigh and the microlow to depths of 5.9 m and 6.1 m, respectively, close to the study site (Soil Survey Staff, 1990). The depth of the soil solum is 3.80 m in microhighs and 3.55 m in microlows with wavy boundaries. A permanent groundwater table was apparent at 5.1 m in 1988 (Soil Survey Staff, 1990) and was mostly below 3 m, as indicated by piezometer measurements. However, episaturation, a perched zone of free water, was observed occasionally in piezometers installed at depths of 0.25, 0.5, 1 and 2 m in a field adjacent to the crack study site.

On 42 occasions from June 1989 to July 1998, length and width of all soil cracks were measured with 5 and 0.5 cm accuracy, respectively (Fig. 1, Table 1). The smallest and largest width of measured crack segments on both microhighs and microlows were less than 0.5 cm and 7 cm, respectively (Kishné et al., 2009). Crack locations were plotted on engineer graphing paper at a 0.0254 to 1.0-m scale, and crack width data was categorized with limits of 0.5, 1, 2, 5, and 10 cm.

<table>
<thead>
<tr>
<th>Microhighs</th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>SD</th>
<th>CV</th>
<th>Skew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack width, cm</td>
<td>42</td>
<td>0.6</td>
<td>2.9</td>
<td>1.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Crack length, m</td>
<td>42</td>
<td>0.36</td>
<td>171.51</td>
<td>13.19</td>
<td>27.56</td>
<td>2.09</td>
<td>4.96</td>
</tr>
<tr>
<td>AD, 10^-4 m² m^{-2}</td>
<td>42</td>
<td>0.9</td>
<td>409.2</td>
<td>46.5</td>
<td>77.0</td>
<td>1.7</td>
<td>3.4</td>
</tr>
<tr>
<td>AD, 10^-4 m² m^{-2}</td>
<td>18</td>
<td>0.9</td>
<td>273.1</td>
<td>59.9</td>
<td>72.7</td>
<td>1.2</td>
<td>2.0</td>
</tr>
<tr>
<td>W, kg kg^{-1}</td>
<td>18</td>
<td>0.16</td>
<td>0.44</td>
<td>0.27</td>
<td>0.08</td>
<td>0.29</td>
<td>0.55</td>
</tr>
<tr>
<td>W, kg kg^{-1}</td>
<td>18</td>
<td>0.16</td>
<td>0.38</td>
<td>0.21</td>
<td>0.05</td>
<td>0.23</td>
<td>2.63</td>
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</table>

<table>
<thead>
<tr>
<th>Microlows</th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Average</th>
<th>SD</th>
<th>CV</th>
<th>Skew</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack width, cm</td>
<td>36</td>
<td>&lt;0.5</td>
<td>3.5</td>
<td>1.4</td>
<td>0.9</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Crack length, m</td>
<td>36</td>
<td>0.01</td>
<td>6.78</td>
<td>1.03</td>
<td>1.50</td>
<td>1.46</td>
<td>2.5</td>
</tr>
<tr>
<td>AD, 10^-4 m² m^{-2}</td>
<td>36</td>
<td>&lt;0.1</td>
<td>88.8</td>
<td>9.4</td>
<td>18.0</td>
<td>1.9</td>
<td>3.2</td>
</tr>
<tr>
<td>AD, 10^-4 m² m^{-2}</td>
<td>15</td>
<td>&lt;0.1</td>
<td>53.6</td>
<td>12.3</td>
<td>16.4</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>W, kg kg^{-1}</td>
<td>50</td>
<td>0.16</td>
<td>0.55</td>
<td>0.30</td>
<td>0.09</td>
<td>0.31</td>
<td>0.51</td>
</tr>
<tr>
<td>W, kg kg^{-1}</td>
<td>15</td>
<td>0.16</td>
<td>0.29</td>
<td>0.22</td>
<td>0.03</td>
<td>0.13</td>
<td>0.54</td>
</tr>
<tr>
<td>W, kg kg^{-1}</td>
<td>15</td>
<td>0.29</td>
<td>0.48</td>
<td>0.38</td>
<td>0.06</td>
<td>0.17</td>
<td>0.01</td>
</tr>
</tbody>
</table>

2.2. Water availability index

Daily minimum and maximum temperature, wind speed, relative humidity, and precipitation along with hourly solar radiation were measured at a weather station at Victoria Regional Airport, Texas, 16 km north of the site. Four months (January 1, 1996–April 30, 1996) of missing precipitation data were filled-in using daily precipitation data collected in Port Lavaca, Texas, about 20 km south of the measurement site. Cumulative precipitation measurements were collected at the site about every two weeks. This cumulative rain data was compared to the daily data collected at the weather stations to check for local anomalies in amounts of rainfall. If the difference between precipitation measured at the study site and the weather station was greater than 2 mm day⁻¹, then the daily precipitation was adjusted to match the site precipitation amount. The precipitation adjustment was distributed proportionally on the days when rain was indicated at the weather station.

Daily reference evapotranspiration (ET₀) was estimated using the FAO version of the Penman–Monteith equation (Allen et al., 1998), following calculations summarized by Ham (2005). To evaluate the relationship between surface cracking and trends in available water, a simple water availability index (WAI) was calculated,

\[ WAI_i = WAI_{i-1} + n \times PCPT_i - n \times ET_0 \]

where \( i \) is a daily index; \( nPCPT_i \) is normalized precipitation; and \( n \times ET_0 \) is normalized reference evapotranspiration (Heinsch et al., 2004). Normalization was achieved by dividing the daily totals of precipitation and reference evapotranspiration by their 13-year average of annual totals. The daily WAI was initialized on January 1, 1986. The first crack measurement began on June 7, 1989.

2.3. Estimation of daily soil water content, antecedent soil water, and data analysis

To analyze the temporal change in soil cracking in relation to prior weather conditions, first, current and antecedent soil water were estimated for days with no soil water data; second, multivariate analysis was applied including both current and antecedent soil water; and finally, the antecedent soil water was investigated in comparison to temporal fluctuation of available water.

Precipitation and evapotranspiration were used to predict soil water content because they are the main driving factors of soil moisture dynamics (Delworth and Manabe, 1988; DeLiberty and Legates, 2003). Additionally, Doris et al. (2008) reported that time resolution, rectified, digitized in ArcView 3.0, and analyzed in ArcGIS 9.0 (Environmental Systems Research Institute, 2005). Polylines, defined as crack segments between junctions or end points, and/or changing crack widths, were clipped according to microhigh, microslope, and microlow categories. The data are available online at http://soilcrop.tamu.edu/research/pedology/crack.html.

Crack area was estimated for each crack segment by multiplying the length of digitized crack segment by the mid-value of width category measured in the field. To assess surface crack area density (surface crack extent), total crack area obtained for a gilgai element was normalized by the area it occupied in the study site. Soil water content was measured gravimetrically in 2–3 replicates with core sample thickness of 3–5 cm centered at 10, 25, 50, 75 and 100 cm depths on microhighs and microlows adjacent to the study site on 50 occasions (Table 1). On 18 and 15 out of 50 dates, soil moisture samples were collected on microhighs and microlows, respectively, within 1–2 days of crack measurements with no or only trace amount of precipitation (Table 1). Field observations on cracking-related conditions were recorded about every 2 weeks on 181 days over the 10-year period.
history of precipitation and temperature up to 8 weeks was significantly related to soil moisture controlling vertical shrink–swell of Vertisols under a concrete block that simulated overburden pressure in Texas and in Australia. In our study, we developed two multiple regression equations to estimate daily gravimetric soil water content using cumulative precipitation and evapotranspiration and 50 measurements of gravimetric soil water content at a depth of 10 cm. Two regression equations were calculated because soil moisture in microhighs and microlows were different on a given day. The soil water content at 10-cm depth was used because the 10-cm depth appeared to be closely related to surface cracking (Kishné et al., 2009) and was strongly affected by weather variability.

To develop these empirical soil moisture equations, various cumulative time intervals of precipitation and evaporation were tested, and the optimal intervals were chosen based on the best p-values, $R^2$ values, and root mean square deviation (RMSE). Model residuals were checked for temporal trends by plotting the residuals with time. Direct effect of runoff and runon on soil water was ignored, particularly because we wanted the soil water estimate to be independent of the soil cracking data. A possible influence of occasional episaturation during prolonged wet periods was assumed to be intrinsically included in the empirical equations through soil moisture and precipitation measurements.

Antecedent soil water content was estimated for all crack measurements using the empirical soil water content model, except for one date when soil moisture was measured. Choosing the value for antecedent soil water content was started by selecting the soil water content at the local soil moisture maximum prior to a date of a crack measurement. This local maximum was found by using a 4-week moving window with daily time steps. Then, the selected soil moisture was compared to soil moisture values closer, in time, to the crack measurement until the lowest peak soil water value was identified to correspond with observations of closed cracks at the soil surface.

In this simple approach for estimating antecedent water content, we did not consider that cracks might have been below the soil surface due to swelling of the surface upon rewetting, nor the uneven moisture distribution related to preferential wetting or drying around macropores, although these conditions can contribute significantly to bypass flow and uneven distribution of soil water content (Bouma and Loveday, 1988). Multiple linear regression, simple correlation, and temporal autocorrelation analyses were performed using S-Plus 7.0 (Insightful Corp., 2005).

To consider the effect of soil moisture hysteresis on the surface cracking as a function of soil moisture, we assessed drying–wetting conditions based on measured moisture difference between depths of 10 and 25 cm (Kishné et al., 2009). The moisture differences were compared to what we considered natural measurement variation. The variation criterion was estimated as the sum of standard errors of replicate soil water content averaged for 50 dates in the two depths. When the moisture difference between 10 and 25 cm exceeded the criterion, positively or negatively, then a wetting or drying condition occurred, respectively. Otherwise, soil moisture was considered uniform in the layer of 10–25 cm.

3. Results and discussion

3.1. Antecedent soil water content

Soil water conditions just before opening of cracks were assessed based on estimates of daily soil water content and the field notes indicating probably closed surface crack conditions. Table 1 presents the summary statistics of measured and estimated soil water contents. In general, the microlows were wetter than microhighs.

In this study, a 16-week history of rainfall and evapotranspiration was found sufficient to predict daily soil water content. Based on 50 near-surface measurements of soil water content, the best regression models for microhighs (MH) and microlows (ML) were as follows:

$$W_{MH,i} = 0.0012PCPT_{w1} + 0.0008PCPT_{w2} + 0.0002PCPT_{w3-16} - 0.0009ET_{w1-7} - 0.0005ET_{w8-16} + 0.4168.$$  

$$W_{ML,i} = 0.0012PCPT_{w1} + 0.0008PCPT_{w2} + 0.0003PCPT_{w3-16} - 0.0011ET_{w1-7} - 0.0004ET_{w8-16} + 0.4321,$$

where $W$ is the gravimetric soil water content (kg kg\(^{-1}\)) at a depth of 10 cm, $PCPT_{w1}$, $PCPT_{w2}$, and $PCPT_{w3-16}$ are cumulative precipitation (mm) of the first, second, and 3rd to 16th week intervals, and $ET_{w1-7}$ and $ET_{w8-16}$ are the reference evapotranspiration (mm) from the first seven, and 8th to 16th week periods prior to day $i$, respectively.

Overall, the prediction models of daily soil water content explained 79% of the variation in soil water content in microhighs, and 73% in microlows (Fig. 3). Model residuals were normal, homoscedastic, and not autocorrelated. The model error (RMSE = 0.04 kg kg\(^{-1}\)) exceeded estimated measurement variability of soil moisture by 0.015 kg kg\(^{-1}\).

The estimated antecedent soil water content ranged from 0.26 to 0.42 kg kg\(^{-1}\) in microhighs, and from 0.29 to 0.48 kg kg\(^{-1}\) in microlows (Table 1). During the longest drying period in 1998, 7 months separated the antecedent moisture and a crack measurement. It is interesting to note that the antecedent soil water content prior to crack opening was not a fixed value, but it varied by ±25% from the average over time. Moreover, the greatest antecedent soil water contents exceeded field capacity values of 0.33 kg kg\(^{-1}\) in microhighs and 0.39 kg kg\(^{-1}\) in microlows. The field capacity values were measured at soil matric water potential of −33 kPa, on soil clods in laboratory (Soil Survey Staff, 1990). The range in antecedent moisture supports the hypothesis presented by Kutilek and Germann (2009) that the threshold between macropores and micropores is time-variant, and has a range of transitions rather than a well-defined boundary that may depend on the history of variations in water content.

The variability of soil moisture just before the start of crack formation has been reported in the literature. No or slight changes in
soil volume have been observed with changes in soil water content during the structural shrinkage phase (e.g. Stirk, 1954; Yule and Ritchie, 1980a; Bronswijk, 1991; Coulombe et al., 1996; Coquet et al., 1998; Olsen and Haugen, 1998; Cornelis et al., 2006). In the basic shrinkage phase, where the change of soil volume is proportional to the volume of water change (Mitchell, 1992), changes in soil volume with water loss were observed but soil crack formation was not consistently observed. These volume changes have been quantified by measuring one-dimensional (vertical) shrink–swell (Favre et al., 1997) and by measuring bulk or wet density of soils (Fox, 1964; Grossman and Reinsch, 2002; Bernard et al., 2006; Dudoignon et al., 2007). But no one-dimensional decrease in soil volume has been found predominantly as a function of water loss by Aitchison and Holmes (1953), Hallaire (1984) and Bronswijk (1990a). Our study, however, did not address the question of whether soils in the field have a one-dimensional (vertical) shrinkage before starting three-dimensional shrinkage (cracking), because no vertical soil movement was measured.

3.2. Relationship of surface crack extent and soil water content

Fig. 4 presents the distribution of crack area density versus current soil water content at a depth of 10 cm on microhighs and microlows. According to analysis of soil water conditions, there was only one crack measurement taken on a distinct wetting event on October 20, 1992. On that day, crack area density was small on the microhighs (4.8×10⁻⁶ m²), which is expected with high soil water content, and there was no cracking in the microlows. Since this date is the only crack measurement under a clear wetting process, the further analysis reflects trends based only on dates with measurements under desiccating conditions. 41 dates on microhighs and 36 dates on microlows. Out of 18 dates with measured cracking and soil water content, there were three dates when cracks were only in microhighs.

Fig. 4 shows the well-known trend of decreasing cracking with increasing soil water content. However, in the dry soil water range, between 0.16 and 0.23 kg kg⁻¹, the spread of crack area density was large, up to 100 fold. Linear regression models of log-transformed crack area density as a function of current moisture content poorly described the process for both microhighs and microlows (Models 1a and 1b in Table 2). Stratifying crack area density according to drying and uniform soil water conditions improved the models for the drying category, but less or not for uniform conditions (Models 2a, 2b and 3a, 3b in Table 2).

An increasing trend of the crack area density with increasing antecedent soil water content was observed in microhighs and microlows (Fig. 5). In other words, desiccation starting from wetter antecedent soil water content resulted in greater surface cracking. Including antecedent soil water content into the models of log-transformed crack area density resulted in stronger models with Rs² values improved to 0.68 and 0.59 for microhighs and microlows,

### Table 2

Regression model results for log-transformed crack area density (m² m⁻²) as a function of current soil water content (Wc, kg kg⁻¹) and antecedent soil water content (Wa, kg kg⁻¹) at a depth of 10 cm. For uniform microlows, no correlation was found.

<table>
<thead>
<tr>
<th>Model</th>
<th>Data set</th>
<th>N</th>
<th>Coefficients for</th>
<th>Intercept</th>
<th>Wc</th>
<th>Wa</th>
<th>Rs²</th>
<th>RMSD</th>
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<tbody>
<tr>
<td><strong>Microhighs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Model 1a</td>
<td>Whole</td>
<td>41</td>
<td>-3.51**</td>
<td>-13.24**</td>
<td>-</td>
<td>-</td>
<td>0.11</td>
<td>1.33</td>
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<tr>
<td>Model 2a</td>
<td>Drying†</td>
<td>10</td>
<td>5.32**</td>
<td>-60.90**</td>
<td>-</td>
<td>-</td>
<td>0.69</td>
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<td>Model 3a</td>
<td>Uniform†</td>
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<td>-56.04**</td>
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<td>-</td>
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<td>1.42</td>
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<td>-14.95**</td>
<td>-</td>
<td>18.67***</td>
<td>0.68</td>
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<td>Model 5a</td>
<td>Drying†</td>
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<td>-2.10**</td>
<td>-41.16**</td>
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<td>10.88***</td>
<td>0.82</td>
<td>0.51</td>
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<td>-6.71**</td>
<td>-39.26**</td>
<td>-</td>
<td>26.48***</td>
<td>0.95</td>
<td>0.43</td>
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<tr>
<td><strong>Microlows</strong></td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td>Whole</td>
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<td>-15.45**</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
<td>1.99</td>
</tr>
<tr>
<td>Model 2b</td>
<td>Drying†</td>
<td>9</td>
<td>-0.86</td>
<td>-41.43**</td>
<td>-</td>
<td>-</td>
<td>0.40</td>
<td>1.39</td>
</tr>
<tr>
<td>Model 3b</td>
<td>Uniform†</td>
<td>6</td>
<td>-1.09</td>
<td>-29.29**</td>
<td>-</td>
<td>-</td>
<td>0.16</td>
<td>2.00</td>
</tr>
<tr>
<td>Model 4b</td>
<td>Drying†</td>
<td>36</td>
<td>-14.07**</td>
<td>-15.63**</td>
<td>-</td>
<td>23.60***</td>
<td>0.59</td>
<td>1.35</td>
</tr>
<tr>
<td>Model 5b</td>
<td>Drying†</td>
<td>9</td>
<td>-7.68**</td>
<td>-37.70**</td>
<td>-</td>
<td>20.19**</td>
<td>0.85</td>
<td>0.70</td>
</tr>
<tr>
<td>Model 6b</td>
<td>Uniform†</td>
<td>6</td>
<td>-30.62**</td>
<td>7.21</td>
<td>-</td>
<td>49.81***</td>
<td>0.95</td>
<td>0.47</td>
</tr>
</tbody>
</table>

† Grouping was based only on measured data which had stratified soil water measurements; ***, **, and * represent significance at p-values less than 0.001, 0.01, and 0.1, respectively.
respectively, and more significant $p$-values for model coefficients (Models 4a and 4b in Table 2). Dividing the crack measurements into drying and uniform moisture conditions improved the multivariate models even more based on $R^2$ and RMSD values; however, the $p$-values were smaller compared to the whole models (Models 5a, 5b and 6a, 6b in Table 2).

As a graphical illustration, Fig. 6 demonstrates the multivariate models for the whole data set of microhighs and microlows (Models 4a and 4b in Table 2). Soil water loss calculated between varying antecedent and corresponding current soil water content correlated linearly with natural log-transformed crack area density, thus exponentially with crack area density. Fig. 7 shows crack data partitioned into three and four groups of antecedent soil water content for microhighs and microlows, respectively. Groupings were chosen based on breaks in the available antecedent water content data. In the first three groups, the group limits are identical for microhighs and microlows, but there is an additional group with even greater antecedent soil water content for microlows. Within each group, the fitted lines represent only trends in surface crack extent and water loss to compare the rates of shrinkage (slope of fitted line). Overall, the rate of shrinkage and the range of water loss increased with increasing antecedent moisture. Shrinkage rates were very similar in the low antecedent moisture groups compared within microtopography categories. The largest shrinkage rate associated with the largest antecedent water content group was outstanding in both microhighs and microlows.

Two possible scenarios might describe the desiccation paths. On one hand, shrinkage may have started with a low rate similar to shrinkage rates exhibited in groups 1 and 2 then followed an increasing shrinkage rate of the line fitted to all measured data in the group of largest antecedent soil moisture. The phase with small shrinkage rate at the beginning of desiccation may correspond to the curvilinear phase between the maximum swelling and the macroporosity limit in the structural phase identified in well structured soil cores, and was demonstrated by several shrinkage curve studies (Braudeau et al., 2004; Boivin et al., 2004; Boivin, 2007; Milleret et al., 2009). On other hand, shrinkage in 1993, 1997 and 1998 may have individual linear shrinkage paths. Although there were no observations to confirm individual shrinkage paths, different paths might be suggested by the large variation in crack extent at large water losses. On microhighs, at water loss of 0.15–0.20 kg kg$^{-1}$ and 0.20–0.25 kg kg$^{-1}$, there were about 2- and 3-fold differences in crack extent.
area density. On microlows, there was a similar difference in crack area density between water loss of 0.25 and 0.30 kg kg\(^{-1}\).

In the group of lowest antecedent soil water content of 0.25–0.3 kg kg\(^{-1}\), the very small cracking and near zero slope of the fitted line indicated a short basic shrinkage phase, and shrinkage starting possibly from soil moisture close to the shrinkage limit. The within-group variation of current soil water content and crack area density was likely influenced by hysteresis, as suggested by Kishné et al. (2009) and some errors in estimation of soil water content. The effect of antecedent moisture on crack length was more distinguishable than on crack width. Under conditions of large water loss, the daily sum of crack length was higher in both microhighs and microlows (data not shown).

In situ observations indirectly relating soil cracking to antecedent soil water content have been reported in the literature (Lin et al., 1998; Das Gupta et al., 2006). In a study on steady-state infiltration of a Shingle clay (very-fine, mixed, active, thermic chromic Hapludert), Lin et al. (1998) showed a greater than 10% increase in apparent steady-state infiltration rate after a week-long tropical rainfall event compared to prior measurements at the same soil water content. This increase in infiltration may have been related to changes in macroporosity, including cracks, and hence to antecedent moisture effects on cracking in the soil surface (Lin, personal communication, 2008). In another study conducted also on a site of Shingle clay in Texas by Das Gupta et al. (2006), hydraulic conductivity measured at zero matric potential was eight times greater following a rainy fall and winter in 2003 and a seasonal drying period than earlier at about the same initial soil water content.

The effect of antecedent soil water content on the relationship of soil water and soil cracking seems to be twofold. The first effect, though potentially minor, is the effect on hysteresis. When drying of soil starts from greater antecedent soil water content the soil will have more retained water at the same matric potential than when a soil starts drying from smaller antecedent soil water content (Croney and Coleman, 1954; Lal and Shukla, 2004, p.437). This hysteretic water retention is expected to influence mainly the capillary flow, and not or negligibly the water flow in shrinkage cracks and permanent macropores (Chertkov and Ravina, 2002; Greco, 2002; Briaud et al., 2003; Gerke, 2006). In microlows, the generally greater antecedent and current soil water contents may also be related to greater retained soil water due to hysteresis from more distinct structure in addition to the lower topographic position of microlows. This hysteresis effect may be strongest near the soil surface and decreases with depth (Mitchell and Mayer, 1998).

The second effect of antecedent soil water content is on the relationship of soil cracking and water loss. In soil shrinkage curves, water loss measured from wetter initial conditions have been shown and modeled to produce proportionally greater shrinkage at the same current soil water content during basic shrinkage (e.g. Yule and Ritchie, 1980a,b; Wilding and Tessier, 1988; Tessier, 1990; Chertkov and Ravina, 1998). At microscopic scale, this effect is attributed mainly to change of water content and energy level in the interparticle pores and in the internal structure of clay fabric (Wilding and Tessier, 1988; Tessier, 1990; Couломbe et al., 1996; McGarry and Yule, 2006). In drying calorific smectitic Vertisols, the walls in clay microstructure fold on each other, as an accordion — an analogy used by Wilding and Tessier (1988, p. 76). The degree of shrinkage depends on the magnitude of previous swelling related to the initial moisture condition and the thickness and composition of microstructure. Great intensity of drought causes increased number of layers comprising substacks in the microstructures, thus the interlayer spacing decreases, and so the overall shrinkage increases (Tessier, 1990). Thus, the collapse of microstructure and intraparticle porosity of Ca-smectite in the soil depends on initial (or antecedent) soil water content, as well as on layer charge, layer flexibility and extensibility of overlapping layers. Intensive, prolonged precipitation with repeated wetting–drying cycles, and consequent high antecedent soil moisture may promote this process. We speculate that the varying antecedent soil water content might relate to slowly changing particle geometry. The microporosity reached at the wet end of basic shrinkage phase (macroporosity limit) and swelling limit may increase or decrease due to rearrangement of particles forming interparticle pores.

In this field study, the positive correlation of crack area density to the antecedent soil water content was significant (Figs. 5 and 6). The complex Vertisol cracking conditions observed probably exhibited both types of antecedent soil water content effect on soil shrinkage. Furthermore, an even earlier history of wetting–drying may have impacted the measured soil shrinking behavior in field conditions. Peng et al. (2007) found on small repacked clayey soil samples that the maximum intensity of previous wetting–drying cycles influenced significantly the magnitude of pore shrinkage. Besides, a possible memory mechanism of soils (Santamarina et al., 2001, p. 142) related to soil shrinkage phenomena and repeated wetting–drying cycles cannot be ruled out.

The influence of antecedent soil water content on soil shrinkage may not be limited to the soil surface. It may also affect shrinking–swelling of deeper soil subhorizons, in addition to current soil water content, although overburden confining pressure may limit its contribution. Consequently, this may be one of the influential variables in varying the shrinkage ratio between height change and water storage change from one soil layer to another (Kirby et al. 2003). It may also explain some of the differences in temporal and spatial variation of shrinking–swelling soils on different landscape positions (Baer and Anderson, 1997).

3.3. Analysis of antecedent soil water content and weather variation

Strikingly, long, generally drying periods in 1988–1990 shown by the decreasing trend in the water availability index (Fig. 8) were associated with small cracking, and relatively low antecedent soil water contents (0.29–0.32 kg kg\(^{-1}\)). On the other hand, extremely wet periods in 1997 and 1998 preceding extensive droughts were associated with large crack area density and relatively large antecedent soil water contents, 0.39 and 0.37 kg kg\(^{-1}\) on microhighs and 0.46 and 0.48 kg kg\(^{-1}\) on microlows, respectively. The varying

![Fig. 8. Temporal distribution of the daily water availability index (WAI) and antecedent soil water content (W_a). Peak WAI values prior to the crack measurements are marked by triangles.](image-url)
antecedent soil water content seemed to follow the long-term fluctuation of available water content because the latter determines the degree of saturation; thus there is a similar temporal distribution of peaks of water availability index and antecedent soil water content (Fig. 8).

As a consequence of this trend, dynamic temporal changes in the surface crack area density developed in microhighs and microwells seemed to follow a long-term cycle (approx. 6 years) of antecedent soil water content superimposed by short-term (within-year) cycles of cracking, related to current soil water content. Because surface crack area density is related to crack volume (Peng and Horn, 2007), we anticipate similar trends in the effect of antecedent soil moisture on crack volume of Vertisols. Because of low water permeability of the soil matrix, the bulk clayey soils may swell or shrink on a very slow rate under cyclic moisture conditions; therefore, reaching their new moisture equilibrium conditions may take years (Lal and Shukla, 2004). As noted in Section 3.2, this slow hydration–dehydration of bulk soil matrix probably drives the change in antecedent soil water conditions while the short-term crack opening and closing is likely triggered by more frequently changing seasonal wetting–drying conditions. Under monotonic conditions of available water, such as homogeneous climate or regular irrigation without long-term fluctuations, the effect of antecedent soil moisture would be minimal.

To overcome the limitations of our study, which were the estimation of antecedent and current soil water content, and only one measurement site, further field studies for monitoring long-term vertical and horizontal shrink–swell processes are needed. To develop a more coherent understanding of the phenomenon observed, further investigations of temporal and spatial dynamics of shrink–swell mechanisms related particularly to antecedent soil water content and prior wetting–drying cycles would be desirable in various Vertisols under different field and climatic conditions.

4. Conclusions

In this study of surface cracking of a Laewest clay with gilgai, we have analyzed the temporal variation of field-measured crack area density of Laewest clay and estimated antecedent soil water content, along with a calculated water availability index. The main results are as follows:

(i) Antecedent soil water content was assessed using daily soil water content estimated from cumulative precipitation and reference evapotranspiration covering a total of 16 weeks, and available field observations on cracking-related conditions.

(ii) Variation in the surface crack extent in microhighs and microwells depended not only on current soil water content negatively, but more strongly on antecedent water conditions positively. Including antecedent soil water content in regression models with current soil water content improved prediction of crack area density significantly on microhighs ($R^2 = 0.68$) and microwells ($R^2 = 0.59$). Accounting for soil water hysteresis (drying or uniform soil water conditions) improved the multivariate regression models with $R$-squared up to 0.95.

(iii) Shrinkage rate in basic shrinkage phase might be a variable of antecedent soil water content in Laewest clay.

(iv) Antecedent soil water content just prior to cracking in microhighs and microwells showed a long-term (multi-year) fluctuation.

More generally, short-term oscillation of daily current soil water seemed to trigger relatively short desiccation cycles which were superimposed on a long-term multi-year cycle of antecedent soil water. This varying antecedent soil water content may depend on slowly changing particle geometry due to repeated rewetting and drying conditions in the bulk smectitic soil matrix. Using antecedent soil water content to account for the long-term variability in available water conditions might enhance modeling crack extent in expansive soils—especially in climates with oscillating wetting and drying cycles. To achieve this, the mechanism of antecedent soil moisture affecting soil cracking needs to be further investigated in carefully designed field experiments to validate the results, to further fundamental understanding and also to explore potential improvements for modeling of water and chemical movement in shrinking–swelling soils at pedon and landscape scales.

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References


