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REVIEW

# Impact of mechanical compaction on crop growth and sustainable agriculture

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KEYWORDS

Soil compaction, mechanical compaction, bio-tillage, agricultural production

## HIGHLIGHTS

- Soil compaction due to intensive agriculture threatens soil quality, crop growth, and food security.
- Study explores the factors contributing to compaction, aiming to develop effective mitigation methods.
- The goal is to reduce soil compaction, improve soil quality, boost crop yield and enhance agricultural sustainability.
- Innovations needed to address soil compaction in modern agriculture.

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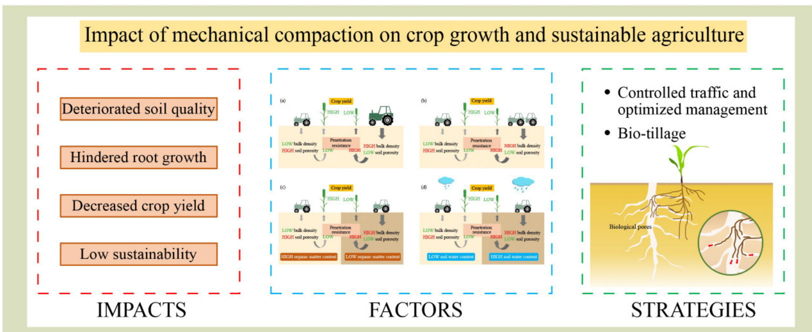
## GRAPHICAL ABSTRACT




## ABSTRACT

With the development of agricultural technology to meet the growing demands of a rapidly increasing population and economic development, intensive agriculture practices have been widely adopted globally. However, this intensification has resulted in adverse consequences for soil structure due to intensified farming activities and increased usage of heavy farm machinery. Of particular concern is soil compaction, which leads to the degradation of physical, chemical and biological properties of the soil. Soil compaction negatively impacts crop growth, reduces yields and poses a significant threat to food security and the overall sustainability of agricultural systems. Recognizing these challenges, this review aims to deepen understanding of the factors contributing to soil compaction and to develop effective mitigation strategies. By doing so, it is intended to attenuate the adverse impacts of soil compaction, improve soil structure, increase crop yield and ultimately enhance the sustainability of agricultural practices.



## 1 Introduction

Soil compaction, defined by an increase in soil bulk density or a decrease in porosity due to external or internal pressures, significantly undermines the integrity of soil structure and diminishes pore connectivity[1–3]. Consequently, it restricts the elongation of crop roots by increasing mechanical resistance during growth, leading to the development of shallower root systems[4]. Also, compaction impairs soil moisture, nutrient and air movement, exacerbating surface runoff and loss of soil carbon and nitrogen, these consequences further reduce nutrient availability and adversely impact crop yield[3,5,6]. Soil compaction has reached a critical level globally, with the Food and Agriculture Organization of the United Nations reporting a significant degradation of soil physical, chemical and biological properties[7]. The adverse effects of compaction stress on crop growth contribute to reduced yields and pose a substantial threat to global food security and the long-term sustainability of agriculture. Current estimates indicate that about 68 Mha of farmland worldwide are affected by soil compaction, highlighting the widespread nature of this problem[8]. China, as a prominent agricultural nation, also faces the challenge of soil compaction. The National Farmland Quality Monitoring Report (2016) revealed that 66% of the evaluated sites had a plow layer thickness of less than 20 cm and 26% exceeded the optimal soil bulk density range for crop growth, exacerbating soil compaction concerns. Thus, comprehensive measures to address soil compaction and restore the quality of agricultural soils in China and globally are extremely important.

The widespread adoption of intensive farming practices in modern agriculture is driven by the urgent need to meet the demands of a rapidly growing population and evolving economic development. This has led to strategies such as shortened crop growth cycles, seasonal monoculture systems and the extensive use of heavy machinery throughout agricultural processes. Notably, the extensive reliance on heavy wheel machinery is observed across various farming activities, spanning from seeding to harvesting. The application of heavy machinery could exert great pressure on soil, thus increase bulk density and reduce soil porosity, causing the problem of mechanical compaction. Research indicates that mechanical compaction is influenced by several factors, including machine weight, frequency of machinery passes, tillage methods, soil texture, soil organic matter, and soil moisture conditions[3,9,10]. These factors exacerbate the negative impacts of mechanical compaction on soil physical, chemical and biological properties.

Additionally, tillage practices in agricultural production also contribute to soil compaction. This phenomenon, characterized by spatial and temporal variability, is influenced by tillage operations. While these operations can effectively loosen surface soil and create larger pores, they may simultaneously lead to a compacted layer beneath the tilled horizon, and reduce the depth of the tillage layer over time[11]. Bio-tillage, using plant roots as a tillage tool, show great potential in improving soil quality, and it is considered as a promising method to alleviate soil compaction stress.

Despite the recognition of various management practices contributing to soil compaction, existing research often isolates the impact of individual factors, leaving a comprehensive understanding of the primary causes of soil compaction unexplored. Therefore, this review aims to identify critical factors contributing to soil compaction and to propose effective mitigation strategies. We will thoroughly summarize the factors leading to soil compaction and evaluate the impact of mechanical compaction on agricultural production, with a particular focus on the potential of bio-tillage methods in mitigating compaction stress.

## 2 The impact of mechanical compaction on crop growth

The significant advancements in agricultural mechanization have brought significant changes to agricultural production practices. While the use of high-power tractors and heavy machinery has undoubtedly enhanced production methods, it has also inadvertently given rise to the prevalent issue of soil compaction[4]. Mechanical compaction adversely affects soil quality, crop production and environmental conditions across different climates, posing a substantial threat to future food security and agricultural sustainability.

Mechanical compaction poses significant challenges to nutrient uptake in crops by affecting soil penetration resistance and pore distribution, which are crucial soil factors governing root growth[12]. Increased bulk density and reduced soil pore size hinder root penetration[12,13], limit root distribution and ultimately lead to slower root growth[14,15]. This impedes access to water and essential nutrients in compacted soils, leading to diminished nitrogen, phosphorus and potassium absorption rates[16,17]. The implications of mechanical compaction on nutrient uptake extend to greenhouse gas emissions, by influencing the physical and chemical conditions of greenhouse gas production[18]. For example, soil compaction may alter oxygen conditions and affect denitrification processes, contributing to $N_2O$ emissions[19]. Compaction severely affects soil gas diffusivity, which determined by air-filled porosity and tortuosity, and thus increasing $N_2O$ emissions[20]. Research indicates that topsoil compaction can augment $N_2O$ emissions by 1.3 to 42 times across various sites and land uses[20]. Also, the impact of soil compaction on gas diffusion also limits root growth by reducing air-filled pores and hindering ethylene diffusion, triggering a hormonal response that restricts root development[21].

Empirical studies have demonstrated that mechanical compaction significantly decreases nutrient absorption in crops. For example, in wheat, nitrogen absorption is reduced by 12% to 35%, phosphorus absorption by 17% to 27%, and potassium absorption by 24% as a result of mechanical compaction[22]. Similarly, sorghum had decreased nitrogen, phosphorus and potassium absorption rates of 23%, 16% and 12%, respectively, under the influence of compaction stress [22]. This reduced nutrient absorption exacerbates nitrogen volatilization and leaching, diminishing nitrogen use efficiency within agricultural systems[8,23,24].

Mechanical compaction significantly restricts crop growth, disrupts the biomass allocation between above and below ground components[13,25], and ultimately resulting in decreased crop yield formation. It has been observed that mechanical compaction restricts maize root length, dry root mass, shoot elongation, and leaf area index by 29%, 38%, 27%, and 68%, respectively[26]. Ishaq et al.[27] reported 38% and 12% reduction in grain and straw yields of wheat due to compaction treatment. Study of Canarache et al.[28] demonstrated that in most locations of their experiment, grain yield of maize linearly decreased by 13 $kg \cdot ha^{-1}$ for each 1 $kg \cdot m^{-3}$ increase in bulk density. Soil compaction degrades soil properties, hinders root growth, limits nutrient absorption, and significantly reduces crop yields, thus posing a substantial challenge to agricultural productivity. Consequently, the development of effective methods to mitigate the adverse impacts of soil compaction, particularly with the increasing use of agricultural machinery in intensive agriculture, is imperative.

## 3 Factors contributing to mechanical compaction in intensive agricultural systems

Soil compaction is influenced by a combination of natural processes and human activities. Natural factors include dense soil layer, mineral composition, soil texture, alternating dry and wet periods, and soil shrinkage due to desiccation[8,29]. Management factors, such as intensified planting practices, inappropriate soil management, the use of heavy machinery and operations on wet soils significantly contribute to soil compaction[3,8,10]. In agricultural management, the impact of management factors on soil compaction is substantial, but it also offers greater potential for mitigation. This part examines management factors influencing soil compaction, with a focus on mechanical compaction contributors including machine weight, frequency of passes, soil texture, soil organic matter, and moisture content. Additionally, the effects of intensive agricultural practices, including tillage methods and excessive fertilizer application, on soil compaction are also examined.

Intensive agriculture, characterized by long-term uniform soil tillage and the use of machinery, has contributed to the emergence of severe soil compaction[10]. Of the various factors contributing to this issue, mechanical compaction has emerged as a crucial driver, posing a substantial threat to the sustainability of agricultural systems[6]. Mechanical compaction, resulting from field traffic, increases soil penetration resistance and bulk density[6,30], reducing soil porosity[31,32], hydraulic conductivity and infiltration rate[30,33]. The vertical pressure and lateral shear forces associated with mechanical compaction contribute to the reduction of large soil pores and a subsequent decline in pore connectivity[9,34,35]. Specifically, study found that the use of heavy tractors (8 Mg) during multiple field operations severely compromises soil structure below 50 cm, leading to reduced soil permeability, air-filled porosity, and gas diffusivity[2]. Canillas and Salokhe[36] report that the first tire pass increases average soil bulk density by about 7% and cone index by 6% compared to zero passes, while bulk density and cone index continued to increase with the increasing number of passes. Blanco-Canqui et al.[37] found that compaction led to a 19% increase in soil bulk density (from 1.16 to 1.38 $g \cdot cm^{-3}$) at the depth of 0–7.5 cm, a 74% increase in cone index (from 1.78 to 3.10 MPa) and a 153% rise in aggregate tensile strength (from 377 to 955 kPa). Meta-analysis conducted by Obour and Ugarte[6] showed that traffic-induced compaction increases penetration resistance by 99%, 94%, and 41% in the medium-, coarse-, and fine-textured soils on average. These findings highlight the detrimental effects of mechanical compaction on soil quality, emphasizing the urgent need for sustainable soil management practices to mitigate compaction stress and ensure long-term agricultural productivity and environmental stability.

Over recent decades, the severity and depth of compaction stress have increased significantly due to the larger size and weight of agricultural machinery. Machinery specifications, including type and weight, tire pressure and cumulative stress from repeated wheel passes significantly affect the degree of soil compaction[3]. One study[38] found that shifting from lighter to heavier equipment can lead to a decrease in soybean yield from 250 to 460 $kg \cdot ha^{-1}$. Also, through soil transfer functions, Keller et al.[4] suggested that the historical growth in agricultural machinery weight intensifies soil stress levels, adversely impacting soil functions. Other parameters of agricultural machinery also contribute to mechanical compaction, a study conducted on silty clay loam soils found that low-pressure tires resulted in the observation of more macropores compared to standard tires[39]. Notably, multiple machinery passes transfer of compaction stress deeper into the soil, exacerbating the negative impacts of soil compaction (Fig. 1). Patel and Mani[40] demonstrated that soil penetration resistance increases by 21% as the number of passes increases from one to six. Other studies[2,41] indicated that soil compaction resulting from multiple passes under light loads can be even more severe than a single compaction event under high loads. Clearly, as agricultural mechanization continues to advance, mechanical compaction has emerged as a primary driver of soil degradation.

The effect of mechanical compaction on soil properties can vary depending on soil type and site characteristics with different soil texture, organic matter content and moisture conditions (Fig. 1). Arvidsson[42] examined the influence of soil texture on bulk density in field compression experiments, indicated the tendency that following three passes by a tractor, an increase in clay and silt content corresponded with a reduction in bulk density, while bulk density increased with the increase of sand content. Brus and Van Den Akker[43] suggested that soils containing less than 17.5% clay content had increased susceptibility to soil compaction. Also, a meta-analysis conducted by Obour and Ugarte[6] demonstrated that soil compaction led to an increase in soil mechanical strength, with a more pronounced effect observed in medium- and coarse-textured soils, particularly in the topsoil (0–30 cm). Although soils with high clay content had lower susceptibility to soil compaction, they may impose more pronounced inhibitory effects on root systems under the equivalent bulk density level, as the threshold of bulk density to restrict root growth for clayey soils (1.4 $g \cdot cm^{-3}$) is lower than sandy soils (1.8 $g \cdot cm^{-3}$)[44]. Soil organic matter contributes substantively to soil structural stability[45], and it has been demonstrated to enhance the resilience of soil to mechanical stress[46]. Arvidsson[42] found that organic matter decreased bulk density and degree of compactness, improved porosity and air content in field experiments. By measuring the maximum bulk density in the Proctor test, Díaz-Zorita and Grosso[47] concluded that high soil organic carbon level reduces the susceptibility of soils to compaction. However, the effectiveness of incorporating

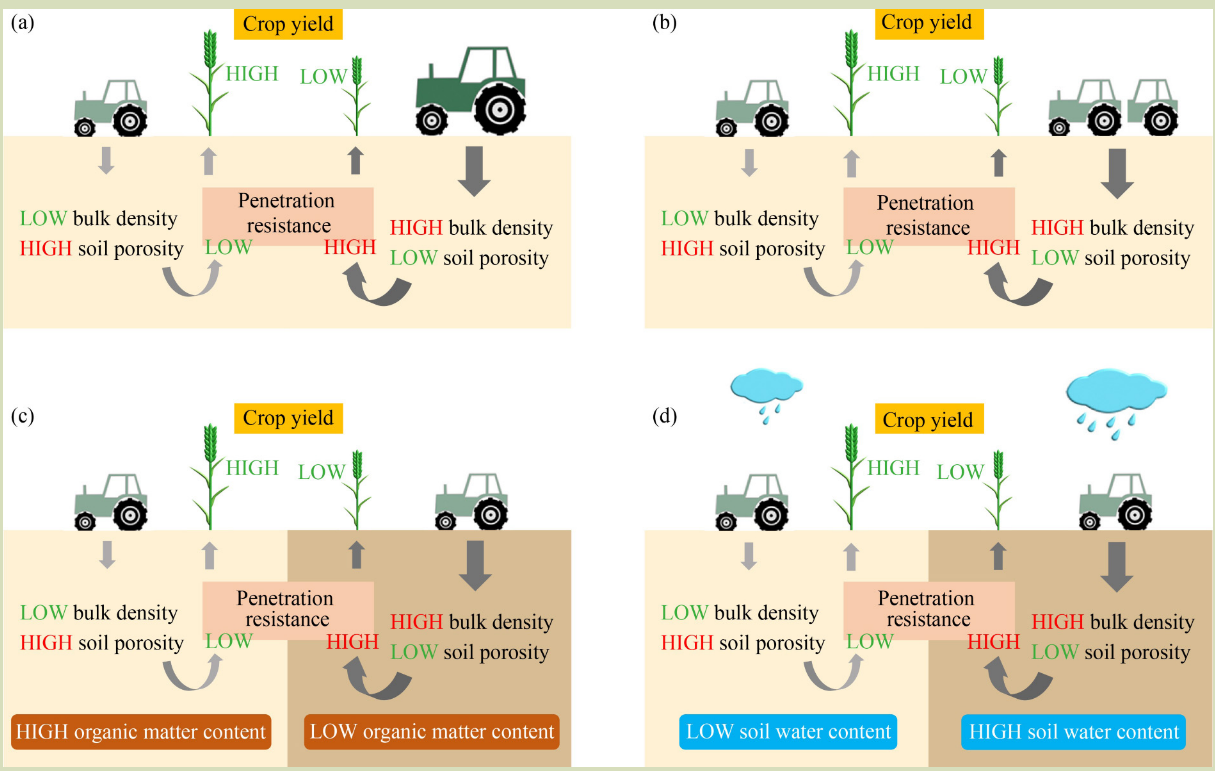



**Fig. 1** Factors affecting mechanical compaction and their effects on soil properties and crop yield: (a) machine weight, (b) frequency of passes, (c) soil organic matter content, and (d) soil water content.

organic matter into soil to alleviate soil compaction may vary depending on the type of organic matter and soil conditions[48]. Generally, compaction impacts tend to be more severe in drier soils[49]. Nevertheless, soil moisture content heavily influences soil strength and determines susceptibility of soil to mechanical compaction, high soil moisture content decreases the load support capacity of the soil, working on poorly drained field increase the risk of compaction[9,10,50].

In intensive agriculture, rotary tillage has been widely adopted, which can significantly induce soil compaction, leading to structural degradation and the formation of a plow pan that impedes root growth of crops[51,52]. Study showed that after 5 years of rotary tillage, bulk density increased by 4.4% and 2.2% in the 0–15 and 15–30 cm depths, respectively[53]. While mechanical loosening methods target plow pan disruption, they can also lead to secondary compaction following repeated mechanical traffic and rainfall[50,54]. In recent years, no tillage farming has been recognized as effective for reducing bulk density and enhancing soil quality[55]. However, the reduction in disturbance with no tillage practices can lead to compaction of the surface soil, Blanco-Canqui and Ruis[56] reviewed 62 studies on soil bulk density and 34 studies on penetration resistance comparing conventional tillage versus no tillage practices, observing that no tillage increased bulk density by 0.6% to 42% in about 39% of cases, and increased penetration resistance by 27% to 99% in 50% of cases, both mostly occurred in the topsoil. It is important to note that the effects of no tillage on soil compaction appear to be complex and can vary across different locations, as there are still many cases indicated that no tillage does not result in an elevation of bulk density and penetration resistance compared with conventional tillage[56]. Also, meta-analysis conducted by Yang et al.[49] suggested that no tillage leads to an increase in penetration resistance in the topsoil, but not in the subsoil. Nevertheless, the negative impacts of no tillage on soil compaction should not be ignored, no tillage under specific soil types may hinder root growth and limit crop yield. For example, Nunes et al.[57] reported that in clayey soil, subsoil compaction under no tillage seriously inhibited root growth of maize to depth. Despite the potential for these tillage methods to raise the risk of soil compaction, they can be adopted and adapted for use in intensive agriculture. In addition, fertilizer application, as a critical component of agricultural management, profoundly affects crop yields, soil fertility and its sustainable use. Excessive fertilizer application remains a concern, as it not only fails to increase crop yields but also leads to agricultural soil pollution and poor soil structure[58]. Thus, well-planned fertilizer application not only reduce costs, improve soil quality and productivity, but also mitigate fertilizer application pollution and enhance soil structure. Consequently, while intensive agriculture enhances agricultural production efficiency, it simultaneously raises the risk of soil compaction.

Based on the understanding of the factors influencing soil compaction in modern agriculture, it is feasible to implement measures to mitigate the adverse effects of soil compaction on agricultural production. These include implementing controlled traffic, minimizing the number of passes, adopting machinery with low-pressure tires and low load, operating machinery under optimal soil moisture conditions, and increasing soil organic matter content to reduce susceptibility of soil to mechanical compaction. In addition, innovative approaches are needed to address the growing risk of soil compaction and advance sustainable agricultural development.

## 4 The impact of bio-tillage on mechanical compaction

In contemporary agriculture, strategies such as deep loosening, plowing, organic fertilizer application, crop straw incorporation, and biochar addition have been used to mitigate soil compaction. However, conventional tillage methods often exacerbate soil compaction and soil erosion risks, while the effectiveness of conservation tillage in alleviating compaction continues to be debated[59]. Bio-tillage, using the root systems of crops as tillage tools to improve soil quality, emerges as a potentially effective method for alleviating compaction stress[59,60]. Using deep-rooted cover crops to penetrate compacted soils and improve soil structure for subsequent crops is a typical case of bio-tillage[61]. Different from the traditional concept of cover crops, bio-tillage emphasizes the functions of crop roots in creating biological pores and enhancing soil structure to improve the growth of subsequent crops. In early days, understanding of cover crops was limited to the advantages of reducing soil erosions and preventing losses of nutrients via leaching and runoff[62], until a few agronomists raised the concept of using plant roots as tillage tools and precipitated more researchers to start the studies of bio-tillage with cover crops[59,63].

Under bio-tillage management, root systems are pivotal to improving the structure of compacted soil through particle rearrangement during elongation[44]. Bio-tillage can improve soil physical quality, particularly under no tillage conditions. For example, in a 5-year no tillage system, planting hairy vetch (*Vicia villosa*) and rye (*Secale cereale*) resulted in decreased soil bulk density and penetration resistance, while increasing soil available water content, total porosity and water aggregate stability[64]. Bio-tillage improves soil physical properties, including pore geometries, aggregate stability, air permeability, and penetration resistance through the root system[65–67]. Study in sandy loam soil indicated that planting fodder radish (*Raphanus sativus*) encouraged the formation of continuous macropores, facilitating water and air movement within the soil and mitigating the adverse effects of compacted plow pan[66]. An X-ray CT study conducted by Cercioglu et al.[68] have observed that planting deep-rooted crops increased the number of macropores and improved pore parameters. Also, bio-tillage with cover crops indirectly improves soil properties by increasing soil organic matter content[69]. Study showed that planting cover crops can lead to an increase in soil organic matter content, and may reduce bulk density through promoting soil aggregation[67].

Additionally, biological pores formed through bio-tillage promote the growth of subsequent crops (Fig. 2). During plant growth, roots create channels that subsequently decompose, leaving behind biological pores that facilitate the growth of subsequent crops[70,71]. Roots tend to preferentially grow within biological pores and use it as pathways to explore deeper soil, which have been proved by field experiments[72–75] and model experiments with artificial pores[76–78]. In compacted soil column systems, Colombi et al.[78] used X-ray CT to observe a portion of wheat, soybean and maize root systems either directly penetrating or growing in artificial pores. Characterized by great penetration resistance, plow pan caused by repeated tillage operations and traffic with heavy machinery could seriously restrict root growth[79]. The increases in penetration resistance with depth confine the root system to existing structural pores[80]. Biological pores created by decomposition of previous crop roots provide subsequent roots with low resistance pathways to grow through the compacted plow pan[81], and also enable crop roots to access nutrients and moisture from deeper soil layers[70,82]. Also, biological pore walls often contain higher nutrient concentrations due to root decomposition, providing a favorable environment for nutrient uptake by crops[75,83]. Thus, by forming biological pores, cover crop root systems function as effective cultivation tools, thereby enhancing soil structure.

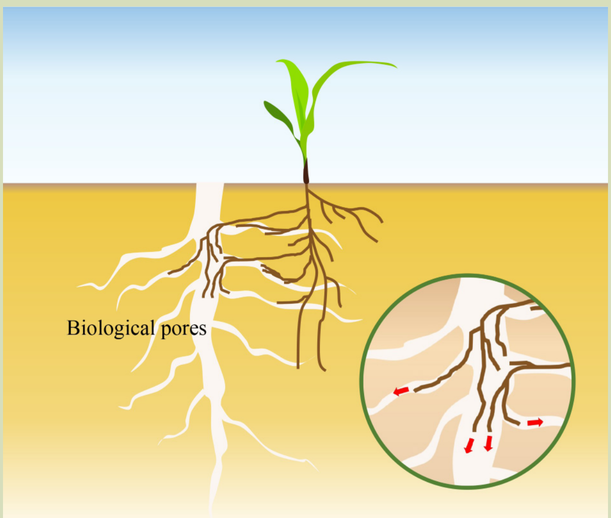



**Fig. 2** Bio-tillage created biological pores for subsequent crop.

At present, the development and application of bio-tillage focus on selecting and breeding crop species with different root architectures, to shape targeted soil pore architecture that benefit subsequent crops. Studies highlight the substantial variability in the ability of the roots of different plant species to alleviate soil compaction. Taproot crops generally had superior penetration capabilities in compacted soil compared to fibrous-root crops. For example, Chen and Weil[60] found that tap-rooted forage radish and rapeseed (*Brassica napus*) penetrated compacted soil more effectively than fibrous-rooted rye. Similarly, Pulido-Moncada et al.[84] compared the potential of various cover crops to restore compacted soil and found larger macropore density, branches number, pores quantity for chicory (*Cichorium intybus*) and lucerne (*Medicago sativa*) compared to barley (*Hordeum vulgare*) in the compacted soil layer. Based on the variability of different root systems to regulate soil structure, selecting specific crop combinations in tillage practices is a promising method to deal with different soil compaction types in different regions. In general, bio-tillage has potential for promoting sustainable agricultural development, offering a viable alternative to current tillage practices.

## 5 Future perspective

Soil compaction represents a multifaceted phenomenon, impacted by an array of variables, including soil type, crop species, climatic conditions and agricultural machinery practices. The employment of heavy machinery alongside suboptimal soil management practices exerts excessive external pressures, resulting in soil compaction. This leads to reduced soil porosity, impaired pore connectivity, and disrupted moisture and nutrient circulation within the soil matrix. The consequences of soil compaction extend beyond reduced porosity to degraded soil structure, impeded crop growth and diminished yields. Also, the broader environmental implications of soil compaction are significant, encompassing increased surface water runoff, escalated soil erosion, enhanced greenhouse gas emissions, eutrophication, reduced groundwater recharge and biodiversity loss.

In the future, the exploration of plant root systems as a strategy to counteract soil compaction and improve soil health holds promising potential. The strategic selection of plants with specific root phenotypes, based on their morphological and exudate characteristics, offers the potential to re-engineer soil pore networks and establishs a root-zone conducive to optimal soil-plant interactions. This approach seeks to harmonize soil structure with its functional dynamics. A deep understanding of how to manipulate root-zone soil structure will be pivotal in mitigating the impacts of soil compaction. Such advancements will not only enhance crop yields but also contribute to long-term food security in alignment with environmental sustainability objectives. This future-focused approach underscores the need for integrated soil management strategies that encompass both physical and biological aspects of soil health.

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## Compliance with ethics guidelines

Zijian Long, Yifei Wang, Baoru Sun, Xiaoyan Tang, and Kemo Jin declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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