Evaluation of the Compaction of a No-Till Vertisol Field Using Methods of Cone Index and Pedotransfer Function in Semi-arid Context of Morocco

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Abstract: This study evaluated compaction level of a 15-year old no-till vertisol field crop (40.91% clay, 44.16% loam and 14.93% sand) having organic matter contents of 2.23% and 2.91% in 0-10 cm and 10-20 cm profiles, respectively. The bulk density ranged from 1.30 g/cm³ to 1.80 g/cm³ in the field boundaries, and from 1.01 g/cm³ to 1.40 g/cm³ in its center. The field showed a gradient of limestone from 3% to 13%. Measurements were done to evaluate soil strength (cone index) and soil plasticity (Atterberg limits). The soil strength showed different levels of compaction from 4.5 MPa to 16 MPa to distinct five spatial clusters in the field. The soil compactness was related to limestone gradient according the correlation found between the soil strength and limestone levels. The soil plasticity test showed occurrence of plastic limits when the moisture content decreased from 26% to 15% within 5 d interval. The Atterberg limits showed the importance of respecting intervention delays to avoid soil compaction due to its plasticity. A pedotransfer function was developed using soil parameters of texture, organic matter, bulk density, cohesion, internal friction angle and moisture content to compute its precompression stress. Results showed importance of compaction in the field extremities due to importance of machines/tools traffic without avoiding cropping interventions during soil plasticity state. The soil strength (as measured value) was correlated to precompression stress (as estimated values) to show the importance of using pedotransfer function as significant method to evaluate indirectly compactness or susceptibility to compaction of the studied vertisol.

Key words: Compaction, vertisol, strength, Atterberg limits, limestone, pedotransfer function.

Nomenclature

BD: Bulk density
OMC: Organic matter content
TOC: Total organic carbon
TL: Total limestone
Pc: Precompression stress
Ss: Soil strength
Atl: Atterberg limits
IDP: Inverse distance to a power
CV: Coefficient of variation
DD: Decimal degree

1. Introduction

Soil compaction is becoming a critical problem facing modern agriculture and impacts with its intensity and extent environment and food production [1]. It is also a main cause of the degraded 33 million hectares of lands in Europe [2], and about 4 million hectares in Western Australia [3]. Several authors [4-11] stated that compaction is an actual problem of many countries (Azerbaijan, Japan, Russia, France, China, Ethiopia, New Zealand and Australia). Heavy machine traffics, and tillage tools are the main sources of agricultural soil compaction, and its severity depends on soil texture and structure, BD, OMC, water content and TL [12-14]. Its dynamic is mainly influenced by soil moisture content [15, 16]. Vertisols have high yield potential and are dedicated to intensive crop production. They are among the most sensitive soils to compaction according to their high clay and water contents during agricultural operations.
The compactness can occur within cropping cycle and affect crop performance [17]. The vertisol can differently behave to compaction depending on its structure state and type of dominant clay [18]. Field crop losses were due to intensity of agricultural traffic and tillage practices [19-22]. In Ref. [23] the researchers stated that BDs of 1.37 g/cm³ and 1.66 g/cm³ in a 0-30 cm profile can be indication of non-compacted and compacted soils, respectively. The BD is frequently used to evaluate soil compactness [12]. Furthermore, Ss is widely used to indicate soil compaction as it reflects soil resistance to root penetration [11, 12, 24-26].

In Ref. [27] the authors showed that up to 90% of roots are observed in the class of penetration resistance below 3 MPa. Some authors [28-31] stated that adequate soil OMC can improve soil structure and its resilience to compaction with reference to shown decrease in BD and Ss. The soil moisture content strongly influences compaction sensitivity and its variation helps to identify liquid, plastic and solid states called ATL. These limits are of importance to show different soil behaviors with reference to its moisture content. Destain [32] studied effect of vertisol moisture content state using ATL and showed importance of respecting delay of introducing machines/tools in the field to avoid its compactness due to soil plasticity.

Pedotransfer functions were used to evaluate spatial compaction at the small and large field scales by computing Pc [32-34]. The Pc computation requires knowledge of pedological (texture and organic matter), mechanical (BD, cohesion and internal friction angle), and hydraulics (available/no available water contents, porosity and hydraulic conductivity) parameters. Horn and Fleige [33, 34] correlated Pc to soil physical parameters as significant pedotransfer function to evaluate soil resistance to compaction at the farm and the regional levels. Soil physical proprieties (texture, structure and moisture content) are widely used for implementing pedotransfer functions [35-39]. Other researchers have characterized soil structure using density or others measurable variables such as permeability [36-38, 40-43]. D’or and Destain [44] classified Pc values into six ranges from very low (Pc < 30) to extremely high (Pc > 150) assigned to different levels of compaction. According to Håkansson and Lipiec [45], compaction of vertisols in Morocco is important soil knowledge that needs to be characterized. Despite the high production potential, vertisol needs adequate management [46] due to difficulty of operating it mechanically. The high moisture content induces clay swelling and intervention for tillage operations cannot be done within the period of liquid and plastic states [47].

This study aimed to evaluate compactness of a no-till vertisol field crop and find spatial correlation between compacted clusters and their physicochemical soil properties through development of a pedotransfer function linking Ss to Pc.

2. Materials and Methods

The experiment was undertaken in a vertisol field crop of 1 ha of 15 years historic of no-till practices. This field was situated in Chaouia region of Morocco (X: -7.6222, Y: 32.9556). Its soil physical parameters (OMC, BD and TL), Ss, plasticity (ATL) were evaluated using systematic sampling for each cluster of a 10 × 10 m² plot.

The OMC was measured by Walkley and Black method [48] based on the measurement of TOC (Eq. (1)):

\[
\text{OMC} (\%) = \text{TOC} (\%) \times 1.724
\]

TL was evaluated by Bernard Calcimeter Method and quantified by Eq. (2):

\[
\text{TL} = \frac{\Delta V \times (PT)}{M} \times 10^{-4}
\]

where: \(\Delta V\), \(PT\) and \(M\) are difference of volume, intersection pressure-temperature and mass of soil sample, respectively.

The Ss was measured by a cone index penetrometer (30°) equipped with a pressure sensor (BoschTM, \(P_{\text{max}}\))
= 250 bar) (Fig. 1). Data were acquired (sampling rate of 2 Hz) using an oscilloscope/ logger (Agilent U1604B) and transformed from volt to pressure based on a curve calibration (Fig. 2). The penetrometer was mounted on a tractor framework and driven by a 12 V DC electric motor with constant speed of 2.5 cm/s.

Vertisol plasticity was evaluated using the ATL method [49]. A hydraulic press (Figs. 3-5) was mounted and used for evaluating plastic limits with reference to standard (ASTMD 4318-17). Evaluation was based on 28 soil samples (seven treatments and four replicates). Each soil sample (269.26 cm³ of granules having less than 2 mm) was poured in a press cylinder and humidified by tap water (150 mL). Each sample was pressed up to 6 bar and evaluated for its Ss (cone index penetrometer) during the 1st, 2nd, 3rd, 4th, 5th, 10th and 15th days in order to show the strength response as a function of moisture content. The field data collected were performed using the spatial interpolation method of IDP and Surfer 13 software. The IDP is a robust method for data interpolation and map realization [50, 51].

Pedotransfer function protocol was based on the computation of Pc using the following equation [32]:

\[
P_c = 70.65X_1 - 0.5X_3 - 7.01(X_4)^{0.33} + 1.32X_3 - 1.08X_2 + 1.72X_6 + 1.05X_7 - 100.94
\]  

(3)

Fig. 1  Protocol design for Ss measurement.

Fig. 2  Ss calibration curve (pressure vs. voltage).
Fig. 3  A scheme of hydraulic press used to evaluate response to compaction, at varying moisture content of soil samples.

Fig. 4  Hydraulic press calibration (pressure vs. voltage).

Fig. 5  Ss calibration curve (Ss vs. voltage).

where: $X_1$, $X_2$, $X_3$, $X_4$, $X_5$, $X_6$ and $X_7$ are the BD, available water content, no-available water content, hydraulic conductivity, OMC, cohesion and internal friction angle, respectively.

The regression linear method (JMP SAS software) was used to correlate between the Ss and limestone and between the Ss and the Pc.

3. Results and Discussion

3.1 Ss Assessment

Ss spatial distribution (Fig. 6) showed a significant compaction level in the boundaries limits of the field matrix. It is due to traffic importance and tractor turns. Results showed also an important compaction gradient
(from simple to quadruple) between upstream and the downstream sides of the field. The compaction gradient was related to importance of limestone distribution. In fact, comparison between Ss and limestone spatial distributions (Figs. 6 and 7) showed that both parameters were proportionally related. There

Fig. 6 Ss map based on cone penetrometer data represented by IDP method.

Fig. 7 TL map based on data analysis represented by IDP method.
is a potential effect of limestones proportion on compaction severity according to presence of limestone slab in the soil matrix. Referring to Laamel [52], susceptibility to compaction is relatively more important in a loamy soil than in a clay soil.

### 3.2 ATL

ATL showed that soil water content dynamic has an influence on its sensitivity to compaction within plasticity limits (Fig. 8). It is of importance to avoid machines traffic during soil plasticity period to overcome compaction problem. Furthermore, soil plasticity state can be evaluated with reference to soil moisture content in order to timely manage introduction of machines to avoid compaction of plastic soil. The soil plasticity can be used as a decision tool to predict compaction on the basis of soil water content dynamic.

Resistance to penetration of the compacted samples by the press was done using the cone index penetrometer. This resistance to penetration is represented as a function of the penetration depth and moisture content for each sample. Fig. 9 showed three ranges of low, high and medium resistance for depths of 0-3, 3-5 and 5-7 cm, respectively. According to the response of samples to penetration resistance, two distinct ranges of 0.2-0.5 MPa and 0.5-1 MPa were shown according to the press timing between the 1st and 15th days. Plasticity evolutions showed different s-shaped curves evolving with an increase in soil penetration resistance, as soil moisture content decreases.

### 3.3 Pc Evaluation

Pre-compression computation was done to evaluate susceptibility index of soil compaction indirectly [44]. In this study, computation of Pc based on physical parameters of the soil matrix showed three distinct classes of compaction (low, medium and high) (Fig. 10).

### 3.4 Pc vs. Ss Correlation (Pedotransfer Function)

Pre-compression stress and Ss were investigated by a pedotransfer function to evaluate soil susceptibility to compaction. In this regard, Table 1 showed that Pc and Ss are highly correlated with an $R^2$ of 90% in the boundaries and in the center of the field. This relationship provided means to assess response of soil

![Fig. 8  Soil sensitivity to compaction as a function of water content and ATL.](image-url)
to compaction using $P_c$ as an indirect method that is pointed out by D’or and Destain [44], for both field and regional scales. The state of water content constitutes a determinant parameter to optimally manage timing for introducing machines in the field and avoiding traffic when soil is in its plastic state. The
Table 1  TL, Ss, Pc and parameters of the linear regression equations (soil Pc vs. Ss) of the five clusters and of the global equation (average of the five cluster).

| Cluster                          | CaCO₃ (CV) | Ss (CV)   | Pc (CV)       | A (SE)    | B (SE)    | R-squared | SE equation |
|---------------------------------|------------|-----------|---------------|-----------|-----------|-----------|-------------|
| Field center                    | 9.442 (0.1)| 14.916 (1.5)| 103.834 (2.58)| 2.027 (0.27)| 73.600 (4.14)| 0.844     | 1.967       |
| Field center                    | 8.245 (0.1)| 10.311 (0.9)| 88.551 (1.44)| 2.600 (0.30)| 61.745 (3.49)| 0.880     | 5.299       |
| Field center                    | 3.235 (0.1)| 4.416 (0.2)| 75.226 (1.11)| 1.922 (0.24)| 66.737 (1.27)| 0.863     | 2.370       |
| South field boundaries          | 12.946 (0.1)| 15.829 (1.6)| 102.004 (1.02)| 3.020 (0.31)| 54.192 (4.97)| 0.904     | 2.325       |
| North field boundaries          | 5.641 (0.1)| 14.974 (1.5)| 97.854 (1.94)| 2.783 (0.26)| 54.176 (4.03)| 0.918     | 2.928       |
| Global equation                 | 2.452 (0.09)| 63.855 (1.20)| 0.926         | 3.784     |           |           |             |

CV: coefficient of variation; SE, A and B represent standard error, slope parameter and intercept, respectively.

Pc pedotransfer function considers the soil water state represented by the potential within the range of field capacity and wilting points. According to positions of the clusters in the field, significant correlations between the limestone, Ss and Pc were shown (Table 1). Clusters having higher limestone concentration (clusters 1, 4 and 5) showed the highest values of Ss and Pc. The clusters 4 and 5 were in the boundary limits of the field that have the highest values of Ss and Pc, indicating in this way the importance of the compaction level. In fact, the field boundaries were often subjected to intensive traffic and machine turning. Data analysis showed a significant correlation between the Ss as measured values and the Pc as estimated value ($R^2 = 0.926$). A linear regression equation of the form [Ss (MPa) = 2.452 Pc (MPa) + 63.855] was found. This relationship can be used to predict an Ss through the computation of the Pc based on soil physical characteristics. Furthermore, Ss was correlated to limestone [Ss (MPa) = 0.645 × CaCO₃ % + 0.844, $R^2 = 0.822$]. Both equations showed the importance of evaluating soil compactness for a field matrix by referring to limestone as a direct indicator and Pc as an indirect indicator to have an index of soil susceptibility compaction.

4. Conclusions

Computation of Pc was based on equation and soil parameters of the field. The Ss data (measured values) were correlated to CaCO₃ (%) (measured values) and Pc (computed values) using a linear regression method. The use of the pedotransfer function of the Pc helped to evaluate soil susceptibility to compaction as an indirect method. However, the importance of CaCO₃ (%) gradient in the field and its correlation to the Ss showed that it is possible to use limestone as a direct indicator to evaluate the soil compactness and/or its susceptibility to compaction.

5. Future Work

The study showed that it is possible to assess the soil susceptibility to compaction using Pc as indirect method according to its correlation to Ss used as direct method for measuring compactness. It is of importance to upscale this method for a regional level.

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