Reprinted from the *Journal of Production Agriculture*
Volume 4, no. 2, April–June 1991
677 South Segoe Rd., Madison, WI 53711 USA

Alfalfa Yield as Affected by Harvest Traffic and Soil Compaction in a Sandy Loam Soil

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Harvesting alfalfa (*Medicago sativa* L.) results in plants being subjected to traffic at different times during the growth cycle with equipment having different wheel sizes and loads. The affect of this traffic could have important ramifications on yield. The objectives of this study were to determine the long-term effects of harvest traffic and soil compaction on alfalfa yield. In the first experiment, two conventional traffic systems were compared to alfalfa production with no traffic. A single traffic event, that covered 100% of the plot area 3 to 5 d after each swathing, compared to no traffic significantly decreased yield by 20% in the 1st yr, 16.5% in the 2nd yr, 14% in the 3rd yr, with no significant difference the 4th yr. There was no difference in total yield between nontrafficked and a typical grower's traffic pattern the 1st yr, but in the succeeding 3 yr there was a 5 to 17% reduction. The effects of soil compaction and harvest traffic on yield were separated in the second experiment. Alfalfa grown in moderately and heavily compacted soil had a 12 and 26% decrease respectively in seasonal total yield compared to the yield from plants grown in noncompacted soil the 1st yr. Annual yields were the same regardless of the degree of soil compaction in the 3rd yr. When harvest traffic was applied to alfalfa grown in extremely compacted soil there was an additional decrease in yield. It was not statistically significant the 1st yr, but in the following 2 yr, 1987 and 1988, yield was significantly reduced by 17.8 and 19.1%, respectively. Alfalfa yields were significantly reduced both by harvest traffic and compacted soil. To achieve optimum long-term alfalfa yields compacted soil must be tilled before planting and operations that reduce the area of the field subjected to traffic must be implemented.

RESEARCH on crop growth and development of alfalfa typically has been done on small plots and addressed the physiology of specific plant organs, single cells, or individual plants. Little or no consideration has been given by the scientific community to characterizing the growth of an entire alfalfa field under commercial agricultural practices. Breeding programs are not designed to select varieties that are adapted to harvest management nor to evaluate varieties under different degrees of soil compaction. Scientific investigations on carbohydrate balance, water use, biochemical relationships, and overall alfalfa yield are usually done on individual plants in growth chambers or greenhouses, or with relatively small field plots for one or two seasons of growth (Wright, 1988; Sammis, 1981; Gifford and Jensen, 1967; Edmisten and Wolf, 1988; Ueno and Smith, 1970). During commercial harvest operations plants may be subjected to traffic 1 to 10 d after swathing which results in soil compaction and crown and stem damage. Because the wheel patterns of harvest equipment are not aligned, traffic may cover up to 70% of the field (Grimes et al., 1978).

One reason for this paucity of field data is the awkward, cumbersome, and expensive nature of maintaining large experimental plots on a long-term basis that adequately quantify and qualify the effects of harvest traffic. Grimes et al. (1978) reported on the effects of harvest traffic and compacted soil on alfalfa shoot growth through one harvest cycle during the first season of production. They reported that as the intensity of harvest traffic increased both yield and stand density decreased. We have shown how harvest traffic in alfalfa production affects infiltration rates, soil bulk density (Meek et al., 1988, 1989), rooting patterns, and forage growth dynamics (Rechel et al., 1990, 1987). To more fully ascertain the dynamics of crop production under field conditions experiments are necessary which have harvest traffic and soil compaction as the primary variables. The objectives of this study were to determine how (i) traffic from harvest equipment and (ii) different degrees of preplant soil compaction affect long-term alfalfa production.

METHODS AND MATERIALS

Research was conducted on the San Joaquin Valley Cotton Research Station, Shafter, CA. The elevation is 367 ft above sea level. The soil is a sandy loam (coarse-loamy, mixed nonacid thermic Typic Torriorthent). Average rainfall is 6.25 in/yr, with little rain from May through September.

Two experiments were conducted during a 7-yr period. The first one was designed to study the affect of harvest traffic on alfalfa production. The nondormant alfalfa 'WL514' was broadcast seeded in October 1982 on 26- by 98-ft plots at 29 lb/acre. The experiment was terminated in October 1986. The alfalfa was subjected to four cultural practices representing different timing and degrees of traffic: (i) [None (NN)] alfalfa was seeded into loosened soil and traffic was excluded during all phases of production, (ii) [Preplant (PR)] light preplant traffic was applied on loosened, dry soil with all production traffic excluded, (iii) [Repeat (RE)] the soil was prepared in the same man-

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Published in J. Prod. Agric. 4:241–246 (1991).

Abbreviations: NN, no traffic; PR, light preplant traffic; RE, repeated traffic; GR, simulated grower traffic; GR-O, lane never trafficked; GR-H, lane received repeated traffic; LI, light compaction; MD, medium compaction; HV, heavy compaction; HVTR, Heavy compaction + traffic; WTRV, wide-tractive research vehicle.

ner as the PR treatment with 100% of the surface area of each plot trafficked 3 to 5 d after every harvest, and (iv) [Grower (GR)] alfalfa was seeded into loosened soil and a traffic pattern simulating a grower's production system applied 3 to 5 d after each harvest and covered 59% of the area of each plot. This wheel pattern created several traffic lanes the length of plot. Two of these were selected for detailing the change in stand density with time and were defined as (i) GR-O, a lane that was never trafficked, and (ii) GR-H, a lane that received multiple tractor passes after each harvest. Details on traffic patterns and management practices are described by Meek et al. (1989) and Rechel et al. (1987).

The second experiment, conducted from 1986 to 1988, was to differentiate the effect of soil compaction from harvest traffic on alfalfa production. Nondormant alfalfa 'CUF 101' was sown on 14 Apr. 1986 at 32 lb/acre onto plots 26 by 65 ft and the experiment terminated October 1988. Triple superphosphate was broadcast at 144 lb P/acre in June 1986. In February 1986, all plots were chiseled to a depth of 1.5 ft with shanks spaced on 1-ft centers to reduce variation due to previous soil management. The soil treatments, established in March 1986, consisted of three levels of preplant soil compaction, and a fourth treatment which combined heavy preplant compaction with additional harvest traffic. Treatments were:

1. Light compaction (LI). An 8-ply, B.F. Goodrich 18.4–34 tire, inflated to 6 psi with a 3000-lb load, was driven over 100% of the area of each plot. This was done to insure high infiltration rates and optimum yields as quantified in the first experiment (Meek et al., 1988).
2. Medium compaction (MD). Plots were first flooded, then 100% of the area was compacted 4 d later with the same tire used in the above treatment inflated to 20 psi with a 6500-lb load.
3. Heavy compaction (HV). Plots were flooded, then 4 d later 100% of the area was compacted with a B.F. Goodrich 10.00–20 12-ply tire, inflated to 40 psi with a 6000-lb load.
4. Heavy compaction + Traffic (HVTR). Plots were established in the same manner as the HV plots. In addition, 100% of each plot was trafficked 3 to 5 d after every harvest with an 8-ply, B.F. Goodrich 18.4-34 tire inflated to 20 psi with a 4000-lb load to simulate rake and baler traffic.

All cultural operations for all treatments in both experiments were accomplished with tools suspended from the wide-tractive-research-vehicle (WTRV) which completely spanned the entire plot width, thus eliminating unprescribed traffic from the cropped area. Foot traffic was not allowed in any plot. Whole plots were harvested for yield data in both studies with a swather attached to the WTRV when 50 to 70% of the regrowth buds were 1/3 to 3/4 in. long. In the first experiment alfalfa was irrigated when treatments averaged 50% of the available soil moisture measured to a depth of 2 ft using a neutron probe. In the second experiment treatments were irrigated when the average Crop Water Stress Index was ≥0.25. Treatments in both experiments received the same amount of water each production season. Plots were flood irrigated using the raised wheel paths, on which the WTRV drove, as levees.

Infiltration rate was determined by measuring the drop in water level in the irrigation basin. Soil bulk density was measured using a two-probe density gauge (Model 2376, Troxler Lab, Triangle Park, NC)[1]. Detailed methods were reported in Meek et al. (1988, 1989). Soil penetration resistance was measured using a semiautomatic penetrometer with a 30° cone with a 0.2-sq in. cross-sectional surface area mounted on the WTRV. Penetrometer measurements were taken 3 d after irrigation. No soil bulk density or penetrometer resistance are presented for the GR treatment because of the wide variability in soil characteristics due to traffic patterns.

Both experiments were randomized complete block designs with four treatments and six replications. Alfalfa yields were analyzed as a split-plot design repeated over time for each year.

RESULTS

First Experiment

The RE treatment reduced annual accumulated yields by 20, 16.5, and 14% in 1983, 1984, and 1985, respectively, compared to NN (Table 1). Yield for GR

[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 by the authors or the USDA.

Table 1. Dry matter yield of alfalfa subjected to harvest traffic during 4 yr (1983-1986), soil bulk density, penetrometer resistance, and infiltration rates.

Year	Traffic treatments	Yield	Bulk density†	Penetrometer resistance‡	Infiltration rates
		ton/acre	lb/cu ft	lb/sq in.	in./h
1983	None	8.6a*	102.3a	65a	0.53b
	Preplant	8.7a	107.9b	118b	0.77a
	Repeat	6.9b	108.5b	142c	0.76a
	Grower	8.4a	–	–	0.59b
1984	None	11.1a	104.8a	98a	1.50b
	Preplant	11.1a	108.5b	155b	1.89a
	Repeat	9.3b	113.5c	231c	0.79d
	Grower	9.7b	–	–	1.06c
1985	None	11.3a	104.2a	100a	1.75b
	Preplant	10.9b	106.0a	135b	1.89a
	Repeat	9.7c	111.6b	286c	1.18d
	Grower	9.4c	–	–	1.25c
1986	None	10.1a	106.0a	86a	2.03ab
	Preplant	10.0a	107.9a	120b	2.34a
	Repeat	9.5a	112.9b	233c	1.26b
	Grower	9.6a	–	–	1.74ab

* Values within a column, within a year, followed by the same letter are not significantly different as determined by LSD ($P \leq 0.05$).

† Data for bulk denisty are taken from the 10-in. depth, which is generally where the maximum values occurred.

‡ Data for penetrometer resistance are taken from the 15-in. depth, which is generally where the maximum values occured.

was similar to NN and PR the 1st yr. In the following years, yields from the GR treatment were reduced by 12.7% (1984) and 16.9% (1985) compared to NN. There was no statistical difference among treatment yields in 1986. Yields from the nontrafficked treatments increased an average of 21% from 1983 to 1984, but showed essentially no change from 1984 to 1985. Annual yields of GR and RE increased an average of 19% from the 1st to the 2nd yr of production and remained essentially unchanged for the remainder of the experiment. In contrast there was an 8 and 10% decrease from 1985 to 1986 in the treatments with no traffic resulting in no statistical difference among all treatments the final year. This reduction in yield could be ascribed to natural changes in plant vigor since stand density was similar among NN, PR and the trafficked treatment RE (Fig. 1A).

Yield differences from individual harvests, actual and absolute, varied as the production season progressed (Fig. 2A). This was a typical production pattern when compared to reports in similar climatic conditions (Donovan and Meek, 1983). Actual yields were low in the spring, improved as day length increased, and dropped in the fall. Yields were generally similar among treatments the first harvest (Fig. 2A). This harvest had no plant damage from traffic since the last application was the previous fall. The significant differences among treatments were a result of yields from the second harvest to the final harvest. Even though yield was declining as the season progressed absolute differences were fairly similar during this time (Fig. 3).

Stand density was not significantly reduced by the single traffic event after each harvest in RE, but was by multiple tractor passes (GR-H) (Fig. 1A). A relatively constant difference between GR-H and the other treatments observed during this time suggests that the initial decline occurred in 1983, the first production year. The similar rate of decline in stand density among treatments from 1984 through 1986 must be attributable to inherent plant growth characteristics and not harvesting procedures.

The effect of traffic on soil physical condition as measured by soil bulk density, penetrometer resist-

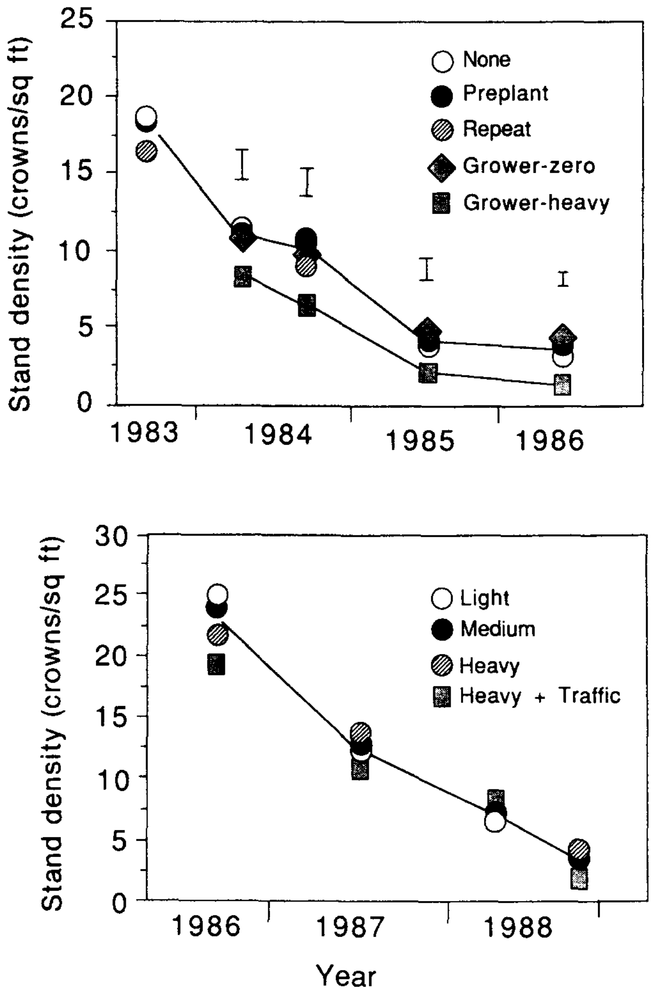

Fig. 1. Stand density of alfalfa subjected to A) harvest traffic, and B) preplant soil compaction and harvest traffic. The vertical bars represent LSD at the 0.05 probability level. Curves in both experiments were fitted by hand.

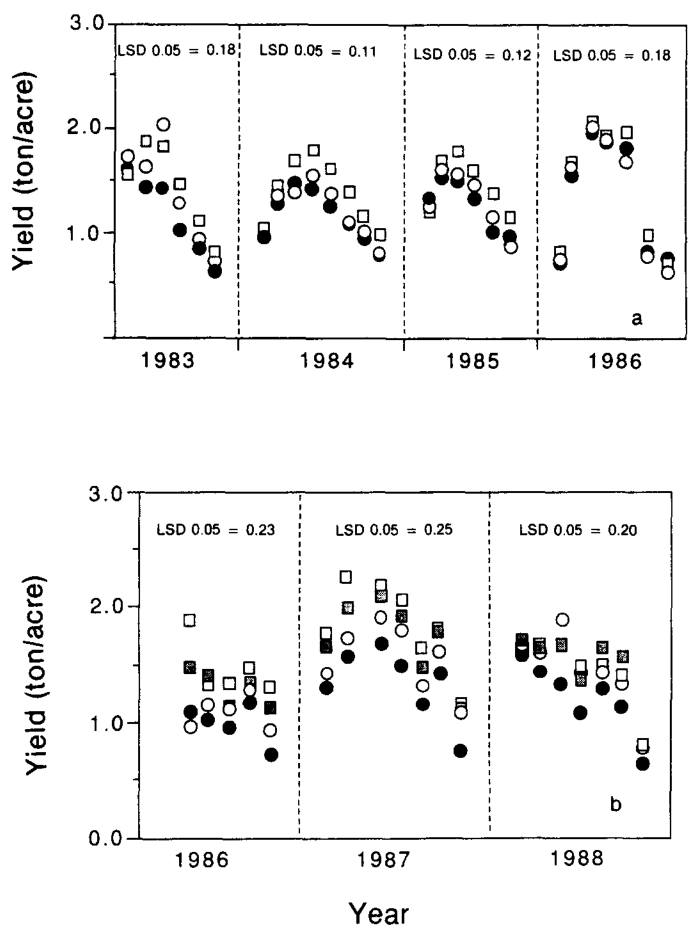

Fig. 2. Alfalfa yield at each harvest as affected by A) no traffic (□), grower's simulated traffic (○), and total area trafficked after each harvest (●) over a 4-yr period, and B) by light (□), medium (■), and heavy preplant compaction (○), and heavy preplant compaction plus traffic after each harvest (●) over a 3-yr period.

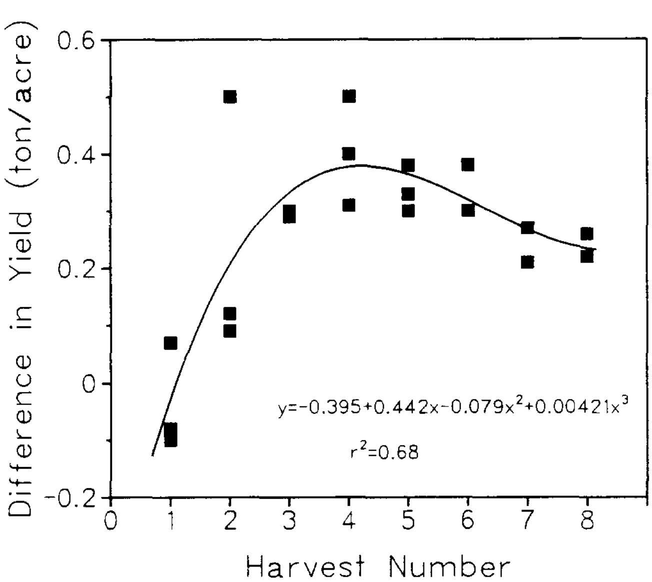

Fig. 3. Absolute differences in yield between nontrafficked (NN) and repeated traffic (RE) treatments with each progressive harvest for the production years 1983 to 1985.

ance, and infiltration rates is shown in Table 1. Maximum bulk density was consistently lower in NN than RE. Maximum penetrometer resistance showed a similar relationship among the NN and RE treatments, while PR was intermediate between the two treatments. Infiltration rate was generally greater in the PR treatment where the entire plot was "lightly" compacted before planting with no traffic during production. After the 1st yr, rates were lowest in treatments receiving traffic during production.

These three soil characteristics, that measured the intensity of each treatment, can generally be related to annual yield. Bulk density was highest in RE which had a lower yield than NN and PR except in 1986. There was a consistent statistical difference in penetrometer resistance among treatments, though the magnitude changed through the experiment. Again RE had the highest resistance and showed a lower yield. The PR had a yield similar to NN, but a statistically higher penetrometer resistance. Infiltration rates increased in all treatments throughout the 4-yr study, while productivity varied with years. There was no statistical difference in yield among treatments in 1986, but the soil characteristics had the same relative relationships as observed in previous years. This suggests an interaction with time which may be related to stand maturity.

Second Experiment

The magnitude of difference in yields among treatments varied among individual harvests and among years (Fig. 2B). Fluctuations in yield with time were not similar to that observed in the first experiment except for 1987. Stand establishment in compacted soil and spring planting may explain the apparent equivalent yields from each harvest in 1986. Yields

Table 2. Dry matter yield of alfalfa subjected to different levels of soil compaction during 3 yr (1986-1988), soil bulk density, penetrometer resistance, and infiltration rates.

Year	Traffic treatments	Yield	Bulk density†	Penetrometer resistance‡	Infiltration rates
		ton/acre	lb/cu ft	lb/sq in.	in./h
1986	Light	7.3a*	111.0a	101a	0.87a
	Medium	6.4b	116.0b	203b	0.23b
	Heavy	5.5c	114.8b	261c	0.16c
	Heavy + traffic	5.0c	118.5b	274c	0.16c
1987	Light	14.4a	108.5a	188a	1.51a
	Medium	13.6ab	115.4b	493b	0.40b
	Heavy	12.4b	114.7b	667c	0.42b
	Heavy + traffic	10.2c	117.2b	638c	0.26b
1988	Light	10.4a	112.2a	174a	3.04a
	Medium	10.4ab	117.2b	377b	1.44b
	Heavy	10.5a	116.6b	638c	0.56c
	Heavy + traffic	8.5b	119.1b	623c	0.45c

* Values within a column, within a year, followed by the same letter are not significantly different as determined by LSD ($P \leq 0.05$).

† Data for bulk density are taken from the 10-in depth, which is generally where the maximum values occurred.

‡ Data for penetrometer resistance are taken from the 15-in. depth, which is generally where the maximum values occured.

from each harvest were relatively more constant in 1988 than 1987 and may reflect stand maturation.

The compacted treatments MD and HV had 12 and 25% lower annual yields than LI, respectively, in 1986 (Table 2). Statistically there was no difference in yield between HV and HVTR the 1st yr. The effect of soil compaction on yield was not as discernable in 1987 as in 1986, with MD statistically similar to both LI and HV and the difference between HV and LI down to 14%. By 1988, the final year, there was no significant differences in yield among compaction treatments. This was not due to an increase in HV from 1987 to 1988, but a substantial decrease of LI and MD by 28 and 23%, respectively. Compared to HV the harvest traffic in the HVTR treatment decreased forage production 18 and 19% in 1987 and 1988, respectively. As in the first experiment this decrease must be attributed to individual plant characteristics since stand density was the same all 3 yr (Fig. 1B).

There was no difference in maximum bulk density among MD, HV, and HVTR in any year although there were differences in tractor wheel weight and pressures when the plots were initially compacted (Table 2). The maximum bulk density in the LI treatment was significantly lower than the others. Maximum penetration resistance was however, different among all compaction levels. Although values increased from 1986 to 1987, the relative relationship among treatments was the same. Infiltration rate was always greatest in LI. Generally the more compaction the lower the rate. Every year there was an increase, but the relationship among treatments was relatively constant.

The difference in yield among treatments in the 1st yr of production could be directly related to these soil characteristics. The physical state of the soil, not traffic, was more important in determining yield. The same edaphic factors deemed important in forage production in 1986 had less impact on yield in 1987, the 2nd yr. Infiltration rates of LI and MD were significantly different, but both treatments had similar yields. The HV and HVTR treatments had different yields, yet had statistically similar maximum penetrometer resistance and bulk density. By the 3rd yr, 1988, there was no statistical difference in yield among the three compaction treatments, but difference were still observed in all soil parameters. With the application of traffic at harvest, yield was significantly less than HV, but bulk density, penetrometer resistance, and infiltration rates were similar.

DISCUSSION

Harvest traffic and soil compaction at times resulted in large reductions in yield, but did not always alter stand density. The RE treatment, single passes of harvest traffic 3 to 5 d after swathing, did not have a significantly different stand density compared to NN and PR over the 4-yr study, yet had a significantly reduced annual yield (Fig. 1A). This reduced yield can be attributed to damaged regrowth buds from the post-harvest traffic (Grimes et al., 1978). The same observation can be made from the results of the second experiment: there was no difference in stand density among treatments throughout the study, but there were differences in yield (Fig. 1B). When plants were subjected to multiple tractor passes at harvest there was a significant decrease in stand density as observed in GR-H (Fig. 1A). Grimes et al. (1978) measured a large decrease in stand density and yield with multiple tractor passes, though their data was limited to one harvest 1.5 yr after planting. Rechel et al. (1987) also observed the same relationship from four individual harvests spread over 2 yr. How much of the yield reduction in GR can be attributed to this heavily trafficked lane is unknown since the entire treatment was harvested as one unit.

Yield from one specific harvest or season may not show the potential economic damage harvest traffic and soil compaction may have on alfalfa production. Because of the apparent interaction between yield, harvest traffic, and soil compaction, as seen in Table 1 and 2, correlating the effects of these variables should also take into account stand age and extent and intensity of traffic. An example was the growers simulated traffic pattern (59% of the soil surface receiving traffic) which caused a 10% decrease in the overall 4-yr yield when compared to no traffic (NN) (Table 3). However, in the 1st and 4th yr there was no statistical difference. The evaluation of long-term results are needed to give important information on evaluating the effects of new management practices.

Sowing alfalfa in soil that has been lightly compacted before planting, as in the PR treatment of the first experiment and the LI treatment of the second experiment, was not detrimental to forage production; on the contrary, this resulted in high infiltration rates and high yields. Lightly compacting a thoroughly loosened soil may establish an artificial orientation among soil particles that prevents their movement during the first irrigation. This resulted in better infiltration (Meek et al., 1988) and soil aeration during plant establishment.

Table 3. Total alfalfa yield, over the experimental period, as affected by harvest traffic and soil compaction.

Experiment	Treatment	Total yield (ton/acre)	Relative percent yield
First experiment			
Harvest traffic	None (NN)	41.2	100
	Preplant (PR)	40.7	98.8
	Repeat (RE)	35.5	86.2
	Grower (GR)	37.1	90.0
Second experiment			
Soil compaction	Light (LI)	32.1	100
	Medium (MD)	30.4	94.7
	Heavy (HV)	28.4	88.5
	Heavy + Traffic (HVTR)	23.7	73.8

The RE treatment, in the first experiment, was planted in non-compacted soil and was not subjected to traffic until 7 months later (Meek et al., 1987). During this time stand establishment proceeded with no damage from equipment traffic and the root system could exploit the soil to a depth of 5.9 ft (1.8 m) (Rechel et al., 1990). It was not until the end of the first production season that the soil reached a maximum bulk density (Meek et al., 1988). All treatments in the second experiment began in a compacted soil e.g., alfalfa growth was hampered from the time of initial establishment by the physical state of soil.

Traffic applied to alfalfa planted in highly compacted soil (HVTR) had a 26.2% total reduction in yield over the 3-yr-growth period compared to alfalfa planted in noncompacted soil and not subject to traffic (LI) (Table 3). When comparing HVTR to alfalfa planted in compacted soil with no traffic (HV) there was a 16.6% reduction. There was a 15.6% reduction in yield when comparing RE (comparable to the traffic of HVTR) to PR (comparable to the preplant soil conditions of LI) in the first 3 yr of the first experiment. Because the difference in varieties, planting dates, and the number of times harvest traffic was implemented, the similarity in yield reduction due to traffic (16.6 and 15.6%) must not be viewed as a universal amount, but only that plants damaged by traffic will substantially contribute to decreased forage production. When 59% of the plants were trafficked, from one to several times after swathing, there was a 10.0% long-term reduction in yield. This would probably be greater in normal harvesting procedures that require 10 to 12 days to complete and damage plants at different growth stages. The percent reduction caused by preplant soil compaction, calculated by comparing HV to LI, was 11.6%. It was unknown how soil compaction after crop establishment affects yield and it may be impossible to determine without confounding the results by damaging existing plants.

INTERPRETIVE SUMMARY

We have shown that harvest traffic and preplant soil compaction significantly reduces alfalfa production. When 59% of the field was trafficked with a grower's operational pattern, long-term yields were reduced by 10% compared to a nontrafficked operation. A reduction in yield by such standard traffic operations may not be observed until the second or third harvest and not significantly affect accumulative annual yield until the 2nd yr of production. One traffic event over the entire plot 3 to 5 d after each harvest compared to no traffic reduced forage production by 13.3% over 4 yr of growth. Depending on the degree of soil compaction, yield was significantly reduced the first 1 or 2 yr of production. Alfalfa subjected to traffic and grown in severely compacted soil had an additionally significant decrease in yield. Compacted soil should be tilled prior to planting or it can be an additional source of plant stress when subjected to traffic. Yields will be adversely affected by relatively moderate and heavy soil compaction the 1st yr and total production and economic return reduced over the long term. Preplant soil tillage and controlling traffic patterns during harvest will benefit growers in realizing optimal alfalfa yields.

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