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Alfalfa (*Medicago sativa* L.) water use efficiency as affected by harvest traffic and soil compaction in a sandy loam soil

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Summary. Traffic during alfalfa harvest operations can cause soil compaction and damage to newly growing stems. Root exploration for soil water and nutrients, forage growth dynamics, and final yield can all be affected. The objectives of this study were to determine the long-term effects of harvest traffic and soil compaction on water-use efficiency (WUE) of alfalfa grown in a Wasco sandy loam (coarse-loamy, mixed, nonacid, thermic Typic Torriorthents). Alfalfa was planted into tilled soil and managed with or without harvest traffic. Plants subjected to traffic during harvest had a significantly lower WUE two out of the three years studied compared to plants that were never subject to traffic. The second experiment examined whether planting alfalfa into compacted soil and managed with or without harvest traffic altered WUE. Soil compaction had no affect on alfalfa WUE. It was significantly lower when grown in compacted soil and subjected to harvest traffic. It is suggested that the decrease in WUE caused by harvest traffic may be explained by plants allocating carbohydrates to damaged shoots and crowns instead of to above ground forage production. The area of the field affected by harvest traffic, which damages newly growing stems, should be minimized to increase crop water use efficiency.

Crop water-use efficiency (WUE) is the linear relationship between production and water use (Tanner and Sinclair 1983; Turner and Burch 1983). For most crops only a single value for each season is available when it is calculated by dividing economic yield by the total amount of water used. Alfalfa is unique in that three to seven harvests per season, depending on location, can be utilized to define WUE. This gives an estimation of water use from harvest to harvest throughout the season. A common WUE for alfalfa in the western United States has been proposed by Sammis (1981), but Sheaffer et al. (1987) argued that the value depended on local climate and management practices. It has also been reported that individual harvests have different efficiencies. In a study by Undersander (1987) there was a high coefficient of determination for the relationship between dry-matter and water use for a single harvest cycle, but when all harvest data for the season were combined it was lower.

Most research on WUE of alfalfa has been done with lysimeters or small field plots where different amounts of water, different cultivars, or other environmental variables were examined (Sammis 1981; Daigger et al. 1970; Wright 1988). However, experiments addressing how harvest traffic can affect the relationship of yield and water use can be cumbersome and data acquisition awkward and expensive. Harvest traffic though can be an important variable to consider given that up to 70% of a grower's field can be subject to traffic during a single harvest operation (Grimes et al. 1978). We have shown that water infiltration rates were reduced by conventional harvest traffic (Meek et al. 1989). That traffic increased soil bulk density to a depth of 0.45 m after one year (Meek et al. 1988). It also caused a significant reduction in dry matter production rates for a given growth cycle (Rechel et al. 1987) and decreased annual total yields (Rechel et al. 1991). Fine root density was significantly less from the surface to a depth of 1.8 m with multiple passes of harvest equipment and to a 0.45 m depth from a single pass compared to no traffic at harvest (Rechel et al. 1990). These changes in soil characteristics and growth dynamics could affect plant water use. The objective of this study was to determine if WUE of alfalfa was significantly altered by harvest traffic and soil compaction.

Materials and methods

The research was conducted on the USDA Cotton Research Station, Shafter, CA, at 35°32′N, 119°16′W, and 113 m above sea level. The soil is a Wasco sandy loam (coarse-loamy, mixed nonacid thermic Typic Torriorthents). Annual average precipitation is 160 mm yr^{-1} with little rainfall from May to September. There are 7 to 8 harvests per year starting in March and ending in November.

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Two experiments were conducted over a 7-year period. The first one was designed to study the affect of harvest traffic on alfalfa water use. All cultural operations in both experiments were carried out with tools suspended from the wide-tractive-research-vehicle (WTRV) which spanned the entire width of the plot. The WTRV traveled on permanent 1-m wide raised wheel paths which ran the length of the plots which also acted as borders between plots and levees for irrigation basins. In August 1982 all plots were initially tilled to 0.15 m with a conventional tractor. Following this the WTRV was used to chisel each plot to a depth of 0.54 m in 0.18-m increments with 0.33-m-spaced shanks. Alfalfa, nondormant cultivar 'WL 514', was broadcast seeded in October 1982 on plots 8 m by 30 m at 33.6 kg ha^{-1}. Triple superphosphate was broadcast at 162 kg P ha^{-1} in February 1983. Tensiometer and soil water content measurements were taken from catwalks which completely spanned each plot. Foot traffic was not allowed in any plot.

Treatments were the presence or absence of harvest traffic at different times during production. The treatment designated NN was established by directly sowing the alfalfa into the chiseled soil using the WTRV and excluding all wheel traffic in subsequent production practices. The second treatment (PR) was established by compacting the entire area of the highly disturbed soil after it had dried, but before sowing with a John Deere 4020. No wheel traffic was applied at any time after this initial compaction. Plots in the third treatment (RE) were initially compacted in the same manner as PR and in addition 100% of the area was subject to single passes from a John Deere 4020 tractor 3 to 5 days after each harvest. The rear tires were 18.4–34, 6 ply, 2020-kg, inflated to 150 kPa, and the front tires were 10.0–16, 6 ply, 823-kg, inflated to 138 kPa.

The objective of the second experiment, conducted from April 1986 to October 1988, was to differentiate the effect of soil compaction from harvest traffic on alfalfa water use. Alfalfa, nondormant cultivar "CUF 101", was broadcast seeded on 14 April, 1986 at 35.8 kg ha^{-1} on plots measuring 8 × 20 m. Triple superphosphate was broadcast at 162 kg P ha^{-1} in June 1986. In February 1986, all plots were chiseled to a depth of 0.45 m with shanks spaced on 0.3 m centers to reduce variation due to previous soil management. Soil treatments, established in March 1986, consisted of three levels of preplant soil compaction with no traffic during harvest and a fourth treatment which combined heavy preplant compaction with harvest traffic applied to each plot. Treatments were: 1) [Light (LI)] Alfalfa was seeded into soil that had been chiseled after which 100% of the area was lightly compacted with an 8-ply tire inflated to 41.4 kPa with a 1362-kg load, 2) [Medium (MD)], Plots were first flooded then 100% of the area compacted 4 days later with the same tire as used in the LI treatment except it was inflated to 137.9 kPa with a 2951-kg load, 3) [Heavy (HV)] Plots were also flooded and 100% of the area of each plot was compacted 4 days later with a 12-ply tire inflated to 275.8 kPa, with a 2769-kg load, and 4) [Heavy compaction plus Traffic (HVTR)] Soil conditions were initially established in the same manner as the HV plots; in addition 100% of each plot was trafficked 3–4 days after each harvest with an 8 ply tire inflated to 134 kPa with a 1816-kg load.

Alfalfa in the first experiment was flood irrigated when 50% of the available water was depleted in at least 25% of the plots to a depth of 0.6 m which held 116 mm of water at field capacity. The second experiment was also flood irrigated when the average Crop Water Stress Index for a given treatment was ≥ 0.25 for two days in a row. Soil water determinations, taken from an access tube placed in the middle of each plot, were made immediately before and 3 days after irrigations and at harvest time to a depth of 1.8 m using a Troxler[1] neutron probe. Water use in the first year of the first experiment, 1983, is not given because of problems in obtaining soil water content. Crop ET was calculatd as the difference between soil moisture depletion, as measured by the neutron probe, and drainage loss. The ET was estimated for the first growth cycle by a backward extrapolation of the pan coefficients from the second growth cycle.

Drainage was estimated by measuring unsaturated hydraulic conductivity at the lower end of the root zone in all plots in both experiments. The procedure used was similar to that of Nielsen et al. (1964), which has been labeled by some as the "instantaneous profile method" (Watson 1966; Baker 1974). Soil moisture and tension, used to develop moisture-retention curves, were taken at the top, middle, and bottom of a 0.3 m thick zone at the bottom of the root zone. Knowing the potential across the zone, the flux through the zone, and assuming Darcy's law valid, the unsaturated-hydraulic conductivity was calculated and plotted as a function of the average moisture content of the zone. Once the conductivity-moisture function was available, along with tensiometer readings and moisture content it was straight forward procedure to calculate the drainage loss out the bottom of the root zone throughout the season.

Bulk density was measured using a two-probe density gauge (Model 2376, Troxler Lab., Triangle Park, NC). Readings were taken from parallel aluminum access tubes, 0.30 m apart, inserted to a depth of 0.65 m. A detailed description of the procedure is provided by Meek et al. (1988).

The experimental design for both experiments was a split-plot with the main plots (traffic patterns) in a randomized complete block design with 6 replications, repeated over time for a given year. The statistical procedure to determine significant differences among regression equations used analysis of covariance as described by Steel and Torrie (1960). The homogeneity of the regression coefficient (slope) was posed as a null hypothesis. Once this was tested and all slopes were verified as homogeneous, all values of the dependent variable (cumulative dry matter) for each treatment were adjusted to a common ET. The means of the adjusted values for each treatment were then compared by normal analysis of variance procedures. The test of homogeneity of regression coefficient for the regressions indicated a highly significant difference among equations. For any two linear equations to be the same they must have the same slope and intercept. Some of the equations did not have the same slope statistically; some which had the same slope did not have the same intercept.

Results and discussion

Both soil bulk density and water infiltration rates were significantly affected by harvest traffic and soil compaction. The depth and rate at which harvest traffic increased bulk density in the first experiment is discussed by Meek et al. (1988). The heavy preplant compaction of the second experiment significantly increased soil bulk density to a depth of 0.45 m while the addition of traffic on this treatment only increased it to 0.25 m (Table 1). Harvest traffic and soil compaction also significantly decreased water infiltration rates (Meek et al. 1989; Rechel et al. 1991). The significant changes in these two parameters indicate that numerous other soil characteristics, such as soil strength, porosity, and aeration, have also changed. All these affect the plants ability to exploit the soil environment for water and nutrients.

Annual yield was significantly affected each year in both experiments. Harvest traffic decreased yield approximately 4 t ha^{-1} per year the first 3 years in the first experiment (1983–1985) (Table 2). There was a smaller, though significant 1.5 t ha^{-1} difference in 1986. The annual yield of RE changed very little from 1984 to 1986, but declined approximately 10% for NN and PR. Preplant soil compaction, in the second experiment, significantly reduced yield the first year of production, 1986 (Table 3). By the

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[1] This paper only reports the results of research. Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the authors or the U.S. Department of Agriculture

third year there were no differences. Simulated traffic on alfalfa grown in compacted soil significantly reduced yield in 1987 and 1988 (Table 3). The difference between the maximum and minimum yielding treatments ranged from 4.2 to 9.6 t ha^{-1} depending on the year. Yield declined 15% from 1987 to 1988 for HV and HVTR compared to 23% for MD and 27% for LI.

Drainage became a critical factor when determining WUE. In both experiments there was generally less drainage from the compacted treatments, which was to be expected (Warkentin 1971). The amount varied from year to year within and among treatments. It accounted for as much as 38% to 23% of the total water lost depending on the treatment and year in the traffic experiment. There was no drainage in the heavily compacted treatments any year in the second experiment, but it accounted for 1 to 29% of the total water lost in the other two treatments.

Table 1. Soil bulk density after three years in the harvest traffic (1985) and soil compaction (1988) experiments

Depth m	Harvest traffic (first experiment)			Soil compaction (second experiment)			
	Treatments (soil bulk density) Mg m^{-3}			Treatments (soil bulk density) Mg m^{-3}			
	None	pre-plant	repeat	Light	medium	heavy	heavy + traffic
0.05	1.59	1.66	1.83	1.54	1.59	1.55	1.73
0.15	1.63	1.65	1.82	1.78	1.84	1.79	1.87
0.25	1.70	1.73	1.81	1.80	1.89	1.87	1.91
0.35	1.70	1.70	1.76	1.70	1.82	1.88	1.88
0.45	1.68	1.59	1.64	1.67	1.77	1.83	1.79
0.55	1.65	1.55	1.63	1.74	1.72	1.75	1.73
0.65	1.67	1.65	1.72				
	LSD ($p = 0.05$) = 0.03			LSD ($p = 0.05$) = 0.03			

Data points used in determining WUE were based on results from the third to final harvest (Fig. 1, 2). The growth dynamics and water use of the first and second harvest show a higher efficiency, thus a different physiological response to the treatments compared to the rest of the season. If these points had been included in an overall seasonal value the slope (WUE) would have been greater, but the coefficient of determination would have been lower. Experiments where the primary variables were fertilizer amounts and cultivars have also reported high WUE of alfalfa during the spring growth (Daigger et al. 1970; Undersander 1987). The low evaporative demand at this time of year was given as a possible explanation for their results. Water use and yield from these harvests in these experiments were excluded in determining the seasonal WUE because 1) actual water use during the winter and spring prior to the first harvest was not measured, but estimated, 2) the seasons first growth cycle was not subjected to harvest traffic, and 3) spring growth can be supplemented by carbohydrates from the roots resulting in a WUE not representative of the remainder of the season (Smith 1962; Cooper and Watson 1968). The data from the second harvest was excluded because 1) the first traffic event of the season did not, for any year, effectively result in yield differences among treatments as shown by Rechel et al. (1991) and 2) water use was equivalent among treatments. The growth dynamics of these two harvests were similar and may be highly dependant on environmental conditions during the previous winter (Sheaffer et al. 1987) and were not used in quantifying a seasonal WUE.

The WUE values obtained in these experiments were similar to those reported for alfalfa grown at a variety of locations. Abdul-Jabbar et al. (1983) reported efficiencies from 11.0 to 16.0 kg ha^{-1} mm^{-1} in New Mexico and Bolger and Matches (1990) reported values of 16.7 and 18.3 kg ha^{-1} mm^{-1} in Texas. At Logan Utah, Retta and Hanks (1980) obtained a WUE of 15.7 to 25.9 kg

Table 2. Dry matter yield and water use characteristics for alfalfa subjected to different traffic patterns at Shafter, California (first experiment)

Year	Traffic treatment	Yield t ha^{-1}	Drainage mm	Pan mm	ET mm	Water use efficiency[a] kg ha^{-1} mm^{-1} [c]	r^2
1983	NN (none)	19.4 a[b]	–	1589	–	–	–
	PR (preplant)	19.6 a	–	1589	–	–	–
	RE (repeat)	15.6 b	–	1589	–	–	–
1984	NN	24.9 a	553	1920	899	21.6 a	0.99
	PR	24.9 a	548	1920	919	20.8 a	0.99
	RE	20.8 b	289	1920	929	16.6 b	0.99
1985	NN	25.3 a	415	1750	1069	22.7 a	0.98
	PR	24.4 b	542	1750	980	22.4 a	0.98
	RE	21.8 c	444	1750	1021	22.0 a	0.99
1986	NN	22.7 a	312	1638	973	23.7 a	0.98
	PR	22.4 ab	340	1638	1008	21.8 b	0.99
	RE	21.4 b	286	1638	967	22.0 b	0.99

[a] Values correspond to the portion of the curve delimited by the regression line in Fig. 1

[b] Data followed by the same letter within a row, within a year, are not significantly different as determined by LSD at a probability level of $p < 0.05$

[c] Statistically significant differences based on LSD ($p < 0.05$) apply only to the slope of the regression line

Table 3. Dry matter yield and water use characteristics for alfalfa at Shafter, California (second experiment) when subjected to different levels of presown soil compaction

Year	Compaction treatment	Yield t ha^{-1}	Drainage mm	Pan mm	ET mm	Water use efficiency[a] kg ha^{-1} mm^{-1} [c]	r^2
1986	LI (light)	16.5 a[b]	161	1413	1115	18.0 a	0.98
	MD (medium)	14.4 b	68	1413	1059	16.3 a	0.97
	HV (heavy)	12.4 c	<1	1413	953	16.8 a	0.96
	HVTR (heavy + traffic)	11.2 c	<1	1413	939	14.7 a	0.97
1987	LI	32.2 a	108	1845	1412	24.1 a	0.99
	MD	30.4 ab	20	1845	1363	23.3 a	0.99
	HV	27.7 b	<1	1845	1283	23.7 a	0.99
	HVTR	22.8 c	<1	1845	1299	19.1 b	0.99
1988	LI	23.3 a	466	1779	1152	18.7 a	0.99
	MD	23.3 ab	159	1779	1283	16.4 b	0.99
	HV	23.7 a	<1	1779	1207	19.0 a	0.99
	HVTR	19.1 b	<1	1779	1301	12.5 c	0.99

[a] Values correspond to the portion of the curve delimited by the regression line in Fig. 2

[b] Data followed by the same letter within a row, within a year, are not significantly different as determined by LSD at a probability level of $p < 0.05$

[c] Statistically significant differences based on LSD ($p < 0.05$) apply only to the slope of the regression line

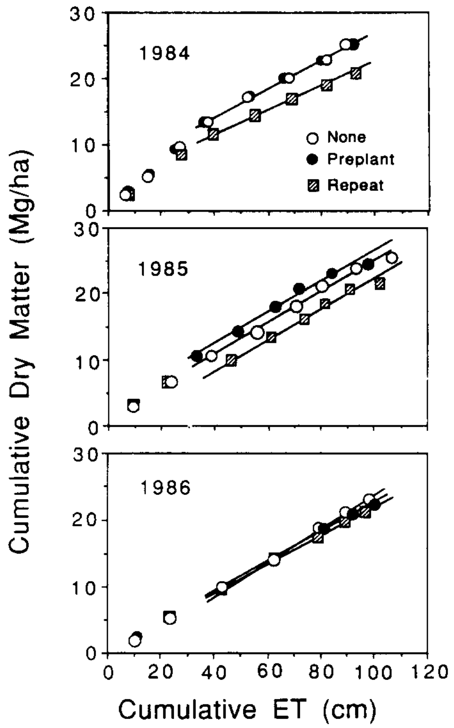

Fig. 1. Yield and evapotranspiration relationships of alfalfa subjected to different harvest traffic treatments. Statistically similar treatments are represented by one line

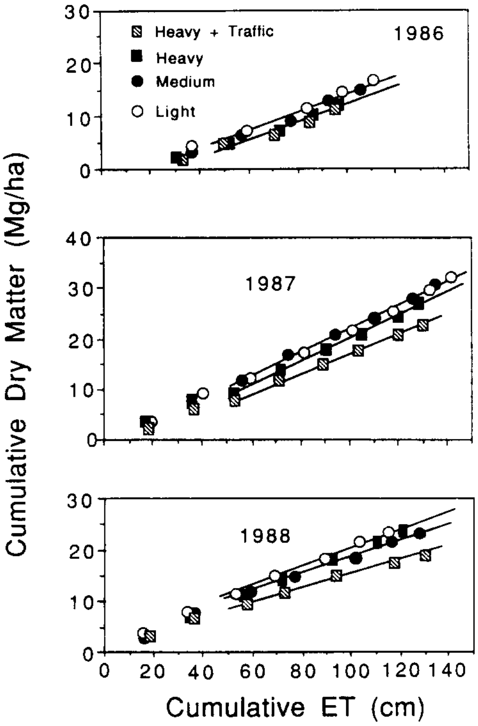

Fig. 2. Yield and evapotranspiration relationships of alfalfa subjected to different levels of soil compaction. Statistically similar treatments are represented by one line

ha^{-1} mm^{-1} depending on the year. The trafficked and non-trafficked, and compacted and non-compacted treatments had WUE comparable to these. The trafficked treatment RE had a WUE that ranged from 16.6 to 22.0 kg ha^{-1} mm^{-1} and was significantly lower, depending on the year, than the non-trafficked treatments which ranged from 20.8 to 23.7 kg ha^{-1} mm^{-1} (Table 1). There was generally no significant difference in efficiency among the three compaction treatments of the second experiment (Table 2). The WUE of alfalfa subjected to traffic and grown in compacted soil (HVTR) was markedly lower in 1986 than the non-trafficked treatments, though not statistically significant. It was however, significantly lower in 1987 and 1988.

Tanner and Sinclair (1983) reviewed how manipulating management practices or the oscillation of environmental variables might change WUE. They concluded that only when there is a change in partitioning of total dry matter to either more or less biomass would WUE be altered. If harvest traffic had only affected the plant by limiting water uptake there would have been a corresponding decrease in yield, but WUE would have remained the same for a given year i.e., WUE is a linear function between yield and ET with an increase or decrease in yield resulting in a corresponding change in ET without a change in the mathematical description of the relationship (Bauder et al. 1978; Retta and Hanks 1980). Though not measured, it was assumed that the traffic event at the beginning of the growth cycle did not change transpirational or photosynthetic rates. We are hypothesizing that the observed lower WUE for alfalfa may be explained by a reallocation of root carbohydrates and photosynthates from increasing forage biomass to injured stems and crowns damaged by harvest traffic.

In summary it must be remembered that only 50 to 70% of a normal producing field is actually subjected to varying intensities of traffic at each harvest (Grimes et al. 1978). It is these damaged plants that will incur lower WUE and lower the average for the entire field. Exactly to what degree the WUE is altered by traffic will depend on the percent area covered, how long after swathing the traffic event occurred, and the intensity of traffic. Aligning wheel configurations to reduce the percentage of the field subjected to traffic will decrease the number of damaged plants. This will increase the plants ability to effectively utilize water in forage production.

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