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Bulk Density of a Sandy Loam: Traffic, Tillage, and Irrigation-Method Effects

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ABSTRACT

Modern crop production creates a cycle between soil compaction caused by traffic and alleviation of this condition by tillage or natural processes such as freezing and thawing. The objective of this study was to evaluate important management practices as they relate to changes in bulk density of a tilled sandy loam soil. Practices evaluated were irrigation method, time between tillage and traffic, tire pressure and wheel load of applied traffic, and controlled traffic. Relationships among bulk density, penetration resistance, and infiltration rate were determined. Experiments were conducted in the San Joaquin Valley of California, on a sandy loam soil (Entisol) with an organic-matter content of <1%. After tillage, settling and trafficking of a soil resulted in rapid changes in its bulk density until a new equilibrium was reached. Tire pressure of 408 kPa and wheel weight of 2724 kg applied at moisture contents near field capacity resulted in a bulk density of 1.92 Mg m^{-3}, compared with a value of 1.67 for no traffic. The time interval between tillage and traffic did not affect final bulk density. Drip irrigation, which did not saturate the soil, resulted in a bulk density of ≈0.1 Mg m^{-3} lower than flood irrigation, which saturated the soil surface. Wheel traffic in the furrow resulted in only small changes in the bulk density within the row. When tillage did not occur between cropping seasons, traffic caused high bulk densities in the furrow but only small changes in the row. An increase in bulk density from 1.7 to 1.89 Mg m^{-3} decreased the infiltration rate by four times and increased resistance to penetration at the end of the season by three times. Knowledge of how management practices affect bulk density can aid growers in reducing recompaction following tillage.

After tillage, settling and trafficking of a soil results in rapid changes in the physical condition of a soil until a new equilibrium is reached. The physical condition of a soil can be defined to a large extent by measuring the bulk density, which is also a measure of porosity; resistance to penetration, which measures particle bonding and matrix properties; and infiltration rate, which is related to pore size and continuity. Increases in bulk density are correlated with increases in resistance to penetration (Bauder et al., 1981) and decreases in infiltration rate (Patel and Singh, 1981). Modern crop production is a continuing cycle between soil compaction caused by wheel traffic and alleviation of this compaction by tillage.

In a sandy loam soil with poor soil structure and low organic matter, bulk density can be reduced by tillage to a range of 1.4 to 1.5 Mg m^{-3} (Meek et al., 1988), but when wheel traffic is applied, bulk density will increase to values that will depend on factors such as tire pressure, soil moisture, and wheel load (Soane et al., 1982). The degree of soil compaction resulting from traffic depends on force applied and soil properties, especially soil water content. Harris (1971) reviewed the soil compaction process and presented stress–compaction relationships but stated that the possibility of rigorous relationships being established by analytical means is remote. Amir et al. (1976) presented an equation that made it possible to predict the amount of soil compaction as a function of contact pressure and soil moisture. Gupta et al. (1985) tested 87 soils and found that the Wasco sandy loam soil (coarse-loamy, mixed, nonacid, thermic Typic Torriorthent), used also in this experiment, had the highest bulk density of any soil studied when compacted under standard conditions.

When soil is tilled and no traffic is applied, irrigation causes an increase in bulk density; the degree of increase will depend on the degree of water saturation achieved during irrigation and the amount of water applied. De Kimpe et al. (1982) measured a decrease in dry bulk density when loose soil was settled, with increasing soil water contents followed by an increase in bulk density as the water content approached field capacity. Onstad et al. (1984) measured an increase in bulk density after tillage for four soils that was correlated (R^2 = 0.84 to 0.96) with the amount of water applied.

The time between tillage and the application of traffic may affect the final bulk density. Utomo and Dexter (1981) measured the effect of uniaxial stress applied to aggregate beds that had been aged for 0 to 10 d. They measured an increase in packing density with increased aging.

The objectives of this research were to evaluate, for one soil after tillage, the effects of traffic, time after tillage, and irrigation method. These three factors have seldom been evaluated in the same study using the same soil. The soil used is unique in that it compacts to a high bulk density.

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MATERIALS AND METHODS

The soil-compaction experiment was situated on a Wasco sandy loam. Unilateral compression at 200 kPa resulted in a bulk density of 1.72 Mg m^{-3} at a soil moisture of 0.131 g g^{-1} (equivalent to a matric potential of −10 kPa) and a bulk density of 1.65 Mg m^{-3} at a soil moisture of 0.058 g g^{-1} (equivalent to a matric potential of −100 kPa). All experiments were conducted within an area 300 by 300 m that had the same soil type.

Tillage was done in the same manner to start each of the experiments. This extensive tillage was done to remove the effect of previous cultural practices. All plots were chiseled to a depth of 0.54 m on 0.33-m centers using a wide tractive research vehicle (Carter et al., 1987), which spans 10 m, so that no wheel traffic was applied in the plot. Wheel-traffic treatments were usually applied using a wheel that was hydraulically controlled and mounted behind the research vehicle. Weight applied to the wheel could be accurately controlled. All cultural operations were done using the research vehicle so that the compounding effect of traffic was eliminated.

To evaluate the effect of irrigation method on settling without traffic, an area was tilled, alfalfa (*Medicago sativa*

L.) was planted and sprinkle irrigated for germination, and the area divided into six plots (9 by 15 m) in June 1985. Bulk density was measured on 24 June 1985, after which three of the plots were irrigated by flood irrigation and three by subsurface drip irrigation (tubes buried 0.20 m deep on 0.45-m centers). Irrigations were scheduled so that water availability did not affect yield. Alfalfa was harvested using the research vehicle, so that no wheel traffic was applied to the plots. After 1 yr, bulk density was measured on 23 June 1986 to evaluate the effect of irrigation methods on settling. Bulk-density measurements were made from the 0.15- to 0.75-m depths at 0.10-m increments at two randomly selected locations in each plot.

The effect of tire pressure and tire load on bulk density was evaluated in plots (9 by 20 m) with four replicates. The area was tilled, irrigated, and traffic applied 3 d after irrigation. Treatments were (i) no wheel traffic, (ii) wheel traffic applied using an 18.4 × 34 tire under a 1248-kg load inflated to 41 kPa, (iii) wheel traffic applied using a 18.4 × 34 tire under a 2906-kg load inflated to 170 kPa, and (iv) wheel traffic applied using a 10.00 × 20 tire under a 2724-kg load inflated to 408 kPa. Traffic was applied on 4 Apr. 1986 using the research vehicle. Bulk density was measured (at one location in each of the 16 plots) on 6 to 9 May 1986.

The effect of time between tillage and compaction on compactibility was evaluated on land that was maintained in fallow. The land was divided into 12 plots each (3 by 20 m). Four plots were tilled on each of 3 d, 14 Oct. 1986, 2 Feb. 1987, and 28 Apr. 1987. Plots were not irrigated but received rainfall of 145 mm from 14 Oct. 1986 to 12 June 1987. Each plot was split and one-half irrigated on 2 June 1987. Compaction was applied uniformly to 100% of the surface area of all plots on 9 June 1987 with tires inflated to a pressure of 136 kPa and a tire load of 2045 kg. Bulk density was measured on 12 June 1987 at 24 locations, one irrigated and one nonirrigated location within each plot.

The effect of (i) traffic in the furrow and (ii) annual tillage was evaluated in plots 9 by 30 m that were initially tilled in 1983. Cotton (*Gossypium hirsutum* L.) was grown in 1983, 1984, and 1985 on beds with 1-m centers. The cotton was furrow irrigated during the season. Traffic was applied to the appropriate plots during the planting, cultivation, and harvesting operations. Weights were adjusted to reflect the weight of the equipment used for the different operations. Annual tillage was applied to the appropriate plots between the 1983 and 1984 crops and between the 1984 and 1985 crops. This tillage was done in the same manner as the tillage conducted before each of the experiments was started. Treatments were replicated 10 times in a randomized complete block with bulk density measured at one location in each plot. Bulk density was measured in the row and in the center of the furrow each year in October before the harvest, which was done in November.

Bulk density was measured using a two-probe density gauge (Model 2376, Troxler Lab., Triangle Park, NC).[1] Equation [3] in Rawitz et al. (1982) was used to calculate bulk density using an unattenuated count rate (I_o = 316000) and mass attenuation coefficients suggested by them for soil and water. Parallel Al access tubes 0.30 m apart were used to take measurements.

Penetrometer resistance was measured using a semiautomated system mounted on the wide tractive frame. All measurements were made at field-capacity soil moisture, defined as 3 d after irrigation.

The relationship between bulk density, penetrometer resistance, and infiltration was resulting from soil compaction and traffic for an annual crop was determined in 1986 for a field planted in cotton. The field was divided into 16 plots (four treatments and four replicates), each 9 by 20 m. The field was initially compacted to four levels before planting and thereafter no wheel traffic was applied to the plots during the season. Respective tire inflation pressures and tire loads for the four levels of compaction were (low) 48 and 1293, (medium) 69 and 2297, (medium-heavy) 172 and 2906, and (heavy) 276 kPa and 2746 kg. Traffic was applied when the soil water content at the 0- to 0.54-m depth was 0.102 g g^{-1} for the low treatment and near field capacity for all other treatments. Penetration resistance was measured in June and November at 72 locations within each plot. Bulk density was measured (one location in each plot) in April and November. The infiltration rate was measured in June of 1986 by forming a basin around each plot and measuring the decrease in water level with time.

RESULTS

Without traffic, soil settled to a bulk density of 1.63 Mg m^{-3} at the depth of 0.15 to 0.45 m when flood irrigated, or to 1.54 Mg m^{-3} when drip irrigated (Fig. 1). Flood-irrigated plots had a significantly higher bulk density at the 0.15-, 0.25-, 0.35-, and 0.45-m depths after 1 yr, compared with drip-irrigated plots. Drip irrigation caused a significant increase in bulk density only at the 0.15- to 0.35-m depth, compared with initial levels. There were no significant differences from one depth to another (0.15–0.55 m) for the flood irrigation, but under drip irrigation the 0.15-m depth was lower in bulk density than the depths of 0.25, 0.35, 0.45, or 0.55 m (significance between depths not shown).

The application of traffic composed of a 2724-kg weight load and tire inflation pressure of 408 kPa at a soil moisture of 0.08 g g^{-1} resulted in a bulk density of 1.92 Mg m^{-3} at the 0.2-m depth (Fig. 2). When the tire inflation pressure was reduced from 408 to 170 kPa (approximately the same wheel weight), it resulted in a 0.10 Mg m^{-3} lower bulk density (0.10–0.25-m depth). Tire pressure affected the bulk density near the surface but, at greater depths, bulk density was more a function of wheel load. Application of traffic resulted in soil compaction to at least the 0.65-m depth.

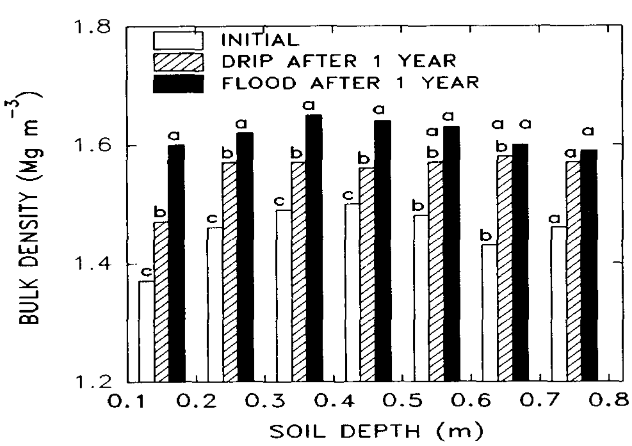

Fig. 1. Effect of irrigation method on soil bulk density of a Wasco sandy loam after 1 yr. Within each depth, values followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

[1]Reference to brand names or companies is made for information purposes only and does not imply endorsement of these companies or brands over any other company or brand.

Table 1. Effect of time interval between tillage and wheel traffic on final soil bulk density of a Wasco sandy loam.

	Bulk density					
Date chiseled	0.10 m	0.15 m	0.20 m	0.25 m	0.30 m	0.35 m
	Mg m^{-3}					
	Irrigated†					
Apr. 1987	1.74a‡	1.77a	1.78a	1.78a	1.75a	1.72a
Feb. 1987	1.74a	1.80a	1.80a	1.78a	1.76a	1.74a
Oct. 1986	1.74a	1.77a	1.78a	1.78a	1.75a	1.72a
	Nonirrigated					
Apr. 1987	1.38b	1.61b	1.67ab	1.69ab	1.68ab	1.68a
Feb. 1987	1.34b	1.45c	1.54c	1.59b	1.65b	1.66a
Oct. 1986	1.36b	1.53bc	1.60bc	1.63b	1.65b	1.64a

† Water was applied to the irrigation treatment on 2 June 1987 and compaction applied uniformly to all plots on 9 June 1987 with tires inflated to a pressue of 136 kPa and wheel weight of 2045 kg. Soil moisture at the time of compaction was 0.066 g g^{-1} for the 0- to 0.3-m depth for the nonirrigated treatment and 0.102 for the irrigated treatment.
‡ Column values followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

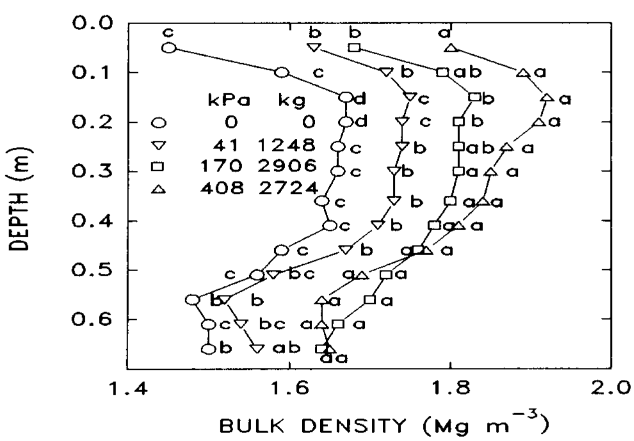

Fig. 2. Effect of tire inflation pressure (kPa) and wheel load (kg) on soil bulk density of a Wasco sandy loam. Soil compaction was done when the soil water content was 0.08 g g^{-1}. Values within each depth followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

There were no differences in bulk density in plots that were irrigated when the interval between tillage and application of standard traffic was varied between 6 and 34 wk (Table 1). There were some differences in bulk density at the 0.15- and 0.2-m depth without irrigation for the treatments tilled in either February or April. Variability in bulk density was higher for the nonirrigated treatment than the irrigated treatment. This variability may have been caused by the irrigated treatment having a more uniform moisture level at compaction. Traffic applied when the soil was dry (nonirrigated soil moisture of 0.066 g g^{-1}) resulted in an average bulk density of 1.59 Mg m^{-3} at the 0.15- to 0.30-m depth, compared with a bulk density of 1.78 Mg m^{-3} for application of the same traffic when the soil was wet by irrigation to a soil moisture of 0.102 g g^{-1}.

Traffic and tillage between crops affected bulk density measured in the row and furrow (Fig. 3). Traffic resulted in bulk densities at the end of the cropping season as high as 1.82 Mg m^{-3}, compared with <1.65 Mg m^{-3} for all treatments that were not trafficked. Without traffic, there were no significant differences

Table 2. Relationship between soil bulk density, soil penetrometer resistance, and soil infiltration rate for a field of cotton subjected to various compaction levels.

Inflation pressure	Wheel load	Bulk density†	Penetrometer‡ resistance June	Penetrometer‡ resistance Nov.	Infiltration§ rate
kPa	kg	Mg m^{-3}	MPa		mm h^{-1}
48	1293	1.71b¶	0.81	1.12	15a
69	2297	1.75b	1.09	1.66	8b
172	2906	1.86a	1.51	2.64	4c
276	2746	1.89a¶	1.68	3.23	3c

† Bulk density was measured in April and November 1986 (depth 0.15–0.30 m) and values averaged.
‡ Penetrometer resistance measured at the depth 0.15–0.30 m.
§ Infiltration rate was measured on 11 July 1986 and the values are the rate at 120 min after 50% of the plot was flooded.
¶ Column values followed by the same letter are not significantly different (Duncan's multiple-range test 0.05 level)

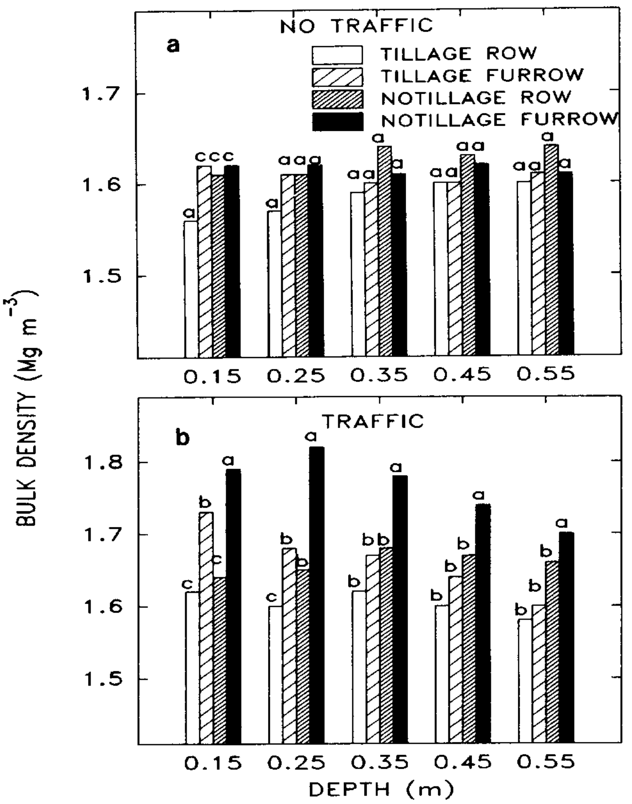

Fig. 3. Effect of annual tillage between crops on soil bulk density of a Wasco sandy loam measured in the furrow or the row under cotton culture for (a) no traffic or (b) traffic treatments. Values are an average of readings taken in October 1984 and 1985. Values within each depth for each traffic treatment followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

(except for small differences at the 0.15-m depth) between the row and furrow position or resulting from tillage between crops. Under traffic, however, there were differences in bulk density between the row and furrow positions (0.15—0.35 depth), with the furrow position averaging 1.74 and the row position averaging 1.63 Mg m^{-3}. Traffic without tillage between crops resulted in an increase in bulk density (0.15—0.35-m depth) of 0.11 Mg m^{-3} in the furrow and 0.05 Mg m^{-3} in the row, compared with the traffic-with-tillage treatment.

Heavy compaction (2746-kg wheel load, 276-kPa inflation pressure) resulted in an increase in bulk density from 1.71 to 1.89 Mg m^{-3}, a decrease in infiltration rate from 15 to 3 mm h^{-1}, and a two or three times increase in penetrometer resistance (Table 2). Increases in tire pressure between the medium–heavy and the heavy treatments resulted in only small changes in bulk density or infiltration rate.

DISCUSSION

Growers can reduce the increase in soil compaction by applying traffic to the soil when it is as dry as possible. In this experiment, soil compacted to a bulk density of 1.59 Mg m^{-3} when standard traffic was applied at a soil moisture content of 0.066 g g^{-1}, compared with 1.78 Mg m^{-3} when compacted at a soil moisture content of 0.102 g g^{-1}. These results agree with those of Weaver and Jamison (1951), who measured a bulk density of 1.53 Mg m^{-3} when standard compaction was applied to a loam soil at a moisture content of 0.059 g g^{-1}, compared with 1.76 Mg m^{-3} at a moisture content of 0.102 g g^{-1}. An example where this is important is in alfalfa production; if an interval of 1 wk can occur between the last irrigation and harvest, then the soil will be drier and will result in less soil compaction than when shorter time intervals are used.

When it is necessary for a grower to conduct operations while the soil is moist, a lower tire pressure or wheel load should reduce the increase in compaction. A reduction in tire pressure from 408 to 41 kPa combined with a reduction in tire load from 2724 to 1248 kg in this study resulted in a reduction in bulk density from 1.91 to 1.74 Mg m^{-3} at the 0.10- to 0.15-m depth. Using the relationship found for this soil in the field by Meek et al. (1992), this would triple the infiltration rate. Operations that must be done when soils are moist, such as planting, need to be done with special care to prevent soil compaction.

The lower bulk densities obtained when the irrigation method did not saturate the soil may be important in the culture of crops such as potato (*Solanum tuberosum* L.) that are sensitive to bulk density. Njos and Nordby (1966) found there was a significant difference in potato yields from fields that had one vs. two passes of a tractor, illustrating sensitivity to soil compaction.

When traffic was applied, fall or spring tillage resulted in the same soil compaction because the time between tillage and wheel traffic did not affect the final bulk densities. These findings differ from those of Utomo and Dexter (1981), who measured an increase in packing density (portion of volume that is occupied with solid particles) when aggregate beds were aged for longer times before a stress of 20 kPa was applied. Packing densities were 0.77 when aged for 10 d, compared with 0.58 for no aging. They evaluated short times (up to 10 d) compared with the long times (26–34 wk) evaluated in this experiment.

Tillage between crops would not be necessary under controlled traffic for rows or nontrafficked furrows. The 1-m-wide rows provided sufficient distance so that traffic did not affect the soil under the row, but with narrower rows tillage in the row may be necessary between cropping seasons. Findings of this study agree with those of Gupta et al. (1985), who measured changes in bulk density only out to 0.30 m from the center of the tire. Growers could restrict traffic to selected furrows and save energy by deep tilling only those furrows between crops.

Improved water management can reduce the effects of soil compaction on crop yield, but at some level (usually at bulk densities >1.85 Mg m^{-3} in this soil) infiltration becomes so slow that irrigation is difficult, with water application times in excess of 1 d to infiltrate 75 mm of water.

These results may apply to only sandy soils low in organic matter, and measured bulk density might be different if measured on another soil with a different texture. Also, findings might have been different if experiments had been conducted in a region where freezing and thawing occurred.

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