SOIL BULK DENSITY IMPACTS OF AN OAK MAT NATURAL GAS DRILL PAD CONSTRUCTION TECHNIQUE[1]

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Abstract: Traditional drill pad construction techniques for natural gas production displace the existing plant community and result in surface disturbances requiring costly soil remediation and revegetation procedures. At the Jonah natural gas field, Sublette County, Wyoming, EnCana Oil and Gas (U.S.A.), Inc. is evaluating the use of oak mats to minimize disturbance to soil and plant resources by facilitating drilling and completion activities atop continuous 15.2 centimeter thick oak platforms. One concern with both traditional and oak mat drill pad construction techniques is the potential for increases in soil bulk density. In this study, dry soil bulk density was measured before-and-after oak mat drill pad construction at 17 drill pad sites for 0-5.1, 0-15.2 and 0-30.5 centimeter depth increments to quantify changes in soil bulk density in relation to growth limiting bulk densities described in the literature. Similar bulk density measurements were taken at six conventional-reclaimed drill pads to allow comparison between the construction techniques. Of the 17 oak mat locations, four drill pad areas exhibited no statistically significant change in bulk density as a result of the oak mat procedure. Of the 13 remaining oak mat drill pads, one or more depth increments had significant soil bulk density increases of 0.06 to 0.17 g/cm^3 as a result of drilling on top of the oak mats. Literature review indicated plant growth may be impaired when the dry soil bulk density is greater than 1.5 g/cm^3. Of the oak mat soil profile depths measured, 95 % remained below this value, while a substantially higher proportion of conventional-reclaimed drill pad soil profile depths exceed this threshold.

Additional Key Words: soil bulk density, natural gas development, drill pad construction, Jonah Field, and land reclamation

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Introduction

Conventional natural gas production on public land in the Jonah Field, Sublette County, Wyoming, is limited to a density of one drill pad per 16.2 hectares by Bureau of Land Management regulation. Drill pad spacing constraints are implemented to balance resource development and the management of wildlife habitat, grazing leases and multiple uses on public land. Due to the nature of "tight sands" natural gas reservoirs within the rocky mountain region, optimum natural gas recovery requires drilling numerous closely spaced wells, a practice that increases the surface footprint of drilling activities and impacts to surface resources. Directional drilling has been the predominant method for maximizing access to these natural gas reservoirs while minimizing the surface footprint, but is often not technically feasible or economically cost effective.

Conventional drill pad construction at the Jonah Field uses a cut-and-fill technique to produce the level drilling surface; an approach that requires the removal of native soil and plant communities as well as costly post-drilling site reclamation and vegetation reestablishment. Site and seedbed preparation techniques have been previously evaluated for conventional drill pad reclamation, and data suggest cut-and-fill drill pads generally produce higher bulk densities compared to undisturbed rangeland. The oak mat technique precludes the need to remove native soil and plant communities, stockpile soil resources, reclaim and re-vegetate drill pad areas. The oak mat technique accomplishes this by placing an interlocking matrix of oak mats directly on top of soil and plant resources, enabling drilling operations with minimal surface disturbance (Fig. 1). At the close of drilling operations, the oak mat matrix is disassembled without trespass on native soil by retreating across the drill pad from the farthest reach back to the access road. The oak mats are then transported to the next drilling location for reuse.

Mats were originally designed for the construction of temporary roads and aircraft landing strips on soft or sandy soils. The use of mats has garnered recent attention by natural gas producers in Canadian muskeg country for the construction of temporary roads and drill pads. In the gas rich regions of the Western Canadian Sedimentary Basin (WCSB), the widespread distribution of wetlands and muskeg has made the transport of infrastructure to remote drill areas impassible after spring thaw. The use of oak and composite plastic mats in the WCSB have benefited producers by extending the window for drilling operations where only winter operations were previously logistically feasible and cost effective. These methods are being incorporated at the Jonah Field as an alternative to the conventional cut-and-fill drill pad construction technique.

Individual oak mat units used in the Jonah Field are 2.4 meters (m) wide by 3.7 m long and consist of three perpendicular oak planks 5.1 centimeters (cm) tall, which contribute to a total mat height of 15.2 cm (Fig. 2). Individual oak planks are 25 cm wide and spaced at 2.5 cm intervals to help distribute the weight of the drilling equipment and increase the strength of the mats. The approximate weight of each oak mat is 1,134 kilograms, which applies a soil bearing pressure of 480 kilograms per cubic meter. Due to the weight of the drill rig and auxiliary equipment, each oak mat transmits approximately 854 kilograms per square meter to the soil surface. Approximately 1,255 kilograms per square meter is exerted on the area directly under the sub-structure of the drilling rig (EnCana Oil and Gas Inc., et al, 2006). Oak mat techniques are proposed in contrast to conventional cut-and-fill drill pad construction, but are not applicable in situations where natural site relief presents infrastructure leveling problems or safety concerns.

Topographic gradients are addressed by using either wood shims or earthen fill to level drill platforms.

Figure 1. View of a drill pad constructed with oak mats.

Figure 2. Cross section of an oak mat constructed from individual oak boards.

At the Jonah Field, 70 drilling locations are currently assigned to the oak mat construction technique. The objective of this study was to evaluate impacts to *in situ* soil bulk density associated with matting techniques and conventional cut-and-fill drill pad construction approaches.

Materials and Methods

A Troxler nuclear density and moisture gauge was used at oak mat and reclaimed conventional drill pads to measure dry soil bulk density (Troxler Electronic Laboratories, Inc, Research Triangle Park, NC.). The Troxler instrument employs an Am-241/Be radioactive source to determine soil moisture content and a Cs-137 radioactive source to determine the wet soil bulk density. An internal processor subtracts the water content from the wet bulk density value to yield the dry soil bulk density in pounds per cubic feet. Values are converted to grams per cubic centimeter (g/cm^3) using the following equation (Equation 1).

$$\text{pounds/ft}^3 * (0.0160184) = \text{g/cm}^3 \quad (1)$$

A 2 cm diameter hole was punched into the soil to 30.5 cm to allow entry of the radioactive probe to the prescribed depth increment.

Bulk Density Measurement at Oak Mat Locations

Previous to drilling activities, dry soil bulk density at oak mat drill pads were measured using a Troxler nuclear density and moisture gauge at 6 random locations across each drill pad area (Fig. 3A). At each of the six locations, dry soil bulk density was measured from 0 to 5.1 cm, 0 to 15.2 cm and 0 to 30.5 cm.

A survey grade GPS with less than 2.5 cm resolution was used to permanently locate each initial bulk density measurement location to facilitate later re-measurement after oak mat removal. A compass was used to orientate the Troxler instrument north of the probe-entry hole to ensure that repeated measures of bulk density represented the same volume of soil for later value comparison. Subsequent to the removal of oak mats, measurement locations were relocated using a survey grade GPS and bulk density was re-measured at depth increments of 0 to 5.1 cm, 0 to 15.2 cm and 0 to 30.5 cm with the instrument once again oriented north. For each drill pad, the comparison of soil bulk density before mat construction and after mat removal passed tests associated with normal data distribution and equal variance. ANOVA statistical procedures were applied to all data at the 0.05 probability level.

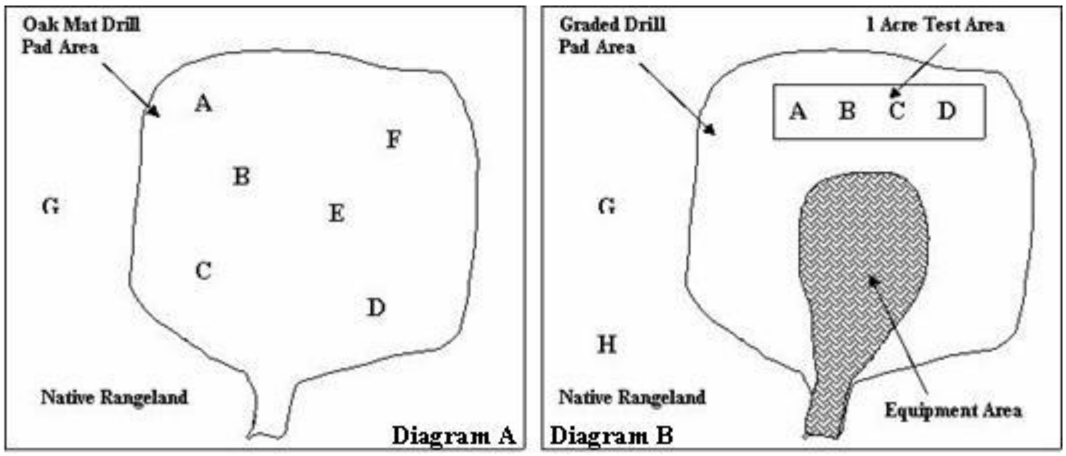

Figure 3: Plan view of generalized bulk density measurement locations at oak mat (diagram A) and conventional drill pad locations (diagram B).

<u>Bulk Density Measurement at Conventional Locations</u>

Six conventionally constructed drill pads were selected to represent the current range in reclamation prescriptions used in the Jonah Field to minimize compaction and prepare the seedbed. Of the six, two sites were ripped previous to coversoil application and then chiseled, two sites were ripped subsequent to coversoil application and then chiseled and, two sites were ripped subsequent to coversoil application with an alternative ripper and then chiseled. A Troxler nuclear density and moisture gauge was used to measure soil profile bulk density at four locations within a 1 acre sub-area of each conventional drill pad and at two off-pad reference locations in the undisturbed native range (Fig. 3B). Soil bulk density measured within conventional drill pads was compared to the undisturbed reference locations. At each of the six locations, dry soil bulk density was measured at 0 to 5.1 cm, 5.1 to 15.2 cm and 15.2 to 45.7 cm increments. To facilitate bulk density measurements within these distinct, non-overlapping depth increments, each sampling depth was excavated after the bulk density was determined to enable measurement of the subsequent depth increment by placing the instrument flush with the newly excavated surface. A t-test was applied to bulk density data collected from the six reclaimed conventional drill pads to determine whether drill pad soil bulk density is significantly different (p=0.05) than soil depths in the adjacent undisturbed rangeland.

<u>Accuracy of the Troxler Gauge</u>

Accuracy of the Troxler Gauge was addressed using four methods: 1) Factory calibration provided the determination of density versus count-rate computations and normalized calibration data to a standard. This effectively eliminates long term effects of source decay and electronic drift (Troxler Electronic Laboratories, Inc., 1975). 2) Annual calibration tests were performed by an independent laboratory using guidelines and standards set forth by the NRC, ASTM and AASHTO. 3) A standard count was performed daily to compensate for the decay process of both radioactive sources which enables the gauge to operate accurately within the range of the factory prescribed calibration. If the instrument accepted the daily calculated standard count, readings could be accurately made in the field. No standard count discrepancies were encountered during soil bulk density measurements in the Jonah Field. 4) Soil bulk densities measured with the Troxler gauge were compared to the bulk density determined by soil sampling and laboratory procedures at a subset of locations and depth increments (n=17). Following a Troxler gauge bulk density measurement at a conventional drill pad, a 5.1 or 15.2 cm long Shelby tube was inserted vertically into the ground using the hydraulic ram of a Giddings soil sampling machine to procure an intact soil core from either 0 to 5.1 or 0 to 15.2 cm depths. Following insertion, a sharpshooter spade was used to excavate the Shelby soil core and a knife was used to pare the sample flush with the bottom of the cylinder. Ten 5.1 cm and ten 15.2 cm Shelby cores were collected in this fashion. Shelby tube soil samples were removed from the steel cylinder and oven dried 72 hours at 100° C to remove water. The dry soil bulk density was determined by dividing the mass of the oven dried sample (g) by the volume of the Shelby tube (cm^3). Linear regression was used to compare bulk density values measured by the Troxler gauge to those derived from the Shelby laboratory method and the correlation coefficient (r) was calculated (Fig. 4). Linear regression indicated that soil bulk density values measured with the Troxler gauge and those measured in the laboratory were closely correlated (r = .94), suggesting that measurements taken with the Troxler gauge were accurate.

Precision of the Troxler Gauge

At seven locations, dry soil bulk density measurements were repeated for the 0 to 5.1 cm, 0 to 15.2 cm and 0 to 30.5 cm depth increments for the determination of relative percent difference (RPD). RPD was calculated using Equation 2.

$$RPD = [(\text{Duplicate 1}-\text{Duplicate 2})/((\text{Duplicate 1}+\text{Duplicate 2})/2)] * 100 \qquad (2)$$

RPD ranged from 0 to 1.6 % and suggests that as much as 1.6 % error can be introduced into dry soil bulk density measurements due to imperfection in the instrument electronics.

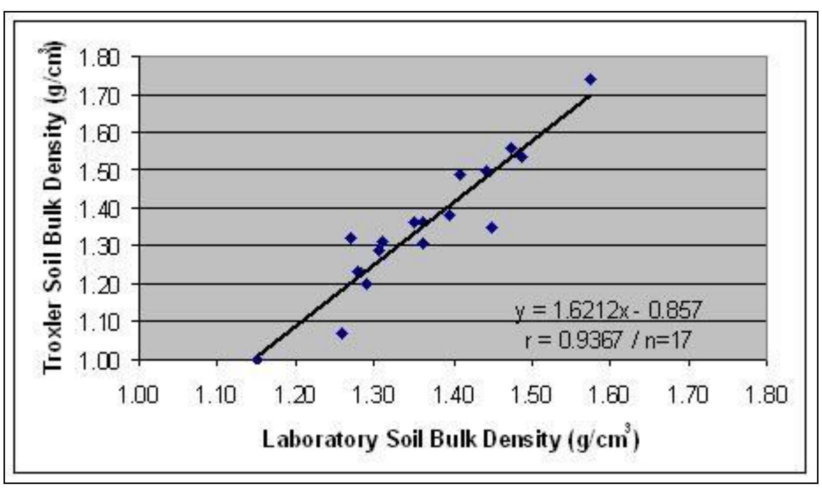

Figure 4. Linear regression between the Troxler gauge and laboratory determined dry soil bulk density (n=17).

Results and Discussion

Soil Compaction Reported in the Scientific Literature

Various research studies have shown the detrimental effects of soil compaction on the establishment and growth of agricultural plants (Taylor et al., 1966; Crockroft et al., 1969; Vorhees et al., 1975; Gerard et al., 1982) and commercially important tree species (Minmore, et al. 1969; Webster, 1978; Zisa et al., 1980), but little research pertains specifically to soil compaction effects on range plant growth in the intermountain west or the impact of heavy machinery to soil and plant resources shielded by mats. The “growth limiting bulk density” (GLBD) (Daddow and Warrington, 1983) is a useful concept that reflects the upper limit, or threshold bulk density where soil resistance to root penetration essentially stops plant growth. Research has also defined threshold bulk density as values where root elongation, root penetration, restriction or cessation of root growth, or reduction in root mass of individual plant species is attributed to a particular bulk density as a function of individual soil texture.

According to Daddow and Warrington (1983), soil texture has the greatest influence on the GLBD because of its effect on soil pore size and mechanical resistance. A soil with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles. Because of this relationship, coarse textured soils will usually have a higher GLBD than fine textured soils. Through their regression analysis, Daddow and Warrington were able to calculate the GLBD for 80 different soils based on the packing density model developed by Gupta and Larson (1979). Isodensity lines on Figure 5 represent equal GLBD values and are used to estimate the GLBD of a soil.

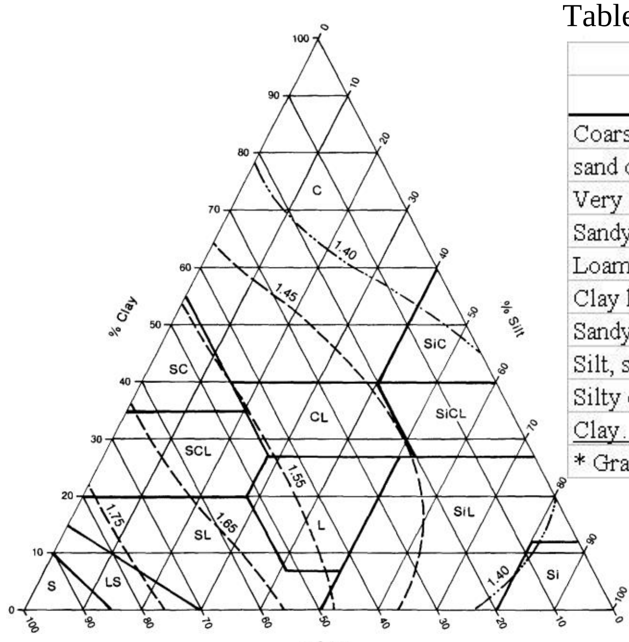

Figure 5. Isodensity lines (g/cm^3) based on soil texture that represent growth limiting bulk densities.

Table 1. Root restricting bulk density values.

Texture	Root Restricting Bulk Density (g/cm^3)*
Coarse, medium and fine sand and loamy sand other than loamy very fine sand	1.80
Very fine sand, loamy fine sand	1.77
Sandy loam	1.75
Loam, sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt, silt loam	1.55
Silty clay loam	1.45
Clay	1.40
* Grams per cubic centimeter	

Table 1 was developed by the USDA Natural Resources Conservation Service (2001) in consultation with other federal agencies (the USDA Soil Quality Group, Grazing Lands Technology Institute, National Soil Survey Center, Agricultural Research Service and the USDI Bureau of Land Management) and reflect the author's perspectives on plant root restriction as a function of soil bulk density and texture-class in rangeland environments.

Textural data collected from the oak mat drill pad locations in the Jonah Field are presented in Fig. 6 and indicate that clay loam and loam textures dominate surface soils. Based on the isodensity lines in Fig. 5, soil bulk densities of 1.45 to 1.60 g/cm^3 are considered growth limiting bulk densities for clay loam and loam textured soils, respectively. Table 1 indicates that bulk density values of 1.65 and 1.70 g/cm^3 will restrict root development. For the purpose of this study, soil bulk densities greater than 1.50 g/cm^3 were considered detrimental to plant emergence and growth at the Jonah Field.

<u>Soil Compaction Associated With Oak Mat Drill Pad Construction</u>

Four drill pads have no statistically significant change in bulk density as a result of the oak mat procedure (Table 2). Measured bulk density values ranged from 1.11 to 1.40 g/cm^3 before construction of the four pads to 1.07 to 1.47 g/cm^3 after drilling and mat removal. Eleven drill pads have no significant change in bulk density in the 0 to 5.1 cm and 0 to 15.2 cm increments, but show a significant increase in the 0 to 30.5 cm increment (Table 2). In the 0 to 30.5 cm increment, measured bulk density values ranged from 1.10 to 1.48 g/cm^3 before construction of the eleven pads to 1.00 to 1.56 g/cm^3 after drilling and mat removal, with significant increases in bulk density ranging from 0.06 to 0.15 g/cm^3. One drill pad shows no significant change in the 0 to 5.1 cm depth, but has significant increases in the 0 to 15.2 cm and 0 to 30.5 cm increments (Table 2). Increases in bulk density there ranged from 0.09 to 0.10 g/cm^3 and soil profile bulk density ranged between 1.11 to 1.49 g/cm^3 before and after the oak mat procedure. Finally, one drill pad had significant increases in density at each depth increment. Significant increases in soil bulk density ranged from 0.10 to 0.17 g/cm^3 and soil profile bulk density ranged between 1.15 to 1.60 g/cm^3 before and after the oak mat procedure.

Textural Class	*Frequency*
Clay	0
Clay Loam	11
Loam	7
Loamy Sand	0
Sandy Clay Loam	0
Silty Loam	0
Sandy Loam	0

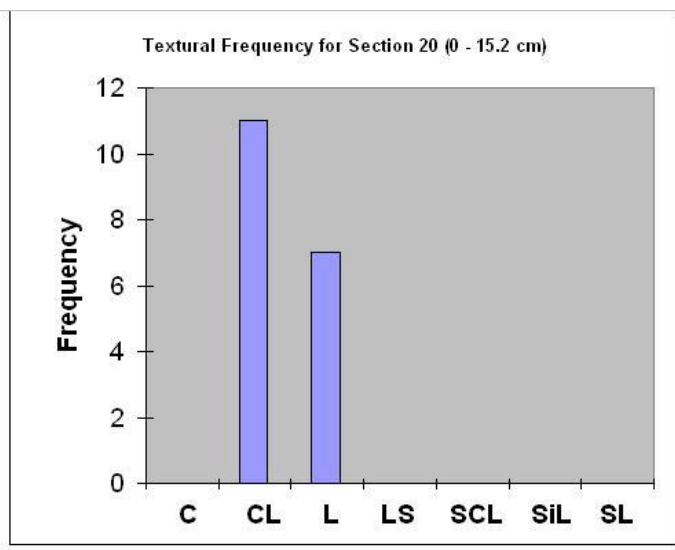

Figure 6. Histogram showing distribution of soil textures found at monitored oak mat locations and used to interpret Fig. 5 and Table 1 (n=18).

Soil Compaction Associated With Conventional Cut-And-Fill Drill Pad Construction.

Two conventional cut-and-fill drill pads have no statistically significant change in mean bulk density values compared to nearby undisturbed rangeland as a result of their reclamation prescription (Table 3). Three pads have significant increases in the 0 to 5.1 cm depth relative to the undisturbed rangeland (Table 3). In that depth, values ranged from 1.27 to 1.53 g/cm^3 and represent a mean bulk density increase of 0.12, 0.14 and 0.24 g/cm^3 respective to the individual pads. Statistically significant bulk density increases in the 5.1 to 15.2 cm depth also occurred at three drill pads (Table 3). In the 5.1 to 15.2 cm depth, dry soil bulk density values ranged from 1.25 to 1.53 g/cm^3, and significant increases of 0.11, 0.14 and 0.24 g/cm^3 were recorded for mean bulk density values respective to individual pads. Finally, one conventional drill pad had a statistically significant increase in the 15.2 to 45.7 cm depth (Table 3). Measured bulk density values ranged from 1.37 to 1.54 g/cm^3 in that depth, with a mean bulk density increase of 0.24 g/cm^3 relative to the undisturbed range.

Table 2. Mean oak mat dry soil bulk density values compared to adjacent undisturbed range.

Drill Pad	Depth Increment (centimeters)	Mean D_b Measurement [1,2] Relative to Construction		Change (%)
		Before	After	
1	0 - 5.1	1.28 a	1.22 a	-4.7
	0 - 15.2	1.27 a	1.32 a	+3.9
	0 - 30.5	1.28 a	1.39 b	+8.6
2	0 - 5.1	1.34 a	1.32 a	-1.5
	0 - 15.2	1.35 a	1.42 a	+5.2
	0 - 30.5	1.35 a	1.47 b	+8.9
3	0 - 5.1	1.21 a	1.29 a	+6.6
	0 - 15.2	1.27 a	1.36 b	+7.1
	0 - 30.5	1.31 a	1.41 b	+7.6
4	0 - 5.1	1.31 a	1.41 b	+7.6
	0 - 15.2	1.34 a	1.49 b	+11.2
	0 - 30.5	1.36 a	1.53 b	+12.5
5	0 - 5.1	1.27 a	1.16 a	-8.7
	0 - 15.2	1.32 a	1.29 a	-2.3
	0 - 30.5	1.27 a	1.35 a	+6.3
6	0 - 5.1	1.25 a	1.21 a	-3.2
	0 - 15.2	1.28 a	1.28 a	+0.0
	0 - 30.5	1.29 a	1.33 a	+3.1
7	0 - 5.1	1.29 a	1.28 a	-0.8
	0 - 15.2	1.32 a	1.33 a	+0.8
	0 - 30.5	1.35 a	1.41 b	+4.4
8	0 - 5.1	1.25 a	1.20 a	-4.0
	0 - 15.2	1.32 a	1.32 a	+0.0
	0 - 30.5	1.30 a	1.37 b	+5.4
9	0 - 5.1	1.29 a	1.27 a	-1.6
	0 - 15.2	1.33 a	1.30 a	-2.3
	0 - 30.5	1.30 a	1.40 b	+7.7
10	0 - 5.1	1.39 a	1.21 a	-13.0
	0 - 15.2	1.37 a	1.38 b	+0.7
	0 - 30.5	1.36 a	1.45 b	+6.6
11	0 - 5.1	1.34 a	1.29 a	-3.7
	0 - 15.2	1.37 a	1.40 a	+2.2
	0 - 30.5	1.35 a	1.45 b	+7.4
12	0 - 5.1	1.28 a	1.31 a	+2.3
	0 - 15.2	1.31 a	1.42 a	+8.4
	0 - 30.5	1.30 a	1.45 b	+11.5
13	0 - 5.1	1.27 a	1.26 a	-0.8
	0 - 15.2	1.30 a	1.33 a	+2.3
	0 - 30.5	1.29 a	1.36 b	+5.4
14	0 - 5.1	1.25 a	1.24 a	-0.8
	0 - 15.2	1.30 a	1.33 a	+2.3
	0 - 30.5	1.34 a	1.40 b	+4.5
15	0 - 5.1	1.30 a	1.29 a	-0.8
	0 - 15.2	1.33 a	1.35 a	+1.5
	0 - 30.5	1.37 a	1.39 a	+1.5
16	0 - 5.1	1.28 a	1.16 a	-3.4
	0 - 15.2	1.30 a	1.29 a	-0.8
	0 - 30.5	1.35 a	1.34 a	-0.8
17	0 - 5.1	1.27 a	1.26 a	-0.8
	0 - 15.2	1.30 a	1.36 a	+4.6
	0 - 30.5	1.30 a	1.39 b	+6.9
Mean of 17 Sites		1.31	1.34	

Mean Drill Pad Bulk Density % Change (0-5.1 cm)	-2.2
Mean Drill Pad Bulk Density % Change (0-15.2 cm)	+2.6
Mean Drill Pad Bulk Density % Change (0-30.5 cm)	+6.3
Unweighted Mean Drill Pad Density % Change	+2.2

[1] Means followed by the same letter, within the same depth increment, are not significantly different. P=0.05.

[2] Mean values were calculated from only those sites (1-6) that had density measurements before and after mat construction.

Table 3. Comparing reclaimed conventional cut/fill drill pads to adjacent undisturbed rangeland.

Drill Pad	Treatment[1]	Depth Increment (centimeters)	Mean Soil Density (g/cm^3)[2]		Change (%)
			Undisturbed Rangeland	Drill Pad	
1	A	0 - 5.1	1.34 a[3]	1.29 a[4]	-3.7
		5.1 - 15.2	1.30 a	1.44 b	+10.8
		15.2 - 45.7	1.36 a	1.57 a	+15.4
2	A	0 - 5.1	1.16 a	1.40 b	+20.7
		5.1 - 15.2	1.18 a	1.42 b	+20.3
		15.2 - 45.7	1.22 a	1.36 a	+11.5
3	B	0 - 5.1	1.42 a	1.43 a	+0.70
		5.1 - 15.2	1.42 a	1.51 a	+6.3
		15.2 - 45.7	1.40 a	1.52 a	+8.6
4	B	0 - 5.1	1.38 a	1.57 a[5]	+13.8
		5.1 - 15.2	1.42 a	1.61 a	+13.4
		15.2 - 45.7	1.44 a	1.64 a	+13.9

Drill Pad	Treatment[1]	Depth Increment (centimeters)	Mean Soil Density (g/cm^3)[2]		Change (%)
			Undisturbed Rangeland	Drill Pad	
5	C	0 - 5.1	1.28 a	1.40 b	+9.4
		5.1 - 15.2	1.20 a	1.38 a[5]	+15.0
		15.2 - 45.7	1.34 a	1.46 a	+9.0
6	C	0 - 5.1	1.20 a	1.34 b	+11.7
		5.1 - 15.2	1.23 a	1.34 a	+8.9
		15.2 - 45.7	1.22 a	1.46 b	+19.7
Mean of 6 sites			1.31	1.45	+11.4

Mean Drill Pad Bulk Density Percent Change (0-5.1 cm)	+8.7 %
Mean Drill Pad Bulk Density Percent Change (5.1-15.2 cm)	+12.4 %
Mean Drill Pad Bulk Density Percent Change (15.2-45.7 cm)	+13.0 %
Depth Weighted Mean Drill Pad Density Percent Change	+12.3 %

1. Treatment A = Site ripped with a grader, stockpiled soil applied with scraper, then tilled with a chisel plow (2005). Treatment B = Stockpiled soil applied with scraper, site ripped with a grader, then tilled with a chisel plow (2005). Treatment C = Site ripped with an alternative ripper, stockpiled soil applied with scraper, then tilled with a chisel plow (2006).
2 Means followed by the same letter, within the same depth increment, are not significantly different. P=0.05.
3. Table values are a mean of 2 observations.
4. Table values are a mean of 4 observations.
5. Mann Whitney Rank Sum test used due to data lacking equal variance. Median soil density values are reported.

Conclusions

Measured bulk density values ranged from 1.00 to 1.60 g/cm^3 throughout the 17 oak mat drill pads after mat removal and 1.24 to 1.82 g/cm^3 throughout the six reclaimed conventional drill pads. Soil bulk density at oak mat drill pads exhibited a 1.7 % decrease in the 0 to 5.1 cm depth, a 2.6 % increase in the 0 to 15.2 cm depth and a 6.3 % increase in the 0 to 30.5 cm depth. The mean change in dry soil bulk density at reclaimed conventional drill pads (across all reclamation treatments) exhibited an 8.7 % increase in the 0 to 5.1 cm depth, a 12.4 % increase in the 5.1 to 15.2 cm depth and a 13.0 % increase in the 15.2 to 45.7 cm depth. Due to differences in the depth increments measured at oak mat and reclaimed conventional pads, these relative bulk density increases and decreases are not statistically comparable. However, a general comparison of these two methods indicates that less soil profile compaction was attained using the oak mat procedure compared to the reclaimed conventional cut-and-fill method of drill pad construction. These data also suggest that increases in compaction stemming from both drill pad construction techniques result in greater compaction at greater depths. From a reclamation perspective, this result poses a constraint to the use of oak mats, as the use of subsoilers or vibratory ripper-shanks for compaction mitigation negate the advantage of its minimum impact approach to *in situ* soil and vegetation disturbance. However, of the 243 Troxler bulk density measurements taken after the removal of oak mats, 12 exhibited bulk density values equal to or greater than 1.5 g/cm^3 (5 % of total) suggesting that measured increases in soil bulk density are relatively benign from a plant growth perspective.

Of the 72 Troxler bulk density measurements taken within reclaimed conventional drill pads, 23 exhibited values greater than 1.5 g/cm^3 (32 % of total), suggesting that additional compaction alleviation may be necessary to reduce plant growth impacts associated with these reclamation prescriptions. Although the growth limiting bulk density value of 1.5 g/cm^3 assigned by this study is relatively tentative, it appears that the growth, establishment and succession of native range grass, forbs and shrubs should be facilitated more readily using the oak mat procedure at the Jonah natural gas field.

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