Shrinkage of Bare and Cultivated Soil

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ABSTRACT

The surface subsidence of shrink–swell soils may be used to estimate the soil profile water content and soil heaving. Roots are known to affect cracking patterns by anchoring the soil mass, thus influencing soil shrinkage. Our hypothesis was that plant roots will influence soil shrinkage measured by vertical surface subsidence. We tested this hypothesis by measuring shrinkage in a large weighing lysimeter for bare soil with no root system and for soils under wheat (*Triticum turgidum* L.) and alfalfa (*Medicago sativa* L.) crops possessing fibrous and tap root systems, respectively. The volume-loss shrinkage curves for both bare and cultivated soil were found to conform to the straight-lines model, with distinct changes in shrinkage zones, in spite of uneven water-content distributions in the profile. The shrinkage characteristic (i.e., the differential change in bulk volume divided by the change in volume water) was greater for fallow (0.677) than for wheat (0.380) and alfalfa (0.377), with the cultivated conditions being similar. These data suggest that plant roots may have large effects on in situ soil shrinkage rates and the water-content zones throughout which they occur. This result means that a soil's shrinkage characteristic may change depending on the cropping condition. It also means that shrinkage measurements from soils without rooting systems (e.g., small cores or clods) are not necessarily representative of actual shrinkage properties observed in the field.

THERE IS CURRENT INTEREST in measuring soil shrinkage from surface subsidence. One application of the resulting data is estimation of soil profile water content, which has potential for irrigation scheduling (Yule, 1984a; Mitchell, 1991) where surface subsidence measurements can be used to calculate the change in total water content of the profile. Another incentive for measuring field shrinkage relationships is to predict field surface shrinkage and swelling under rainfall. For example, Bronswijk (1989) constructed a model of soil heaving and surface subsidence based on water-content changes. Surface subsidence is an in situ measurement of shrinkage in the field, unlike methods based on the sampling of cores and clods, or even laboratory columns. Although the measurement of subsidence occurs solely at the soil surface, it has been shown to estimate crack volume within 10% of more accurate measurements that include swelling gauges at multiple depths (Bronswijk, 1991). This study is concerned with measuring the effects of roots on soil shrinkage. More specifically, we will use surface-subsidence measurements as a means to compare shrinkage for different rooting patterns. We will not use extracted soil for this purpose, as soil sampling would disrupt the effects of the root network on soil shrinkage.

Shrinkage of field soil may be affected by cropping practice. In general, soils with good aggregation have lower shrinkage than labile soils. This is presumably due to the greater void space and aggregate-stabilizing organic-matter content of aggregated soils. McGarry and Daniells (1987) compared two soil plots cultivated at different water contents, and found the shrinkage rate to be greater for soil cultivated dry than for soil cultivated wet. Daniells (1989) reported no differences in the shrinkage rate for soil clods subject to dry- and wet-soil cultivation, but found the specific volume (V_s) of the clods to be lower for the more structured, dry-tilled soil. Lauritzen and Stoltzenberg (1940) compared shrinkage of extracted clods for a Houston black clay (fine, montmorillonitic, thermic Udic Pellusterts) with good soil structure in a virgin prairie as opposed to a 30-yr continuously cultivated field. They found the clods from the virgin soil to have less total shrinkage and higher infiltration rates. Johnston and Hill (1944) related soil shrinkage measurements in the laboratory to field observations where cracking patterns were different under fallow soil, cotton (*Gossypium hirsutum* L.), and sorghum [*Sorghum bicolor* (L.) Moench]. In another study, Kuznetsova and Danilova (1988) showed that well-developed soil structure affects the swelling and shrinkage properties; they found a critical threshold of compaction above which the soil loses its ability to spontaneously gain optimal tilth.

Cropping practice can also induce a variety of cracking patterns in the soil. When a mature crop exists in a row or furrow cultivation system of an expansive soil, large cracks often appear between the rows of plants. Between-row cracking has been reported for Houston black clay and Austin clay under nonirrigated corn (*Zea mays* L.) by Johnston and Hill (1944); and for grey clay with furrow-irrigated cotton in New South Wales, Australia (Chan and Hodgson, 1984). Fox (1964) also observed between-row cracks for cultivated soil in Queensland, Australia, where smaller cracks transversed the plant row but did not intersect the plants. Fox (1964) proposed a theory of *root anchoring* to explain these observations. He described how plants with tap roots provide a skeleton to which the soil adheres as it shrinks, resulting in larger cracks along the outer boundaries of the rooted volumes in the soil. Large cracks also form between the plant rows where the soil is wetter; this occurs because soils under a shrinkage stress produce cleavage planes at the point of highest water content. Mitchell (1991) used the term *skeletal shrinkage* to describe the phenomenon of soil shrinkage toward the plant root skeleton and the associated cracking margins of soil between the roots. He attributed the variability of surface subsidence measurements under an alfalfa crop to skeletal shrinkage. Skeletal shrinkage may be a function of several factors including root architecture, root strength, the distribution of various-sized aggregates in the soil and the resulting macropore locations, and the water potential at the root–soil interface. While not changing shrinkage properties at the particle level, skeletal shrinkage leads to a different spatial distri-

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bution of the shrinkage voids. This distribution creates more stable voids, which, in turn, cause the measurable shrinkage to decrease. A lower shrinkage rate under cultivated soil may be due to skeletal shrinkage of soil around the root anchor, a process that can stabilize more voids. Johnston and Hill (1944) observed skeletal shrinkage patterns for soils under corn, but not under crops with fibrous roots, which exhibited a mud-crack pattern between islands of polygonal-shaped soil. To our knowledge, no studies have addressed the magnitude of root-anchored, skeletal shrinkage for different root systems of crops.

Since plant roots affect the location of cracks in a soil, and consequently influence the shrinkage rate, we hypothesized that root systems of different crops will yield different shrinkage and surface subsidence relationships. The objective of this study was to determine the effects of plant-root systems on soil shrinkage in the field. Our hypothesis was tested by measuring surface subsidence in a large weighing lysimeter under bare (fallow) and cultivated soil. The comparison of shrinkage under conditions of fallow, wheat, and alfalfa should indicate the existence of skeletal shrinkage. These three cropping systems differ greatly in their rooting characteristics (i.e., no roots for the fallow soil, fibrous roots for wheat, and tap roots for alfalfa), thus yielding a wide range of conditions under which to test our hypothesis.

THEORY

A complication of the surface subsidence method is that the soil does not dry evenly with depth. A nonuniform water-content distribution makes the method distinctly different than studies done on soil clods (McGarry and Daniells, 1987) or small cores (Yule and Ritchie, 1980a), where the water content is assumed uniform throughout the clods or core or, alternately, where clods are allowed to equilibrate so that water content becomes uniform (Perroux et al., 1974). Soil shrinkage data are often presented as the specific volume change (the reciprocal of the bulk density) of the soil as a function of water content; however, the uneven water-content distribution in the soil profile prevents the use of a single value for water content, and instead soil drying must be considered in terms of water lost from the entire soil profile. Consequently, we will present our results in terms of the *volume-change ratio*, which Lauritzen and Stewart (1941) defined as the change in soil bulk volume divided by the change in volume of water between the saturated and air-dry water contents. The shrinkage, or volume loss, of the soil can be derived from surface subsidence measurements and isotropic shrinkage assumptions (Hardy, 1923; Bronswijk, 1989).

From the volume-change ratio, the shrinkage characteristic (m) has been defined (Mitchell, 1991) as its differential, or

$$m = \frac{\partial V_s}{\partial V_w} \quad [1]$$

where V_s is the volume of the soil and V_w is the volume of soil water. In other words, m is the slope of the volume loss vs. water loss curve at any point or, equivalently, the slope of a V_s–water content curve. Either of these shrinkage curves may conform to the three-straight-lines model of McGarry and Malafant (1987), which includes the straight-line shrinkage phases of structural, residual, and basic (or normal) shrinkage (Fig 1). As a consequence, three values of m are needed to describe the three shrinkage phases. For

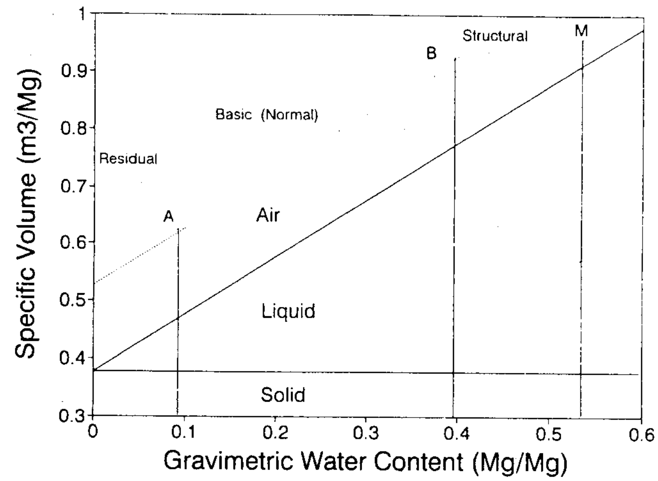

Fig. 1. Three-straight-lines shrinkage curve, after McGarry and Malafant (1987).

many soils, shrinkage often deviates from the value $m = 1$ that characterizes normal or unitary shrinkage (Mitchell, 1992), although a linear response within specific shrinkage zones is common, i.e., the residual, structural, or basic zones of Fig. 1. Extensive measurement of field shrinkage of soil with swelling gauges (Jayawardane et al., 1984) has shown that moderate (less-than-normal) shrinkage occurs in the field (Jayawardane and Greacen, 1987). Other investigators have also found m to be <1 in the field (Woodruff, 1937; Lauritzen and Stewart, 1941; Jamison and Thompson, 1967; Yule, 1984a; Mitchell, 1991).

A simple way of estimating volume changes due to shrinkage is to measure the vertical surface subsidence, ΔZ, which is the change in the length of the soil in a single direction relative to a fixed reference. Usually the vertical direction is measured (Yule and Ritchie, 1980a; Yule, 1984b; Bronswijk, 1989). By assuming isotropic shrinkage, ΔZ can be related directly to changes in bulk volume. For a core in the laboratory, the reference may be the bottom or side of a cylinder holding the core (Yule and Ritchie, 1980a). In the field, reference rods must be anchored at or below the lower boundary of the expansive soil horizon that is being measured (Woodruff, 1937).

The shrinkage characteristic, m, can be calculated from measurements of surface subsidence, ΔZ, and water loss (Mitchell, 1991) by

$$m = \frac{3\Delta Z - \dfrac{3(\Delta Z)^2}{Z} + \dfrac{(\Delta Z)^3}{Z^2}}{\Delta W} \quad [2]$$

where ΔW is the water loss per unit area (ΔW has a dimension of length), Z is the length of the soil in question, and ΔZ is the change in vertical length due to shrinkage. There are two advantages to using Eq. [2] for measurements involving a large weighing lysimeter. First, lysimeters provide accurate and direct measurements of the water loss, ΔW. Thus, the problem of measuring water loss from changes in water content will be avoided. Second, many measurements of surface subsidence may be averaged to arrive at a reasonably accurate mean ΔZ.

The largest source of error in determining m is related to the estimate of Z, or the depth of soil that shrinks in response to water-content changes. Still, this error can be shown to have a relatively small effect on m because the numerator (ΔV_s/area) in Eq. [2] is dominated by the term $3\Delta Z$. For example, suppose ΔZ is measured as 1.0 cm. If $Z = 30$ cm, then ΔV_s/area $= 2.901$ cm, and if $Z = 100$

cm, then ΔV_s/area = 2.9701 cm. This indicates a difference of only 0.0691, or 2.3%, in the calculation of ΔV_s/area and m. To summarize, m is relatively insensitive to changes in Z because of its magnitude relative to ΔZ (Aitchison and Holmes, 1953). In this study, we estimated Z as the depth of drying as determined from neutron-meter measurements at six depths. Water loss occurred at lower depths for the cultivated soil than the bare soil.

It may be argued that the use of a single value of ΔZ as measured at the surface is insufficient to describe the shrinkage of the entire profile since different layers of the soil profile may be shrinking at different rates, depending on their water content and length of the shrinkage zone. Such a single value of ΔZ will not identify exactly where in the profile the shrinkage occurs, nor indicate the water-content value at which the shrinkage properties change. An alternative would be to measure shrinkage at multiple depths (Woodruff, 1937); however, such an approach would require instrumentation that may significantly influence the root-anchored shrinkage properties that we are attempting to measure. For this reason we decided to measure only the profile- integrated ΔZ value as derived from soil surface subsidence data. The utility of collecting only surface subsidence data for shrinkage characterization will be substantiated below, where it will be shown that the soil profile acts as a single unit in its abrupt changes in m, which signify the shrinkage inflection points.

MATERIALS AND METHODS

Lysimeter Description

The large weighing lysimeter used in this study was located at the USDA-ARS Irrigated Desert Research Station near Brawley, CA, and was situated in the middle of a 2-ha field. The lysimeter consisted of a steel box 3 by 3 m by 1.5 m deep, which rested on an industrial-size truck balance. Soil in the lysimeter could be gravity drained into a 75-L tank. The evapotranspiration precision was 0.25 mm of water.

The soil in the lysimeter was disturbed during installation in 1966, but was repacked by layers to simulate the soil profile of the surrounding field. The lysimeter has been used extensively to determine consumptive use of water for several crops including wheat, alfalfa, cotton, and guayule (*Parthenium argentatum* L.). Guayule occupied the lysimeter from 1983 to 1986. The lysimeter was left fallow for all of 1987, before the start of this shrinkage study. The Holtville silty clay near the lysimeter is classified as a clayey over loamy, montmorillonitic (calcareous), hyperthermic Typic Torrifluvent (Zimmerman et al., 1980). Soil texture is silty clay, with 60% clay, 38% silt, and 2% sand, as determined by the hydrometer method.

Surface subsidence was measured as the average elevation change of 11 ceramic plates placed on the soil surface throughout the lysimeter. The ceramic plates (60-mm diam. by 4 mm thick) were selected for their material properties of density and water diffusion (to prevent excess moisture build-up beneath the plate). Elevations were measured by means of a caliper clamped to a steel rod, which was mounted to a fixed reference, i.e., a steel neutron meter access tube. The caliper was precise to within 0.1 mm.

Crop Information

The soil in the lysimeter was saturated by irrigating with small amounts of water while keeping the bottom outlet closed to prevent drainage. Multiple small irrigations from 19 Jan. to 6 Mar. 1988 were required because of the low water infiltration rate. On 7 Mar. 1988, the lysimeter was covered with two layers of black plastic to prevent evaporation from the surface, and the bottom outlet was opened to allow drainage. The lysimeter had measurable drainage until 19 Apr. 1988, at which time the black plastic and straw were removed and soil subsidence measurements commenced. The subsidence and weight measurements were taken twice a week during the first 4 wk, when most of the evaporation occurred. Measurements were subsequently obtained at biweekly intervals until 13 Sept. 1988. Water contents taken before and after drainage, and after an extended period of evaporation (Fig. 2a), showed that the soil in the lysimeter did not dry uniformly under the influence of evaporation; hence, total water loss (as measured by lysimeter weight) could not be directly transformed into a single value of soil water content. The bare soil relationship between bulk density and water content (Table 1) was established from the shrinkage characteristic (m) and volumetric water-content measurements. The bulk density was determined from neutron measurements of water content (θ_v) and gravimetric soil samples for mass water content (θ_g) taken on 19 Apr. 1988 at the beginning of the shrinkage study. Use of neutron-probe data, which are generally suspect for swelling soils, was justified since field measurements for the Holtville silty clay showed a linear calibration curve (Mitchell, 1991). Calibration data were collected from four core samples from each of 11 10-cm layers at three locations in the field. Water contents varied from 0.10 to 0.46 m^3 m^{-3}.

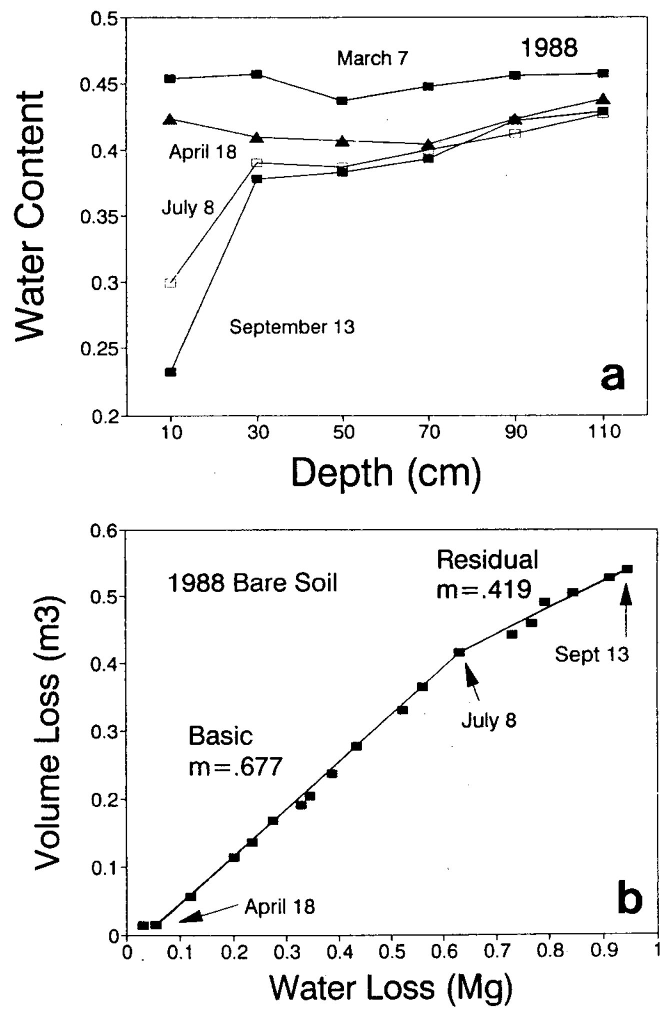

Fig. 2. Bare-soil (a) water-content profiles and (b) volume-loss curve for 1988 before drainage (March 7), after drainage (April 18), at the residual inflection point (July 8), and following an evaporative period (September 13).

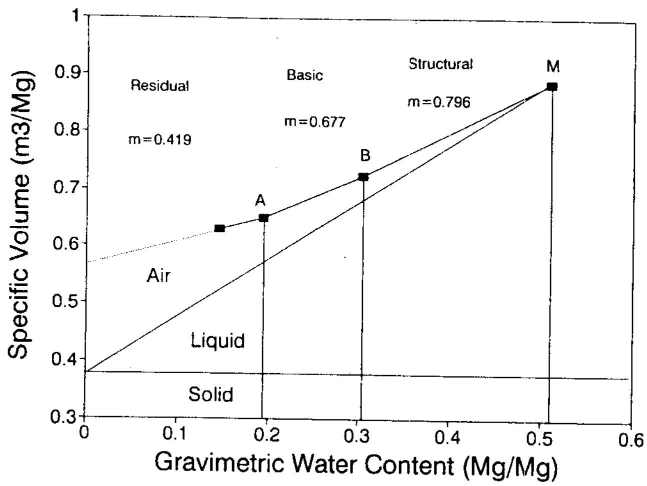

Fig. 3. Shrinkage curve for the 1988 fallow soil.

In 1989, soil subsidence was measured during the growth of wheat (cv. Yecoro Rojo). Wheat was planted in December 1988 and harvested in June 1989; shrinkage measurements began in January 1989. In October 1990, the lysimeter was irrigated, then broadcast planted in alfalfa (cv. CUF 101) without tillage. In the following spring, surface subsidence was measured from 11 Jan. to 19. Apr 1990, which included a 5-wk period without irrigation or precipitation.

RESULTS

The 1988 bare-soil volume-loss shrinkage curve and accompanying soil water profiles are shown in Fig. 2b. The shrinkage data show a distinct change between the basic and residual shrinkage zones on 8 July 1988. The 1988 fallow soil shrinkage is also graphed as a V_s–θ_g curve in Fig. 3. Determination of the V_s–θ_g curve was possible because only the surface 20 cm of the soil had dried during evaporation (Fig. 2); we assumed that the water content was uniform throughout that surface layer. The values of m were 0.677 and 0.419 for basic and residual shrinkage, respectively. Values of parameters for the shrinkage curve, listed in Table 1, were estimated using the three-straight-lines model of McGarry and Malafant (1987) and shrinkage relationships from Bridge and Ross (1984).

The 1989 wheat shrinkage curve (Fig. 4a) was not strictly linear, as was the case for the 1988 fallow data. The scattered nature of the points is probably due to settling of the soil following early-season irrigations, since the soil was tilled prior to planting. The vertical surface subsidence for the soil probably included a near-surface consolidation of the tilled soil. The settling of soil during the wetting and drying cycles is in accordance with Kuznetsova and Danilova's (1988) observations of soil settling during studies of shrinkage cycles of Sod-Podzolic soils in the USSR. The soil may have lost its ability to swell and regain its initial elevation and density, as predicted by Kuznetsova and Danilova (1988). However, it is impossible to delineate the relative contributions to volume change from the settling of the surface layer and from the shrinkage. In either case, the surface-subsidence method of measuring shrinkage will be affected by wetting and drying cycles until the soil becomes consolidated.

In order to eliminate the effects of post-tillage consolidation, a subset of the data used for Fig. 4a are plotted in Fig. 4b. These data were taken from the interval between 28 Feb. to 10 Apr. 1989, and plotted such that the 19 Mar. 1989 data point coincided with the origin. The shrinkage curve exhibits the typical basic and residual shrinkage zones, with residual shrinkage occurring during the final 0.6 Mg of water loss. The residual inflection point in this case was impossible to determine without more data points; hence, the residual m was not calculated and its curve not plotted. Linear regression analysis of data in the basic shrinkage zone gave a slope (m) of 0.380, an intercept of 0.005, and an r^2 of 0.97.

The 1990 alfalfa shrinkage and corresponding water-content profiles are shown in Fig. 5. Linear regression (Fig. 5b) of all but the driest points of 6 and 19 Apr. 1990 resulted in a slope of 0.377. A straight line from the origin (11 Jan. 1990) to the residual inflection point (29 Mar. 1990) had a slope of 0.375. The extended-drying data of April (upper right corner) obviously belonged to the residual shrinkage zone. The swelling (wetting) volume changes that occurred following irrigation are plotted with different symbols to illustrate that all swelling points lie below the linear regression line. This feature is indicative of a hysteretic swelling phenomenon between wetting and drying soil.

DISCUSSION

Comparison of the Shrinkage Characteristic for Bare and Cultivated Soil

All soils had basic shrinkage zones within similar water-content ranges. This suggests that the difference in shrinkage between cultivated and uncultivated soil

Table 1. Shrinkage inflection points for fallow Holtville silty clay (corresponds with Fig. 3).

Inflection point	Shrinkage	Water content: volumetric θ_v	Water content: gravimetric θ_g	Bulk density ρ	Clod specific volume V_s	Shrinkage characteristic m
		$m^3\ m^{-3}$	$Mg\ Mg^{-1}$	$Mg\ m^{-3}$	$m^3\ Mg^{-1}$	
M		0.451†	0.509	1.13	0.887	
	Structural					0.796
B		0.421†	0.305†	1.38	0.725	
	Basic					0.677
A		0.299†	0.194	1.54	0.649	
	Residual					0.419
L		0.232†	0.146	1.59	0.629	

† Measured data.

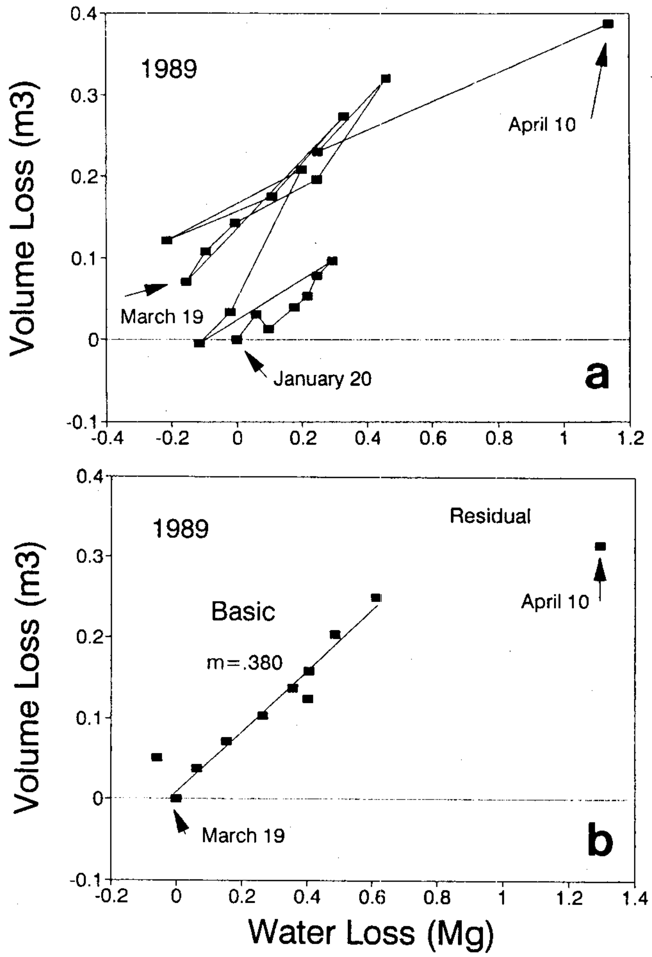

Fig. 4. Volume-loss curve for (a) the wheat-cultivated soil in 1989 and for (b) a subset of the data taken after 28 Feb. 1989.

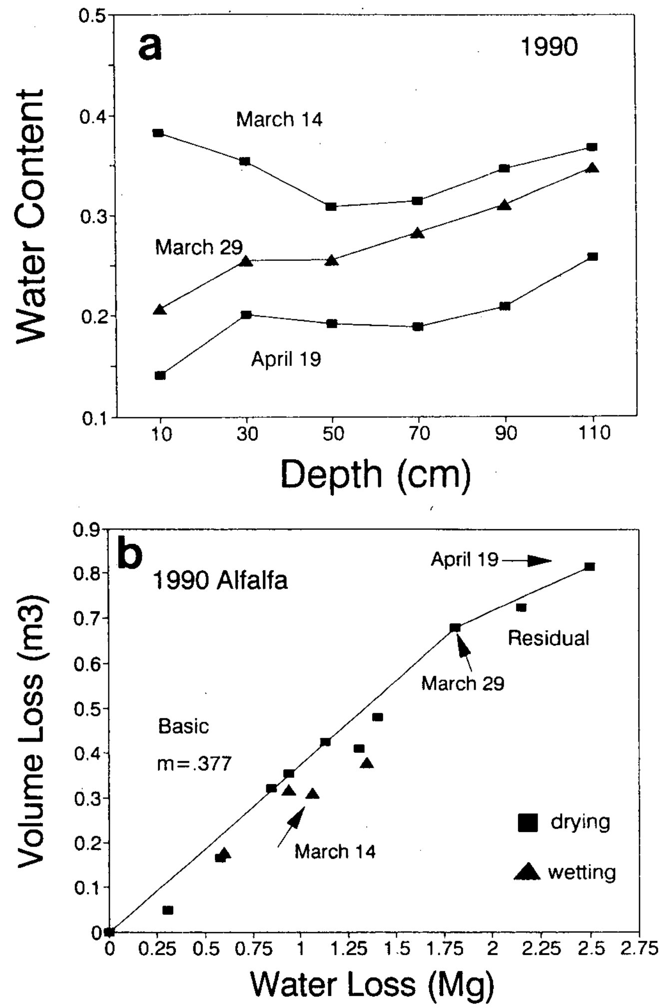

Fig. 5. Alfalfa-cultivated soil (a) water-content profiles and (b) volume-loss curve. The inflection point joining the two lines occurred on Mar. 29 1990.

is due to root-anchored skeletal shrinkage. Soil shrinkage behavior greatly differed between the bare soil (m = 0.677) and the cultivated soil; however, very little difference existed between the alfalfa (0.377) and wheat (0.380) crops. The bare-soil residual shrinkage (m = 0.419) approached the value of the alfalfa's basic shrinkage. This is in spite of the fact that the alfalfa basic shrinkage zone occurred at much higher water contents (i.e., as high as 0.38 m^3 m^{-3}; see the March 29 data of Fig. 5a) than the residual shrinkage zone for bare soil (see Table 1.) The occurrence of skeletal shrinkage, such as under cultivated soil, indicates that shrinkage voids are distributed in the form of stable voids within the soil, a situation that will reduce the surface-measured shrinkage. The 1988, fallow soil evidently did not produce many internal microvoids; hence, ΔZ must have represented most shrinkage voids, thus causing m to become relatively large (0.677). On the other hand, the skeletal shrinkage of the alfalfa and wheat soils produced stable voids within the soil volume, which caused ΔZ to be smaller and m less (0.380). A smaller m does not necessarily mean that the soil material changed its shrinkage properties, rather it may indicate that the shrinkage voids were distributed differently because of root anchoring.

The existence of skeletal shrinkage in this study suggests that shrinkage relationships may change depending on whether the soil is cultivated or not. Shrinkage measurements of disturbed, molded soil in the laboratory (e.g., Franzmeier and Ross, 1968; Parker et al., 1977) can give a good indication of the inherent ability of a soil to expand under uniform, standard conditions. However, this type of disturbed-soil measurement cannot be expected to represent soil behavior in the field, where roots are present.

Shrinkage data from undisturbed small cores also cannot be expected to reflect the behavior of a field soil, since the soil-extraction process will disrupt the root network. Our observation that in situ shrinkage measurements are needed for cracking soils is similar to the conclusions of Ritchie et al. (1972) and Kissel et al. (1973) that water flow in cracking soils cannot be accurately measured on small cores. The disparity of field- and core-measured shrinkage is in agreement with results from an earlier study (Mitchell, 1991), which found that field shrinkage is less than the shrinkage of extracted, undisturbed cores. This disparity-of-scale result contradicts the conclusions of Yule and Ritchie (1980b) that small (10-cm-diam. and 10-cm-long) cores possess the same shrinkage properties as large cores (73-cm-diam. and 140-cm-long) planted in sorghum. However, a close look at their data indicates that the larger cores (see Fig. 2 of Yule and Ritchie, 1980b) exhibited a smaller shrinkage rate than the unitary shrinkage process ($m = 1$) observed for the smaller cores (Yule and Ritchie, 1980a). This suggests that their large cores may have also experienced root anchoring.

Comparison of Shrinkage between Crops

The similarity of the basic m under alfalfa (0.377) and wheat (0.380) suggest that the same mechanism is responsible for determining shrinkage under both crops and that it deviates considerably from that of bare soil. The concept of root anchoring has been invoked here to explain the differences with bare soil, although an alternate explanation may be the persistence of a residual effect of the wheat crop, which could have influenced subsequent soil shrinkage during alfalfa cultivation. Exactly what would constitute this residual effect is unclear, unless the dead roots continued to anchor the soil after the wheat harvest. This reasoning appears unlikely because of the small size of the wheat roots. Another possible explanation may be that the configuration of cracks and clods in the soil persisted into the next crop. Unfortunately, the carryover of the same aggregate distribution into the next crop would produce effects that would be hard to distinguish from those associated with root anchoring.

Soil consolidation through settling could not have been responsible for the similarity in m between crops and the dissimilarity with bare soil. This is because soil consolidation should have the effect of increasing m by decreasing the pore space that buffers the shrinkage volume changes (Eq. [1]), but our data showed m decreasing. Furthermore, consolidation should have the effect of reducing the maximum attainable water content, according to Kuznetsova and Danilova (1988); however, this was not found to be the case.

Comparison of Residual Inflection Points

The bare soil profile in the field acted as a single unit in abruptly changing to a residual shrinkage zone. The field data show a decrease in shrinkage rate that typifies the start of residual shrinkage. Figure 2b shows a distinct inflection point between the basic ($m = 0.677$) and residual ($m = 0.419$) shrinkage zones on July 8. In order to arrive at the water content when this occurs, we observed that only the 10-cm depth has a marked change in water content (Fig. 2a). Therefore, we assumed that shrinkage occurred only in that depth increment, with the residual inflection point being at $\theta_v = 0.299$ m^3 m^{-3} (Table 1). The uppermost surface of the soil was drier than the 10-cm depth prior to the 8 July inflection point, yet the bare soil shrank linearly up to that time. This suggests that the dry surface of the soil is a minor constituent of the total shrinkage. After 8 July, soil shrinkage was residual and linear. The shift from a basic shrinkage phase to a residual shrinkage phase is well documented for extracted soil material (Yule and Ritchie, 1980a). Haines (1923) described residual shrinkage as air entry into voids, rather than their complete collapse, which typifies unitary shrinkage. One may envision the residual inflection point as a point at which air enters a different set of pores. The fact that a cultivated field soil experiences an abrupt shift in linear shrinkage zones indicates that bare and cultivated soil both respond to shrinkage forces in a similar manner, except that air enters into different types of pores. Pores may form at locations in the soil where roots exhibit a less cohesive force, suggesting that the residual inflection point would also be influenced by skeletal shrinkage in cultivated soil.

Shrinkage for the bare and alfalfa-cropped soils did not shift to the residual shrinkage zone at the same water contents. The residual inflection point for alfalfa of 29 Mar. 1990 (Fig. 5) corresponded to water contents in the profile that ranged from 0.21 to 0.30 m^3 m^{-3}. This indicates that determining a single water content for the residual inflection point was problematic: an average water content would be less than the 0.299 m^3 m^{-3} inflection point of the bare soil. It is not surprising that the alfalfa residual inflection point differed from bare soil since the alfalfa basic m also differed. What is interesting is the variability in the water contents of the profile at the time that shrinkage abruptly shifts from basic to residual. We suspect that this may be a result of skeletal shrinkage, which could suddenly shift the location and size of pores at which air entry occurs. This, in turn, would lead to a change in the shrinkage rate (rate of surface subsidence). Exactly how this occurs is not presently known. While this study documents the roots' effects on shrinkage, more research is needed to describe the soil subsidence phenomenon, and especially the mechanisms of root anchoring.

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