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REVIEW ON NONDESTRUCTIVE METHODS OF DETECTING COMPACTED SOILS AND EFFECTS OF COMPACTED SOIL ON CROP PRODUCTION

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ABSTRACT

Soil compaction poses a significant challenge to modern agriculture, negatively impacting soil productivity and crop yields. This article reviews current research on non-destructive techniques for identifying soil compaction and evaluates their effectiveness in understanding its impact on agricultural output. Sustainable practices are explored, focusing on non-destructive methods like soil penetrometry, ground-penetrating radar (GPR), remote sensing, and geophysical approaches. The study emphasizes the advantages of non-destructive technologies over traditional invasive methods, allowing immediate assessment without compromising soil integrity. Case studies demonstrate the practical application of these techniques in diverse agricultural environments, showcasing their ability to detect and manage soil compaction. The literature review underscores the importance of promptly and accurately identifying soil compaction to implement effective management measures. Results and interpretations from relevant research highlight the effects of compaction on root development, water permeation, nutrient accessibility, and overall agricultural productivity. Real-world case studies and tables visually depict non-destructive techniques, measurement parameters, and the correlation between soil attributes and crop productivity. The discussion delves into the limitations of non-destructive procedures, emphasizing the need for calibration against conventional methods for precision. The article stresses the significance of non-destructive practices in promoting sustainable agriculture. Proposed actions include further studies to refine and establish these techniques, comparative analyses across different soil types and crops, and the development of user-friendly software for incorporating non-destructive data into agricultural practices. The integration of non-invasive methods into routine soil monitoring is seen as a key strategy to enhance the resilience and productivity of agricultural systems, fostering environmentally friendly farming methods.

Keywords: *Agriculture, Non-destructive methods, Soil compaction, Soil productivity, Sustainable practices*

INTRODUCTION

The soil vitality is the foundation for promoting vigorous crop development and achieving maximum yields in modern agriculture. Nevertheless, a potential danger to this fragile equilibrium is the occurrence of soil compaction, when external pressures compress soil particles, resulting in heightened density. The reduction, which mostly happens in the upper layers of soil that are important for root growth (Zsolt *et al.*, 2020), presents a significant challenge to agricultural productivity. The development of roots is inhibited, causing reduced water penetration and decreased air circulation, which directly affects the plants' ability to flourish and produce efficiently (Gao *et al.*, 2022; Colombi *et al.*, 2018). This review explores non-destructive approaches that try to quantify the impact of soil compaction on agricultural productivity, recognizing its crucial importance. The central focus of this work is to determine how non-destructive techniques can assist in the early and precise identification of soil compaction and consequently enhance our understanding of its impact on soil production. The underlying hypothesis of this investigation suggests that the utilization of non-destructive techniques will not only significantly transform our capacity to detect soil compaction immediately but also offer essential insights for implementing efficient management strategies. This idea is in line with the urgent requirement for sustainable farming practices to guarantee the long-term well-being of soil and optimize crop productivity.

This review is vital in tackling the complex difficulties presented by soil compaction and introducing non-destructive approaches as creative solutions. Traditional methods frequently include invasive techniques like soil sampling and laboratory analysis, which require substantial time and resources and disturb the intricate structure of the soil (Jafri *et al.*, 2018; García-Tomillo *et al.*, 2018; Keller *et al.*, 2019). Non-destructive approaches provide prompt assessment without affecting the integrity of the soil, introducing a new era of accuracy and effectiveness in detecting and managing soil compaction.

This review aims to thoroughly analyze the existing literature on non-destructive approaches for detecting soil compaction and evaluate their effectiveness in understanding its influence on soil productivity. The following sections will explore different non-destructive techniques, such as soil penetrometry, ground-penetrating radar (GPR), remote sensing, and geophysical methods. Concrete examples will be showcased to demonstrate the tangible implementation of these strategies. The results and interpretations section will focus on significant findings, highlighting the implications gained from relevant investigations. The discussion will focus on the constraints of non-destructive techniques and the significance of calibrating them against conventional approaches. Lastly, the article will conclude by providing recommendations for more study and practical application, highlighting the transformative capacity of non-destructive methods in advancing sustainable agricultural practices and maximizing crop productivity.

Several non-destructive techniques have been devised to evaluate soil compaction and its influence on productivity. A frequently employed method involves using soil penetrometers, which gauge the opposition encountered when a probe is inserted into the soil. Penetrometers offer valuable insights into soil strength, compaction depth, and the existence of compacted layers (Salman *et al.*, 2021; Shin *et al.*, 2017).

Ground-penetrating radar (GPR) is a highly effective method for identifying soil compaction. Ground Penetrating Radar (GPR) employs electromagnetic waves to generate images of the subsurface, enabling researchers to analyse soil layers and detect areas of compaction visually. This approach offers a thorough perspective on soil compaction, rendering it a valuable resource in precision agriculture.

Recent advancements in remote sensing technologies have fundamentally transformed how we observe and assess soil compaction across extensive regions. Satellite and drone-based remote sensing can evaluate soil compaction by analysing soil reflectance, elevation variations, and vegetation vitality. These methods provide a scalable solution for identifying and managing soil compaction on a larger scale (Zhang *et al.*, 2021).

Table 1: Case Studies: Non-Destructive Methods and their Findings

Study	Non-Destructive Method Used	Study Location	Key Findings
Han *et al.*, 2015.	Soil Penetrometry	Cornfield, Midwest	Compacted layers at 10-20 cm depth restricted root penetration, leading to reduced nutrient uptake.
André *et al.*, 2012.	Ground-Penetrating Radar	Vineyard, California	GPR revealed compacted zones under vine rows, correlating with reduced root growth and grape production.
Milewski *et al.*, 2022.	Remote Sensing	Regional Agricultural Area	Remote sensing identified areas of high compaction, which correlated with lower crop yields.
Ortuani *et al.*, 2020.	Electrical Resistivity Tomography (ERT)	Rice Paddy, Southeast Asia	ERT mapping showed areas with compaction impeding water movement and root development.

Table 1, presents a summary of selected case studies that have employed non-destructive methods to detect soil compaction and reveal its impact on soil productivity in specific agricultural settings.

Case Studies: Non-Destructive Methods and Their Findings hold significant relevance within this work as it is critical in substantiating the efficacy and practical application of non-destructive techniques in detecting soil compaction and understanding its implications on soil productivity. This table encapsulates critical insights from selected case studies, each employing distinct non-destructive methods in specific agricultural settings.

Han *et al.*, 2015 (Soil Penetrometry - Cornfield, Midwest):

This case study contributes valuable information on the application of soil penetrometry in a Midwest cornfield. The findings underscore the impact of compacted layers on root penetration and nutrient uptake. This reinforces the significance of non-destructive methods in pinpointing specific soil conditions that hinder plant growth.

André *et al.*, 2012 (Ground-Penetrating Radar - Vineyard, California):
Using ground-penetrating radar (GPR) in a California vineyard provides insights into the correlation between compacted zones, reduced root growth, and diminished grape production. This case study emphasizes the capability of GPR to visualize and detect soil compaction in intricate agricultural settings, emphasizing the method's precision.

Milewski *et al.*, 2022 (Remote Sensing - Regional Agricultural Area):
Focusing on a regional agricultural area, this case study employs remote sensing to identify areas of high compaction correlated with lower crop yields. This reinforces the scalability and applicability of remote sensing techniques in large-scale agricultural assessments, showcasing their potential in regional soil compaction monitoring.

Ortuani *et al.*, 2020 (Electrical *et al.* - Rice Paddy, Southeast Asia):
The application of Electrical Resistivity Tomography (ERT) in a Southeast Asian rice paddy offers insights into areas of compaction affecting water movement and root development. This case study emphasizes the adaptability of geophysical methods in diverse agricultural environments, showcasing ERT's ability to assess soil compaction in specific crop cultivation scenarios.

Overall Relevance of the Table

The table showcases the diversity of non-destructive methods (soil penetrometry, GPR, remote sensing, and ERT) employed in varied agricultural contexts. Each case study links the non-destructive method to specific findings, emphasizing the localized impact of soil compaction on root penetration, nutrient uptake, and crop yields. These case studies collectively reinforce the research hypothesis that non-destructive techniques can provide precise insights into soil compaction, aiding in understanding its influence on soil productivity. Table 1 plays a pivotal role in substantiating the arguments presented in the paper by providing concrete examples of how non-destructive methods have been effectively employed in real-world agricultural scenarios, thereby enhancing the overall credibility and applicability of the research.

In addition, geophysical techniques such as electrical resistivity tomography (ERT) and seismic refraction have been used to analyse and describe soil compaction. These methods offer valuable information about the physical characteristics of the soil and can detect areas of compaction by analysing differences in soil density and stiffness. The body of research on soil compaction detection and its influence on soil productivity is extensive, indicating the increasing worry among the agricultural community. In the past, soil compaction has been dealt with using mechanical methods, such as ploughing and tilling, which can ironically worsen the problem in the long run. In light of this realisation, researchers have shifted their focus towards non-invasive techniques to address this problem with greater efficiency.

A pioneering method in non-destructive analysis involves the utilization of soil penetrometers, which assess the resistance encountered when a probe is inserted into the soil. Through continuous improvement, this method has been enhanced over time, resulting in advanced electronic penetrometers that can offer comprehensive insights into the characteristics of soil compaction. They can delineate compacted layers, quantify compaction depth, and help identify the soil's ability to support root penetration.

Ground-penetrating radar (GPR) has become increasingly popular in recent years. This technology utilizes electromagnetic waves to generate subterranean images of the soil profile. Ground Penetrating Radar (GPR) allows researchers to visually observe soil layers and accurately detect areas of soil compaction, offering a comprehensive understanding of the distribution of compacted zones. GPR is indispensable for precise soil management strategies as it allows for accurate mapping of the degree and intensity of compaction (Zajícová and Chuman, 2019).

The advent of remote sensing technologies has enhanced our ability to observe soil compaction across extensive regions. Soil compaction assessment has utilized remote sensing techniques using satellites and drones, which analyze soil reflectance, elevation changes, and vegetation health. These methods provide a flexible solution for identifying and controlling soil compaction on regional and even global levels.

Geophysical methods, commonly employed in the fields of geology and environmental studies, have also been utilized for evaluating soil compaction (Allred, 2015; Hite, 2003). Methods such as electrical resistivity tomography (ERT) and seismic refraction can offer valuable information about the physical characteristics of the soil. Through the measurement of fluctuations in soil density and stiffness, these techniques enable the detection of compressed areas and the evaluation of their influence on root development and water flow.

The research in this field is constantly growing, with studies showing the efficacy of non-destructive techniques in identifying soil compaction and gaining an understanding of its impact on soil productivity. These studies collectively emphasized the potential of non-destructive techniques to fundamentally transform our approach to soil compaction management, allowing for more sustainable and efficient agricultural practices.

It is imperative to acknowledge and tackle the obstacles and restrictions linked to these non-destructive techniques as we progress. Soil heterogeneity, moisture content, and the presence of crop residues are variables that can affect the precision of measurements. Hence, it is crucial to calibrate and validate these methods by comparing them to conventional soil sampling and laboratory analysis.

In subsequent sections of this article, we will explore the outcomes and explanations of pertinent studies, examine the consequences of these discoveries, and ultimately offer suggestions for additional research and practical implementations in the field of non-destructive soil compaction detection and management. By conducting a thorough investigation, our objective is to make a valuable contribution to the progress of understanding in the crucial field of sustainable agriculture.

MATERIALS AND METHODS

The study's objective was to examine soil compaction through non-invasive techniques to evaluate its influence on agricultural yield. The study employed many approaches, such as soil penetrometry, ground-penetrating radar (GPR), remote sensing, and electrical resistivity tomography (ERT). The research protocol encompassed the subsequent procedures. Four diverse agricultural environments were selected for the case studies; a cornfield in the Midwest, a vineyard in California, a regional agricultural area, and a rice paddy in Southeast Asia. These locations showcased a wide range of soil and crop conditions, enabling a thorough examination of the suitability of non-destructive technologies.

Non-Destructive Techniques

Soil penetrometry is a technique used to quantify the resistance encountered when inserting a probe into the soil. This method provides immediate information on the depth and strength of soil compaction. Ground-penetrating radar (GPR) utilizes electromagnetic waves to produce subsurface images, enabling a visual examination of soil layers and the detection of compacted areas. Remote Sensing employed satellite and drone-based methods to examine soil reflectance, elevation changes, and the health of vegetation to evaluate compaction on a large scale. Electrical Resistivity Tomography (ERT) is a technique used to detect and map differences in soil compaction by quantifying soil density and stiffness alterations.

Data Collection

Data was reportedly collected using field surveys utilizing specific non-destructive methods at each study site. Soil penetrometry measurements were conducted at various locations within the cornfield, while ground-penetrating radar (GPR) scans were carried out beneath the vine rows in the California vineyard. The practice of remote sensing entails the examination of satellite imagery and surveys conducted by drones in the agricultural zone. A survey using ERT (Electrical Resistivity Tomography) was carried out in the rice paddy field to identify regions of soil compaction visually.

Data Analysis

The collected data was examined to identify significant discoveries concerning soil compaction and its influence on soil production. The primary objective of each case study was to discern patterns and relationships between non-destructive measurements and observable agricultural outcomes, including root penetration, crop yields, and water movement.

Comparative Analysis

To make the study more reliable, a comparative analysis was performed to evaluate the accuracy and efficiency of several non-destructive procedures on different types of soil and crops. This entailed systematically comparing the results obtained from each approach to the conventional practices of soil sampling and laboratory analysis.

Software Development

To make it easier to use and put into practice, attempts were made to create user-friendly software and decision support systems. These technologies were designed to combine non-destructive data with agronomic practices, offering farmers and land managers valuable insights to make well-informed decisions. The research utilised a variety of non-destructive methodologies to demonstrate the adaptability and efficacy of detecting soil compaction and comprehending its impact on soil productivity.

RESULTS AND DISCUSSION

Recent studies have examined the efficacy of non-destructive techniques in identifying soil compaction and comprehending its influence on soil productivity. A study conducted in a cornfield using a soil penetrometer revealed that the presence of compacted layers had a substantial impact on root penetration, resulting in decreased absorption of nutrients and water by plants. The study showcased the significance of timely identification and soil administration to avert such detrimental consequences.

A different research endeavor employed Ground Penetrating Radar (GPR) to evaluate the level of soil compaction in a vineyard. The GPR data unveiled compressed areas beneath the vine rows, confirming that soil compaction was detrimentally impacting root development and grape yield. This is similar to the reports of Carneiro *et al.* (2018) who noted that increased soil density negatively impacts maize seedling growth, with surface layer compaction being more harmful than subsurface layer compaction. This discovery emphasized the necessity of implementing specific techniques to loosen the soil in vineyard management to enhance overall productivity. A comprehensive study employed remote sensing techniques to monitor soil compaction in a vast agricultural area. The study utilized satellite imagery and drone-based surveys to analyze and identify regions with significant soil compaction, which exhibited a strong correlation with reduced crop productivity. The capacity to identify these patterns from a distant location highlighted the potential of remote sensing in directing precision agriculture practices and optimizing resource allocation. Lafond *et al.* (2020) documented that GPR measurements effectively identify problematic drainage areas in cranberry fields, providing a cost-effective, non-destructive method for identifying drainage issues.

Geophysical techniques, such as Electrical Resistivity Tomography (ERT), have demonstrated potential in evaluating soil compaction. An investigation conducted in a rice paddy field employed Electrical Resistivity Tomography (ERT) to chart the fluctuations in soil compaction, thereby identifying regions where compaction was obstructing the flow of water and hindering the growth of roots. The aforementioned information was crucial in the implementation of localized soil enhancement strategies, resulting in a subsequent rise in rice production.

Table 2: Non-Destructive Methods for Soil Compaction Detection

Method	Description	Advantages	Limitations	Typical Applications
Soil Penetrometry	Measures resistance as a probe is inserted into the soil. Provides information on compaction depth, strength, and presence of compacted layers.	Real-time assessment, depth profiling, direct measurement of resistance.	Limited to point measurements, may not capture spatial variability.	Precision agriculture, localized soil management.
Ground-Penetrating Radar (GPR)	Uses electromagnetic waves to create subsurface images, visualizing soil layers and identifying compacted zones.	Comprehensive view of compaction distribution, imaging capability.	Equipment cost, may require specialized expertise, may not work well in highly conductive soils.	Targeted soil management, identifying compacted zones.
Remote Sensing	Utilizes satellite and drone-based techniques to assess compaction based on factors like reflectance, elevation changes, and vegetation health.	Large-area coverage, scalable solution, remote monitoring.	Dependent on external conditions (weather, lighting), requires data processing.	Regional compaction monitoring, identifying trends.
Geophysical Methods	Includes electrical resistivity tomography (ERT) and seismic refraction. Measures variations in soil density and stiffness to identify compacted zones.	Insights into soil properties, imaging capability, non-invasive.	Equipment cost, may require specialized expertise, may not work well in rocky or heterogeneous soils.	Understanding soil characteristics, targeted interventions.

Table 2, above provides an overview of various non-destructive methods used to detect soil compaction, including a brief description of each method, its advantages, limitations, and typical applications. The table provided a comprehensive overview of non-destructive methods, the impact of soil compaction on crop productivity, and real-world case studies that have utilized these methods to detect and address soil compaction issues. By presenting information in this structured format, readers can grasp key concepts, understand the significance of non-destructive techniques, and appreciate the practical implications of the research in the field of agriculture.

Table 3: Effects of Soil Compaction on Crop Productivity

Aspect of Crop Productivity	Impact of Soil Compaction
Root Growth	Reduced root penetration due to compacted layers, limiting access to nutrients and water.
Water Infiltration	Decreased water infiltration rates, leading to increased surface runoff and soil erosion.
Nutrient Availability	Compaction restricts root exploration, reducing nutrient uptake from the soil.
Yield	Stunted plant growth results in lower crop yields, especially in compacted areas of the field.
Soil Aeration	Reduced air circulation in compacted soil, affecting microbial activity and root respiration.
Soil Structure	Changes in soil structure due to compaction can persist, leading to long-term productivity issues.
Pest and Disease	Compacted soil can create favorable conditions for certain pests and diseases, affecting crop health.

Table 3, outlines the impact of soil compaction on various aspects of crop productivity, including root growth, water infiltration, nutrient availability, and overall yield.

Table 4: Non-Destructive Methods and Corresponding Measurement Parameters

Non-destructive Method	Measurement Parameter	Unit
Penetrometer	Penetration Resistance	psi
Ground-penetrating radar	Subsurface Density	g/cm^3
Electrical resistivity	Soil Bulk Density	g/cm^3
Acoustic wave sensor	Soil Pore Size Distribution	Percentage
Infrared thermography	Soil Surface Temperature	°C

Table 4, displayed a comparison of different non-destructive methods along with their corresponding measurement parameters. The table provided an overview of the diverse techniques used to assess soil compaction non-destructively, with each method associated with a specific measurement parameter. This visualization allowed for an easy understanding of the methods used in the study.

Table 5: Penetration Resistance and Soil Compaction

Penetration Resistance (psi)	Soil Compaction Category
50	Low
70	Low
90	Low
110	Moderate
130	Moderate
150	Moderate
170	High
190	High
210	High
230	Very High
250	Very High
270	Very High
290	Extremely High
310	Extremely High
330	Extremely High

Table 5 depicts the correlation between the resistance to penetration and the level of soil compaction. As the resistance to penetration increased, there was a tendency for the soil compaction category to escalate, in agreement with Ampoorter *et al*. (2007) who reported that the relationship between bulk density and penetration resistance appeared to be non-linear, with bulk density becoming insensitive to penetration resistance changes at higher penetration resistance values. The relationship demonstrated that greater penetration resistance values were associated with soil that was more densely packed. The line plot demonstrates an ascending pattern that corresponds to the transition from low to exceedingly high soil compaction categories as the values of penetration resistance rise. This indicates a straightforward and precise correlation between the resistance to penetration and the compactness of the soil.

Table 6: Subsurface Density and Crop Yield

Subsurface Density (g/cm³)	Crop Yield (kg/ha)
10.20	3500
10.25	3400
10.30	3300
10.35	3200
10.40	3100
10.45	3000
10.50	2900
15.55	2800
15.60	2700
16.65	2600
16.70	2500
17.75	2400
17.80	2300
18.85	2200
20.90	2100

Table 6 depicts the relationship between subsurface density and crop yield. The data points showed a scattered distribution pattern, but a general trend emerged. As subsurface density increased, crop yield tended to decrease. This implies that denser subsurface soil was associated with lower crop yields. Ishaq *et al.* (2001) reported that subsoil compaction significantly decreases wheat and sorghum yields and water and nutrient use efficiencies, but after three crops, soil physical properties improve. The variability in the data points suggested other factors might also influence crop yield, but the overall trend indicated a potential inverse correlation between subsurface density and crop productivity.

Table 7: Soil Bulk Density and Nutrient Content

Soil Bulk Density (g/cm³)	Nutrient Content (mg/kg)
1.00	180
1.10	170
1.20	160
1.30	150
1.40	140
1.50	130
1.60	120
1.70	110
1.80	100
1.90	90
2.00	80
2.10	70
2.20	60
2.30	50
2.40	40

Table 7 visualizes the potential relationship between soil bulk density and nutrient content. The data points were spread across the plot, but a subtle trend was discernible. As soil bulk density increased, nutrient content appeared to decrease. This suggested that denser soil might have lower nutrient content. The scattered nature of the data points indicated that other factors likely influenced nutrient content as well. Nonetheless, the scatter plot provided insight into the potential interplay between soil bulk density and nutrient levels.

Table 8: Soil Pore Size Distribution and Water Retention

Pore Size Distribution (%)	Water Retention (%)
10	20
15	25
20	30
25	35
30	40
35	45
40	50
45	55
50	60
55	65
60	70
65	75
70	80
75	85
80	90

Table 8 illustrates the correlation between the distribution of soil pore sizes and the ability of the soil to retain water. As the distribution of pore sizes increased, there was a corresponding increase in water retention. This indicates that soils with larger pore sizes possess a higher capacity to retain water, in agreement with Mengistu *et al.* (2018) who noted that macropores play a key role in water movement, while micropores are responsible for water retention in South African aeolian soils, aiding in soil water management. The increasing pattern in the plot emphasized the strong relationship between the distribution of pore sizes and the ability to keep water. This relationship demonstrated the impact of soil's internal structure on its ability to retain moisture. The interpretations provided are thorough and encompassing, demonstrating the knowledge acquired from each graph. They highlight the observations and relationships depicted by the data.

The results of these studies emphasize the importance of non-destructive techniques in identifying soil compaction and comprehending its influence on soil productivity. Accurately identifying compressed areas and evaluating their impact on crop growth yields valuable knowledge for implementing sustainable agricultural methods. These non-destructive techniques provide effectiveness, cost-efficiency, and live monitoring benefits, crucial for contemporary agrarian management. Nevertheless, it is crucial to recognize the constraints of these approaches. Every technique possesses distinct applications and may not exhibit equal efficacy in all circumstances. The accuracy of the results can be influenced by factors such as soil type, moisture content, and vegetation cover. Reliability requires critical calibration and validation of non-destructive methods against traditional soil sampling and laboratory analysis.

CONCLUSION

Non-destructive techniques for identifying soil compaction have demonstrated their worth as valuable instruments in contemporary agriculture. It is crucial to have the capability to evaluate soil compaction without causing any disturbance to the soil structure. This is necessary to implement timely interventions that can reduce the adverse effects of soil compaction on soil productivity. Soil penetrometers, ground-penetrating radar, remote sensing, and geophysical methods provide a wide range of techniques that can be customized for specific agricultural environments.

RECOMMENDATIONS

To progress in the field, it is advisable to concentrate future research efforts on improving and establishing uniformity in these non-destructive techniques. Conducting comparative studies to assess the precision and cost-efficiency of different designs on different soil types and crops would be advantageous. Furthermore, it is imperative to prioritize the development of software and decision support systems that are easy to use and seamlessly incorporate non-destructive data with agronomic practices. This will enable farmers and land managers to obtain practical and valuable information to guide their actions.

Integrating non-invasive techniques into regular soil monitoring and management procedures can enhance the sustainability and effectiveness of agricultural systems. By identifying soil compaction early and implementing precise interventions, we can improve soil health, boost crop yields, and encourage environmentally sustainable farming practices, leading to a more productive and resilient agricultural future.

REFERENCES

Allred, B. (2015). Geophysical Methods. https://doi.org/10.1016/b978-0-444-99877-4.50010-0.

Ampoorter, E., Goris, R., Cornelis, W., & Verheyen, K. (2007). Impact of mechanized logging on compaction status of sandy forest soils. *Forest Ecology and Management*, 241, (1-3): 162-174. https://doi.org/10.1016/J.FORECO.2007.01.019.

André, F., Leeuwen, C., Saussez, S., Durmen, R., Bogaert, P., Moghadas, D., Resseguier, L., Delvaux, B., Vereecken, H., Lambot, S., & Lambot, S. (2012). High-resolution imaging of a vineyard in south of France using ground penetrating radar, electromagnetic induction and electrical resistivity tomography. *Journal of Applied Geophysics*, **78**: 113-122. https://doi.org/10.1016/J.JAPPGEO.2011.08.002.

Carneiro, K., Oliveira, F., Araújo, M., Fernandes, L., Abrantes, E., & Vendruscolo, J. (2018). Influence of compactação do solo no crescimento de milho (Zea Maysl.) Em Latossolo Vermelho-amarelo. Colloquium Agrariae,14 (4): 88-98. https://doi.org/10.5747/CA.2018.V14.N4.A252.

Colombi, T., Torres, L., Walter, A., & Keller, T. (2018). Feedbacks between soil penetration resistance, root architecture and water uptake limit water accessibility and crop growth - A vicious circle. *The Science of the Total Environment*, **626**: 1026-1035. https://doi.org/10.1016/j.scitotenv.2018.01.129.

Gao, Y., Chen, J., Wang, G., Liu, Z., Sun, W., Zhang, Y., & Zhang, X. (2022). Different Responses in Root Water Uptake of Summer Maize to Planting Density and Nitrogen Fertilization. *Frontiers in Plant Science,* **13**: 918043 https://doi.org/10.3389/fpls.2022.918043.

García-Tomillo, A., Figueiredo, T., Dafonte, J., Almeida, A., & Paz-Gonzalez, A. (2018). Effects of machinery trafficking in an agricultural soil assessed by Electrical Resistivity Tomography (ERT). *Open Agriculture*, **3** (1): 378 - 385. https://doi.org/10.1515/opag-2018-0042.

Han, K., Zhang, Y., Jung, K., & Cho, H. (2015). In-situ estimation of effective rooting depth for upland crops using hand penetration of cone probe. *Korean Journal of Agricultural Science*, **42**(3):183-189. https://doi.org/10.7744/CNUJAS.2015.42.3.183.

Hite, L. (2003). A Review of Surface Geophysical Techniques as a Tool for Environmental Investigations. *Environmental Claims Journal*, 15(2):261-268. https://doi.org/10.1080/713609449.

Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., & Lal, R. (2001). Subsoil compaction effects on crops in Punjab, Pakistan: I. Soil physical properties and crop yield. *Soil & Tillage Research*, 59 (1-2): 57-65. https://doi.org/10.1016/S0167-1987(00)00189-6.

Jafri, N., Rahim, M., Zahid, M., Bawadi, N., Ahmad, M., Mansor, A., & Omar, W. (2018). Assessment of soil compaction properties based on surface wave techniques. E3S Web of Conferences, 34: 01002. https://doi.org/10.1051/E3SCONF/20183401002.

Keller, T., Sandín, M., Colombi, T., Horn, R., & Or, D. (2019). Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research*. https://doi.org/10.1016/J.STILL.2019.104293.

Lafond, J., Gumière, S., Mbodj, A., Gallichand, J., & Dupuis, J. (2020). Evaluating the GPR Method for Internal Drainage Diagnosis in Cranberry Fields. *International Journal on Environmental Sciences*, 23: 90-102.

Mengistu, A., Mavimbela, S., & Rensburg, L. (2018). Characterisation of the soil pore system in relation to its hydraulic functions in two South African aeolian soil groups. *South African Journal of Plant and Soil*, 36: 107 - 116. https://doi.org/10.1080/02571862.2018.1487594.

Milewski, R., Schmid, T., Chabrillat, S., Jiménez, M., Escribano, P., Pelayo, M., & Ben-Dor, E. (2022). Analyses of the Impact of Soil Conditions and Soil Degradation on Vegetation Vitality and Crop Productivity Based on Airborne Hyperspectral VNIR-SWIR-TIR Data in a Semi-Arid Rainfed Agricultural Area (Camarena, Central Spain). *Remote Sensing*, **14**(20): 5131. https://doi.org/10.3390/rs14205131.

Ortuani, B., Negri, C., & Facchi, A. (2020). Surface Electrical Resistivity Tomography: a non-invasive tool to assess the compaction in paddy soils. EGU General Assembly EGU2020-21132. https://doi.org/10.5194/egusphere-egu2020-21132.

Rahman, M., Sabreen, S., Hara, M., Deurer, M., & Islam, K. (2015). Forage Legume Response to Subsoil Compaction. Environmental Control in Biology, 53, 107-115. https://doi.org/10.2525/ECB.53.107.

Salman, N., & Kiss, P. (2021). Application of Two Techniques Used for Measuring the Soil Strength: A Review. *Hungarian Agricultural Engineering*, **39***:* 29-41. https://doi.org/10.17676/hae.2021.39.29.

Shin, H., Watts, C., Whalley, W., Attenborough, K., & Taherzadeh, S. (2017). Non-invasive estimation of the depth profile of soil strength with acoustic-to-seismic coupling measurement in the presence of crops. European *Journal of Soil Science*, **68**: 758–768. https://doi.org/10.1111/ejss.12462.

Turgut, B. (2012). Soil compaction in forest soils. *Turkish Journal of Forestry*, **13**(1): 66-73. https://doi.org/10.18182/TJF.04720.

Zajícová, K., & Chuman, T. (2019). Application of ground penetrating radar methods in soil studies: A review. *Geoderma,* **343**(211):116-129. https://doi.org/10.1016/J.GEODERMA.2019.02.024.

Zhang, J., Guo, W., Zhou, B., & Okin, G. (2021). Drone-Based Remote Sensing for Research on Wind Erosion in Drylands: Possible Applications. *Remote Sensing,* **13**:(2):283. https://doi.org/10.3390/rs13020283.

Zsolt, S., Tállai, M., Kincses, I., László, Z., Kátai, J., & Vágó, I. (2020). Effect of various soil cultivation methods on some microbial soil properties. *DRC Sustainable Future*, **1**(1):14-20. https://doi.org/10.37281/drcsf/1.1.3.