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Selection of a stress-based soil compaction test to determine potential impact of machine wheel loads

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Abstract

The use of heavy machinery is increasing in agricultural industries, and in particular cotton farming systems in Australia, which induces an increased risk of soil compaction and yield reduction. Hence, there is a need for a technical solution to use available tools to measure projected soil compaction due to farm machinery traffic. The aim of this work was to compare the effects of static and dynamic loads on soil compaction. In this study, three Vertisols (soils commonly used for cotton production in Australia) were selected to examine soil compaction under a range of static and dynamic loads, respectively, using uniaxial compression equipment and a modified Proctor test. In general, soils behaved similarly under static and dynamic loads with no significant difference between bulk density values for all moisture contents with a high index of agreement ($d = 0.96$, $\mathrm{RMSE} = 0.056$). The results further indicate better agreement between soil compaction produced under static and dynamic loads. Uniaxial compression test (static loads) produced greater compaction compared with the modified Proctor test (dynamic loads), in particular at moisture contents less than the plastic limit condition. The variation in soil compaction for static and dynamic loads was often evident for loads $\geq$600 kPa, with the greatest soil compaction induced under loads $\geq$1200 kPa. The findings of this study confirm the suitability of a modified Proctor method to assess soil compaction as an alternative tool under a range of moisture contents and machinery loads for Vertisols.

KEYWORDS

dynamic load, farm traffic, soil bulk density, soil compaction, soil moisture, static load

1 | INTRODUCTION

Soil compaction is generally defined as a reduction in soil total porosity and increase in bulk density (ρ_d) due to mechanical loads applied to surface soil during farm traffic (Chamen et al., 2015). Soil compaction poses a major soil constraint on soil health, limiting root penetration, crop development, water availability, and gas exchange, leading to reduced crop yields (Antille et al., 2016; Ferreira et al., 2022; Raper, 2005). It is a significant constraint for plant growth in agriculture (Roberton et al., 2021; Shaxson & Barber, 2003), involving in an estimated annual agricultural production loss of A $1330 million due to subsoil constraints in Australia (Orton et al., 2018; Rengasamy, 2002). In the last decades, soil compaction concern has become much higher globally, due to the development of the modern and increased mass of agricultural machinery. This trend is particularly notable in the Australian cotton industry, where the introduction of advanced machinery has exacerbated soil compaction issues. Increased machinery mass or axle weight simultaneously increases the risk of soil compaction, in particular, subsoil compaction, due to high load at the wheel (Antille et al., 2016; Chamen et al., 2003; Keller et al., 2007). The axle mean weight of modern machinery varies depending on the type of agricultural machinery (Keller et al., 2019). Soil bearing capacity depends on soil structure, texture and moisture, with coarse-textured soils typically having higher capacity at moderate moisture levels, while moist clay soils may show poor capacity. Site-specific testing is crucial for accurate assessment in construction or foundation design (Alakukku et al., 2003).

The increased axle weight on the soil interface for modern and heavy machineries tends to exceed the bearing capacity of most soils, and farm traffic becomes a major threat to land degradation due to compaction (Batey, 2009; Schjønning et al., 2009; Techen et al., 2020). This indicates the irreversible damage caused by heavy machinery and small machinery which confirms the concerns about soil compaction (Alakukku, 1999; Chamen et al., 2003; Keller & Arvidsson, 2004). Håkansson (1990) suggests the maximum load at the soil interface should be less than 200 kPa to prevent soil compaction risks. However, the degree of compaction induced by heavy machinery may vary from one soil to another depending on the soil strength, the specifications of the traction device (i.e., tyre vs track, tyre inflation pressure and wheel load, and tyre size and type), the travel speed (loading time) and the frequency of wheeling (i.e., the number of passes) (Antille et al., 2013; Augustin et al., 2020; Bennett et al., 2015; Suzuki et al., 2013). Crop residue mulching and standing stalks can also help relieve soil compaction caused by heavy machinery (Blanco & Lal, 2023). The potential for soil compaction due to heavy machinery is reasonably soil-specific and depends on the land condition, root depth, moisture content and organic matter (Bennett et al., 2019; Correa et al., 2019; Suzuki et al., 2013).

The accurate determination of potential compaction for using any machinery in a particular soil is essential and often requires specific tools and equipment in the soil engineering laboratory. Uniaxial compression equipment remains a common tool, but its accessibility is limited. Various soil compaction tests, including cone penetration tests, dynamic cone penetrometers, and static cone penetrometers, offer a more accessible means to assess soil compaction effects under static loads (Beckett et al., 2018; Chukka & Chakravarthi, 2012). These soil compaction tests play distinct roles in assessing soil conditions. Uniaxial compression tests, while providing standardised measurements, often require specialised equipment (Keller et al., 2011). Cone penetration tests, whether dynamic or static, offer expedited assessments under static loads, yet may not fully replicate field conditions (Lunne et al., 2002). The Proctor test, recognised as a widely accepted standard, demands specific equipment and controlled conditions (Kodikara et al., 2018). The Proctor test stands out for its accessibility and simplicity, enabling expedient assessments of soil compaction under both dynamic loading conditions. Each test carries its own set of advantages and limitations, and the selection process hinges on factors such as accessibility, standardisation and equipment requirements (White, 2005). The accessibility of these tools is often challenging, for instance, uniaxial compression equipment as a common tool for soil compaction determination under static loads might not always be available in many soil engineering laboratories in Australia. The Proctor test is also approved as a universal standard test for soil compaction under dynamic loads and is often available in most soil engineering laboratories. The substitution of the uniaxial test by the Proctor test (static load to dynamic load) would potentially assist soil scientists and landholders to test the soil strength against specific heavy machinery loads during sowing or harvesting traffic seasons. This further allows land managers to quickly ascertain the safe selection of traffic and the potential for soil compaction to occur using particular machinery. Therefore, this study aims to compare the bulk density induced by the effect of dynamic and static loads at different levels of moisture contents to test the hypothesis that the modified Proctor test is proportional to a specific uniaxial load in terms of the resulting compaction magnitude (Equation (1)).

$$\rho_{\mathrm{Dyna}} = \rho_{\mathrm{Stat}} \tag{1}$$

Highlights

- Similar soil compaction occurs under the static and dynamic loads at various soil moisture contents and applied loads.
- Maximum soil compaction occurs in soils with 15%–20% moisture content at any applied load.
- Static loads generally produce higher compaction compared with dynamic loads for all soils.

where ρ_{Dyna} is the bulk density induced by dynamic loads (from modified Proctor test) and ρ_{Stat} is the bulk density induced by static loads (from uniaxial compression loads). Should the hypothesis hold, then a modified Proctor test can be utilised in place of a uniaxial compression test for soil compaction determination under projected loads and moisture contents.

2 | MATERIALS AND METHODS

2.1 | Site description and soil sampling

The study was conducted in three sites situated in South East Queensland, Australia, near Goondiwindi for Sites 1 and 2, and in Yalangur for Site 3, all characterised by a humid subtropical climate according to the Köppen Climate Classification (Figure 1). The region features a predominantly flat terrain comprising plains and gentle undulations, with extensive agricultural land surrounding the towns. Altitude measurements for Sites 1 and 2 were recorded at 208 metres, while Site 3 was at 435 metres, with slope angles ranging from 0.09% to 0.55% (Table 1).

Soil samples were collected from the surface, through the common plough depth (0–30 cm) from each site using a stratified random sampling approach, with multiple soil cores obtained using soil augers. Soils are classified as Vertisols (IUSS Working Group WRB, 2014) which are usually used for cotton production in Queensland, Australia (Table 1). The soils were air-dried and crushed with sufficient energy to break down the aggregates to pass through a 2.3 mm sieve; care was taken to not apply energy greater than required in order to

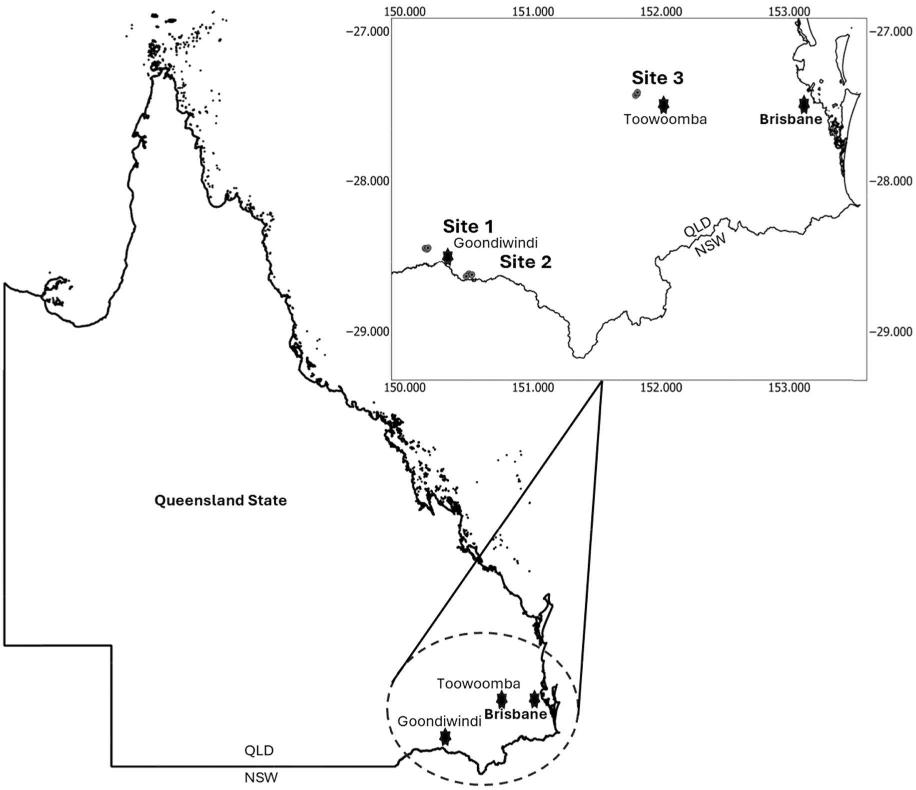

FIGURE 1 Map of study sites in southeast of Queensland state, Australia.

TABLE 1 Particle size distribution, Atterberg limit moisture content for used soils, altitude (above sea level) and slope angle of the land areas from Queensland.

Soils	Location	Clay%	Silt%	Sand%	Texture class	Liquid limit MC%	Plastic limit MC%	Total organic carbon %	Altitude m	Slope angle %
Soil 1	28°27′02.3″ S 150°09′35.2″ E	63.1	18.8	18.1	Clay	53.6	30.2	0.7 ± 0.02	208	0.11
Soil 2	28°37′20.2″ S 150°29′59.3″ E	50.6	12.5	36.9	Clay	45.4	25.2	0.61 ± 0.03	230	0.09
Soil 3	27°25′20.4″ S 151°48′35.6″ E	50.0	25.0	25.0	Clay	47.8	27.1	0.62 ± 0.09	435	0.55

Note: Soils are classified based on the World reference base for soil resources (IUSS Working Group WRB, 2014).
Abbreviation: MC, gravimetric moisture content.

maintain the physical bonds of the aggregates <2.3 mm. Published methodologies were used to determine soil particle size distribution (Gee & Bauder, 1986) using the hydrometer method, with Atterberg limits, liquid limits and plastic limits determined following standard procedures (AS 1289.3.1.1-2009 and AS 1289 3.1.1, 3.1.2). Liquid limit was determined using the Casagrande apparatus, measuring the moisture content at which soil exhibits specific flow behaviour, while plastic limit is identified by the moisture content at which soil can be moulded into a 3 mm thread without crumbling. The soil characteristics are presented in Table 1.

2.2 | Experimental design

The experimental design was established to compare soil compaction behaviour between applied dynamic loads (Proctor test) and static loads (uniaxial test). These tests were conducted at five gravimetric moisture contents (MC) (~8.24 [±0.43] [air-dry], 13.8 [±0.77], 18.6 [±0.9], 29.2 [±0.63] and 39% [±0.44]). Three replicates for each targeted moisture content were used to determine reference bulk density under each static and dynamic load.

2.3 | Uniaxial compression

Soil bulk density was determined in a drained uniaxial compression test using the modified method of Håkansson (1990) (Figure 1). The test was modified procedurally to suit a single pass of heavy machinery and to provide a comparison to Suzuki et al. (2013). The soil was moistened to targeted moisture contents via a fine spray bottle and left to equilibrate overnight (~16 h) in a sealed container. The applied stresses were monitored using a load cell (Anyload, 100 kN, USA), and Vishay System 5000 StrainSmart software was used to record the measured data. The soil was placed in the uniaxial cell (90 mm in diameter, and 165 mm in height) (Figure 1) and dropped three times from the height of 50 mm to attain uniform packing. The soil was then loaded from small to large loads (from 200 to 3200 kPa) for 5 min and allowed to rebound for 1 min for each sequential load before the sample height and volume were determined. The deformation of the sample was then measured at five points on the surface of the sample and the average was taken. Finally, the soil was removed from the uniaxial cell, weighed, and dried at 105°C for at least 48 h to calculate the exact moisture content. The dry reference bulk density was then calculated for the sequential static loads.

2.4 | Modified proctor test

The modified loading of the Proctor test was achieved by altering the number of blows per layer. The testing procedure was conducted in accordance with the Australian standard for Proctor tests (AS1289.5.1.1). In the Australian standard Proctor test, a soil specimen undergoes compaction at various moisture contents using a standard effort, typically 25 blows per layer, to determine the maximum dry bulk density and optimum moisture content, providing crucial insights into the soil compaction characteristics for engineering purposes. The number of blows was changed to match the static loads as detailed in Table 2. The test was repeated three times for each Static pressure load (Static pressure equivalence [kPa]). The Static pressure for the Proctor test is described by Raghavan and Ohu (1985) (Equation (2)).

$$\mathrm{SPE}\,(\mathrm{kPa}) = 66.7 + 22.1 \times \mathrm{ProcB} \tag{2}$$

where SPE is Static Pressure Equivalence in kPa, and ProcB represents the Proctor test blow number.

The same amount of moist soil was placed in the mould similar to the uniaxial test (Figure 1). Both Uniaxial and Proctor tests were conducted on the same day for each soil moisture content to avoid inconsistency from moisture content. The Proctor hammer was then used to compact the soil to produce various dynamic loads from 200 to 3200 kPa (Table 2). These blows were spaced evenly over the surface of the soil. The manual adjustment was made around the edge of the mould to ensure an even soil surface during the application of blows. The height of the soil was calculated, and soils were removed from the moulds, weighed and dried at 105°C for at least 48 h. The dry reference bulk density was then calculated for the sequential dynamic loads using the Proctor test.

2.5 | Relative bulk density

The comparison between reference bulk density for static and dynamic loads can be denoted by the ratio of compaction or the relative compaction defined as follows in this study (Equation (3)).

$$\mathit{Relative\ compaction} = \frac{\rho_{\mathrm{Dyna}}}{\rho_{\mathrm{Stat}}} \tag{3}$$

where relative compaction is the percentage difference in soil bulk density produced by static and dynamic loads. ρ_{Dyna} is bulk density produced by dynamic load (Proctor test), and ρ_{Stat} is the bulk density produced by static load (uniaxial compression test).

TABLE 2 Applied loads to determine soil compaction under static and dynamic loads at different moisture content.

Target static load (kPa)	Number of blows (Proctor test)	Equivalent static load[b] (kPa)	Load (KN)
200	6	199.3	1.27
400	15	398.2	2.53
600[a]	25	609.2	3.85
800	33	796.0	5.06
1200	51	1193.8	7.59
1600	69	1591.6	10.13
2400	105	2387.2	15.19
3200	142	3204.9	20.39

[a] Standard Proctor test load (kPa).

[b] Applied loads by uniaxial compression.

2.6 | Statistical analysis

The reference bulk density of static and dynamic load results was analysed using a calculated Pearson's product–moment correlation coefficient and the analysis of variance. The root mean square error (RMSE), index of agreement (d) (Willmott et al., 2012), the coefficient of determination (R^2) where predicted values fitted to $y = x$ line were used to assess the level of agreement between the reference bulk density of static and dynamic load results. Three replicates were conducted for each laboratory measurement, and a probability level of P-value < 0.05 was accepted for assessing the model's performance using R^2 and d index. Relationships between static and dynamic loads were considered very good when R^2 was greater than 0.7 and d was 0.8.

3 | RESULTS

3.1 | Static versus dynamic stresses

The relationship between soil compaction obtained from both static and dynamic stresses is presented in Figure 2 and Table 3. In general, there was a greater agreement between soil compaction for static and dynamic loads despite some discrepancies in higher bulk densities >1.6 g.cm^{-3}. This agreement was greatest for Soil 1 and Soil 3 with high coefficients of determination ($R^2 = 0.82$ and 0.88), respectively. There was also a very great agreement index ($d = 0.96$) between reference bulk density values for compression and Proctor tests (Figure 3). No significant difference was observed ($p_{\text{value}} = 0.13$) between ρ_{Stat} and ρ_{Dyna} values with high coefficients of determination ($R^2 = 0.83$, RMSE $= 0.056$) for all soils (Figure 2). The dataset was further split into two datasets for bulk density greater and less than 1.6 g.cm^{-3}. The results indicate that ρ_d produced under dynamic and static is in greater agreement ($R^2 = 0.8$, $d = 0.94$ and RMSE $= 0.03$) compared to ρ_d larger than 1.6 g.cm^{-3} ($R^2 = 0.34$, $d = 0.83$ and RMSE $= 0.088$) (Figure 3 and Table 3). Figure 4 demonstrates that this agreement is greater with increasing moisture content ≥19%.

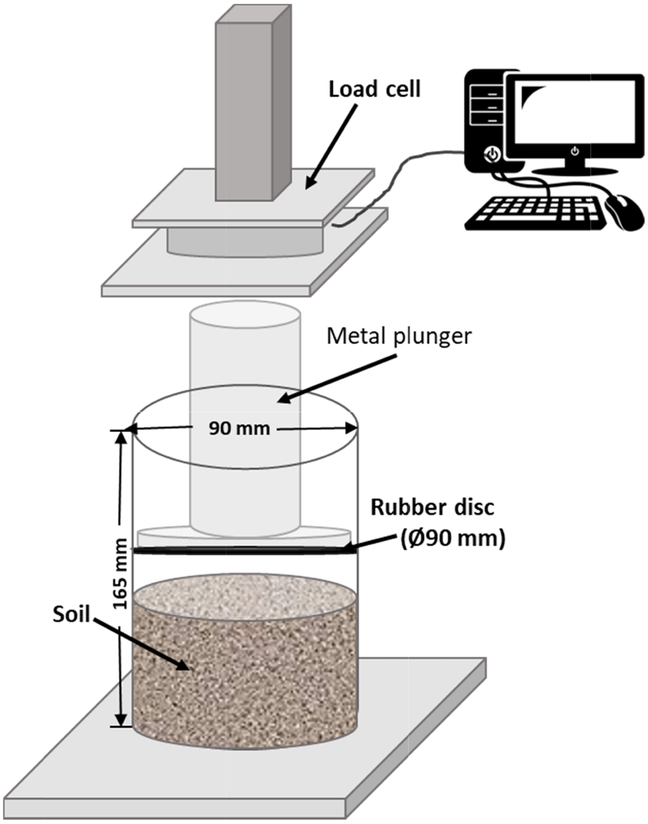

FIGURE 2 Schematic diagram of uniaxial compression tool used for determining bulk density under static loads.

However, the compression test (static loads) generated greater compaction compared to the Proctor test (dynamic loads) in particular at moisture contents smaller than the plastic limit (Figure 5). Thus, the static and dynamic loads are effectively equivalent to producing soil compaction at various soil moisture content and loads.

Soil compaction values for all loads and moisture contents were further analysed to predict static loads from produced bulk density by dynamic loads. Equations (4)–(6) can be used for bulk densities ≤1.6 g.cm^{-3}, >1.6 g.cm^{-3} and all bulk density values, respectively.

$$\rho_{\text{Stat}}\ (\text{g.cm}^{-3}) = 1.085\rho_{\text{Dyna}} - 0.00185\text{MC} - 0.074 \quad (4)$$

$$\rho_{\text{Stat}}\ (\text{g.cm}^{-3}) = 0.75\rho_{\text{Dyna}} + 0.49 \quad (5)$$

TABLE 3 Bulk density (g.cm^{-3}) according to the applied load in the static (compression test) and dynamic load (Proctor test) tests.

	Soil 1								
Loads (kPa)		**200**	**400**	**600**	**800**	**1200**	**1600**	**2400**	**3200**
Static loads	Mean	1.37	1.46	1.53	1.58	1.62	1.64	1.68	1.69
	Min	1.32	1.36	1.41	1.49	1.50	1.50	1.51	1.51
	Max	1.44	1.69	1.78	1.85	1.85	1.85	1.88	1.89
Dynamic loads	Mean	1.38	1.46	1.52	1.56	1.59	1.63	1.65	1.66
	Min	1.33	1.39	1.44	1.50	1.51	1.50	1.50	1.51
	Max	1.49	1.62	1.66	1.69	1.75	1.79	1.91	1.93
	Soil 2								
Static loads	Mean	1.42	1.49	1.53	1.55	1.59	1.62	1.64	1.67
	Min	1.35	1.39	1.42	1.44	1.48	1.48	1.48	1.48
	Max	1.47	1.63	1.73	1.78	1.82	1.83	1.83	1.85
Dynamic loads	Mean	1.42	1.48	1.50	1.53	1.56	1.60	1.61	1.65
	Min	1.35	1.38	1.43	1.46	1.51	1.51	1.51	1.51
	Max	1.53	1.56	1.58	1.62	1.67	1.79	1.81	1.89
	Soil 3								
Static loads	Mean	1.39	1.46	1.50	1.53	1.59	1.62	1.65	1.65
	Min	1.30	1.32	1.34	1.37	1.41	1.47	1.48	1.48
	Max	1.46	1.60	1.70	1.77	1.97	1.93	1.95	1.95
Dynamic loads	Mean	1.40	1.43	1.48	1.51	1.56	1.58	1.61	1.63
	Min	1.21	1.29	1.34	1.37	1.42	1.43	1.46	1.47
	Max	1.51	1.55	1.61	1.67	1.77	1.79	1.84	1.89

$$\rho_{\mathrm{Stat}}\left(\mathrm{g.cm}^{-3}\right)=0.84\rho_{\mathrm{Dyna}}-0.00047\mathrm{MC}+0.24 \qquad (6)$$

where ρ_{Stat} is bulk density produced by static loads (uniaxial hydraulic press), ρ_{Dyna} is bulk density produced by dynamic loads (modified Proctor method), and MC is the gravimetric moisture content in percentage.

3.2 | Effect of soil moisture on stress agreement between methods

The moisture content of soil samples used in the uniaxial compression and Proctor tests to obtain the bulk density curves is shown in Figure 5. Given that the compressive behaviour of the soil is highly dependent on soil moisture, soil samples with different moisture reached greater bulk densities under increasing both static and dynamic stress, resulting in a different degree of compaction. In general, the obtained bulk density for both methods indicates that stresses are largely dependent on the soil moisture contents. Stress agreement between static and dynamic loads was dependent on the moisture content level, this agreement was relatively poor for smaller moisture contents (Figure 4). High moisture contents (≥18%) generally resulted in better agreement between both static and dynamic loads.

The results showed that the greatest compaction occurred for 15% and 20% MC values where 15% MC resulted in optimum compaction for all stresses and soils in particular for the loads greater than 1000 kPa (Figure 5). The ~15% MC (optimum MC) resulted in a significant difference in bulk density values compared with other moisture contents ($p_{\mathrm{value}} < 0.001$), where there was no significant difference among other moisture contents. High moisture contents generally resulted in better agreement between both static and dynamic loads (Figure 4). In wet soils (above plastic limit moisture content), water acts as a lubricant between soil particles, resulting in relatively consistent compaction under stresses (Hamzaban et al., 2019).

3.3 | Stress selection to obtain the bulk density

The bulk density values obtained from the compression curve and Proctor tests for different levels of stresses and moisture content are presented in Figure 5. There was no

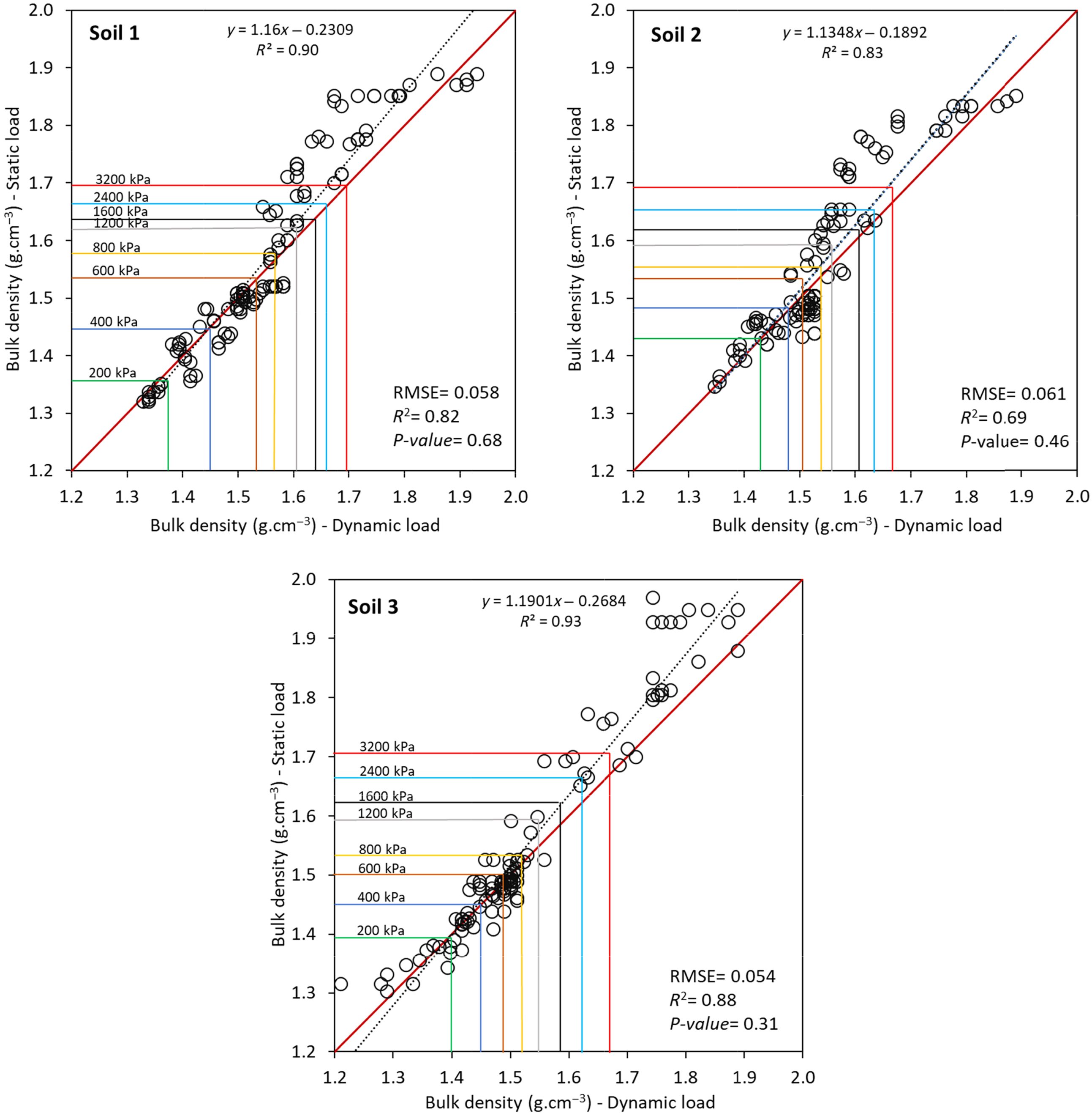

FIGURE 3 Relationship between soil bulk density obtained from compression test (static load) and Proctor test (dynamic test) under different stresses and moisture contents. The diagonal solid line represents the 1:1 line, and the dotted line is the regression fit for the observed data. Root mean square error (RMSE) is root mean square error relative to the 1:1 line, R^2 is the coefficient of determination, d is index of agreement (Willmott et al., 2012) and the p-value is the probability that the null hypothesis is true obtained from analysis of variance. The presented coloured lines represent average values of bulk densities obtained from both static and dynamic loads (200–3200 kPa).

significant difference between bulk density values obtained from the compression curve and applying stresses from the Proctor test ($p_{\text{value}} = 0.13$, RMSE $= 0.056$) for all soils. The static loads generally produced greater compaction compared with dynamic loads for all soils. The statistical analysis of obtained bulk density values indicates that there was a significant difference for stress $\leq$600 kPa and $\geq$800 kPa (p-value < 0.001). There was also no significant difference for large stresses $\geq$1200 kPa and further compaction occurred with increasing loads for both static and dynamic loads.

All soils behaved similarly under static and dynamic loads where there was no significant difference between reference bulk density values for all moisture contents.

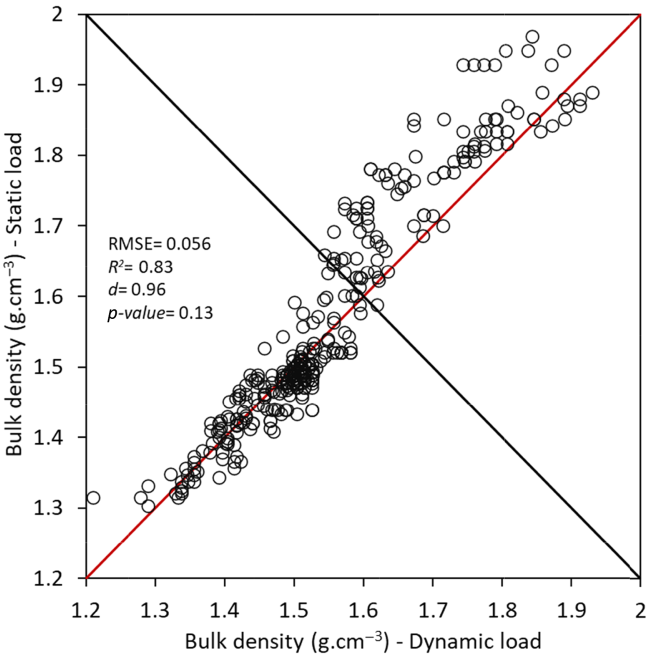

FIGURE 4 Bulk density produced by dynamic loads (Proctor test) and bulk density produced by static loads (uniaxial test), plotted against the line $y = x$ (red line), with the line $y = -x$ (black line) intercepting the data at the threshold of increasing variability ($y = 1.6$, $x = 1.6$). Statistics are presented in Table 3.

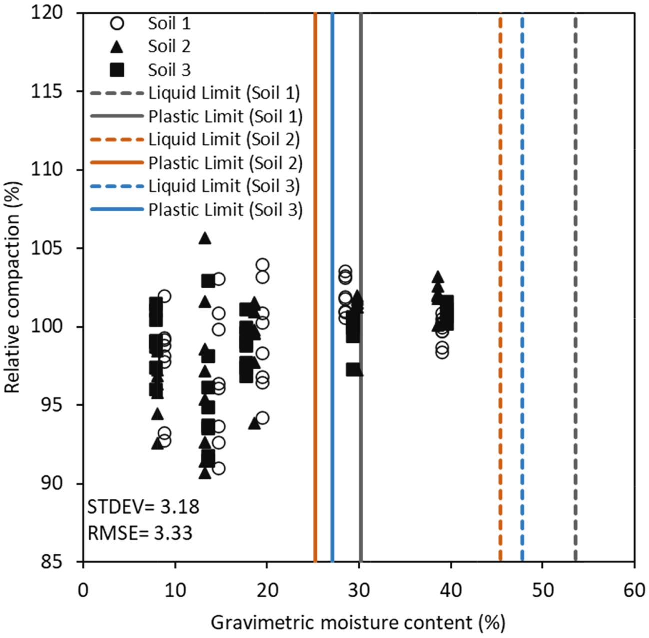

FIGURE 5 Relative compaction obtained from the ratio of reference bulk density of Proctor test to reference bulk density of compression test at different levels of moisture content. STDEV is standard deviation and RMSE is root mean square error.

The results indicated that static bulk density can be predicted from dynamic bulk density produced by the modified protector test (Equations (4)–(6), Tables 4 and 5). For $\rho_d \leq 1.6\,\text{g.cm}^{-3}$ greater accuracy of ρ_{Stat} can be predicted compared with $\rho_d > 1.6\,\text{g.cm}^{-3}$ (Figure 6).

4 | DISCUSSION

Soil compaction is a critical factor in various engineering and environmental applications, influencing soil properties and performance. Understanding the mechanisms and effects of compaction induced by different load types is essential for effective soil management and design. This discussion section aims to compare the effects of dynamic and static loads on soil compaction, investigating their respective influences on soil structure, pore characteristics, and mechanical behaviour. However, the actual pore water pressure, relevant matric potential and shearing behaviour of the soil that defines the actual strength and resilience of the soil and their properties are not discussed. By examining the similarities and differences between these load types, valuable insights can be gained to optimise compaction techniques and mitigate potential adverse effects on soil quality and functionality.

4.1 | Mechanisms of soil compaction for static versus dynamic loads

Excessive soil compaction that results from the impact of the wheels of agricultural machines and other traffic is one of the major concerns of modern agriculture. Soil compaction is generally dependent on the soil strength and applied loads by machinery traffic in agricultural lands. The soil strength is impacted by moisture content, soil texture, soil structure and organic matter content (Alakukku, 1999; Bennett et al., 2019; Chamen et al., 2003; Suzuki et al., 2013). The frequent passage of machinery (dynamic loads) over soil can increase bulk density and compaction risk in both topsoil and subsoils and produce less suitable physical conditions for water storage, aeration, microbial activity and seedling emergence (Assouline et al., 1997; Augustin et al., 2020; Bennett et al., 2019; Botta et al., 2006; Chamen et al., 2015; Liu et al., 2022). However, during wheeling, shearing and compaction occur simultaneously. Unlike compaction that causes volume changes, shearing results in minor deformation while altering the soil's shape. Excessive shearing without proper drainage can lead to soil homogenisation and reduced strength (Horn & Peth, 2011; Huang et al., 2022).

The results of this study confirmed that soil compaction occurs almost equally under both static and dynamic loads ($p_{\text{value}} = 0.13$, RMSE $= 0.056$), with slightly greater compaction for static loads (single pass of heavy

TABLE 4 Descriptive statistics for the full dataset from Figure 3 of used soils, and where the bulk density (ρ_d) is used to split the dataset.

Dataset	*n*%	Min	Max	AED	$2\sigma_{ED}$	RMSE	R^2	*d*	*p*-value
Total	100	0	0.130	0.028	0.056	0.056	0.83	0.96	0.130
$\rho_d \geq 1.6$	32	0	0.130	0.053	0.068	0.088	0.48	0.83	0.067
$\rho_d < 1.6$	68	0	0.074	0.016	0.028	0.030	0.80	0.94	0.159

Note: *n%*, number of observations as a percentage; *Min* and *Max*, the minimum and maximum value for the datasets, respectively; *AED*, average Euclidean distance from the line $y = x$; $2\sigma_{ED}$, two standard deviations of the Euclidean distance; *RMSE*, root mean square error of the datasets, R^2 is coefficient of determination for $x = y$; d is index of agreement and *p*-value is the probability value of significant difference at the 95% confidence interval ($\alpha = 0.05$).

TABLE 5 Statistical characteristics pertaining to Equations (4, 5) and (6) from validation data.

Statistic	Unit	Equation (4)	Equation (5)	Equation (6)
R^2	%	0.92	0.76	0.82
R^2_{ADJ}	%	0.91	0.76	0.81
R^2_{PRED}	%	0.91	0.75	0.81
RMSE		0.05	0.048	0.028
F-stat		2230	264.3	658
DWS		1.08	1.07	1.11
C_p	%	2	2	2
PRESS		0.76	0.25	0.17
p-value		<0.001	<0.001	<0.001

Note: R^2 is the explained variance of the response by the predictors; R^2_{ADJ} is the adjusted R^2 to compare the explanatory power of regression models; R^2_{PRED} is the predicted R^2; *Cp* is Mallow's measure of precision; *DWS* is Durbin-Watson statistics to detect the presence of autocorrelation; and *PRESS* is the predicted residual sum of squares. The *p*-value was <0.0001 for both regression analysis.

machinery), in particular, for moisture contents less than the plastic limit. This indicates that multiple passes of light machineries and a single pass of heavy modern machineries can have a non-significant influence on soil compaction depending on the soil moisture content and organic matter content. Compared with static loading, cyclic loading resulted in further deformation and dilative shear behaviour in soils (Huang et al., 2022). However, Silva et al. (2008) reported that major soil compaction is caused by the first passage of machinery, or early movement of machinery, and increasing subsoil compaction with increasing number of passes. Previous studies also stated that there is no significant difference between ρ_d values induced under static and dynamic loads with greater accuracy under static loads (Al-Radi et al., 2018; Hafez et al., 2010; Lebert et al., 1989). This study further confirms that the agreement between soil compaction produced from static and dynamic loads differs slightly depending on the degree of compaction where greater agreement observed for $\rho_d > 1.6\,\mathrm{g.cm^{-3}}$. However, there was no significant difference between both approaches for $\rho_d < 1.6\,\mathrm{g.cm^{-3}}$ ($p_{\text{value}} = 0.067$, RMSE $= 0.088$). Therefore, the static and dynamic loads are effectively equivalent to produce soil compaction and soil moisture, and loads are major factors in its severity.

Given that the compressive behaviour of the soil is largely dependent on soil moisture, soil samples with different moisture result in a different degree of compaction. Soil moisture content smaller than plastic limit generally resulted in greater compaction, where ~14% gravimetric moisture content produced optimum and significant bulk density ($p_{\text{value}} < 0.001$) for both static and dynamic loads. It can be noted that soil strength increases with increasing ρ_d values while it decreases with decreasing soil moisture content. Therefore, one should be prudent when using machinery on farms because moisture content varies between the seasons due to different climates. It was further found that soil compaction was much more sensitive to the varying moisture content than changing applied loads. Similar results were observed from previous studies and advising to limit traffic to avoid compaction in wet seasons (Jamali et al., 2021; Raghavan et al., 1979; Raper, 2005).

Soil compaction occurs from static and dynamic loads induced from farm trafficking, animal trampling in grazing lands and military exercises (Nawaz et al., 2013; Silva et al., 2008; Webb, 2002). The moisture condition of the soil needs to be considered along with the applied loads (i.e., axle loads) of machinery or any other activities on agricultural lands. Therefore, precautions are necessary

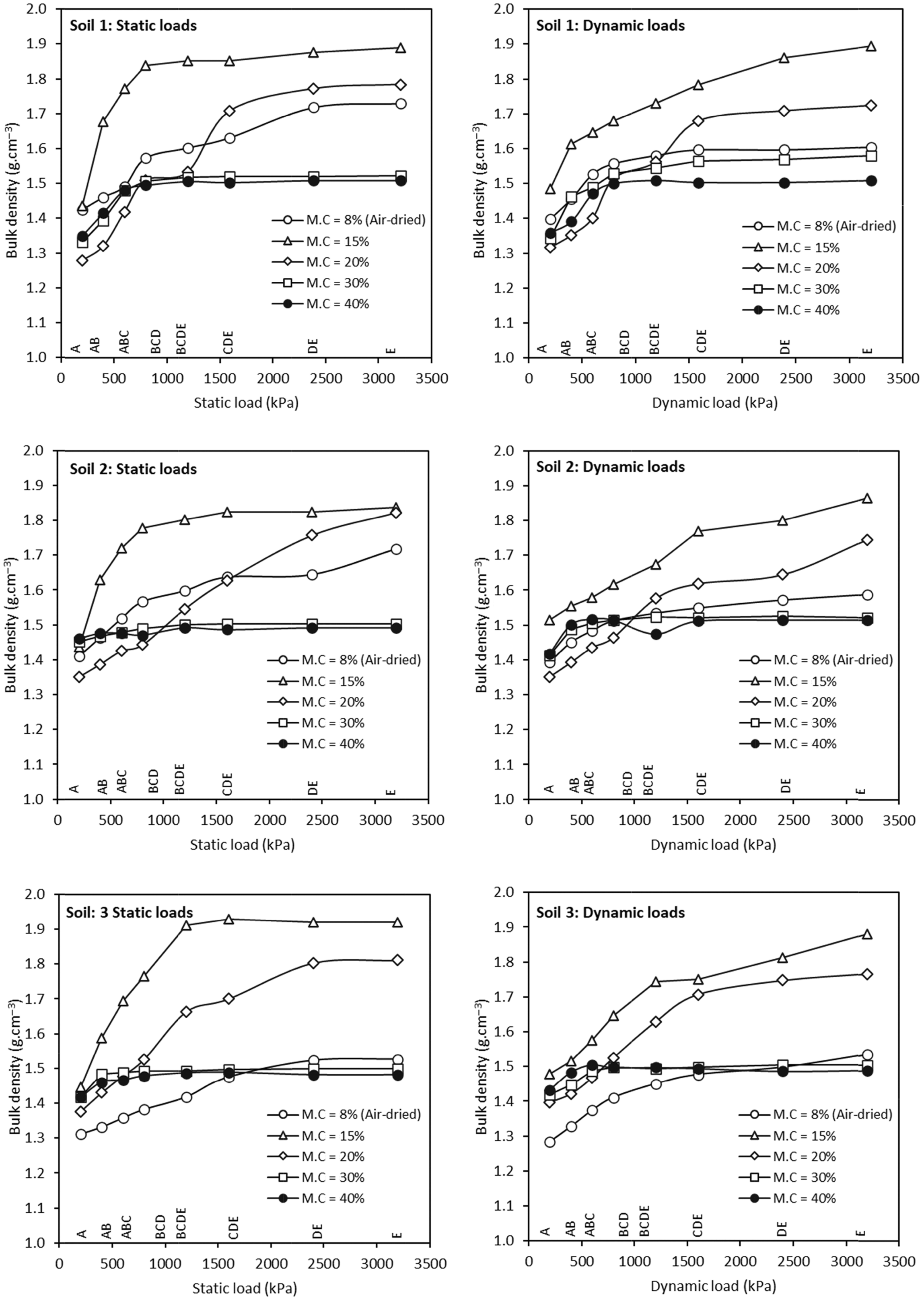

FIGURE 6 Bulk density obtained by the compression curve (static loads) and Proctor test (dynamic loads) under 200, 400, 600, 800, 1200, 1600, 2400 and 3200 kPa) for (a) Soil 1, (b) Soil 2 and (c) soil 3 at a range of moisture contents. Upper-case pronumerals represent Tukey's honest significant difference, differing pronumerals indicate significant changes in bulk density due to the change in applied loads.

to avoid soil compaction with considering soil moisture, axle loads and the degree of compaction in order to sustain agricultural yield.

4.2 | Prediction of soil compaction under dynamic loads

This study sought to test the hypothesis that the soil compaction produced by static loads was equivalent to the soil compaction caused by dynamic loads via the use of bulk density as a criterion for soil compaction. In our case, the soil compaction was tested under a uniaxial hydraulic press as a source of static loads and dynamic loads stimulated by a modified approach of protector test for various moisture content levels. Results allowing the acceptance of the hypothesis was obtained (Figures 2 and 3, and Tables 3 and 4), with soil compaction in great agreement for both static and dynamic loads ($R^2 = 0.83$, $d = 0.96$ and $\text{RMSE} = 0.056$). The bulk density slightly diverged when $\rho_d > 1.6\,\text{g.cm}^{-3}$, suggesting that compacted soil may behave separately under static and dynamic loads. This indicates that the first or early passages of machinery can cause soil compaction regardless of the type of applied loads (Silva et al., 2008). However, the strength required to form further compacted soil can differ slightly for static and dynamic loads. The findings of this study provide confidence for the substitution of the hydraulic press method with the modified Proctor test depending on the availability of these tools in soil engineering laboratories.

A range of standard compaction tests are available for determining soil compaction and its relationship with soil moisture and loads. The choice of test mainly depends on the availability of tools and soil type. The Proctor test is one of the earliest tests that was developed by Ralph Proctor in California in 1933 (Wiltshire, 2004). The Proctor test is considered a conventional method and is often available in most soil and geotechnical laboratories while the uniaxial hydraulic press might not always be accessible. Given the results presented in this study for accepting the hypothesis, the use of the modified Proctor test can be considered as an alternative method for the determination of soil compaction under different loads and moisture content. Our data further suggest the prediction of bulk density for static loads using the modified Proctor method (Equation (4), $R^2 = 0.92$ and $\text{RMSE} = 0.05$), with greater accuracy for $\rho_d < 1.6\,\text{g.cm}^{-3}$ (Equation (6), $R^2 = 0.82$ and $\text{RMSE} = 0.028$). This implies that one could undertake soil compaction determination using the modified Proctor method and obtain equivalent soil compaction for static loads.

4.3 | Management implications

The comprehensive investigation into the interaction between static and dynamic stresses on soil compaction, as outlined in this research, holds significant implications for soil and agricultural management strategies. These findings include profound consequences for the sustainability of agriculture and the effectiveness of engineering practices in this field.

The selectivity of a high level of concordance between soil compaction under static and dynamic loads highlights the importance of gaining a nuanced understanding of compaction dynamics (Al-Radi et al., 2018). This finding underlines the need for a holistic approach to soil management, where the choice between static and dynamic loading methodologies is not only dictated by operational limitations but rather informed by soil bearing capacity and soil behaviour under varying loading regimes (Hafez et al., 2010). Moreover, the delineation of the influence of soil moisture content on stress agreement shows the complex relationship between environmental conditions and soil compaction dynamics (Bennett et al., 2019). The agreement between static and dynamic loads under higher moisture levels (>18%) underlines the fundamental role of moisture management in shaping soil compaction outcomes, offering a compelling rationale for the integration of sophisticated irrigation and drainage schemes in soil management practices (Augustin et al., 2020). The identification of optimal moisture content levels, such as around 15% gravimetric moisture content, transcends simple empirical observation to constitute a strategic imperative for sustainable soil and agriculture management (Jamali et al., 2021). This finding not only underlines the criticality of precision moisture control but also leads the need for adaptive management strategies that account for temporal and spatial variability in moisture levels (Raghavan et al., 1979).

Furthermore, the development of prediction models for estimating bulk density under static loads using dynamic loading tests represents a paradigm shift in soil engineering methodologies (Silva et al., 2008). By leveraging predictive analytics, land managers can transcend the limitations imposed by equipment availability, thereby guiding in a new era of accessibility and applicability in compaction-testing methodologies (Taffese & Abegaz, 2022; Webb, 2002).

The implications attained from this study drive a reassessment of traditional paradigms in soil and agriculture management, progressing a shift towards holistic, data-driven approaches that integrate dynamic loading methodologies, moisture management strategies, and predictive analytics. By embracing these insights, land managers can navigate the complex terrain of soil compaction with confidence, adopting a cooperative relationship between agricultural productivity, engineering efficacy, and environmental sustainability.

5 | CONCLUSION

This study was conducted to test the hypothesis that soil compaction generated by static loads is equivalent to soil compaction under dynamic loads. By examining three clay soils, we evaluated bulk density using both the uniaxial hydraulic press compression and modified Proctor method across varying moisture contents and loads. Our findings robustly confirm a great degree of concordance between bulk density values for both static and dynamic loading conditions, despite some minor discrepancies observed at elevated bulk density levels. This supports the initial hypothesis. Moreover, we developed predictive models to estimate soil compaction for static loads based on data derived from the modified Proctor method.

The results emphasise the viability of the modified Proctor test as a reliable alternative for soil compaction assessment in agricultural settings. This methodology not only enhances accessibility but also ensures the accuracy of soil compaction determinations. Overall, our study provides valuable insights for land managers and researchers, emphasising the importance of adopting an accessible approach to soil compaction assessment in agricultural contexts. These insights help for informed decision making and effective soil management practices in agricultural lands.

AUTHOR CONTRIBUTIONS

Aram Ali: Methodology; writing – review and editing; formal analysis; software; data curation; resources; conceptualization; writing – original draft; validation; visualization. **John McLean Bennett:** Conceptualization; investigation; writing – review and editing; methodology; resources; supervision. **Stirling Roberton:** Conceptualization; writing – review and editing. **Diman Krwanji:** Visualization; writing – review and editing. **YingCan Zhu:** Writing – review and editing; visualization. **David West:** Resources; writing – review and editing.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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