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Bio-pores and crop growth:

Understanding the complexities of bio-tillage with cover crops

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Bio-tillage utilizes cover crops, and offers a sustainable alternative to traditional tillage methods by improving soil structure and boosting crop productivity. This approach harnesses the deep root systems of selected cover crops to create bio-pores, enhancing the movement of air and water through the soil and reducing both compaction and erosion. Studies show that the timing of cover crop planting and termination is critical in fully realizing their benefits. In addition to suppressing weeds and increasing soil organic carbon, bio-tillage can contribute to long-term soil health. However, challenges such as the potential negative effects of large bio-pores on root growth and nutrient uptake need careful attention. Despite these challenges, bio-tillage holds significant promise for advancing sustainable agricultural practices.

Keywords: Bio-pores, Bio-tillage, Cover crops, Soil compaction, Sustainable agriculture

TILLAGE has been a foundational practice in agriculture, evolving alongside human civilization from nomadic hunting and gathering to settled farming. For thousands of years, tillage has been crucial for agricultural productivity, offering benefits such as improved soil structure, weed suppression, and enhanced nutrient availability through the incorporation of organic matter. However, it also possesses significant challenges, particularly regarding soil health and environmental sustainability. Conventional tillage, often conducted with heavy machinery, leads to soil compaction. Besides, activities such as planting, spraying, harvesting, and even walking across fields also compress the soil. This compaction occurs when the mineral components of the soil are pressed together, reducing the air and water spaces within it, ultimately restricting root growth and crop yields. Additionally, conventional tillage can degrade soil fertility, as the loosening of soil accelerates the oxidation of soil organic matter which leads to increased soil erosion, particularly during heavy rainfall or windy conditions. The Dust Bowl of the 1930s exemplified the consequences of unsustainable tillage practices, resulting in widespread soil degradation across the American Midwest. In response to these challenges, conservation tillage techniques have gained traction. Methods such as minimum tillage, zero tillage/no-till, and strip tillage aim to reduce soil disturbance and maintain soil cover, which can mitigate erosion and enhance soil organic carbon levels. However, in a no-till system, we depend on the soil's organic matter to act like a spring. This allows the mineral particles to compress while maintaining their structure, enabling them to rebound to their original position once the force is removed. But when the pressure exerted on the soil exceeds a certain threshold, compaction can still occur, even in a no-till scenario. Alternative strategies, such as strip or chisel tillage, have been proposed to address the compaction issues of no-till practices, but they can also conflict with the principles of conservation agriculture and hinder broader adoption. Therefore, developing innovative approaches that optimize conservation agriculture is essential to enhance soil productivity and sustainability.

This is where bio-tillage can help, as it plays a vital role in enhancing soil structure and promoting optimal conditions for crop growth by leveraging the natural abilities of plant roots. The strategic use of specific cover crops, particularly those with thick, deep roots grown during fallow periods, serves as a biological substitute for mechanical tillage. These plants improve soil porosity and reduce compaction, leading to healthier root environments for subsequent crops. Cover crops such as lucerne (alfalfa), chicory, forage radish, forage cabbage, oilseed rape, kale, turnip, vetiver, and tall fescue are particularly effective in this regard.

Crop roots growing in a bio-pore

Deep-rooted crops

(*Source*: Zhang and Peng 2021)

For instance, forage radish is well-known for its deep taproots that penetrate compacted layers of soil, breaking up hardpan and creating bio-pores that enhance water infiltration and root penetration for future crops. Similarly, chicory, another taproot species, excels at growing through dense soil layers, thereby improving subsoil aeration and water movement. When comparing different root systems, taproot species like lucerne and forage radish tend to be more efficient in bio-tillage since they can drill deep into the soil, breaking through compacted layers. In contrast, species with fibrous root systems, such as grasses, have roots that spread horizontally near the surface. While these fibrous roots are excellent for enhancing topsoil structure and reducing erosion, they are less effective at penetrating deeper soil layers compared to taproot species. Furthermore, perennial species, such as lucerne and vetiver, often perform better in bio-tillage than annual species because they have more time to develop extensive root systems, leading to greater long-term improvements in soil structure. Although annual species like radish and turnip are effective in the short term, they typically decompose faster, leaving behind bio-pores that are beneficial but not as enduring.

Cover crops effective for bio-tillage are widely recognized for enhancing soil physical properties by creating bio-pores that improve soil aeration, water transport, and root penetration. These bio-pores allow for preferential movement of air and water, reducing surface runoff and erosion while providing pathways for roots to access nutrients and oxygen in the soil. Research indicates that growing perennial leguminous crops, such as stylo, for two years can significantly improve compacted soil layers by forming macropores. This improvement is particularly evident in no-till systems, where bio-pores can persist longer without disturbance compared to conventional tillage. A meta-analysis found that in no-till systems, infiltration rate increased by 44.6% with cover crops, while conventional tillage showed only a 13% increase. Furthermore,

Table 1. Effects of bio-tillage with cover crops on soil physical properties and root characteristics

Study area	Cover crops	Soil type	Findings
Nanjing (China)	Alfalfa, oilseed rape, radish + hairy vetch	Vertisols (Black soil)	↑ 173.2% (2018), 35.6% (2019) root biomass density of maize ↑ 50.9% (2018), 51.8% (2019) root length density of maize ↓ Soil water content
Hubei (China)	Two oilseed rapes, lucerne, one-year-old vetiver grass, 6-year-old vetiver grass	Ultisols (Red soil)	↑ Root length density, root diameter, fine roots %, macroaggregates % (highest in case of vetiver grass) ↓ Soil bulk density
Hubei (China)	Rape, deep rape, lucerne, vetiver grass	Clayey red soil	↑ Penetrating ability, root length density, root diameter (highest in case of vetiver grass)
Tjele (Denmark)	Lupin, chicory, lucerne, tall fescue, perun, cocksfoot (plus spring barley as reference crop)	Sandy loam	↑ Gas, water transport on the compacted subsoil layer (in case of lupin, chicory, lucerne) ↑ Unsaturated hydraulic conductivity (2nd year of evaluation in case of chicory and lucerne)

studies highlight that cover crops can enhance near-surface hydraulic properties and reduce soil compaction susceptibility, thereby improving the effectiveness of no-till farming practices. Incorporating cover crops not only mitigates the risks associated with excessive soil compaction but also contributes to overall soil health and productivity, making them a valuable tool in sustainable agricultural practices.

Bio-tillage presents a sustainable alternative to conventional and conservation tillage, significantly reducing soil erosion, fuel, and labour costs. While no-till practices also offer these benefits, their effectiveness often hinges on herbicide-based weed control. In contrast, bio-tillage can suppress weeds through the mulch created by cover crop residues, providing an effective level of weed management comparable to chemical methods. Research indicates that bio-tillage has a lasting impact on crop yields, unlike traditional plough or chisel tillage, which may yield short-term benefits. For instance, while chisel tillage can initially boost soybean yields, these gains are typically temporary. In contrast, cover crops have been shown to produce equal or even higher soybean yield over the medium to long term compared to occasional chisel tilling. Therefore, there is considerable potential for integrating bio-tillage with no-till practices as a viable alternative to conventional tillage for promoting sustainable agriculture.

The ultimate impact of bio-tillage on crop yields is influenced by the selection of suitable cover crop species, and the timing and methods used for planting and terminating these crops. Timely planting is crucial for achieving high root biomass, which aids in soil penetration. To extend the growing period, cover crops can be sown by broadcasting or aerial seeding slightly before the harvest of cash crops, provided soil moisture conditions. This approach enables rapid growth after harvest and ensures good establishment before winter. For bio-tillage, the optimal termination time for cover crops balances the need for maximum root development with the planting schedule of subsequent crops. While non-selective herbicides are commonly used to terminate cover crops in no-till practices, their frequent application can lead to herbicide-resistant weeds and may negatively affect soil biodiversity and groundwater quality. Therefore, it is recommended to eliminate non-selective herbicides entirely and instead use mechanical control methods that do not disturb the soil. Mowing is a common and effective mechanical method for terminating cover crops and shredding residue into surface mulch. However, small pieces of residue from mowing tend to be unevenly distributed and decompose quickly, which can diminish their benefits for weed suppression and soil protection. An alternative to mowing is the roller-crimper, which flattens biomass to create a thick, uniform mulch layer. This method provides longer-lasting soil coverage, enhancing weed suppression, moisture retention, and soil conservation while requiring less energy. The effectiveness of the roller-crimper depends on the timing of its application. It is most effective when used at the late bloom or early pod set stage of cover crops.

Additionally, climate conditions and management practices also play a crucial role. In regions with low precipitation, cover crops may negatively impact the yields of succeeding crops by consuming significant amounts of stored soil water. Conversely, in areas with higher rainfall, bio-tillage with cover crops can lead to increased crop yields. Additionally, the benefits of bio-tillage tend to improve over time, as the cumulative effects of cover crop planting become more pronounced in subsequent years.

Soil bio-pores created by bio-tillage may not always benefit crop growth. The grain yield decreases when bio-pore diameters exceed 0.8 mm, according to a computer simulation study. Additionally, a pot experiment demonstrated that large artificial bio-pores with a diameter of 3.2 mm create an unfavorable environment for root growth due to poor soil-root contact. In dense soils, roots may clump inside these large bio-pores, which can inhibit water and nutrient uptake. Furthermore, surface-applied fertilizers can be transported directly to groundwater through preferential flows in large bio-pores, potentially beyond the reach of plant roots. To address these limitations associated with bio-tillage, effective management practices are essential.

SUMMARY

While bio-tillage offers great potential for sustainable agriculture, several knowledge gaps need to be addressed before widespread adoption. These include understanding ideal bio-pore architecture for root growth, identifying more effective bio-tillage cover crop species, and developing effective field management practices for bio-tillage. Some key considerations for advancing bio-tillage research and adoption include determining the optimal size, density and continuity of bio-pores for enhancing root growth and crop yields; screening and breeding cover crop cultivars with traits like deep, thick taproots and rapid decomposition for improved bio-tillage efficacy; investigating long-term impacts of bio-tillage on soil health indicators like organic matter, nutrient cycling, and biological activity; developing integrated weed management strategies that minimize reliance on herbicides in bio-tillage systems; adapting bio-tillage practices to different climates, soil types and cropping systems through on-farm research and demonstration. With continued research and innovation, bio-tillage can become a cornerstone of sustainable agriculture, enhancing soil health while reducing inputs and environmental impacts. However, a system approach is needed that considers cover crop selection, planting and termination timing, soil-crop-climate interactions, and economic factors.

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