Root-soil-microbiome management is key to the success of Regenerative Agriculture

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Building soil health and manipulating the soil microbiome, alongside targeted plant breeding that prioritises preferential root architectural development, hold the key to the future success of Regenerative Agriculture. Greater integration is needed between disciplines focused on the rhizosphere scale with plant, microbiome and soil scientists working at the wider farm scale.

The management of plant and soil systems for crop production has never been as challenging. Farmers are having to contend with a rapidly changing climate and strong governmental pressures to increase production to satisfy expanding populations. This goal must be achieved while the pace of global urbanisation accelerates, combined with increasing demands to reduce agrochemical interventions and intensive operations which have promoted soil degradation. Against this backdrop, there is renewed interest in conservation-focused farming practices, commonly called 'regenerative agriculture', defined as an alternative means of producing food with lower—or even net positive—environmental and/or social impacts[1]. To achieve this demands an interdisciplinary and collaborative research agenda with a specific focus on the management of the root-soil-microbiome interface. Here, we highlight future research priorities that build on current best practice and reveal new areas for translational knowledge exchange.

Conflicts of delivering healthy soil

The principles of sustainable soil management associated with regenerative agriculture primarily comprise reducing soil disturbance, building carbon stocks through soil amendments and priming the soil via crop rotation (Figure 1a). In contrast, large-scale cultivation systems have historically prioritised financial gain. Encouragingly, regenerativebased practices that prioritise 'soil health' are now embedded in most government and agri-industry future land-use plans. While exemplars such as utilising cover crops between cash crops have been used extensively, adopting other practices such as reducing tillage has been slower in some regions of the world due to uncertainties around potential yield decline, cost of equipment and concerns that benefits for soil and the wider environment have been oversold.

Relatively few studies have compared long-term differences between tilled and no-till soils while adequately controlling potentially confounding variables such as differences in soil type, underlying geology, climate etc. Recent research has demonstrated no-till systems could lead to a reduction in global warming potential of c. 30% (primarily attributed to an increased soil pore connectivity driven by undisturbed soil fauna), with additional benefits for carbon sequestration, which further developed over a time scale > 5 years[2]. Despite this, alternative research has suggested the benefits for soil organic carbon (SOC) under reduced tillage are exaggerated[3]. A study of 1061 pairs of tilled versus no-till soils and concluded SOC only increased in the 0-10 cm soil layers under no-till and decreased at depth, leading to an overall reduction[4]. However, this has since been rebutted in another study after analysis of the same dataset which found no-till led to preferential SOC storage[5], highlighting the conjecture in this area.

Opportunities for plant breeding

Rapid changes in soil management practices adopted by farmers such as no-till represent a major challenge for crop breeders, given the urgent need to select new varieties better adapted for 'regenerative agriculture' approaches and a changing climate. For example, reducing tillage results in a harder topsoil, especially near the surface, though this may dissipate over time[2].

A future hope is that breeders could select new crop varieties adapted to deal with enhanced compaction resistance and thus counteract harder soil. Selecting crops with roots exhibiting improved compaction resistance is a very labour-intensive process given the challenges of field root phenotyping[6]. However, the recent identification that the plant hormone ethylene controls root responses to hard soil opens new opportunities to rapidly select compactionresistant crops[7]; especially important as soil compaction is widespread. To date, root growth sensitivity to ethylene appears to be a good proxy for sensitivity to compaction stress in important cereal crops such as maize[6] and rice[7]. This provides breeders with a new, high-throughput phenotyping method to rapidly select new crop varieties with improved compaction resistance, likely to be a key requirement for growth in the soils of the future.

Climate change is having an increasing impact on soil moisture. As topsoil dries, a vertical gradient in water availability forms. Roots experiencing water deficit increase their angle to better access deeper soil profiles[8]. Reduced moisture in the topsoil leads to suppression of lateral and crown root growth in many crop species. A crop ideotype with fewer but longer laterals could be more efficient during water stress, ensuring valuable plant resources are used to extend the root system into the subsoil. Similarly, a crop ideotype with a steeper root angle would support water acquisition in subsoils, especially if there were more biopores (Figure 1b&c). Several regulatory genes have been identified in major cereal crops that control root angle[8]. However, root colonization of subsoils is often challenging due to increased mechanical impedance created by overburden pressure. Cereal roots, such as wheat, growing at depth (e.g. >50 cm) are predominantly found in soil biopores[9] (Figure 1b). Maize and soybean roots can preferentially grow towards vertical biopores using an adaptive process called *trematotropism*[10]. Discovering the mechanism of how roots respond to overburden pressure is crucial for future selection of deeper rooting varieties adapting to soils under climate change.

A steeper root angle also promises to improve the sustainability of crops. For example, nitrate is a challenge for roots to capture due to its high mobility, causing it to leach deeper into the soil profile. Breeders could exploit steeper root angle for more efficient capture of nitrate (Figure 1b). Alternatively, plants that proliferate fine roots in the topsoil can reduce nitrate losses via the establishment of micropores where water/solute retention is enhanced[11]. Conversely, phosphate is a highly immobile macronutrient, often concentrated in the topsoil. To improve the capture of phosphate (and reduce the need to apply this non-renewable macronutrient), breeders could select ideotypes with shallower root angles (Figure 1b), an approach which has worked very well for beans[12]. A key regulatory gene through which phosphate limitation controls root angle has been identified in rice[13], opening new opportunities to develop novel varieties with adaptive traits for future soil environments.

Manipulation of the soil microbiome

Soil-grown plants are colonised by a wide range of taxonomically diverse soil microbial communities which establish both beneficial and detrimental associations with plants that impact their growth and fitness across different ecological contexts, including agricultural settings. Hence, plant microbiota and soil health are inextricably linked through a circular regulatory mechanism in which factors impacting on soil health also alter properties of beneficial plant-associated microbiota and vice versa (Figure 1d).

Disease-suppressive soils are a clear example of the soil-plant connection as they protect plants against infections by soil root pathogens offering great potential to increase agricultural sustainability. Future research must take advantage of advances in culture-independent technologies to study soil microbiomes, such as metagenomics, to reveal the ecological and molecular mechanisms behind pathogen suppression and facilitate the use of disease suppressive soils. For example, metagenomics can identify the bacterial taxa and functions responsible for the different layers of defence against pathogens in the rhizosphere and root endophytic compartment, respectively[14].

Understanding microbial community dynamics, metabolic interactions among microbial community members, and microbial characteristics associated with pathogen suppression will help to predict if soils will develop pathogen suppressive characteristics supporting future crop production. However, to fully leverage microbial advantages, we need to increase efforts to define and understand the co-evolutionary processes governing the assembly of the plant microbiota. This will allow us to optimise the interaction of plants with beneficial microbes, and to use the advantages of the microbiota efficiently and reproducibly in plant health conferring subsequent benefits for soil health.

Effective management of the root-soil-microbiome

Sustainable approaches for soil management that maximise carbon inputs and facilitate a naturally-derived soil structure, closely integrated with crop breeding programmes that target root adaptive traits to thrive under changing conditions are essential. At the heart of this is an urgent requirement to develop a greater understanding about how to manage the root-soil-microbiome most effectively in regenerative agri-systems. In addition, greater engagement between plant (shoots as well as root specialists) and microbiome researchers with soil scientists, crop breeders and farmers is vital to achieve this urgent objective. For example, the association between plant genotypes, root and shoot microbiota composition, and the molecular mechanisms underpinning plant-microbiota interactions could inform breeding to optimize crops in response to environmental fluctuations such as those anticipated in the soils of the future[15,16].

The effective engagement outlined here requires imaginative public and/or private funding initiatives to promote inter-disciplinary interactions between researchers and commercial partners beyond that at present. Without such urgent intervention, the ability to translate new research findings to underpin and enhance the enormous potential impact of regenerative agriculture will be severely limited.

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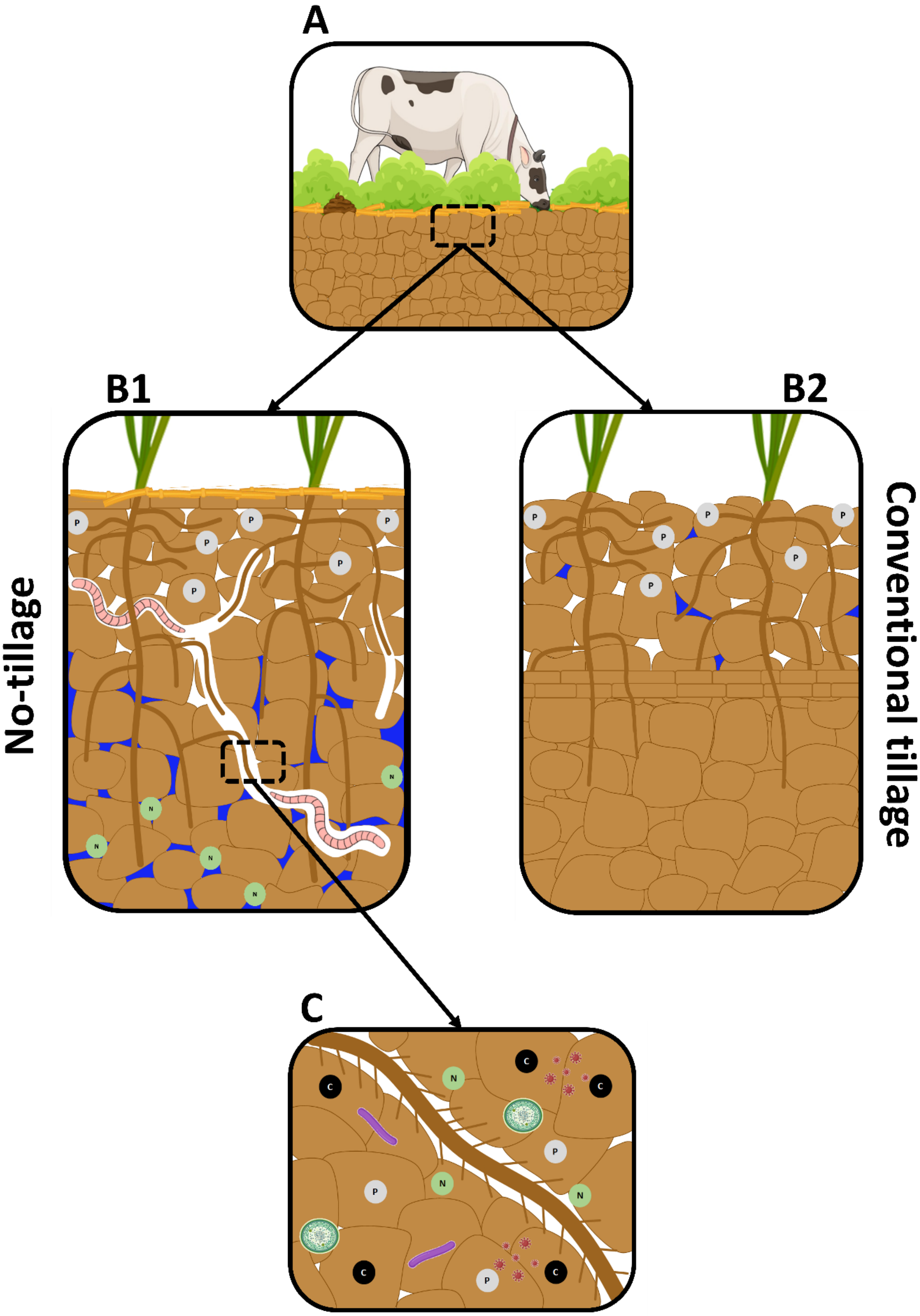
A
B1
B2
No-tillage
Conventional tillage
C

Figure 1: Multiscale representation of how the principles of regenerative agriculture might be supported by new efforts in plant breeding and manipulation of the root-soil-microbiome to enhance food security. *(a) Field Scale: Integrated crop-livestock system where manures and residues are left on the soil surface under a no-till approach; Soil Profile Scale: b) Under long term (>10 years) no-till, a thriving soil faunal community creates a network of extended biopores facilitating deeper root penetration to access water and N where extended biomass in the topsoil enhances P acquisition, in comparison to c) conventional tillage where a plough pan and reduced faunal activity limit deeper rooting especially in the subsoil and (d) Root Scale: manipulation of the soil microbiome in the rhizosphere create an oxic environment supporting enhanced water and nutrient use efficiency and disease resilience due to root-microbe interactions.*

Competing interests

The authors declare no competing interests.