

Effect of canopy and grazing on soil bulk density

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Abstract

This study compared soil surface bulk density between: 1) sites not grazed by cattle > 26 years; 2) sites not grazed for 6 years; 3) sites grazed for 15 years to October residual dry matter levels of > 1100 kg ha⁻¹; 4) sites grazed for 15 years to October residual dry matter levels of 670 to 900 kg ha⁻¹; 5) sites grazed for 15 years to October residual dry matter levels of < 450 kg ha⁻¹; and 6) sites subject to concentrated cattle use (trails, corrals, and supplemental feed-water stations). Sites were collected from across the 1,772 ha San Joaquin Experimental Range (SJER) in Madera County, Calif. to represent canopy cover (open grassland, blue oak (*Quercus douglasii* Hook and Arn.), live oak (*Quercus wislizenii* A.D.C.), foothill pine (*Pinus sabiniana* Douglas), wedgeleaf ceanothus (*Ceanothus cuneatus* (Hook) Nutt.), and ceanothus interspace) and topography (swale, uplands) typical of the rocky coarse sandy loam soils of the southern Sierra Nevada foothill oak savannah. Soil surface (0 to 7.62 cm) bulk density (g cm⁻³) was determined for 1489 soil cores collected across all available combinations of grazing management, canopy cover and topographic position at the SJER. Soil surface bulk density was 0.23 to 0.30 g cm⁻³ lower under canopy compared to open grasslands. Bulk density was not different ($P > 0.05$) between sites not grazed > 26 years and sites not grazed for 6 years. Grazing to residual dry matter levels of > 1100, 670 to 900, and < 450 kg ha⁻¹ created bulk densities which were 0.08, 0.18, and 0.21 g cm⁻³ greater than non-grazed sites, respectively. Cattle concentration sites had bulk densities 0.37 to 0.47 g cm⁻³ greater than areas not grazed > 6 or 26 years. For the purpose of maintaining soil surface bulk density current residual dry matter recommendations for sites with canopy cover > 50% appear appropriate, but recommendations for open grasslands need additional review. In particular, residual dry matter level must be directly linked to soil surface infiltration capacity.

Key Words: compaction, residual dry matter, RDM, annual rangeland, Sierra Nevada

Annual rangelands occupy an estimated 7 million ha in California, and provide 75% of the State's forage base (Griffin 1977). These rangelands contribute surface water to more than half of the State's drinking water reservoirs (FRRAP 1988). Minimizing surface runoff and pollution transport by maintaining the infiltration capacity of annual rangeland soils is important for protecting the State's water supply. Blackburn (1984) summa-

Resumen

Este estudio comparó la densidad aparente de la superficie del suelo entre: 1) sitios no apacentados por ganado > 26 años; 2) sitios no apacentados durante 6 años; 3) sitios apacentados por 15 años hasta Octubre dejando niveles de materia seca residual de >1100 kg ha⁻¹; 4) sitios apacentados por 15 años hasta Octubre dejando de 670 to 900 kg ha⁻¹ de materia seca residual; 5) sitios apacentados por 15 años hasta Octubre dejando niveles de materia seca residual de < 450 kg ha⁻¹ y 6) sitios sujetos a concentraciones de ganado (camino, corrales, y agujas y estaciones de suplementación). Los sitios se seleccionaron a través de las 1772 ha de la estación Experimental de Pastizales San Joaquin (SJER) en el condado de Madera, California para representar la cobertura de copa (pastizal abierto, y el interespacio de "Blue oak" (*Quercus douglasii* Hook and Arn.), "Live oak" (*Quercus wislizenii* A.D.C.), "Foothill pine" (*Pinus sabiniana* Douglas), "Wedgeleaf ceanothus" (*Ceanothus cuneatus* (Hook) Nutt.) y "Ceanothus") y la topografía (valles y terrenos altos) típica de los suelos franco arenosos pedregosos de la savana de encino de piedemonte del sur de la Sierra Nevada. La densidad aparente (g cm⁻³) de la superficie del suelo (0 a 7.62 cm) se determinó en 1489 muestras de suelo colectadas a través de todas las combinaciones disponibles de manejo del apacentamiento, cobertura de copa y posición tipográfica en el SJER. La densidad aparente de la superficie del suelo fue de 0.23 a 0.30 g cm⁻³ menor bajo la copa que en el pastizal abierto. La densidad aparente no fue diferente ($P > 0.05$) entre sitios no apacentados por mas de 26 y sitios no apacentados por 6 años. Apacentar hasta dejar niveles de materia seca residual de > 1100, 670 a 900 y < 450 kg ha⁻¹ crearon densidades aparentes que fueron 0.08, 0.18, y 0.21 g cm⁻³ mayores que la de los sitios no apacentados. Los sitios de concentración de ganado tuvieron densidades aparentes de 0.37 a 0.47 g cm⁻³ mayores que las áreas no apacentadas por > 6 o 26 años. Con el proposito de mantener la densidad aparente del suelo las recomendaciones actuales de materia seca residual en sitios con cobertura de copa > 50% parecen ser apropiadas, pero las recomendaciones para los pastizales abiertos necesitan una revisión adicional. En particular, los niveles de materia seca residual deben ser directamente relacionados con la capacidad de infiltración de la superficie del suelo.

ri- zed the concerns that grazing may lead to soil compaction which increases soil bulk density, reduces soil porosity and infiltration capacity causing increased surface runoff, soil erosion, and transport of non-point source pollutants. These concerns were reiterated in the Sierra Nevada Ecosystem Project Report, which serves as the science base for the amendment of grazing manage-

ment plans for the 10 National Forests in the Sierra Nevada Mountain Range (UCWRC 1996). Soil compaction from domestic livestock is attributed to hoof action, particularly under moist to wet soil conditions, and to reductions in soil organic matter content due to removal of above-ground herbaceous plant material and reduction in rooting density and depth. A potential benefit of moderate soil compaction is increased water holding capacity, which could benefit on-site plant production.

The most commonly reported measure of soil compaction is soil dry bulk density, expressed as the oven dry mass of soil per volume of soil (g cm^{-3}) (Blake and Hartage 1986). In general as the soil surface is compacted, the volume of pore space in the soil's O and A horizon is reduced and its dry bulk density increases. This results in reduced pore space for surface water to infiltrate the soil surface, resulting in greater runoff. Several rangeland studies have shown that soil bulk density is negatively correlated with infiltration capacity and positively correlated with surface runoff (Packer 1953, 1963, Liacos 1962, Rauzi and Hanson 1966, Spaeth et al. 1996). Atwill et al. (2002) found soil surface bulk density to be positively correlated to the transport of the pathogen *Cryptosporidium parvum* from annual grass vegetated soil boxes under simulated rainfall conditions. In this experiment, soil bulk density interacted with percentage slope to determine pathogen transport. At a slope of 5%, Atwill et al. (2002) reported a 12 to 49% increase in pathogen transport in overland flow per 0.1 g cm^{-3} increase in soil bulk density across silty clay to sandy loam soil textures. Soils used in the experiment were typical of California's annual rangelands and agricultural regions.

A few experiments have compared soil surface bulk density under various levels of grazing management on annual rangelands. A common grazing management recommendation on California annual range is the achievement of end of dry season (October) residual dry matter (RDM) levels expected to promote sustainable forage production and quality levels, soil surface protection from erosion, and other benefits (Bartolome et al. 1980, 2002, and Clawson et al. 1982). On Los Osos clay loam soils east of Berkeley, Calif., Liacos (1962) found that soil surface bulk density on non-grazed sites (RDM $\sim 3800 \text{ kg ha}^{-1}$) averaged 1.4 g cm^{-3} , on heavily grazed sites (RDM $\sim 670 \text{ kg ha}^{-1}$) averaged 1.6 g cm^{-3} , and that lightly grazed sites (RDM $\sim 1400 \text{ kg ha}^{-1}$) were interme-

diated. On coarse sandy loam soils at the San Joaquin Experimental Range (SJER) north of Fresno, Calif. Ratliff and Westfall (1971) found that soil surface bulk density was 24% lower within a 36 year non-grazed site than on adjacent grazed sites. At the SJER, Assaeed (1982) observed higher mean soil surface bulk densities on grazed sites (1.38 g cm^{-3}) compared to 10 year non-grazed sites (1.22 g cm^{-3}).

Increased soil surface bulk density can be mitigated by natural processes such as burrowing rodents and freeze-thaw events. The presence of blue oaks (*Quercus douglasii* Hook and Arn.) and other trees is a major factor effecting soil properties across California's annual rangelands (Dahlgren et al. 2003). The effects of tree canopy on soil properties is generally attributed to organic matter contributions from leaf litter and from nutrients contributed as through-fall during precipitation events. Frost and Edinger (1991) compared soil physical and chemical properties in open grasslands to soils under blue oak, interior live oak (*Quercus wislizenii* A.DC.), foothill pine (*Pinus sabiniana* Douglas) canopy under grazed and non-grazed conditions at the SJER. They report a general trend toward greater amounts of organic carbon, lower bulk densities, larger cation exchange capacity, and greater amounts of most nutrients below tree canopy compared to open grasslands at both the 0 to 5 cm and 5 to 20 cm soil depth. Jackson et al. (1990), Dahlgren et al. (1997), and Camping et al. (2002) report significantly higher overall soil quality (lower bulk density, higher organic matter, increased nutrient cycling, etc.) under oak canopy relative to open sites on oak woodland sites with clay loam soils at the Sierra Foothill Research and Extension Center near Browns Valley, Calif. Camping et al. (2002) also examined soil quality between sites not grazed for 28 years and moderately grazed sites (residual dry matter levels $> 900 \text{ kg ha}^{-1}$). The authors report that soil surface bulk density (0 to 5 cm) was 12 and 9% higher under grazed conditions for sites under blue oak canopy and open grassland, respectively. There was no significant difference in bulk density between grazed and non-grazed sites below a soil depth of 5 to 15 cm.

The specific objective of this study was to compare soil surface bulk density between 6 levels of grazing management across canopy and topographic conditions typical of southern Sierra Nevada annual rangelands. Annual grasslands and associated tree and shrub communities occupy

approximately 1.8 million ha in the southern Sierra Nevada foothills (FRRAP 1988). Grazing levels examined were: 1) not grazed by domestic livestock for greater than 26 years, 2) not grazed by domestic livestock for 6 years, 3) 15 year history of light ($> 1100 \text{ kg ha}^{-1}$ RDM) grazing by beef cattle, 4) 15 year history of moderate ($670\text{--}900 \text{ kg ha}^{-1}$ RDM) grazing by beef cattle, 5) 15 year history of heavy ($<450 \text{ kg ha}^{-1}$ RDM) grazing by beef cattle, and 6) sites of cattle concentration (trail, corral, supplemental feeding – watering stations).

Methods

Study Area

The study was conducted on the 1,772 ha San Joaquin Experimental Range (SJER) in Madera County, Calif. ($37^{\circ} 6'8''\text{N } 119^{\circ}43'33''\text{W}$). The SJER has been operated by the USDA Forest Service as a rangeland research station since the early 1930's and has been grazed year around since that time with cattle. Elevation ranges from 213 m to 518 m. Climate is Mediterranean with 485 mm average annual precipitation falling almost entirely November through May as rainfall. Topography at the SJER is rolling with 0 to 30% slopes and significant swale areas formed from alluvial deposits. Swales at the SJER are intermittent wetlands which become saturated during the rainfall season, gradually drying as the rainfall season ends. Swales produce green forage later into the summer months than adjacent uplands, leading to preferential grazing of swales by cattle.

Vegetation is oak savannah with annual grassland understory. Blue oak, interior live oak, foothill pine, and wedgeleaf ceanothus (*Ceanothus cuneatus* (Hook) Nutt.) dominate the overstory, while wild oats (*Avena fatua* L.), ripgut brome (*Bromus diandrus* Roth), soft chess (*Bromus mollis*, L.), and redstem filaree (*Erodium cicutarium* (L.) L'Her) dominate the open grassland and understory. Mean aerial canopy cover by trees and shrubs at SJER is approximately 30%. Isolated trees and intermixed stands of live oak, blue oak, and foothill pine trees are both common. Wedgeleaf ceanothus stands are characterized with open interspaces of 0.5 to 2 m between small (2–4 m) groups of ceanothus.

The only soil type present at SJER is the Ahwanhnee - Vista rocky coarse sandy loam (a coarse-loamy, mixed, thermic Mollic Haploxeralf) (Ulrich and

Stromberg 1990). The soil dominates the southern Sierra Nevada foothills, for instance occupying 54,000 ha or 15.3% of Madera County's surface area. The soil occurs in a north-south belt approximately 16 to 24 km wide ranging in elevation from 150 to 450 m, and is found in association with oak savannah vegetation communities. The soil is derived from decomposing granite parent materials with soil depths from 0.5 to 1.0 m in upland positions (8 to 30% slope) and 1.0 to 3.0 m in swale positions (3 to 8% slopes). Granite bedrock outcrops are common. Representative texture reported as percentage sand/silt/clay for the soil is 74.3/17.7/8.0, 74.1/16.9/9.0, and 86.5/7.5/6.0 for profile depths 0 to 30 cm, 31 to 70 cm, and 70 cm to bedrock, respectively. Organic matter contents for these same profile depths are 1.0 to 2.7 %, 0.5 to 1.5 %, and 0.1 to 0.5%, respectively.

Grazing Management

Livestock enclosures have been constructed and maintained at the SJER for various research related purposes. Livestock enclosures were used in this study based upon the criteria of: 1) availability of canopy cover type and topographic position within the enclosure, 2) certainty of duration and effectiveness of livestock exclusion, and 3) comparability to grazed sites in terms of vegetation type, percentage slope, percentage rock outcrop, etc. Two livestock enclosures greater than 26 years of age (total area = 70 ha) at the time of sample collection (2001) and 3 enclosures created 6 years prior to sample collection (total area = 15 ha) met these criteria and were selected for use in this study.

Detailed mapping of residual dry matter has been conducted annually in October across the SJER since 1985. Geographic information system technology was used to generate a 15 year average residual dry matter map for the entire SJER from the 15 individual annual residual dry matter maps (Harris et al. 2002). For this study, areas (10 to 30 ha) across the SJER with a 15 year residual dry matter history of less than 450 kg ha⁻¹, 670-900 kg ha⁻¹, and greater than 1100 kg ha⁻¹ were randomly selected for inclusion in this project. Also existing across the SJER are various cattle concentration areas including corrals, supplemental feed and water stations, and trails. For this study we used cattle concentration sites which were confirmed to have been in use for 15 years prior to sample collection.

Soil Surface Bulk Density

Soil surface bulk density (g cm⁻³) was determined via the core method (Blake and Hartage 1986) using a 7.62 cm long by 4.78 cm diameter cylindrical metal core. All live vegetation and litter at each sample site (0.1 m²) was clipped to the mineral soil surface and removed prior to collection of the soil core. Soil cores were dried at 105° C in a forced air oven until a constant weight was achieved (24 to 48 hours). Soil cores were weighed on an analytical balance accurate to 0.001 g, and bulk density calculated as soil dry weight (g) divided by total core volume (136.74 cm³). A total of 1,489 soil cores were collected across the SJER during the fall, early winter, and spring of 2001, when soils were moist but not saturated.

Experimental Design

This study was a stratified random survey of soil surface (0-7.5 cm) bulk density across all available combinations of 3 factors at SJER. The 3 factors were: 1) grazing management, 2) canopy cover, and 3) topographic position. Grazing management levels examined were: 1) not grazed by domestic livestock > 26 years, 2) not grazed by domestic livestock for 6 years,

3) 15 year history of light (> 1100 kg ha⁻¹ RDM) grazing by beef cattle, 4) 15 year history of moderate (670-900 kg ha⁻¹ RDM) grazing by beef cattle, 5) 15 year history of heavy (< 450 kg ha⁻¹ RDM) grazing by beef cattle, 6) cattle trails, 7) cattle corrals, and 8) cattle supplemental feeding and watering stations. Canopy cover types examined were: 1) open grassland, 2) blue oak, 3) live oak, 4) foothill pine, 5) wedgeleaf ceanothus, and 6) ceanothus interspace. Topographic positions examined were: 1) swale, and 2) upland.

Sample areas with each level of grazing management were identified across the SJER (stratification). Sample areas ranged in area from 5 to 30 ha. Soil surface bulk density samples were randomly collected across all available canopy cover types and topographic positions within each sampling area. Where there was blue oak, live oak or foothill pine canopy, trunk diameter at breast height (DBH) was measured for each individual tree by bulk density sample combination. This cross-sectional survey is inherently unbalanced because: 1) not all combinations of grazing management, canopy cover, and topographic position exist at the SJER, and 2) combinations do not exist in equal num-

Table 1. Mean soil surface (0 to 7.6 cm) bulk density (g cm⁻³) across oak savannah rangeland sites with different grazing management practices and canopy cover on the San Joaquin Experimental Range, Madera County, Calif.

Factor	Mean ¹	95% CI Mean ²	SE Mean ³	n ⁴
----- (g cm ⁻³) -----				
Grazing Management				
Not grazed > 26 yrs ⁵	1.21a	1.222, 1.190	0.008	390
Not grazed 6 yrs ⁶	1.22a	1.243, 1.191	0.013	194
> 1100 kg ha ⁻¹ RDM ⁷	1.29b	1.312, 1.267	0.012	149
670-900 kg ha ⁻¹ RDM ⁸	1.39c	1.403, 1.366	0.009	331
< 450 kg ha ⁻¹ RDM ⁹	1.42c	1.438, 1.396	0.011	292
Corral ¹⁰	1.58d	1.617, 1.536	0.020	65
Cattle Trail ¹⁰	1.61d	1.661, 1.562	0.024	46
Feed-Water Station ¹⁰	1.68d	1.745, 1.609	0.033	22
Canopy Cover				
Open Grassland	1.42a	1.435, 1.413	0.006	909
Ceanothus Interspace	1.39a	1.430, 1.344	0.021	48
Live Oak	1.19b	1.215, 1.167	0.012	195
Blue Oak	1.18bc	1.199, 1.152	0.012	225
Foothill Pine	1.15bc	1.196, 1.096	0.025	62
Ceanothus	1.12c	1.162, 1.068	0.023	50

¹Within factor (management history and canopy cover), means with different letters were determined to be significantly different (P < 0.05).

²95% confidence interval (upper, lower) of the mean.

³Standard error of the mean.

⁴Number of samples for each factor, total sample size = 1489.

⁵Not grazed by cattle for more than 26 years prior to sample collection.

⁶Not grazed by cattle for 6 years prior to sample collection.

⁷Grazed with cattle to an annual residual dry matter level of >1100 kg ha⁻¹ over the 15 year period prior to sample collection.

⁸Grazed with cattle to an annual residual dry matter level of 670 to 900 kg ha⁻¹ over the 15 year period prior to sample collection.

⁹Grazed with cattle to an annual residual dry matter level of less than 450 kg ha⁻¹ over the 15 year period prior to sample collection.

¹⁰Cattle concentration sites (corral, trail, and supplemental feed - water station) for the 15 year period prior to sample collection.

bers across all sample areas available at the SJER. For example, there were no cattle corrals with tree cover, nor were there foothill pine or wedgeleaf ceanothus in swales. While open grassland, blue oak and live oak were prevalent across all sample areas, foothill pine and wedgeleaf ceanothus were less prevalent resulting in a smaller sample size relative to the oaks. Table 1 reports the sample size for each level of grazing management and canopy cover. Sample size for uplands and swales was 1011 and 478, respectively.

The data set ($n = 1489$) was analyzed via backward stepwise general linear model procedures with a test criterion of $P \leq 0.05$ (SPSS, Inc. 2000) to identify significant main factors effecting soil surface bulk density. Independent variables included in the original model were grazing management history; topographic position; and canopy cover. Soil surface bulk density was the dependent variable. Mean separation for levels of significant factors was accomplished using a Bonferroni test ($P \leq 0.05$). Two-way interactions were examined for all main factors. Evaluation of residual error plots indicated that assumptions of normality, independence and constancy were met. Simple linear regression was used to examine relationships between tree size as measured by DBH (independent variable) and soil surface bulk density (dependent variable). It would be reasonable to expect soil surface bulk density to decrease with tree age-size, or time that the soil has been under the influence of canopy cover.

Results and Discussion

Backward stepwise analysis produced a final general linear model (multiple $R^2 = 0.56$, $n = 1489$) identifying grazing management and canopy cover as significant factors ($P < 0.001$) associated with soil surface bulk density at SJER. Topographic position was not a significant predictor of soil surface bulk density ($P = 0.89$). No interactions were found to exist between any of the main factors (grazing management, canopy cover, and topographic position). Figures 1 and 2 illustrate mean soil surface bulk density with 95% confidence intervals for grazing management and canopy cover, respectively. Table 1 reports the mean, mean standard error, and sample size for each factor.

Grazing Management

Livestock Exclusion. Soil surface bulk density was not different ($P = 0.22$) between sites not grazed for > 26 years and sites not grazed for 6 years; however, variation in surface bulk density was greater at sites not grazed for 6 years (Fig. 1, Table 1). The significant reduction in surface bulk density associated with livestock exclusion compared to any level of grazing supports results reported from previous research on annual rangelands (Liacos 1962, Ratliff and Westfall 1971, Assaeed 1982). While this result provides information on potential surface bulk density condition in the absence of grazing by cattle, it provides limited information for making grazing management decisions to minimize soil compaction in the presence of grazing.

Our results indicate that the reversal of soil compaction from grazing on these coarse sandy loam soils is relatively rapid. Assaeed (1982) observed a significant reduction in surface bulk density (mean of 1.22 g cm^{-3}) on sites not grazed for 10

years compared to grazed sites (mean of 1.38 g cm^{-3}) at the SJER. The mean surface bulk densities reported by Assaeed (1982) are approximate, and supporting, to our findings (Table 1). One potential mechanism is an increase in activity of burrowing mammals within the enclosures, which was our casual observation in the non-grazed sites and the conclusion of Ratliff and Westfall (1971). Another mechanism could be increased soil surface organic matter due to high levels of residual dry matter within the enclosures. The mild climate at the SJER does not generate soil freezing and thawing, known to effect soil bulk density in colder climates. The rate at which soils recover from compaction from livestock grazing will likely vary based upon soil properties such as texture and structure, as well as antecedent grazing intensity.

Residual Dry Matter Level. Sites with grazing to any residual dry matter level had significantly higher bulk density ($P < 0.001$) than sites not grazed for > 26 years or for 6 years (Fig. 1, Table 1). Of grazed

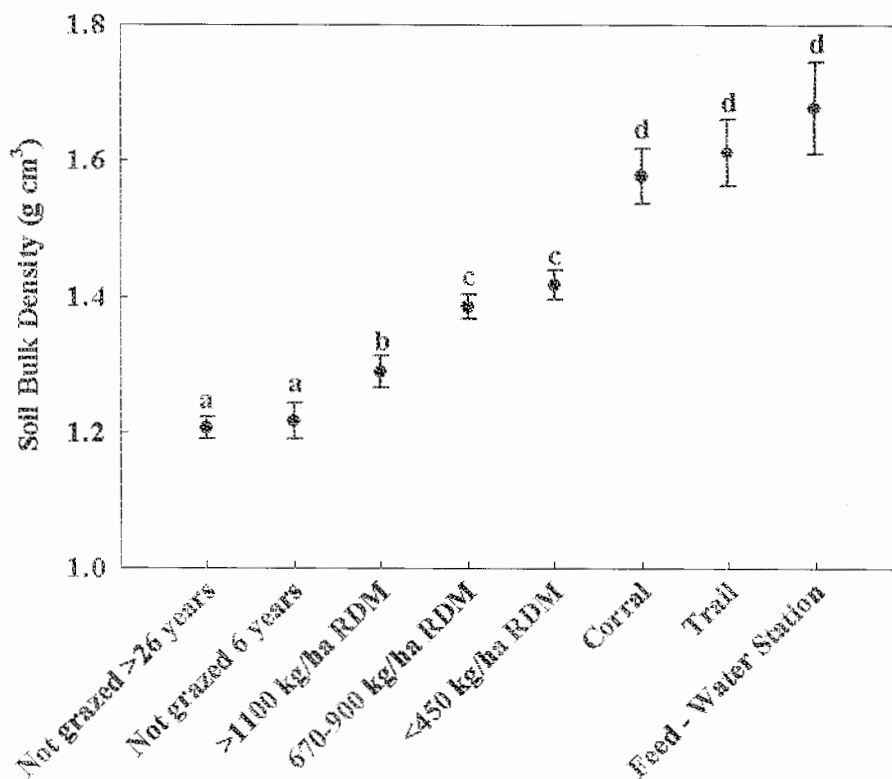


Fig. 1. Mean soil surface bulk density (g cm^{-3}) for oak savannah rangeland sites subject to grazing management practices at the San Joaquin Experimental Range, Madera County, Calif. Grazing management practices are not grazed by domestic livestock for > 26 years and not grazed for 6 years; sites grazed annually by cattle for 15 years to residual dry matter (RDM) levels of > 1100 , 670 to 900 , and $< 450 \text{ kg ha}^{-1}$; and cattle concentration areas including corrals, trails, and feed-water stations. Bars represent the 95% confidence interval of the mean. Means with different letters are significantly different ($P < 0.05$).

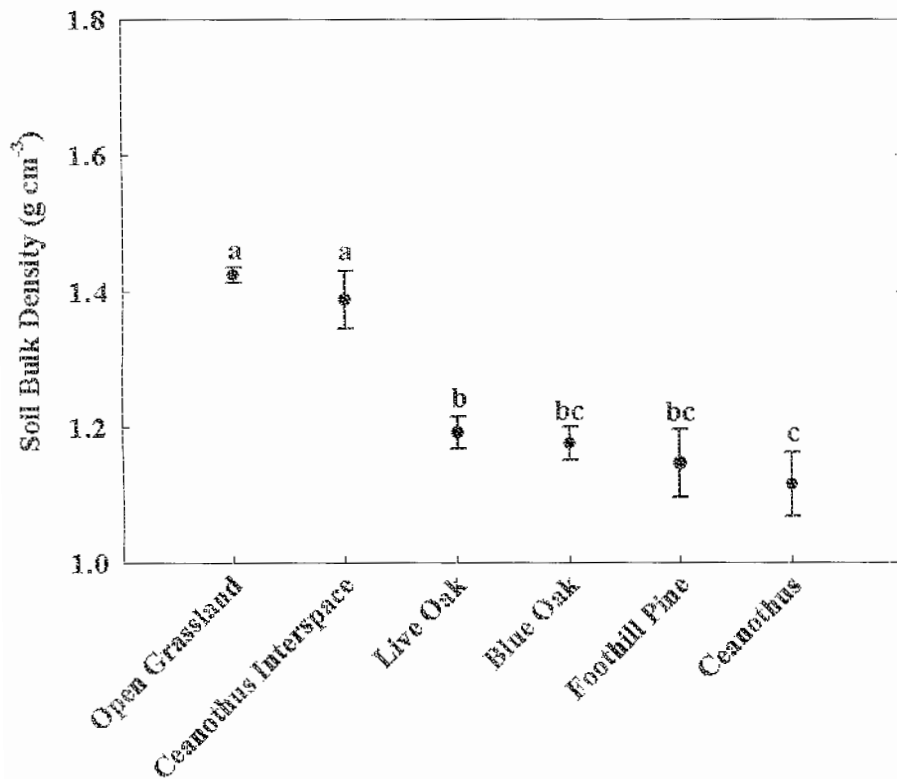


Fig. 2. Mean soil surface bulk density (g cm^{-3}) for oak savannah rangeland sites with different canopy cover types at the San Joaquin Experimental Range, Madera County, Calif. Bars represent the 95% confidence interval of the mean. Means with different letters are significantly different ($P < 0.05$).

sites, those with a 15 year history of $> 1100 \text{ kg ha}^{-1}$ residual dry matter had the lowest mean bulk density, followed by sites with a 15 year history of grazing to residual dry matter levels of 670 to 900 kg ha^{-1} and $< 450 \text{ kg ha}^{-1}$, which were not significantly different ($P = 0.98$). Sites grazed > 1100 , 670 to 900, and $< 450 \text{ kg ha}^{-1}$, had soil surface bulk densities which were 6, 15, and 17% greater than non grazed sites, respectively.

Our results agree with work by Liacos (1962) indicating that the level of soil compaction due to grazing on annual rangeland can be managed, at least in part, by managing for specific residual dry matter levels. Analyzing soil surface infiltration data collected on northern Great Plains grasslands, Spaeth et al. (1996) found infiltration capacity to be positively correlated with mulch levels, similar to our results showing soil surface bulk density to be negatively correlated with residual dry matter or mulch levels. It is likely that the season of grazing (winter growing season, summer drought period, continuous) also determines soil compaction. The predominant grazing season on annual rangelands in the south Sierra Nevada

foothills is during the winter rainfall growing season when soils are moist and most susceptible to compaction. Season of grazing records are not available for the SJER, making it impossible to test for season of grazing effect, or a season of grazing by residual dry matter level interaction, on soil surface bulk density. The study areas used in this survey represent the range of season of use, but the season of use was certainly not constant at each site over the past 15 years.

Cattle Concentration Activities. Activities which concentrate cattle were associated with the greatest soil compaction encountered in this study having bulk densities 30 to 40% greater than areas not grazed > 26 years, and 18 to 22% greater than surrounding grazed areas (Fig. 1, Table 1). While there was an apparent increase in soil surface bulk density from corrals to trails to supplemental feed - water stations, these sites were not significantly different ($P > 0.85$ for all comparisons). This result clearly illustrates the importance for managers to consider the location of cattle concentration sites relative to waterbodies of concern. Compacted soil conditions at cattle con-

centration sites pose the greatest livestock related risk of increased surface runoff and transport of non-point source pollutants on these rangelands. Significantly higher cattle fecal loading rates are associated with concentration sites compared to other grazed areas (Larsen 1996, Bailey and Welling 1999, Tate et al. 2003). Trails almost always lead to and from cattle concentration sites, crossing streams and wetlands, and thus greatly increasing the hydrologic connectivity between sources of contaminants and waterbodies. George et al. (2002) report 136 to 550% greater sediment transport from livestock trails than adjacent grassland at the SJER.

Canopy Cover

Canopy cover by any tree or shrub species used in this survey significantly reduced soil surface bulk density (16 to 22%) compared to open grassland or wedgeleaf ceanothus interspace ($P < 0.001$ for all comparisons) (Fig. 2, Table 1). Soil surface bulk density was not significantly different for open grassland sites and sites located in ceanothus interspace ($P = 0.99$). Soils under live oak and ceanothus had significantly different ($P = 0.02$) surface bulk density, but all other canopy types were statistically similar ($P > 0.31$ for all comparisons). Our results confirm that canopy cover is a major factor determining soil bulk density on annual rangelands, agreeing with work conducted by others illustrating that oaks create enhanced fertility beneath their canopy through organic matter incorporation and nutrient cycling, leading to elevated soil quality relative to adjacent grasslands (Kay 1987, Jackson et al. 1990, Frost and Edinger 1991, Dahlgren et al. 1997, 2003). Low soil surface bulk density is one component of high soil quality.

Simple linear regression revealed no significant relationships between tree size as measured by diameter at breast height (DBH) and soil surface bulk density for live oak ($P = 0.85$, $n = 195$). Significant relationships between DBH and soil bulk density were found for blue oak ($P = 0.03$, multiple $R^2 = 0.02$, slope = -0.003 , intercept = 1.22, $n = 225$) and foothill pine ($P = 0.002$, multiple $R^2 = 0.16$, slope = -0.01 , intercept = 1.39, $n = 62$). Minimum and maximum DBH for live oak, blue oak and foothill pine used in this study was 16 to 200, 7 to 137, and 16 to 86 cm, respectively. Due to the multi-stem growth habit of live oak, the relationship between age and DBH is weak at best. While age and DBH are positively correlated for blue oak, numerous researchers have concluded that

the relationship is highly variable across sites and within stands (McClaran 1986, McClaran and Bartolome 1989, Kertis et al. 1993). Foothill pine has a short life-span (< 100 years) relative to blue oak (200 to 300 years) which probably accounts for the stronger relationship between soil surface bulk density and DBH compared to blue oak.

Topographic Position

Topographic position was not a significant predictor of soil surface bulk density despite swales having a higher grand mean bulk density (1.41 g cm⁻³) compared to upland bulk density (1.29 g cm⁻³). Grazing management and canopy levels accounted for the differences between topographic positions due to the fact that there is limited canopy cover by trees or shrubs in swales, and that swales are almost always associated with low residual dry matter levels (heavy grazing pressure) due to the late season green forage they produce.

Residual Dry Matter Recommendations

The results of our research are directly comparable to published residual dry matter recommendations for the sustainable management of annual rangelands in California. Current residual dry matter recommendations are based upon research and observation linking residual dry matter to herbaceous plant community composition, forage production and ground cover. Recently revised residual dry matter recommendations are based upon precipitation amount, percentage slope and percentage canopy cover (Bartolome et al. 2002). Recommended residual dry matter levels increase as precipitation amount and percentage slope increase, and decrease as percentage canopy cover increases. Recommendations for oak savannah range sites in the south Sierra Nevada foothills range from a minimum of 110 kg ha⁻¹ for > 75% canopy cover at < 10% slope to 900 kg ha⁻¹ for < 25% canopy cover at > 40% slope (Bartolome et al. 2002). Original recommendations given by Clawson et al. (1982) for the same range type were from 450 kg ha⁻¹ at "low" slopes to 900 kg ha⁻¹ at "steep" slopes. The original recommendations by Clawson et al. (1982) did not account for the variable effect of canopy cover on potential herbaceous production. While scattered blue oaks will increase herbaceous production, canopy cover reaches a level (~50%) where shading negatively affects herbaceous production.

Our results and other published research indicate that canopy cover will maintain mean soil surface bulk density at or below the mean bulk density for non-grazed conditions, off-setting soil compaction by livestock (Table 1) (Frost and Edinger 1991, Dahlgren et al. 2003). For the purposes of maintaining soil surface bulk density, recommended residual dry matter levels for canopy levels > 50% (110 to 560 kg ha⁻¹) appear appropriate. However, for canopy cover < 50%, recommended residual dry matter levels (450 to 900 kg ha⁻¹) correspond to a 15 to 17% increase in soil surface bulk density compared to non-grazed conditions (Fig. 1, Table 1). The results reported in this paper for open grassland sites, and published studies of grazing intensity effects on soil surface bulk density and infiltration capacity, clearly illustrate that any level of grazing will increase soil bulk density, and likely reduce infiltration capacity, relative to no grazing (Liacos 1962, Ratliff and Westfall 1971, Gifford and Hawkins 1978, Assaeed 1982, Dahlgren et al. 2003).

From a water quality protection perspective, the important issue is whether the level of soil compaction associated with accepted residual dry matter recommendations reduces infiltration capacity sufficiently to increase surface runoff and transport of pollutants to nearby waters. There is limited published information available on the infiltration capacity of the coarse sandy loam soils typical of the south Sierra Nevada foothills, particularly relative to residual dry matter levels. Infiltration capacity on these rangelands is inherently high due to soil texture (74.3% sand, 17.7% silt, 8% clay). In a previous rainfall simulator experiment examining pathogen transport at the SJER we applied 7.62 cm hour⁻¹ of rainfall to a saturated open grassland plot having soil surface bulk density of 1.50 g cm⁻³ and a 15 year residual dry matter level of < 450 kg ha⁻¹ (Tate et al. 2000). This rainfall rate exceeds the 100 year return interval 30 minute duration rainfall event (Hershfield 1961). During the course of the 90 minute application period, only 4% of the applied rainfall was realized as overland flow, 96% of the applied water was infiltrated. Thus, the increase in soil surface bulk density associated with recommended residual dry matter levels potentially does not result in increased surface runoff in this landscape, given the inherently high infiltration capacity of these soils. This possibility must be examined in future studies which directly link residual dry matter, infiltration and runoff. A potential benefit of moderate soil

compaction associated with grazing to recommended residual dry matter levels, particularly in these sandy soils, is increased water holding capacity which would benefit on-site plant production.

Summary and Conclusions

We found canopy cover and grazing management to significantly affect soil surface bulk density on oak savanna rangelands at San Joaquin Experimental Range. Soil surface bulk density was 16 to 22% lower under canopy compared to open grasslands or wedgeleaf ceanothus interspace. There was no significant difference in soil surface bulk density between sites not grazed > 26 years and sites not grazed for 6 years, indicating that reversal of soil compaction from grazing occurs rapidly in this landscape. Sites with a 15 year history of grazing to residual dry matter levels of > 1100, 670 to 900, and < 450 kg ha⁻¹ had soil surface bulk densities 6, 15, and 17% greater than non-grazed sites, respectively. Cattle concentration sites had bulk densities 30 to 40% greater than areas not grazed > 26 years, and 18 to 22% greater than surrounding grazed areas, and clearly represent the largest risk of increased runoff and contaminant transport on these rangelands. Current residual dry matter recommendations for sites with canopy cover > 50% appear appropriate for maintaining soil surface bulk densities. Residual dry matter recommendations for open grassland sites need further critical review to determine if the observed increases in soil surface bulk density translate to sufficient reductions in soil infiltration capacity to increase surface runoff and subsequent contaminant transport. The decrease in soil surface bulk density associated with decreasing residual dry matter level may not correlate to a proportional increase in surface runoff.

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