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Soil surface shrinkage to estimate profile soil water

A. R. Mitchell

USDA-ARS, U.S. Salinity Laboratory, 4500 Glenwood Dr., Riverside, CA 92501, USA

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Summary. The surface elevation of a shrinking soil provided good estimates of the change in profile water content under alfalfa. Surface shrinkage was found to change linearly with water content as measured by neutron and gamma attenuation devices. Extracted soil cores were tested in the laboratory to obtain the linear shrinkage ratio, *b*. In the field, shrinkage was calculated as the average elevation change of small ceramic plates. Compaction of the soil by harvesting machinery had no adverse effect on the linearity of the shrinkage/water loss relationship, but lack of compaction resulted in nonlinear shrinkage as the soil was unconsolidated and may have exhibited subsurface horizontal cracking. These cracks were attributed to roots which anchored the soil during shrinkage. In a second study, local values of swelling (b') from initial measurements before and after irrigation were superior estimators of measured water loss compared to a single universal *b* value from independent tests.

Research on the swelling behavior of vertisols has led to the concept of using the shrinkage of the soil surface to predict water content (Yule 1984a). Application of this concept under field conditions may be influenced by compaction caused by machinery traffic. Compaction would be expected to affect the cracking properties upon drying. This paper first addresses the basic principles underlying the interactions between water content and shrinkage to provide a basis to analyze field data obtained under different traffic regimes. The first experiment has as its objectives: (1) to appraise the utility of using surface elevation as a means for estimating changes in water content throughout the entire soil profile, and (2) to compare field shrinkage-water loss relationships with those of extracted soil cores. The purpose of the second experiment reported here was to validate the method of using surface elevation measurements to estimate changes in profile water in the field from soil shrinkage properties determined earlier.

Swelling soils are distinguished from rigid soils by the relationship between water content and volume. Tempany (1917) observed that volume of shrinkage in a molded (hand-worked) soil is numerically equal to the volume of water loss during the early stages of shrinkage. Tempany also detected a "shrinkage lag" of less volume change per volume water loss, which occurred as the soil was dried further. Subsequently, *normal* shrinkage has been defined as soil shrinkage where bulk soil volume loss is equal to water volume loss. Because of the ambiguity of the word "normal", the word *unitary* will be used to describe shrinkage that is equal to water loss. Conceptually, *unitary* soil shrinkage occurs when pores collapse entirely as water leaves them. The range in water content that is governed by *unitary* shrinkage will be called the *basic* shrinkage zone.

Shrinkage rates decrease at the extremities of water content. Tempany's (1917) "shrinkage lag" became known as *residual* shrinkage. *Residual* shrinkage occurs at low water contents when further drying results in less shrinkage. This type of shrinkage has been explained in terms of water films that do not cause complete contraction of the voids between soil particles during drying (Haines 1923). *Residual* shrinkage has been found to change linearly with water content but not a 1:1 ratio (Haines 1923). At high water contents, *structural* shrinkage occurs as water is removed from the stable soil voids of a saturated soil during initial drainage. The stable voids, which are influenced by the soil structure, give "structural shrinkage" its name. Between these two phases lies the *basic* shrinkage zone that reflects the soil's fundamental shrinkage. *Moderate* shrinkage describes shrinkage that is less than *unitary* throughout the *basic* shrinkage zone.

Shrinkage data can be described in a three-straight-lines model (McGarry and Malafant 1987) that includes the phases of *structural, residual,* and *basic* shrinkage. Alternately, one may use the general soil volume change equation of Giraldez et al. (1983) or the logistic model of McGarry and Malafant (1987).

Present address: Oregon State University, Central Oregon Agricultural Research Center, P.O. Box 246, Redmond, OR 97756, USA

Lauritzen and Stewart (1941) defined the *volume change ratio* as the change in volume of bulk soil induced by the loss of a given volume of water divided by the volume of lost water. The *volume change ratio* is a measure of the effective rate of shrinkage between two water contents in the soil (such between the saturated and the air dry water contents.) In contrast, the shrinkage characteristic (m) is defined here as

$$m = \frac{\partial V_s}{\partial V_w} \tag{1}$$

i.e., the change in bulk volume, V_s, divided by the change in the volume of soil water, V_W. In other words, m is the differential volume change or the slope of the shrinkage vs. water loss curve at any point on the shrinkage curve.

Lauritzen and Stewart (1941) observed that shrinking soils differ in their response to drying. Davidson and Page (1956) concluded that the swelling tendency of a soil is not governed completely by the clay mineralogy, but that high organic matter and calcite concretions perform an important role by contributing structure, or stable pores, to the soil. Parker et al. (1977) enumerated the factors governing in situ volume change, such as adsrobed cation species, soil solution characteristics, cementing agents, density, stress path, stress history, confining pressure, sample (or strata) dimensions and geometry, time, and temperature. Several of these factors may interact to create structural voids which remain stable during drying, resulting in shrinkage that deviates from the value ($m = 1$) that characterizes *unitary* shrinkage, but with m's that remain constant over a wide range of water contents (Jayawardane and Greacen 1987). Throughout this report, shrinkage that is characterized by a constant m over a specified range will be termed *linear* shrinkage. Several investigators have also found m to vary in the field (Woodruff 1937; Lauritzen and Stewart 1941; Jamison and Thompson 1967; Yule 1984b; Mitchell 1987).

A simple way to estimate shrinkage is to measure the surface subsidence of the soil, ΔZ, as shown in Fig. 1 (Yule and Ritchie 1980; Yule 1984a; Bronswijk 1989). By assuming *isotropic* shrinkage, the Δz will be directly related to changes in bulk volume. The surface subsidence is a simple measurement of the elevation change relative to a fixed reference. For a core in the laboratory, the reference may be the bottom or side of the cylinder holding the core (Yule and Ritchie 1980). 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).

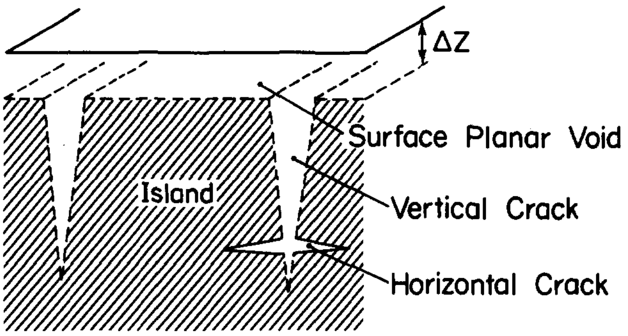

Fig. 1. Schematic of shrinking field soil under wet and dry conditions

The isotropic change in volume of a cube (or V_s of a soil ped) is given as (Hardy 1923; Giraldez et al. 1983)

$$\Delta V_s = Z^3 - (Z - \Delta Z)^3 = 3Z^2 \Delta Z - 3Z(\Delta Z)^2 + (\Delta Z)^3 \tag{2}$$

where Z is the length of the cube, and ΔZ is the change due to shrinkage. From the definition of *unitary* shrinkage

$$\Delta V_s = \Delta V_w = \Delta W Z^2 \tag{3}$$

where ΔW is the water loss per unit area, with dimensions of length. Substituting (3) into (2), we have

$$\Delta W = 3\Delta Z - \frac{3(\Delta Z)^2}{Z} + \frac{(\Delta Z)^3}{Z^2}\,. \tag{4}$$

Assuming unitary shrinkage, Eq. (4) may be used to calculate the volume of water loss from measurements of the surface subsidence.

From the definition of the shrinkage characteristic, we can relate m to surface subsidence by combining Eqs. (1), (3), and (4):

$$m = \frac{3\Delta Z - \dfrac{3(\Delta Z)^2}{Z} + \dfrac{(\Delta Z)^3}{Z^2}}{\Delta W}\,. \tag{5}$$

This equation permits us to calculate m from measurements of ΔZ and ΔW. Aitchison and Holmes (1953) showed that the last two terms of Eq. (4) were negligible for small changes in Z. Hence we can simplify (5) to

$$\frac{m}{3} = \frac{\Delta Z}{\Delta W}\,. \tag{6}$$

If the last two terms of (4) are not assumed negligible, we can define a new term, b, called the *surface shrinkage ratio*,

$$b = \frac{\Delta Z}{\Delta W} \tag{7}$$

which should approximately be equal to ⅓m. Equation (7) is valuable for field use because of the relative ease of measuring ΔZ. Since m ranges from 0 to 1, b should vary from 0 to 0.33.

The above analysis of shrinkage from measurements of soil dimensions relies on the assumption of *external* shrinkage (McIntyre 1984), i.e., volume change that occurs completely outside of (external to) the soil matrix. Conceptually, *external* shrinkage describes a condition where no cracks from within the soil matrix; hence, shrinkage is measurable as volume change in the ped's outside boundary. The horizontal contraction of soil produces large cracks, with "islands" of soil between them, as shown in Fig. 1. The vertical component of shrinkage, ΔZ, creates a planar void at the surface. The weight of the overlying soil discourages the formation of horizontal voids below the surface. If large horizontal cracks exist, the *external* shrinkage assumption no longer holds, and it is erroneous to use Eq. (7) and the surface shrinkage analysis.

A phenomenon that can upset the *external* shrinkage assumption for whole profile studies is the effect of plant roots on shrinkage. When a mature crops 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 maize (Johnston and Hill 1944) and furrow-irrigated cotton (Chan and Hodgson 1984). Fox (1964b) also observed between-row cracks, with smaller cracks transversing the plant row, but found no case where the crack intersected the plants. Fox (1964b) used the term "root anchoring" to describe his observations. He described how plants with tap roots provide a skeleton to which the soil adheres as it shrinks, resulting in a large crack on the margins of the rooting area between the rows. The large cracks 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. Johnston and Hill (1944) observed root-anchored shrinkage for maize, but not for crops with fibrous roots which exhibited a "mud crack" pattern between islands of polygonal-shaped soil. Their observation suggests that fibrous roots were not sufficiently strong to act as the anchor to the soil.

Shrinkage and compaction

Yong and Warkentin (1975) recognized that, in the field, the overburden pressure consolidates sediments causing the water content to decrease, and repeated wetting and drying cycles will arrange soil particles until an equilibrium is reached where swelling and shrinking occur between constant limits. This fact implies that m is not a constant for a soil, but may approach a constant value after repeated wetting and drying cycles.

Because soil shrinkage depends on several factors that also affect soil structure, shrinkage has been related to soil tillage management on swelling soils. Johnston and Hill (1944) related differences in soil shrinkage measured in the laboratory to field observations where cracking patterns were different under fallow soil, compared to cotton and sorghum crops. Kuznetsova and Danilova (1988) showed that humus content, humus quality, and the soil structure affect the swelling and shrinkage properties. They found a critical threshold of compaction above which the soil loses its ability to spontaneously gain optimal tilth. McGarry and Daniells (1987) examined shrinkage curves for parameters that could serve as indicators of soil structural degradation. Comparing two treatments cultivated at different water contents, they found m to be greater for dry soil cultivation than for wet-soil cultivation. However, Daniells (1989) reported no differences in m, but found V_s of the clods to be lower for the more dry-tilled soil with greater structure. In general, the more structured a soil, the smaller the specific volume (V_s) and shrinkage characteristic (m). Compaction by machinery traffic would be expected to increase the soil density (decrease V_s) and reduce m.

Materials and methods

Both studies were conducted on a field of alfalfa (*Medicago Sativa* L.) cv. CUF 101 at the USDA-ARS Irrigated Desert Research Station, Brawley, CA. The soil is a Holtville cilty clay (typic Torrifluvent) with a clay fraction comprised of 46% montmorillonite and characterized by a loamy-textured substrata with an abrupt upper boundary approximately 0.5 m below the surface (Perrier et al. 1974).

Trial 1

Five machinery traffic regimes were tested for soil shrinkage response. The traffic treatments were those imposed on a comprehensive alfalfa traffic-compaction experiment, and included alfalfa grown on raised beds (1 m wide and 0.20 m high), a regional practice to prevent waterlogging of alfalfa. A "no traffic" treatment consisted of non-compacted areas between traffic lanes, while the "grower" treatment reflected common practice with 100% of the field area trafficked every two harvests. The 5 traffic regimes were

NT = no traffic on a level field
TB = top of bed, no traffic
GR = "grower" treatment, 1 traffic pass every second harvest
WB = wheel track between beds
WH = wheel track between NT zones.

WB and WH were trafficked 5 times each harvest.

Measurements of field surface elevation, water content, and bulk density were taken on 9 occasions between 4 and 30 Sep 1986 for an extended drying cycle after an irrigation on 2 Sep 1986. Soil moisture and density measurements were determined by double tube gamma attenuation (Rawitz et al. 1982) at increments of 0.05 m to the 0.30 m depth, and 0.10 m increments from 0.30 m to 0.60 m. Gamma attenuation is a measure of absolut density betwen a source and counter 0.30 m apart, and is a line measurement, as opposed to bulk density from sampling, which is a volume measurement. The rate of change in density with water content will be less for the double-tube system than for a volumetric one, since the system measures linear and not volume soil shrinkage. Water contents for the 0.05 to 0.25 m depths were determined gravimetrically by sampling near the double tubes, and with a neutron moisture meter in the 0.25 to 0.60 m region. Shrinkage in the loamy soil below 0.60 m was assumed to be negligible. Since water contents could not be precisely measured for each gamma meter depth increment, they were approximated by using the neutron and gravimetric data as initial estimates, then used to solve for bulk density and water content from the gamma probe data. Density and water content values from each depth increment were then compared with adjacent values in time and space, and the process was repeated until the values converged.

Field surface elevation was measured for 3 small ceramic plates (60 mm diameter) located on the soil surface between the double tubes. For each treatment a surveyor's level and staff were used to measure their height relative to a benchmark, which consisted of a steel rod anchored to a depth of 1.5 m. The staff could be read to 1 mm. Measurements were taken at the same time as soil data.

Extracted cores

Undisturbed cores (100 mm diameter and 76 mm long) were extracted from the top 100 mm of each treatment 2 days after a flood irrigation on 4 Sep 1986. For the WB and WH, cores were taken underneath the wheel track. Procedure for measuring shrinkage was similar to Yule and Ritchie (1980). Cores with rings were mounted to boards in the lab. Seven surface positions were measured relative to the top of the ring, with a caliper mounted to a stand. The caliper could be read to 0.025 mm. Cores were weighed with a top-loading balance to 1.0 g. Measurements were taken daily during the first week, and then at longer intervals as the rate of drying decreased.

Trial 2

A validation study was conducted in Oct 1987 at a different location within the same field following a flood irrigaton. The study had a grower (GR) machinery traffic treatment and a control (NT) factored with an irrigation treatment and check (NT, NT-irr, GR, and GR-irr). The irrigated treatments were sprinkled on day 17 and 22. Measurements of water content and surface elevation were taken on 8 occasions over 30 days. Water contents were measured by the neutron probe at 20 cm increments to a 1.2 m depth. Soil moisture for the 0 to 15 cm depth was determined gravimetrically from samples take within 1 m of the neutron probe access tube. Surface elevation was determined from 5 ceramic plates placed within 40 cm of the access tube. The steel access tube (1.4 m deep) was used as a benchmark for each set of elevation readings.

The use of neutron moisture measurements in swelling soil usually requires a correction to account for the changing density of the soil, such as the square-root correction proposed by Greacen and Schrale (1976). However, a neutron calibration of the Holtville silty clay over the entire range of water contents showed no improvement using the square-root correction (Mitchell 1990). Other researchers have used a linear calibration for the Holtville silty clay with apparent success (Donovan and Meek 1983; Rhoades et al. 1988). These findings suggest that other *moderately* swelling soils may respond to neutron moisture measurement with a linear relationship, similar to rigid soil behavior.

Results and discussion

Linear shrinkage was observed for cores of all treatments throughout the water content range of 0.04 to 0.28 kg^{-1} (Table 1 and Fig. 2). There was some variation in the slopes of the regression, although this variation was not considered significant. All treatments were then pooled, which resulted in a high r^2 value and a b value (0.216) that was less than the value for *unitary* shrinkage (0.33).

Field shrinkage/water loss regressions (Table 1) were similar for all compaction treatment except NT (Fig. 3). Data for the NT treatment was not pooled with the field data, for reasons to be discussed later. The pooled b value was 0.216, which was slightly higher than for cores. The curves were slightly convex on the dry range, which indicated that a *residual* shrikage phase may have occurred in the field. A statistical test for the difference between the cores and field regressions showed that they were the equal at the $\alpha = 0.10$ confidence level, but not at the standard $\alpha = 0.05$ level. The smaller b for field soil as opposed to cores may be attributed to root anchoring. Alfalfa has a strong tap root system that could serve as an anchor for soil shrinkage. The extracted cores did not have the whole plant's root system as an anchor, and thus exhibited larger b values. The anchoring seemed to be greater as the soil dried as shown by the lesser shrinkage response with water (Fig. 3).

The NT treatment differed from the others in its high rate of initial shrinkage and subsequent plateau. The b value was initially greater than 0.33 and approached that of *unidimensional* shrinkage (Fox 1984a), which is thought to occur only for unconsolidated saturated soil (McIntyre 1984) although initial water contents were nearly identical for all treatments (Table 2). The NT treatment could be termed an unconsolidated soil (Yong and Warkentin 1975).

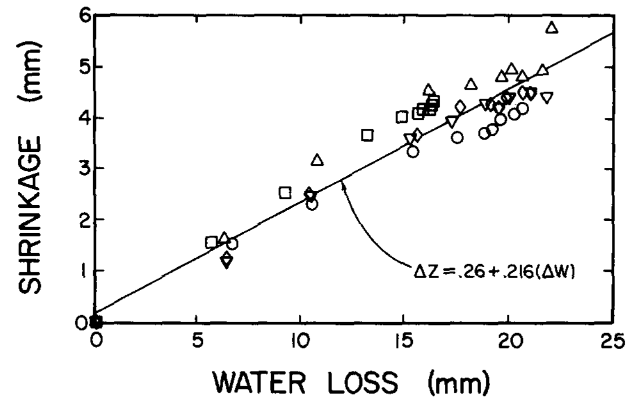

Fig. 2. Core shrinkage as a function of water loss for NT (○), TB (□), WB (△), WH (▽), and GR (◇)

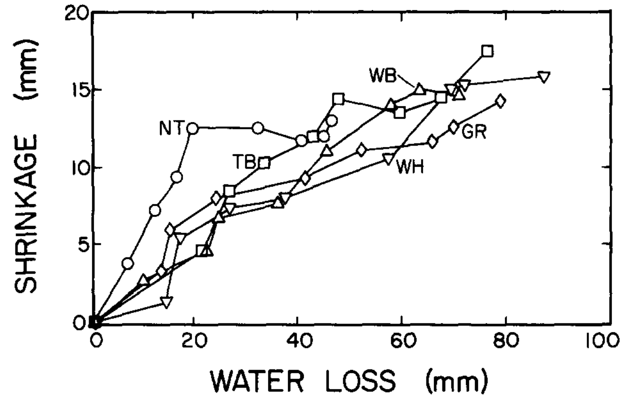

Fig. 3. Field shrinkage as a function of water loss for Trial 1 with the same symbols as Fig. 2

Table 1. Regression terms for shrinkage as a function of water loss ($\Delta Z = a + b\,\Delta W$)

	Cores			Field		
	a	b	r^2	a	b	r^2
NT	0.10	0.202	99	3.5	0.208	75
TB	0.06	0.258	99	1.6	0.224	91
GR	0.02	0.221	99	2.2	0.167	92
WB	0.06	0.267	99	0.4	0.221	97
WH	0.01	0.217	99	0.6	0.233	95
Pooled	0.26	0.216	91	1.9	0.203	86
Pool-NT*				1.2	0.195	91

* Pool of all treatments except NT

As NT continued to dry, shrinkage ceased entirely (Fig. 3). The assumption of *external* shrinkage requires that bulk density increase as the soil dries, but the data of Table 2 show several decreases in bulk density for the NT treatment. The only explanation for decreases in bulk density with drying are the shrinkage of soil away from the measurement zone in the form of cracks. Because vertical cracks were not observed, we deduced that these cracks were horizontally oriented. As mentioned earlier, horizontal cracks occurring below the soil surface, violate the *external* shrinkage assumption, and make b unsuit-

Table 2. Bulk density with depth, and water content for 4 Sep. and 30 Sep. 1986. Bold type denotes bulk density values that *decreased* from 4 Sep. to 30 Sep.

Depth (m)	Bulk density ($Mg\ m^{-3}$)									
	No traffic (NT)		Bed (TB)		Wheel bed (WB)		Wheel track (WH)		Grower (GR)	
	4 Sep.	30 Sep.	4 Sep.	30 Sep.	4 Sep.	30 Sep.	4 Sep.	30 Sep.	4 Sep.	30 Sep.
0.05	1.29	**1.16**	1.27	**1.19**	1.34	**1.24**	1.43	1.46	1.32	1.36
0.10	1.45	1.46	1.32	1.36	1.43	1.55	1.47	1.49	1.40	1.52
0.15	1.39	1.42	1.36	1.49	1.45	1.55	1.52	1.65	1.46	1.56
0.20	1.46	**1.37**	1.53	1.55	1.45	1.47	1.48	1.61	1.50	1.57
0.25	1.47	**1.22**	1.50	1.60	1.44	1.42	1.43	1.52	1.41	1.46
0.30	1.43	**1.08**	1.53	1.62	1.42	1.51	1.47	1.54	1.41	1.41
0.40	0.46	**1.35**	1.56	1.57	1.51	**1.46**	1.42	**1.41**	1.39	**1.36**
0.50	1.52	**1.42**	1.51	**1.45**	1.48	1.51	1.46	1.48	1.48	1.49
0.60	1.49	1.53	1.48	1.51	1.50	1.49	1.41	1.47	1.44	1.52
Avg	1.47	**1.39**	1.48	1.50	1.46	1.47	1.44	1.51	1.43	1.46
	Water content ($kg\ kg^{-1}$)									
Avg	0.185	0.135	0.199	0.130	0.202	0.120	0.207	0.137	0.209	0.128

able for analysis. Decreases in bulk density with drying occurred in the NT treatment at depths from 0.20 to 0.50 m, and at the 0.40 m depth for the other treatments (Table 2).

Horizontal cracks occurring in the NT treatment could have resulted from the lack of traffic-induced soil compaction. The fact that bulk density (Table 2) varied more between traffic treatments when dry (30 Sep) than when wet (4 Sep) implies that the efect of traffic machinery compaction on the soil bulk density is manifest when the soil is dry, but not when it is wet and swollen. Horizontal cracking is believed to result from roots anchoring the soil as it goes through its drying cycle. The extensive horizontal cracking in the NT treatment is attributed to the lack of consolidation of the undisturbed soil which did not experience downward compaction forces from machinery. Horizontal cracking below the soil surface could have implications in studies of water and solute movement in shrink-swell soils. Root-anchored shrinkage may also result in water-conducting cracks that will alter the physical boundary conditions of water and solute flow.

All of the treatments decreased in bulk density near the 0.40 m depth (Table 2). The decrease probably resulted from the clayey-over-loamy textural interface located there, which may have increased the likelihood of horizontal cracking, or else caused error in the soil water measurement. If water content was inaccurately overestimated for the textural interface (note that neutron measurements integrate over large regions of soil), then the error may have appeared in the bulk density measurement.

Decreases in dry bulk density at the 0.05 m depth can be explained as an inconsistency in the soil density measurement caused by wide vertical cracks which were observed at the surface.

In general, Eq. (7) appeared to have utility in describing soil water content. The second experiment tested the method.

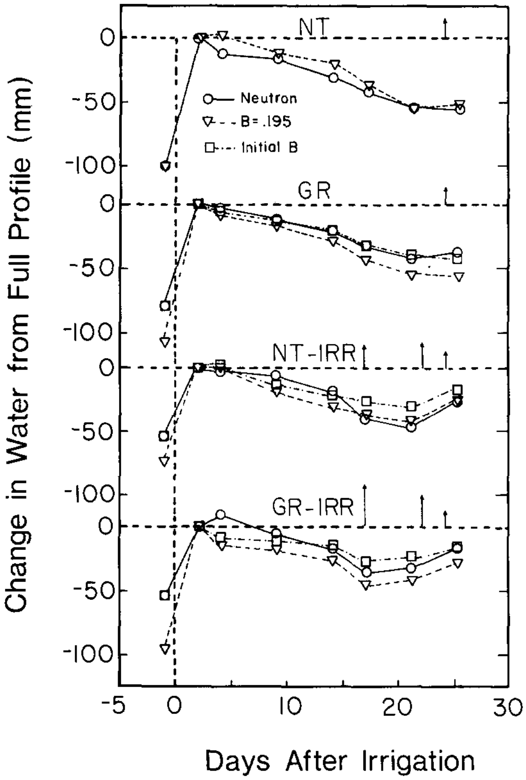

Fig. 4. Water loss for Trial 2 referenced to a wet soil 2 days after irrigation as calculated from neutron moisture meter, a surface shrinkage with universal $b = 0.195$, and local surface shrinkage using b' values. Arrows indicate time and magnitude of precipitation event

Trial 2

Prediction of water loss by surface elevation is compared with neutron probe measurements in Fig. 4. Water loss was calculated in two ways: first using the pooled average of all treatments of Trial 1 (0.195). The second method used the initial value of b determined by the change in elevation before and after the initial surface irrigation, or b'. Hence b' was a local value of swelling treatment for each access tube. Values of b' were b' (NT) = 0.194, b' (NT-irr) = 0.265, b' (GR) = 0.262, and b' (GR-irr) = 0.336. The NT treatment b' was identical to the universal value, but the other treatments had greater b' values, meaning the soil swelled at a higher rate. The b' values were unrelated to traffic treatment, unlike Trial 1. The variability in the b' values suggest that shrinkage is not uniform in a field settling. The cause of this variability was not determined, but it may be attributed to root anchoring, and/or proximity to large cracks.

The b' values closely paralleled the water loss measured from neutron probe (Fig. 4). The universal b was not as accurate as b' over the period, and was not a good predictor of soil swelling for the initial surface irrigation. Both surface elevation and neutron probe soil water measurements were responsive to irrigation and rainfall events.

Conclusions and summary

Shrinkage of a Holtville soil is proportional to water loss but less responsive than a *unitary*-shrinking soil. The field shrinkage ratio, b, was statistically similar to that of undisturbed cores at the $a = 0.10$ confidence level. Any difference between the field and core shrinkage may be attributed to the anchoring of the soil by roots.

Lack of soil compacting forces resulted in a unconsolidated soil with inconsistent shrinkage, and the possibility of horizontal cracking below the surface. Without compaction, the surface elevation will not be proportional to profile water content. Otherwise, surface shrinkage was a good predictor of water content. Local, site-specific b' values were superior to a universal b value for predicting profile soil water because of the variability of shrinkage in the field.

The soil surface shrinkage method can be used to estimate water loss in the soil profile and schedule irrigation. Since the only measurement is the surface elevation, it has a potential to be monitored remotely, by using either a linear variable differential transformer transducer, or laser (Huang et al. 1988). Soils should be calibrated in the field for b. Caution should be used to measure areas which have consolidated to shrink consistently.

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