Flood Irrigation of a Cracked Soil

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ABSTRACT

An understanding of water flow into cracking, irrigated soils is necessary in order to address problems of plant water stress, inefficient water application, lack of aeration, and salt accumulation in the soil due to inadequate leaching. The objectives of this study were to investigate water infiltration into a cracked clay soil during flood irrigation, and to observe the differences in infiltration and cracking patterns between fallow soil following wheat (*Triticum turgidum* L. 'Yecoro Rojo') and soil under alfalfa (*Medicago sativa* L. 'CUF 101'). A large weighing lysimeter was used to measure infiltration and evaporation. The infiltration was analyzed as consisting of three phases of crack filling, sorption, and transmission. The infiltration curves were found to be similar for all irrigations, with a larger percentage of the total infiltrated water initially entering the cracks of the drier alfalfa soil (74%) than the wheat-cropped soil (63%). Final infiltration rates were 0.4 and 0.6 mm h^{-1} for the alfalfa and wheat irrigations, respectively. Evaporation was shown to be a large component of water loss during the later stages of irrigation, sometimes exceeding the infiltration rate. Cracking patterns could be observed because of the presence of foam, which consists of organic acids picked up by water rising in the cracks. The wheat-cropped fallow soil had more numerous cracks than alfalfa-cropped soil, which was attributed to its fiberous root system, which is weaker than the alfalfa taproot system. The difference in cracking patterns between the two crops has implications for water flow.

A BETTER UNDERSTANDING of the nature of infiltration in cracking soil under flood irrigation is necessary in order to address the problems of poor permeability in irrigated, arid-zone soils. Poor permeability during infiltration and redistribution may have severe economic consequences for irrigated agriculture when it results in inadequate water storage, inefficient and nonuniform water application, lack of aeration, or excess salinity (Oster and Singer, 1984). Many of the poorly permeable soils, such as those in California's Imperial Valley, are alluvial soils (fluvic Entisols) with smectite mineralogy (Perrier et al., 1974). Seventy percent of the irrigated soils there are fine-textured with relatively low infiltration rates (IRs) (Zimmerman et al., 1980). Flood irrigation is widely used because of several management considerations, including the presence of level fields, and the availability of relatively inexpensive irrigation water from the Colorado River. Silt makes up a large component of these soils, which causes them to shrink at rates that are less than the unitary shrinkage rate (Mitchell and van Genuchten, 1992), a phenomenon not uncommon for cracking soils (Jayawardane and Greacen, 1987).

Water flow in cracking soil consists of a dichotomy of rapid flow in cracks and very slow flow in the swelling soil. Water can be conducted rapidly in the cracks of an otherwise impermeable soil (Yong and Warkentin, 1975). For example, agronomic practices that disturb the soil surface, such as intensive grazing, having been shown to have no negative effect on water infiltration because of the flow of water into cracks (Mitchell et al., 1991). As suggested by Swartz (1966), the total infiltrable volume of water may be more indicative of the irrigation process than the IR of the soil, especially if the final IR is very low. Soils in the Imperial Valley of California have been documented to have low final IRs (Perrier et al., 1974), as do other irrigated swelling soils, including Vertisols in India (Shanware and Gawande, 1989) and soils in Queensland, Australia (Swartz, 1966). The challenge of irrigation management of cracking soils is to take advantage of the rapid water intake rate of a dry, cracked soil, while keeping plant water stress at a minimum.

Infiltration equations for nonmacroporous soil need to be modified for cracking soil. Water flow in nonmacroporous soil is theorized as consisting of sorptive flow and gravitational flow, and corresponding terms may be found in versions of the classic Richards' equation, where a diffusivity-like term determines sorptive flow and a conductivity term described gravitational flow. Likewise, empirical infiltration equations usually contain a sorption term that parameterizes water sorption and a gravity-driven term that is associated with the saturated hydraulic conductivity (e.g. Philip, 1957; Collis-George, 1977). For soils dominated by macropores, an additional term is needed in the equation to describe the water intake into the cracks (Collis-George, 1977). During the crack-filling (CF) phase of flood irrigation, the IR is equal to the water application rate. The initial intake of water into soil cracks prior to ponding has been estimated by Bridge and Ross (1984) to be approximately two-thirds of the total intake.

Unfortunately, there is little published field data to support the two-thirds rule. One reason may be the difficulty of measuring the amount of water added during CF; this measurement is not amenable to the standard cylinder infiltrometer (Bouwer, 1986) measurement of ponded irrigation because of the lateral loss of water from the measurement area through cracks. Attempts to use extracted cores to describe the hydraulic properties have failed since they are not representative of the cracks (Ritchie et al., 1972). Studies of rainfall infiltration into cracked clay have produced valuable information about cracking morphology (Bouma, 1984), but are inadequate to describe water intake during the flood irrigation process. Under rainfall conditions, only runoff water will flow into the crack; whereas during flood irrigation the water flows *first* into the large cracks. Sprinkler irrigation may result in the closure of cracks near the soil surface, which would limit water intake compared with flood irrigation. For these reasons, sprinkler infiltrometer

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Abbreviations: IR, infiltration rate; CF, crack filling; ER, evaporation rate.

methods (Peterson and Bubenzer, 1986) are not applicable to flood irrigation conditions for cracking soils.

Since cracks play a major role in the infiltration process, it is important to consider their size and location. Different crops may have dissimilar root systems, which could result in unequal water extraction and different cracking patterns. The spatial distribution of cracks in an expansive soil can be influenced by the anchoring of swelling soil by roots, called *root anchoring* by Fox (1964). This effect will be discussed in greater depth below.

We observed differences in infiltration during flood irrigation applied to a single lysimeter supporting wheat and alfalfa at different times. The specific objectives of this research were to: (i) investigate the nature of water infiltration into a cracked clay soil during flood irrigation, and (ii) observe the differences in cracking that are induced by two different crops (alfalfa and wheat).

MATERIALS AND METHODS

Lysimeter Description

A large weighing lysimeter was used to accurately measure water application and evaporation during flood irrigations. The lysimeter was located at the USDA-ARS Irrigated Desert Research Station, 1 km north of Brawley, Imperial County, California. The lysimeter was situated in the middle of a 2-ha field, at a distance of 80 m from farm roads on the north and south. The lysimeter consisted of a steel box 3 by 3 by 1.5 m deep, which rested on an industrial-size truck balance. It had an underground access hole nearby, which enabled measurement of both weight and drainage. The lysimeter was gravity drained into a 75-L tank that allowed collection of drainage water. Installed in 1966, the lysimeter has been used to determine consumptive use of water for several crops.

The soil in the lysimeter was disturbed during installation, but was repacked in the lysimeter by layers to simulate the soil profile of the surrounding field. The Holtville silty clay near the lysimeter was classified as a clayey-over-loamy, montmorillonitic (calcareous), hyperthermic Typic Torrifluvent (Zimmerman et al., 1980). Soil texture at the surface was silty clay with 60% clay, 38% silt, and 2% sand, as determined by the hydrometer method.

Because most standard methods for measuring infiltration are inadequate for cracking soils, and to avoid installing new plots with barriers to prevent lateral flow, the large weighing lysimeter was chosen since it already had barriers in place. Lysimeter measurements were used during water application to determine the rate of application; thereafter the measurements were equivalent to evaporation. Evaporation measurements were extremely important because, as will be shown below, evaporation data can introduce large errors in the IR measurements during the later stages of irrigation. The lysimeter's weight measurements (including evaporation) were precise to within 0.25 mm of water. This precision applies to the total amount of applied water; hence, an irrigation of 120 mm translates to a maximum reading error of 0.2%. The irrigations did not permit multiple measurements at any one time, hence standard statistical tests for variability are not applicable (Kempthorne and Allmaras, 1986). The precision of the time factor in application rate was estimated at 10 s per 100 s of irrigation, or $\approx 1\%$. Thus the lysimeter provided application rate measurements that were more precise than direct measurements of water inflow rates by the irrigation system.

The IR was measured using a measuring stick with a millimeter scale that was attached to a neutron access tube anchored to the bottom of the lysimeter. The precision of the IR measurements was dependent on the water surface declination in time, which was precise to ≈ 0.5 mm. For the sorption phase, the rate was measured every 0.2 h, during which time the water height dropped at least 2 mm. Thus the IR measurement errors did not exceed 0.5 mm per 2 mm, or 25%, while the time measurements were precise to within 10 s for a 360-s period, or 3%. During the final irrigation stages, a measurement period of 1 h could have produced an error of 0.5 mm, or 0.5 mm h^{-1}, in the IR. This error is similar in size to the IR for that period. However, since the measurements were taken for at least 8 h, the error during the final hours was estimated at 0.5 mm for a 5-mm lowering, or a maximum reading error of <10%.

Crop Preparation and Irrigation

The flood irrigations were conducted with Colorado River water having an electrical conductivity of 1.4 dS m^{-1}, and a sodium adsorption ratio of 3.2 (mmol $L^{-1})^{1/2}$. The first fallow irrigation occurred on 13 Sept. 1989 following a wheat crop. A second fallow irrigation the following day on the same lysimeter was judged to be necessary since a very low final IR had not yet been reached. Prior to the first fallow irrigation, soil drying took place during a long summer fallow period that followed a wheat harvest in June of that year. Cracks were measured to a depth of 150 mm by forcing a narrow measuring tape as far as possible down the cracks. The soil below the cracking depth was relatively moist.

Following the 1989 irrigation, alfalfa was grown in the lysimeter for the purpose of inducing soil drying and cracking at greater depths. Alfalfa was sown in October 1989 and irrigated at regular intervals to encourage stand establishment and root growth. The alfalfa was first harvested on 6 Mar. 1990, after which it was irrigated with 63 mm of water. Then the lysimeter was allowed to dry for 6 wk (235 mm of water lost) until the alfalfa irrigation on 19 Apr. 1990.

Prior to the alfalfa irrigation, the plants were harvested and removed from the lysimeter so that they would not interfere with later observations and measurements. Prior to irrigation, the minimum cracking depth was measured to be 650 mm. During all irrigations, the water's turbulent energy was dissipated by a perforated plastic tube with a plastic sheet underneath. Drainage was monitored in the lysimeter's drainage tank during the irrigations. During the alfalfa irrigation, neutron meter measurements were taken to determine wetting front penetration at 0, 0.4, 0.8, 3.8, 22, 27, and 95 h. Unlike other swelling soils (Greacen and Schrale, 1976), the neutron meter calibration was reported to be linear for the Holtville silty clay (Mitchell, 1991) with an r^2 of 94% and a standard error of estimate of 0.024 m^3 m^{-3}.

RESULTS AND DISCUSSION

The analysis of the data was based on three processes of CF, sorption into dry soil, and transmission through wet soil. The total applied water was separated into components of (i) CF water up until time of ponding, (ii) water that infiltrated after ponding through the sorption and transmission processes, and (iii) water loss through evaporation. The transmission phase is defined here as the period when water flows solely due to gravity in saturated swollen soil.

Irrigation components and IRs for the first fallow irrigation are shown in Fig. 1, with more detailed data given in Table 1. Colorado River water (121 mm) was applied at a rate of 440 mm h^{-1}, which is equivalent to the initial IR. The infiltration functions (Fig. 1, 2, and 3) are plotted on both logarithmic (left) as well as the linear (right) axes in order to better show the sharp drop in IR after the CF stage. This initial IR was simply the

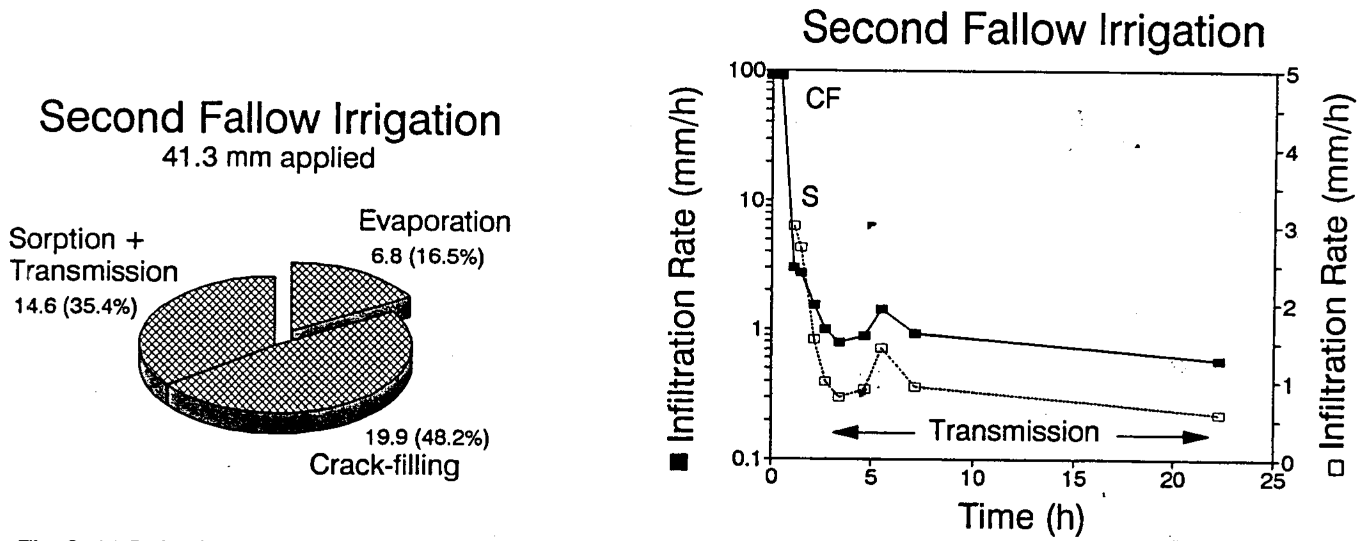

Fig. 2. (a) Irrigation components and (b) infiltration rates for the second fallow irrigation on 14 Sept. 1989. The irrigation rate is plotted using both logarithmic and linear axes.

may have been the result of swelling of the soil that raised the soil surface and the water level, resulting in lower readings during that time period. It can be seen that the soil surface elevation increased 40 mm between the first and second fallow irrigations (Table 2). Although no surface elevation change was noted for the ponding heights of Table 1, it is possible that swelling elsewhere resulted in a surface rise of a few millimeters that may have offset the drop in ponding height by which the IR was measured. The end effect would be a temporary decrease in the IR, such as was observed.

Redistribution

Soil water content data during and after the alfalfa irrigation (Fig. 4) show that there was a large change in water content between the dry lysimeter (time = 0) and the next measurement (time = 0.8 h). The next 3 h exhibited little change in water content (data not shown). Water contents measured the following day (time = 22 h) were less in the top 50 cm of the profile, indicating a combination of drainage, evaporation, or horizontal flow away from the neutron access tube. Because drainage was zero, the change in the water content can be attributed to evaporation or lateral flow away from the neutron tube. Small changes in water content below 90 cm after 95 h (Fig. 4) were well within the measurement error ($s_{y.x}$ = 0.024 $m^3 m^{-3}$). The data indicate that little, if any, downward redistribution of water occurred below the bottom of the cracks between 0.8 and 95 h.

Intake from Crack Filling

Crack filling was a large component of irrigation amounts. For the first irrigation, the CF water was 63% of the total *infiltrated* water, not the total applied water

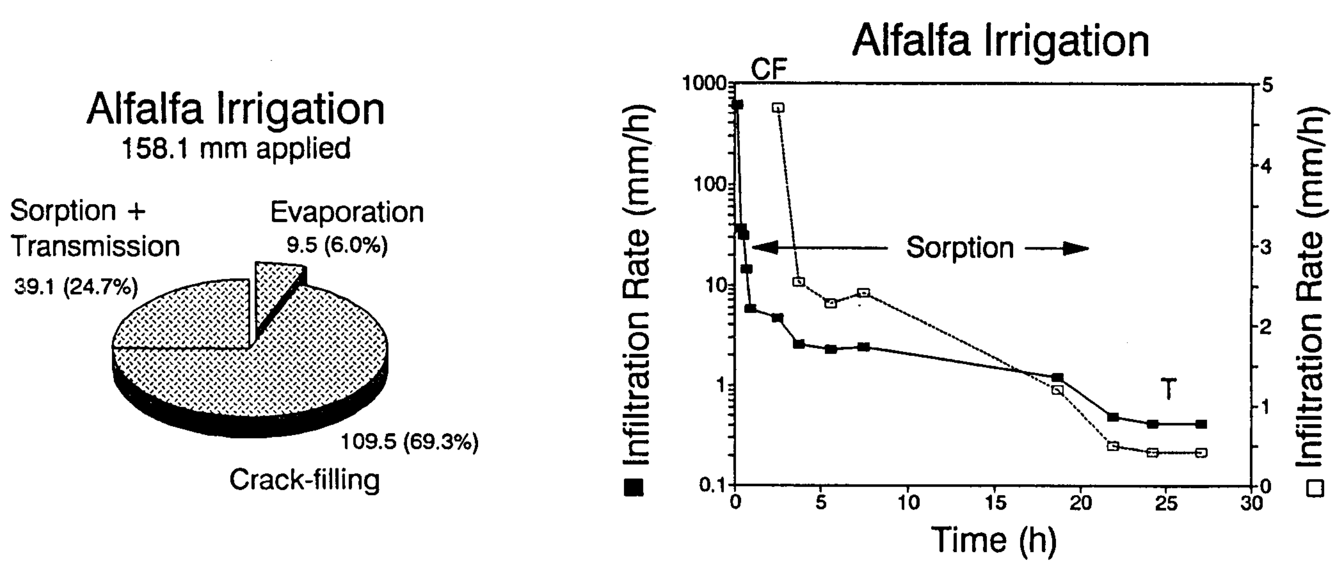

Fig. 3. (a) Irrigation components and (b) infiltration rate for the alfalfa irrigation on 19 Apr. 1990. The irrigation rate is plotted using both logarithmic and linear axes.

Table 2. Lysimeter-measured components of the first fallow irrigation on 14 Sept. 1989. Applied water is the amount of water added to the lysimeter; Ponding ht. is the height of water above the soil above the original soil surface of the previous irrigation, and which swelled overnight; ER is the evaporation rate as measured by changes in lysimeter weight; IR is the infiltration rate corrected for evaporation.

Time	Cumulative time	Water applied	Ponding ht.	ER	IR
	h	mm		mm/h	
0800	0.00	0.0	40§		
0815.5†	0.22	19.9			91.7
0818	0.30	27.5			91.7
0827‡	0.45	41.3	64		
0907	1.12	41.0	62		3.0
0929	1.48	40.9	61		2.7
1008	2.13	40.6	60		1.5
1045	2.75	40.2	59	−0.6	1.0
1127	3.45	39.8	58	−0.6	0.8
1242	4.70	38.9	56	−0.7	0.9
1332	5.53	38.1	54	−1.0	1.4
1532	7.17	37.6	52	−0.3	0.9
0620	22.33	34.5	40	−0.2	0.6

† Time of ponding.
‡ Time when water application was concluded.
§ Height relative to previous day's zero reading starts at 40 mm due to soil swelling overnight.

Table 3. Lysimeter-measured components of the alfalfa irrigation on 19 Apr. 1990. Applied water is the amount of water added to the lysimeter; Ponding ht. is the height of water above the soil; ER is the evaporation rate as measured by changes in lysimeter weight; IR is the infiltration rate corrected for evaporation. The ER during the period from 0.258 to 0.542 h included a correction for leakage from the sides of the lysimeter when the water was ponded at its highest level.

Time	Cumulative time	Water applied	Ponding height	ER	IR
	h	mm		mm/h	
1100.5	0	0			
1110.8†	0.172	109.5	0		613
1116‡	0.258	158.1	87		613
1123	0.375	157.9	82.5	−1.8	37
1133	0.542	157.5	77	−1.8	31
1143	0.708	157.4	74.5	−0.7	14
1157	0.942	157.3	73	−0.7	5.8
1329	2.475	156	64.5	−0.9	4.7
1445	3.742	155.2	60.5	−0.6	2.5
1636	5.592	153.9	55	−0.7	2.3
1830	7.492	153	49.5	−0.5	2.4
540	18.658	151.8	35	−0.1	1.2
855	21.908	151.4	33	−0.1	0.5
1113	24.208	150.6	31.5	−0.3	0.4
1407	27.108	148.6	28	−0.7	0.4

† Time of ponding.
‡ Time when water application was concluded.

as shown in Fig. 1, 2, and 3. In this case, 63% represents 74.3 mm divided by 118 mm. The second irrigation had a slightly smaller CF of 58% (19.9/34.5 mm infiltrated) due to reduced cracking caused by the irrigation the day before. For the alfalfa irrigation, the CF water (at time of ponding) was 74% of the total water infiltrated minus evaporation. The greater CF of drier alfalfa soil agrees with Stirk (1954), who found that infiltration increased for a drier soil.

Results from all three irrigations were nearly equal to the two-thirds rule of Bridge and Ross (1984) mentioned above. The rationale for the two-thirds rule originates from the assumption of isotropic shrinkage, which implies that one-third of the void space will be located in a surface shrinkage void (Bridge and Ross, 1984). The remaining two-thirds of the void space will be in cracks. In reality, slightly more than one-third of the void space will be at the surface and less than two-thirds in the cracks (see Eq. [2]–[4] of Mitchell, 1991). During the CF stage, sorptive flow will also contribute to the amount of water required to fill the cracks, so that the CF amount may approach or exceed the two-thirds ratio. Bridge and Ross (1984) equated the total void space with the profile water deficit below saturation, thereby assuming unitary shrinkage (water loss = void space). The Holtville silty clay shrinks at lower rates (Mitchell and van Genuchten, 1992), therefore the crack volume will be less than two-thirds of the water deficit. The nearness of our data to the two-thirds rule, in spite of smaller crack volume, indicates a large amount of water infiltrated by sorption during the CF stage.

The infiltration curves indicate that high efficiency is achievable for flood irrigation, provided runoff is minimized. The high CF intake promotes quick water entry, whereas the low final IR prevents excess water from leaching through the root zone. In a 5-yr study on irrigation efficiencies in the Imperial Valley (Oster et al., 1986), more than half the crops studied had efficiencies >70%, with some as high as 79%. When drainage was below 10% of applied water, the efficiency was usually >70%. Uniformity of irrigation can be high for cracking soils. Flood irrigation of most noncracking soils usually results in the head end of the field receiving excess water, and the tail end insufficient water. For cracking soils, the tail end of the field receives a large amount of water in a short time period due to CF, while the low final IR limits leaching at the head end, even if ponded for long periods. Another advantage of cracking soils is the lateral, subsurface flow of water in cracks, which ensures that the water reaches all areas of the field. Of course, variability of soil types or topography can result in non-

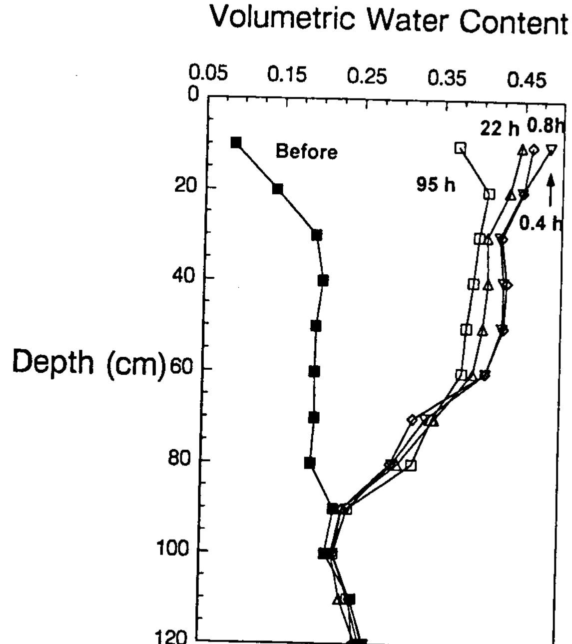

Fig 4. Water content of the lysimeter soil profile at several times during and after alfalfa irrigation on 19 Apr. 1990.

to rise upward in the cracks. We observed that the rising water picked up debris (mostly organic acids), which manifested itself as foam on the water surface. The foam remained in place over the opening of the crack as the water ponded (Fig. 5) and served as a marker of the water-conducting cracks. The foam markers are generally not observable during a field irrigation event because the flowing surface water will wash the debris downstream. Both the first fallow and alfalfa irrigations manifested the foam, but in drastically different patterns and spacings. The wheat-fallow soil produced foam patterns that were 20 cm apart in most cases. The alfalfa irrigation produced foam that marked only a few large cracks spaced up to 1 m apart.

These differences in cracking patterns are probably caused by the different rooting characteristics and water extraction processes of the two crops. The size of an island, or soil matrix between the cracks, reflects the ability of a crop to anchor soil. Root anchoring has been observed to induce between-row cracking in corn (*Zea mays* L.) (Johnston and Hill, 1944) and furrow-irrigation cotton (*Gossypium hirsutum* L.) (Chan and Hodgson, 1984). Johnston and Hill (1944) did not find between-row cracking for crops with fibrous root systems; instead, the cracks were randomly oriented. This results from the relative weakness of the fibrous root systems, which cannot offset the mechanical stresses imposed by shrinkage. Alfalfa, with its strong taproot and lateral roots, binds the soil together like a netting. However, the shrinkage forces must be resolved somewhere, and eventually the root netting is broken, resulting in a relatively few, but large, cracks. Thereafter, cracks will grow wider with further soil drying. The wheat crop, on the other hand, possesses fibrous roots that are not as strong, which results in cracks occurring closer together. The water extraction pattern also contributes to the final crack location, especially for plants grown in rows (Johnston and Hill, 1944). In a row-crop system, water contents are higher between the rows than under the plant rows; hence, the soil between the rows is mechanically weaker than the drier root-anchored soil, and cracks are formed between the crop rows.

Root systems may influence water flow through their effect on crack spacing. Since infiltration is dominated by water flow into cracks, the spatial pattern of water flow in a cracked soil will depend on the crack spacing. For a taprooted crop with large and strong roots (e.g., alfalfa and cotton) one may expect large cracks with greater distances between them; conversely, for a fibrous-rooted crop one may anticipate more numerous, smaller cracks. The distance between cracks is an important parameter for understanding water flow in cracked soils because it specifies the size of a basic soil volume, and the locations of free water flow. Greater distances between cracks will not only lead to larger cracks, but also to greater distances for water to permeate horizontally through the soil. It is possible that the lower final IR of the alfalfa irrigation was due to the larger distance between cracks for the water to travel. The different cracking patterns have additional implications for formulating two-dimensional solutions of water flow in a flood-irrigated cracking soil. For example, a soil with greater distances between cracks may require more time to become fully saturated due to the greater distance between the water-flow boundary and the interior of the structural units.

Although the differences in cracking patterns may be attributable to root anchoring, as claimed here, another possible explanation is soil consolidation with time. Kuznetsova and Danilova (1988) showed that swelling soils in the field consolidate as a result of mechanical forces and wetting and drying cycles. In their view, the soil volume eventually consolidates to a point below a critical compaction threshold where the soil loses its ability to spontaneously achieve a favorable condition of low density. These compacted, expansive soils must then be remediated by tillage to restore their optimal density. It is conceivable that the low final IRs observed in our study were signifying the need for remedial tillage. Note that the alfalfa in our experiment was sown without tillage following wheat. It would also be reasonable to conclude that soil consolidation may contribute to the lower final IR under the alfalfa crop than the wheat-fallow.

SUMMARY AND CONCLUSIONS

Water intake processes were similar for two fallow irrigations and an alfalfa irrigation with 63, 58, and 74% respectively, of the total infiltrated water entering the soil during the CF stage. High efficiencies for flood irrigation can be attributed to the dominant CF stage followed by a low final IR. Small increases in the IR during the sorption stage is a phenomenon that may result from soil surface swelling. The final IRs of this study (0.6 and 0.4 mm h^{-1}) are less than 1.0 mm h^{-1} threshold suggested by the U.S. Salinity Laboratory Staff (1954) as the minimum necessary for crop production on irrigated soils. This threshold may not be appropriate for cracking soils, which initially have large water intake rates.

The IR functions can improve our understanding of how water intake occurs in time by highlighting the importance of the CF stage. The foam markers provided information on the larger crack spacings of the alfalfa, compared with the wheat. Together, these two observations reveal how large amounts of water enter the deep cracks and flow horizontally into the soil volume. The size of the soil volume between cracks was found to depend on crop type or soil consolidation.

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Soil Water and Nutrient Change in Stands of Three Perennial Crops

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ABSTRACT

Perennial grains have potential as alternative crops for low-input agricultural systems. This study was conducted to describe seasonal and spatial patterns of soil water and nutrient change in experimental stands of wildrye [*Leymus racemosus* (Lam.) Tsvelev], eastern gamagrass [*Tripsacum dactyloides* (L.) L.], and Illinois bundleflower [*Desmanthus illinoensis* (Michx.) MacM.]. Changes in soil water pressure, organic C, and nutrient concentrations were monitored regularly at three depths (5–15, 35–45, and 90–100 cm) from March 1988 through October 1989, and soil nutrients were sampled again in April 1991 and March 1992, to document species differences in resource use and effects on soil nutrient balance with time. During the first two growing seasons, crops showed strong seasonal and spatial differences in resource extraction. Annual precipitation in 1988 and 1989 was below normal. Soil water pressure under bundleflower stands declined rapidly by mid-summer 1988 and approached −1.5 MPa at 100 cm by late summer 1988. Water pressure declined more gradually in the grass stands, remaining generally highest in wildrye. Bundleflower and gamagrass depleted relatively more soil water in summer, whereas wildrye used relatively more soil water in spring and autumn 1989. Inorganic N increased at 10 and 40 cm in wildrye stands in the first year and remained higher than in stands of the other two species from late 1988 through late summer 1989. In general, P increased at 10 cm in grass stands, especially in wildrye. Otherwise, there were few consistent differences among species in levels of soil C, P, K, Ca, Mg, and pH during the first two growing seasons. After three years, soil organic C was generally highest in gamagrass stands, whereas NO_3^- concentration was highest for wildrye. The next year, however, NO_3^- was highest in wildrye at 100 cm only.

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A MAJOR OBJECTIVE of research in sustainable agriculture is to develop innovative methods of crop production that minimize negative environmental impacts. Mixtures of new perennial seed crops that are complementary in pattern of resource use would provide a continuous cover of vegetation that could both reduce erosion on sloping ground (Maass et al., 1988) and build soil organic matter through the gradual turnover of belowground organs (Dahlman and Kucera, 1965; Reid and Goss, 1981; Dormaar and Smoliak, 1985) while minimizing the need for fossil-fuel-based energy, synthetic fertilizers, and pesticides (Soule and Piper, 1992). On restored cropland, perennial vegetation can improve some soil biological and physical properties within periods of only a few growing seasons (Jastrow, 1987).

In natural plant communities, most of the differences among coexisting species that enable minimal overlap in resource demand involve the location and timing of resource interception (McKane et al., 1990). Similarly, in agricultural mixtures roots of different species may explore different soil layers, exhibit complementary nutrient requirements or uptake abilities, or differ in length of growing period or in seasonality of nutrient uptake. Understanding the long-term net effects of new perennial crops on soil is important both for managing fertility as well as predicting interactions between crops in mixtures.

First, temporal displacement of peak growth period may provide a means of reducing competition between crops for soil resources in mixed plantings. For example, C_3 grasses typically display most of their growth