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EDITORIAL

Exploring the plant and soil mechanisms by which crop rotations benefit farming systems

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Introduction

Crop rotation, which involves growing a sequence of different plant species on the same land (Karlen et al. 1994), has been a valued farm practice for thousands of years. According to Parker (1920), crop rotation evolved primarily from experiential learning. This technique was developed by early farmers to improve soil productivity, as they had experienced low yields due to continuous cropping with a single species. However, monoculture, cultivating the same crop year after year on the same land, has re-emerged in many parts of the world, driven by the goals of food security and economic benefit. Increased use of inorganic fertilizer in the monoculture system has masked land degradation trends and avoided crop yield loss but there have been impacts on sustainability of farming systems.

Crop rotations support nutrient cycling (i.e., nutrient recycling from subsoils, nutrient turnover from crop residue), enhance soil ecosystem services (e.g. maintain soil microbial diversity, use of residual moisture, improve soil hydrological properties), break weed, pest & disease transmission cycles and improve resource use efficiency (e.g. use of residual soil water) (Tilman et al. 2002; Castellazzi et al. 2008; Bender et al. 2016; German et al. 2017). This practice offers several economic and environmental benefits and is helpful for long-term soil and farm

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The crops in a rotation may include pasture species or mixed species. While fallow is a component of some rotations it is not addressed in the present studies.

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management (Malik et al. 2017; Sehgal et al. 2023). Furthermore, crop rotation adds market diversity and economic resilience to a farming system.

The crop rotation patterns vary depending on environmental and soil conditions. Agricultural production in Asia, Africa, and Latin America is generally more diverse and labor-intensive, dominated by smallholder farmers with inherent rotation systems. However, there is a general trend in rotation systems. For example, the Midwest United States commonly uses the corn-soybean (*Zea mays* L.—*Glycine max* L.) rotation (Plourde et al. 2013), while the rice–wheat (*Oriza sativa* L. – *Triticum aestivum* L.) rotation is more common in Asia (Mishra and Singh 2012) and provides food for about 20% of the world's population. In South America, soybean and corn summer crops are widely grown in rotation with Italian ryegrass (*Lolium multiflorum* Lam) (Neto et al. 2014), while in Europe, planting wheat after rapeseed (*Brassica napus* L.) and small-grain cereals is common (Peyraud et al. 2014). Many of these rotational cropping systems integrate legumes and cereals which supports arguments that this combination in a rotation is more sustainable for increasing food production (Preissel et al. 2015; Cernay et al. 2018). By contrast, continuous cropping with cassava (*Manihot esculenta* Crantz.) without any inputs is facing the challenge of yield reduction in Southeast Asia, Latin America, and Africa (Leihner and Lopez 1988; Howeler 1991; Nguyen et al. 2002; Chua et al. 2020). However, according to a review by Delaquis et al. (2018), 189 cassava intercropping studies involving 330 instances with various companion crops showed positive effects on soil and water-related parameters.

Maintaining and improving soil quality in continuous cropping systems is critical to sustaining agricultural productivity. It has been reported that crops grown in rotation can produce higher yields for each crop than corresponding monoculture under the same nutrient conditions (Porter et al. 1997) – this yield enhancement from rotation has been referred to as the "rotation effect" (Pierce and Rice, 1988). Furthermore, the implementation of diverse cropping systems serves to mitigate soil erosion in vulnerable areas, ultimately fostering long-term soil health (Liu et al 2021).

Two of The United Nations sustainable development goals (SDGs)are directly related to the topic of declining soil health caused by agricultural practices (SDGs 2-Zero Hunger and 6-Clean Water and Sanitation), and dependence on synthetic fertilizers and pesticides to maintain high productivity (SDG 2). As shown in the Special Issue, croprotation is an agricultural approach that increases efficiencies in the use of inputs, decreases dependence on external inputs prioritizes practices supporting biodiversity and environmental services, and takes into consideration the social implications of production practices, market dynamics, and product mixes. This shift towards sustainable agriculture is being encouraged by the emergence of payments for Ecosystem Services and multifunctional agriculture within rural landscapes (Bowman and Zilberman 2013).

Historically, crop rotations were adopted to increase the yield of cash crops (Bullock, 1992). However, the benefits of crop rotations are still mostly framed in generalized benefits such as increased soil fertility. This Special Issue aims to explore more specific processes altered by crop rotations. Here we discuss the benefits of rotation systems and their mechanisms, as well as highlighting how underutilized rotational systems can contribute to the well-being of millions of smallholder farmers who are striving for sustainable agricultural growth and food security, particularly in challenging environments.

Nutrient cycling and soil management

The productivity, nutrient loading and nutrient use efficiency in rotation systems, can vary depending on specific management practices and overall farm intensity. Moreover, seasonal variation affects soil nitrogen mineralization, and the potential synchronization of soil available nitrogen supply with crop demand. For example, when legumes such as mungbean are incorporated into cereal rotations like maize-wheat, it boosts the absorption of nitrogen (by 34%), phosphorus (46%), potassium (36%), and sulfur (56%) in maize, whereas, when chickpeas are included in the rotation every other year, it increased the uptake of these nutrients by 18%, 19%, 22%, and 32%, respectively (Venkatesh et al. 2017). In a wheat/pasture rotation, accumulation of soil P was evident (2 kg ha^{-1} $year^{-1}$), but no accumulation was evident under continuous cropping (Bünemann et al. 2012). Furthermore, in the same legume pasture system, soil P availability was augmented for the subsequent crop (Damon et al. 2014).

Long-term studies have consistently shown that crop rotation, adequate fertilization, and the use of manures help maintain agronomic productivity by increasing carbon inputs into the soil. For instance, a 5-year cropping sequence that included a cover crop increased soil organic carbon (SOC) at shallow depths compared to continuous mono-cropping of wheat for 5 years (Feng et al. 2020). Long-term application (36 years) of green manure can enhance SOC sequestration in paddy soils by altering the clay mineral composition and aggregate size, which has implications for soil fertility and carbon storage strategies in agricultural systems (Huang et al. 2023). A global meta-analysis by Oldfield et al. (2019) concluded that there were potential yield increases of 10 ± 11% for maize and 23 ± 37% for wheat with increased soil organic matter. Increases in soil organic matter up to 2% appeared to increase crop yield, but further increases had minimal effects. However, there are still very few studies that quantify how much increase in yield can be attributed to increased soil organic matter (Kätterer and Bolinder 2024). In a 20-year study in Sweden with various soil organic amendments, Kätterer and Bolinder (2024) determined that maize yields increased by 14–16% for every 1% increase in soil organic matter (0–20 cm depth). Two-thirds of the increase was attributable to improved soil physical properties, in this case mostly due to increases plant-available water content with increased organic matter. The difficulty of raising soil organic matter levels by 1%, especially in dryland cropping environments, should not be underestimated (Hoyle et al. 2013). Indeed, the greatest potential for increased soil organic matter storage appears to be in the subsoil.

Residue resistance level and the C:N ratio are also important factors in crop residue decomposition and their effectiveness in improving soil health. Both of these factors are influenced in rotations by residue mass, diversity, quality, and crop photosynthetic pathway (Omonode et al. 2006; Six et al. 2006). Therefore, the composition and mass of the substrate determine not only the decomposition rates but also the proportion and duration of C stored in soils.

Pulido et al. (2023) found that specific cover crop species, rather than just functional groups, play a crucial role in nitrogen uptake and minimizing nitrogen losses. This suggests that selecting cover crops for crop rotations based on traits that increase biomass can effectively manage nitrogen. Ma et al. (2023) demonstrated that incorporating winter cover crops, such as hairy vetch, into the agricultural system of the North China Plain can reduce reliance on nitrogen fertilizers and enhance nitrogen use efficiency. Additionally, Baxter et al. (2023) revealed that applying manure can significantly increase SOC and nutrient levels. Furthermore, including winter triticale in a crop rotation can improve forage production and the utilization of manure-supplied nutrients, offering a sustainable nutrient management approach in dairy farming.

Greenhouse gas emissions

Crop rotations with legumes reduce greenhouse gas emissions compared to cereal monocultures. This reduction in greenhouse gas emissions becomes significant over a long rotation period, highlighting the effectiveness of this approach (Barton et al. 2013; Lötjönen and Ollikainen 2017). Another six-year field experiment conducted in the North China Plain has suggested the potential benefits of diversifying traditional cereal monoculture (wheat–maize) with cash crops like sweet potato, and legumes such as peanut and soybean (Yang et al. 2024). The diversified rotations while increasing equivalent yield by up to 38%, decreased N_2O emissions by 39%, and a decrease of up to 88% in the system's greenhouse gas balance. Furthermore, Yang et al (2023) found a direct correlation between increased SOC stocks and a reduction in carbon footprints, along with an increase in crop yield. Their analysis revealed that the most effective treatment for promoting soil organic carbon sequestration and reducing greenhouse gas emissions, while still maintaining a relatively high yield, is the cultivation of winter wheat-summer maize-spring maize with irrigation. This suggests that more intensive crop rotations leading to increased aboveground biomass growth are more likely to effectively reduce carbon footprints and contribute significantly to achieving emissions reduction targets. Indeed, Ladha et al. (2016) reported that cropping systems intensification including best management practices, Conservation Agriculture, and crop diversification in the rice–wheat system in the Indo-Gangetic Plain achieved 54% more grain energy yield, a 104% increase in economic returns, 35% lower total water input and a 43% lower global warming potential per unit of grain produced.

Root foraging, rhizosphere modification and biopores

By employing diverse root growth strategies, a feature of crop rotations, cropping systems can optimize the use of nutrients and mitigate abiotic stresses, thereby enhancing crop productivity (Zhang et al. 2024). For example, in soils with high salt concentrations or metal contamination, integrating hyperaccumulator plants or halophytes with traditional crops through intercropping has been identified as a promising approach (Liang et al. 2020; Liu et al 2023). To fully realize the potential of diversified cropping systems, it is essential to explore and implement innovative methods and technologies for studying root systems.

Cover crops play a pivotal role in creating biopores within compacted soils, which in turn allows for better root penetration of subsequent crops and overall improvement of soil structure. For example, Zhang et al. (2022) demonstrated that using cover crops such as alfalfa (*Medicago sativa* L), oilseed rape (*Brassica napus* L.), and a mixture of radish (*Raphanus sativus* L.) and hairy vetch (*Vicia villosa* Roth) did not change the bulk density of the soil, but did reduce soil water content in both compacted and non-compacted soils compared to the control treatment where maize (*Zea mays* L.) was grown as the succeeding crop in compacted soil. All three cover crop treatments resulted in increased maize root growth and density in the compacted soil. Furthermore, the mixture of radish and hairy vetch, and the oilseed rape treatment significantly increased maize production in the compacted soil. This indicates that these cover crops could help ameliorate the effects of soil compaction on root elongation.

Breaking weed, pest & disease transmission cycles

The diverse range of crops in farm rotations can effectively mitigate the damage caused by pests and diseases in multiple ways. Firstly, this approach diminishes the available resources for pests, thereby inhibiting their ability to thrive. Secondly, it can influence pest behavior, disrupt their life cycles, and enhance the natural resistance of crops to pest infestations. Moreover, the crop diversity in rotations can bolster the population of natural pest predators and induce physical transformations in the environment that deter pests. Long-term crop rotation in drylands increases soil multifunctionality, particularly enhancing the carbon cycle, and alters the soil fungal community composition by reducing the proportion of pathotrophs, with saprotrophs being more influenced by soil variables (Wang et al. 2023). Crop rotation practices play a significant role in shaping soil microbial communities (Bai et al. 2024), which in turn have the potential to improve soil health and functionality in agricultural systems.

Soil microbial community including disease suppression

The composition of microorganisms in the soil is highly influenced by changes in plant diversity. As a result, crop rotation systems show greater microbial diversity, enzymatic activities, and soil respiration compared to monoculture or fallow fields (Woo et al. 2022). Crop rotation involving cereals with legumes has a positive impact on microbial diversity, mainly due to the presence of nitrogen-fixing bacteria. Furthermore, Wang et al. (2023) found compelling evidence to suggest that the practice of crop rotation has a multifaceted impact on soil health. Not only does crop rotation enhance soil multifunctionality, but it also brings about notable changes in the composition of the soil fungal community.

In Argentina, the inclusion of cover crops such as oat, vetch, and radish in a crop rotation was found to enhance microbial biomass and soil enzyme activities (Chavarria et al. 2016). Two cover crop mixtures were tested: oat/radish and oat/radish/vetch, alongside soybean monoculture and soybean/corn as cash crops. The inclusion of cover crop mixtures led to an increase in bacterial phospholipid fatty acid biomarkers, particularly Gram-positive bacteria, in the short term. These changes were associated with increases in soil enzyme activities and the availability of essential nutrients such as nitrogen and phosphorus.

In a long-term field experiment conducted in Michigan, USA the most diverse cropping systems, including cover crops and fallow periods, resulted in different bacterial communities compared to systems with lower crop diversity (1–3 crop species) (Peralta et al. 2018). The soil bacterial diversity was about 4% lower in the most diverse crop rotation (corn-soybean-wheat + 2 cover crops) compared to monocrop corn, while an increase in disease-suppressive bacteria (prnD gene) abundance of about 9% was observed in the more diverse rotation compared to monocrop systems. Additionally, it was reported that the disease-suppressive potential was significantly reduced in the non-crop fallow treatment compared to the most diverse crop rotation treatments.

Crop rotation was found to be beneficial for banana farming. According to Fan et al. (2020), rotating bananas with other crops such as pepper, sugarcane, wax gourd, and pumpkin reduced Fusarium wilt and increased yields compared to growing bananas as a mono crop. The study also found that the soil contained Proteobacteria (25%), Acidobacteria (21%), and Gemmatimonadetes (13%) as the main bacterial phyla, while Ascomycota (73%) was the dominant fungal phylum. These crop rotation practices increased the diversity of bacteria in the soil, with some types of bacteria becoming more abundant and others decreasing. Furthermore, the study identified soil pH, organic matter, and available phosphorus as the main factors influencing the composition of bacterial and fungal communities.

Asghar and Kataoka (2023) demonstrated that volatile organic compounds emitted by fungi associated with green manure can promote the growth of lettuce and enhance antifungal properties. This can be particularly beneficial in combating soil-borne pathogens such as *Fusarium oxysporum*, highlighting the significant impact of microbial interactions on plant health.

Crop rotations in conservation agriculture

Diverse crop rotations is one of the three pillars of Conservation Agriculture (CA), which is now practiced on over 204 million hectares or 15% of crop land globally (Kassam et al. 2022). The effects of diverse crop rotations where CA is practiced warrant further consideration due to the potential additional impacts of minimal soil disturbance and increased crop residue retention on crop productivity and soil processes. When there is a switch to CA, even without a change in crop rotation, a range of effects on crop yield, profitability and on soil properties progressively emerge over time (Bell et al. 2019). While the benefits of CA practices on yield can occur in the first crop after switching from conventional tillage and low crop residue retention (e.g. Kader et al. 2022), in other cases it takes 2 or more years before yields responded to CA (Islam et al. 2022a). In intensive triple-cropping rotations in the Eastern Gangetic Plain, the yield of rice did not respond until year 7 (Kader et al. 2022). Yield increases in the CA crops were attributed to improved soil physical properties, notably to positive changes in soil water content, bulk density and penetration resistance (Salahin et al. 2021a; Islam et al. 2022a, b).

Apart from soil physical changes in diverse rotations under CA compared to conventional tillage and low crop residue retention, large increases in SOC and in C stock have been reported particularly after 2–3 years (Islam et al. 2022a, b; Alam et al. 2018; Salahin et al. 2021a; Kader et al. 2022). In a cereal-dominant rotation (wheat- mungbean-rice), after 7 consecutive crops there was a net increase in SOC stock under CA, but a decline in the conventional practice (Islam et al. 2022a, b). By contrast, on a legume-dominated rotation (lentil-mung bean- rice) neither the CA nor conventional practice increased SOC stocks possibly because of lower overall C input in retained crop residue, but CA slowed the decline in SOC. With prolonged practice of CA in diverse crop rotations, a 65% increase in SOC was reported in the 0–30 cm layer after 5 years (Alam et al. 2018). Similarly, Kader et al. (2022) reported SOC stocks increased after 8 continuous years of CA in a wheat-mungbean-rice rotation from 21.5 to 30.5 t/ha.

Under CA in diverse rice-based crop rotations, there was an increase in total N (Alam and Bell 2020; Salahin et al. 2021b; Islam et al. 2022a, b) and total S (Kumar et al. 2022). There was also an increase in stratification of extractable P and Zn under CA with higher levels accumulating in the surface soil layers (0–5 cm) (Salahin et al. 2021b). The mineralisation pattern on N under CA in a number of diverse rice-based crop rotations in the EGP has changed under CA. The rate of N release is slowed during the early crop growth (Alam and Bell 2020; Salahin et al. 2021b). Alam et al. (2018) suggests that the mineralization pattern under CA is more likely to match the pattern of crop demand during the growing season resulting in increased N use efficiency(e.g. Kader et al. 2022), and possibly decreased losses of soil N. Decreases in the weed seed bank by about 30% were also reported from 3–5 years of continuous CA practice in diverse rice-based crop rotations (Hossain et al. 2021).

Kumar et al. (2023) reported that the combination of incorporating legumes, applying appropriate fertilizers, and incorporating crop residues are essential practices for enhancing productivity and soil carbon and nitrogen sequestration in intensive rice-based cropping systems in the Indo-Gangetic plain. Furthermore, Zhang et al. (2023) have shown that vegetable-rice production systems in subtropical China can improve soil fertility (e.g. enhance alkaline N, Olsen P, and Olsen K during the vegetable growth period), and rice yields.

Rotation studies on CA in intensive rice-based cropping systems are an unique opportunity because within 3–5 years the effects of 9–15 crops and large inputs of crop residue (10 + t/ha/yr; Islam et al. 2022a, b) can accelerate changes in soils that in dryland cropping systems, growing only one crop per year, may take a decade or more to be expressed. However, even in these rotations, effects on soils and crop yield were still emerging after 6 years (i.e. 18 continuous crops: Kader et al. 2022) emphasizing the need for long term studies on the effects of rotations.

Conclusions

The present collection of 10 papers on crop rotations covers a diverse array of topics, reflecting the broad scope of research in this field. The interdisciplinary approach taken in studying the advantages of crop rotation is particularly intriguing. It is well-established that crop rotation plays a crucial role in maintaining soil health and enhancing productivity. Apart from this collection, other recent papers shed light on the substantial benefits of crop rotation, especially in arid and high-intensity agricultural settings.

In summary, the present collection of studies underscore the importance of crop rotation, green manure use, and the integration of legume crops in improving soil health, productivity, and economic outcomes for farmers. They offer evidence-based strategies that contribute to sustainable agricultural development and food security in the face of increasing global food demands. We are optimistic about the future of research on crop rotation and the underlying mechanisms that enhance agricultural production. The growing recognition of the significance of crop rotation in cropping systems will lead to more sustainable crop production and help achieve the zero-hunger goal, which is one of the major Sustainable Development Goals (SDGs).

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