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REVIEW ARTICLE

Crop Rotations: Effects on Soil Health and System Productivity

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ABSTRACT

Background: Crop rotation (CR) is a key conservation practice for sustaining soil health and productivity, but evidence on its effects is scattered across many soils, crops and climates.
Objective: To review how CR influences soil physical, chemical and biological characteristics and the productivity of cropping systems.
Methodology: Published field and long-term studies on rotations of cereals, legumes, vegetables and oilseed crops were reviewed and synthesised under soil physical, chemical, biological and productivity headings.
Results: Diversified rotations, particularly those including legumes and forage crops, generally reduced bulk density and improved porosity and hydraulic properties, although short-term trials showed little effect on macroporosity. Such rotations increased soil organic carbon (by up to 22% over maize–wheat), total nitrogen, available nutrients, exchangeable bases and enzyme activities (dehydrogenase by 52–79%). Rotation affected soil pH, electrical conductivity and cation exchange capacity in a system- and depth-dependent manner. Longer rotations reduced weed cover (from 40% to 20%) and soil-borne diseases (by 10–52%), and diversified rotations improved the robustness of crop productivity by 14%.
Conclusion: CR is an effective, multi-benefit strategy for sustainable soil management. Responses depend on crop sequence, soil type and duration, and the microbial mechanisms of disease suppression need further study.

INTRODUCTION

The colloquial use of the term "rotation effect" has a long history in agronomic research. Crop rotation (CR) and residue incorporation are recommended techniques for building conservation agriculture with minimal soil disturbance, which concurrently conserve soil and water while reducing input costs (Jiang *et al.* 2011; Zhang *et al.* 2018). Residue retention and CR enhance soil quality by reducing soil breakdown, controlling soil erosion, increasing the soil infiltration rate, improving nutrient cycling and soil organic carbon, and protecting the soil from raindrop impact (Dube *et al.* 2012; Zhang *et al.* 2018; Struijk, 2026). Rotation effects are expressed in the physical, chemical and biological components of soil health and, ultimately, in the productivity of the whole cropping system. For example, Borase *et al.* (2020) found that a pigeon pea–wheat rotation had 15% higher soil respiration than a maize–wheat rotation. The objective of this review article is to review the effects of CR on soil physical characteristics: hydraulic properties, bulk density and porosity; to synthesize evidence on soil chemical and biological responses to CR: organic matter, nutrients, pH, electrical conductivity, cation exchange capacity, exchangeable bases, enzymes and microbes and to examine the effects of CR on weed and disease management and on system productivity

CROP ROTATION AND SOIL PHYSICAL CHARACTERISTICS

Soil hydraulic properties

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CR strongly influences soil hydraulic properties. Soils with low porosity and high bulk density have a negative impact on the infiltration rate and saturated hydraulic conductivity (Bhattacharyya *et al.* 2006; Miriti *et al.* 2013). In this regard, Dexter *et al.* (2001) included a mustard or clover–grass mixture in the rotation and found higher hydraulic conductivity in a loamy sand soil in Poland. In another study, Głąb *et al.* (2013) compared the long-term effect of CR on the hydraulic properties of a loam soil under different cropping systems: winter triticale–spring triticale; spring triticale–winter triticale–oat; and sugar beet–spring triticale–faba bean–winter triticale. They observed that water retention properties were significantly enhanced by rotation, especially with triticale, which increased the quantity of available water. However, the crop effect was not stable, and longer-term CR did not prove beneficial. McVay *et al.* (2006) investigated the effects of CR and tillage in five long-term trials on silt loam soils in Kansas, USA, and noted changes only in the upper soil layer (0–5 cm). Blair *et al.* (2006) reported that long-term CR on two clay-rich Vertosols under semi-arid conditions in Australia changed the aggregate mean weight diameter and hydraulic conductivity by increasing soil organic carbon, especially with more frequent inclusion of forage legumes (*Medicago sativa* L.) in the rotation (Fig. 1-2)

Armstrong *et al.* (1999) reported that, in a legume-to-sorghum rotation, higher hydraulic conductivity was associated with significantly improved macroporosity of a clay soil. Studies of CR clearly demonstrate that roots are directly involved in improving hydraulic activity at the field scale (Dexter *et al.* 2001). Similarly, Pala *et al.* (2007) indicated that an improved biennial rotation with wheat is imperative for better yield and improved water-use efficiency. Wei *et al.* (2020) reported that soil water content was significantly higher under a lentil–wheat–maize rotation (9.81%) than under a wheat–maize–potato rotation (8.43%). Based on 40 years of observation, they suggested a key role of CR in changing soil water content.

Overall, the evidence indicates that CR is an effective way to improve soil hydraulic properties, though the size and persistence of its benefits depend on soil type, crop sequence, and duration. Rotations that include legumes, forage species, or deep-rooted crops generally increase soil organic carbon, aggregate stability, and macroporosity. These changes raise hydraulic conductivity and improve water retention and available water, as shown in loamy sand, loam, and clay-rich Vertosol soils. The benefits are often strongest in the surface layer, are not always stable over time, and may not increase with longer rotation periods. Rotations that include legumes also increased soil water content over the long term and supported higher yield and water-use efficiency. Roots appear to be the main driver of these improvements at the field scale. Well-designed, site-specific rotations that combine legumes and cereals are therefore a sustainable strategy for improving soil structure, water availability, and resilience, particularly in water-limited environments. However, multi-site research is needed to clarify the mechanisms and the stability of these effects under different environmental conditions.

Soil bulk density

Karlen *et al.* (2006) found that extended CR including legume, forage and oat reduced soil bulk density compared with continuous corn and corn–soybean rotation. Shaver *et al.* (2003) observed that sorghum–wheat and corn–wheat rotations had lower bulk density and higher soil porosity than continuous wheat. Stone and Silveira (2001) reported the highest bulk density in a soybean–wheat rotation relative to other combinations. Likewise, Wei *et al.* (2020) found that soil bulk density was significantly higher under lentil–wheat–maize (1.19 Mg m^{-3}) than under wheat–maize–potato (1.16 Mg m^{-3}). Similarly, Degu *et al.* (2019) found that land under maize–wheat–faba bean had a higher mean bulk density (1.06 g cm^{-3}) than land under other rotations (1.02–1.04 g cm^{-3}).

Taken together, these studies indicate that diversified rotations, particularly those that include forage or legume phases, tend to reduce bulk density relative to monocultures or short two-crop sequences. However, the magnitude of effect is often small and varies with crop identity, so rotation design should match the specific soil and cropping context.

Soil porosity and aeration

Natural cracking, soil faunal activity and macropores created by previous root growth can provide better pathways for root growth of the following crop; otherwise, hard soil layers restrict root growth and nutrient availability. The beneficial consequences of such pores depend on their strength in the soil matrix, their frequency and size, and nutrient and water availability (Ball *et al.* 2005).

Nebo *et al.* (2020) reported that maize following maize had the highest bulk density (1.4 g cm^{-3}), compared with a maize–wheat–maize rotation (1.36 g cm^{-3}), and the lowest bulk density was observed in the maize–soybean rotation (1.29 g cm^{-3}). The authors further concluded that the interactions of CR × tillage, tillage × residue management and CR × residue management were non-significant ($p > 0.05$) and had no impact on water-conducting macroporosity and hydraulic conductivity. They suggested that CR had little effect on macroporosity in the short term (3 years). Recently, Singh *et al.* (2020) examined the effect of a 2-year maize–soybean rotation and a 4-year maize–soybean–oat–winter wheat rotation on the near-surface pore characteristics of a silty clay loam under field conditions. They noted that the 4-year rotation increased the number of pores measured by X-ray computed tomography, coarse mesopores (226–1000 μm diameter), macropores (>1000 μm diameter), macroporosity and mesoporosity compared with the 2-year maize–soybean rotation. In addition, Fuentes *et al.* (2009) reported a greater water infiltration rate and pore frequency in wheat than in corn-dominated rotations.



Fig 1: Crop rotation effect on soil physical, chemical, biological and system productivity

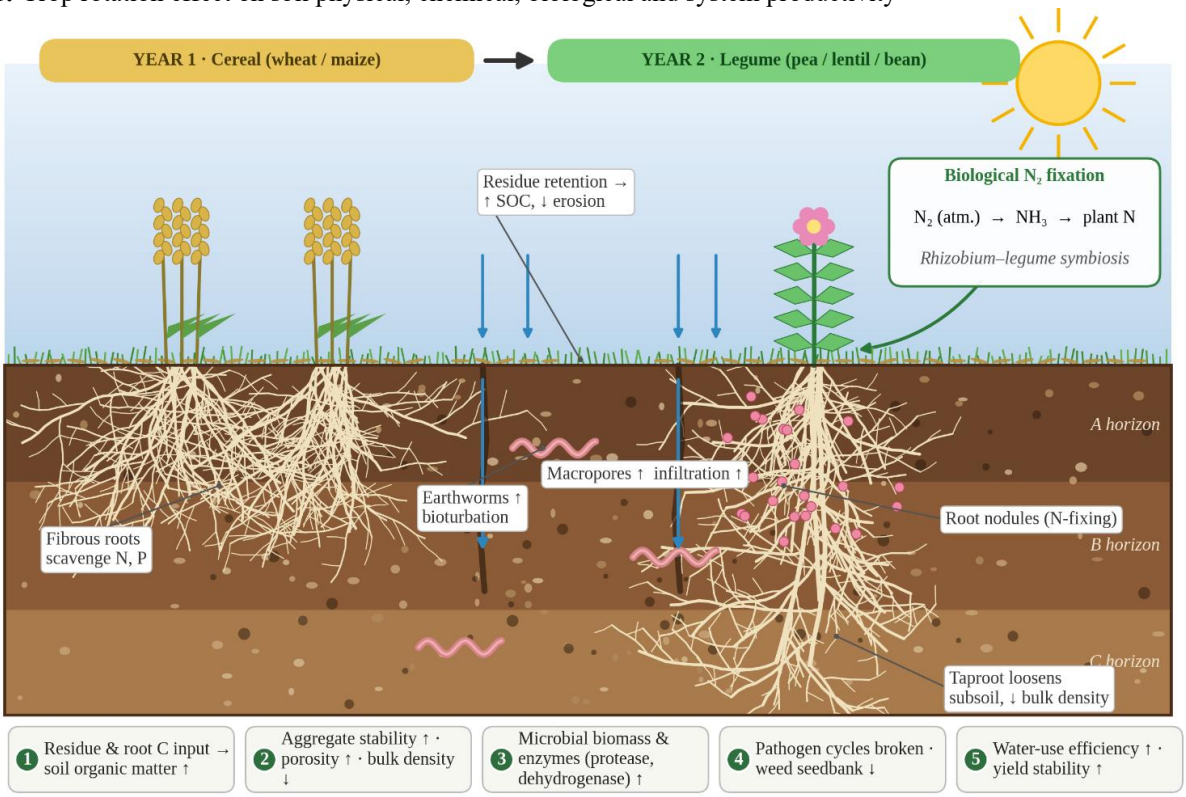

Fig. 2: Soil cross-section comparing a cereal year with a legume year.

Stone and Silveira (2001) confirmed that a rotation of upland rice with common bean and calopogonium showed the highest macroporosity and the lowest microporosity compared with the other rotation systems, including corn–common bean, soybean–wheat–soybean–common bean and upland rice–common bean, whereas the highest microporosity and lowest macroporosity were observed in soybean–wheat. Similarly, Bodner *et al.* (2014) provided evidence for the impact of cover crops on soil pore size distribution. They found that root axes had a distinct effect on hydraulic properties and that root growth influenced different pore size classes, with fine root systems dominating in brassica and coarse root systems in legume crops.

In summary, the evidence indicates that rotation influences soil pore structure mainly through the rooting traits of the crops involved, and that measurable changes in macroporosity are more likely under longer, more diverse rotations than over short experimental periods.

CROP ROTATION AND SOIL CHEMICAL CHARACTERISTICS

Soil pH and cation capacity determine the chemical state of soil, which in turn affects microbial activities and has direct consequences for soil health and environmental quality.

Soil organic matter dynamics

Diversified rotations have an almost consistently positive effect on soil organic matter (OM), which improves soil health in all respects. Charman and Roper (2007) found a higher soil OM content on all land rotated with cereals and legumes. The highest OM was found in maize–pepper–pepper and maize–wheat–pepper rotations, at about 5.12% and 5.05%, respectively (Degu *et al.* 2019). The authors suggested that this is likely due to the slow decay of the biomass and roots of pepper through various forms of active soil OM, which supply nutrients slowly and stabilise soil aggregates. Huang *et al.* (2002) similarly noted that, since organic carbon and total N are stoichiometrically linked in soil OM, greater OM invariably led to an increase in N and organic carbon in rotations where faba bean and pepper were included over time.

Singh *et al.* (2020) found that the 4-year maize–soybean–oat–winter wheat rotation had 4%, 14% and 16% higher wet aggregate stability, total nitrogen and soil organic carbon, respectively, than the 2-year maize–soybean rotation. According to Karlen *et al.* (2006), extended CR with legume, forage and oat increased soil organic carbon and wet aggregate stability compared with continuous corn and corn–soybean rotation. In contrast, including soybean in a short rotation with corn has been found to lead to lower soil organic carbon than corn monoculture, owing to lower residue production and rapid residue decomposition of soybean (Coulter *et al.* 2009; Benjamin *et al.* 2010). Bhattacharyya *et al.* (2009) showed that soybean–pea and soybean–lentil rotations had higher soil organic carbon than soybean–wheat only in the whole-soil fraction (<4.57 mm) at 0–15 cm depth.

Borase *et al.* (2020) observed the following order of rotations for soil organic carbon: pigeon pea–wheat > maize–wheat–mung bean > maize–wheat–maize–chickpea > maize–wheat. They reported that maize–wheat–mung bean and pigeon pea–wheat rotations increased soil organic carbon by 12% and 22%, respectively, over maize–wheat during 13 years of experimentation. Degu *et al.* (2019) found that mean soil organic carbon was significantly higher under maize–pepper–pepper (2.97%), followed by maize–wheat–pepper (2.93%), and lowest under continuous maize (2.63%). McDaniel *et al.* (2013) recommended legume and crop rotation to increase soil carbon and N by up to 3.6% and 5.3%, respectively, compared with monoculture.

Diversified rotations that include legumes, forages or high residue crops generally raise soil organic matter, organic carbon, total nitrogen and aggregate stability, and the gains tend to increase with rotation length and crop diversity. The benefit is not universal, however, because short sequences dominated by low-residue crops such as soybean may give little or no improvement, and can even lower soil organic carbon relative to continuous corn. Rotation design should therefore emphasise crops that return substantial and slowly decomposing residues.

Nutrient cycling

According to Malobane *et al.* (2020), CR and residue incorporation increased ammonium, nitrate, calcium, potassium and cation exchange capacity. Alemayehu *et al.* (2020) studied the potential of CR for restoring the productivity and health of degraded highland crop fields and confirmed higher exchangeable potassium, available phosphorus and total nitrogen. Laamrani *et al.* (2020) reported that diversified CR increased the total carbon concentration of soil. The highest carbon content was found in the corn–corn–oat–barley rotation with red clover as a cover crop in both cereal phases. The authors noted a descending order for corn–corn–alfalfa–alfalfa and corn–corn–soybean–winter wheat with one year of seeded red clover, followed by continuous corn. The lowest total carbon concentrations were noted in corn–corn–soybean–soybean and corn–corn–oat–barley without red clover as a cover crop, and in corn–corn–soybean–winter wheat. Plots under soybean–lentil and soybean–pea rotations had about 19% and 21% higher total soil nitrogen, respectively, than soybean–wheat (Bhattacharyya *et al.* 2009). In addition, Haruna and Nkongolo (2019) found a significant improvement in total carbon ($p = 0.0304$) under corn–soybean rotation compared with continuous soybean and continuous corn during a 3-year study. According to Wei *et al.* (2020), based on 40 years of observation, soil organic carbon did not differ significantly between the 20-year

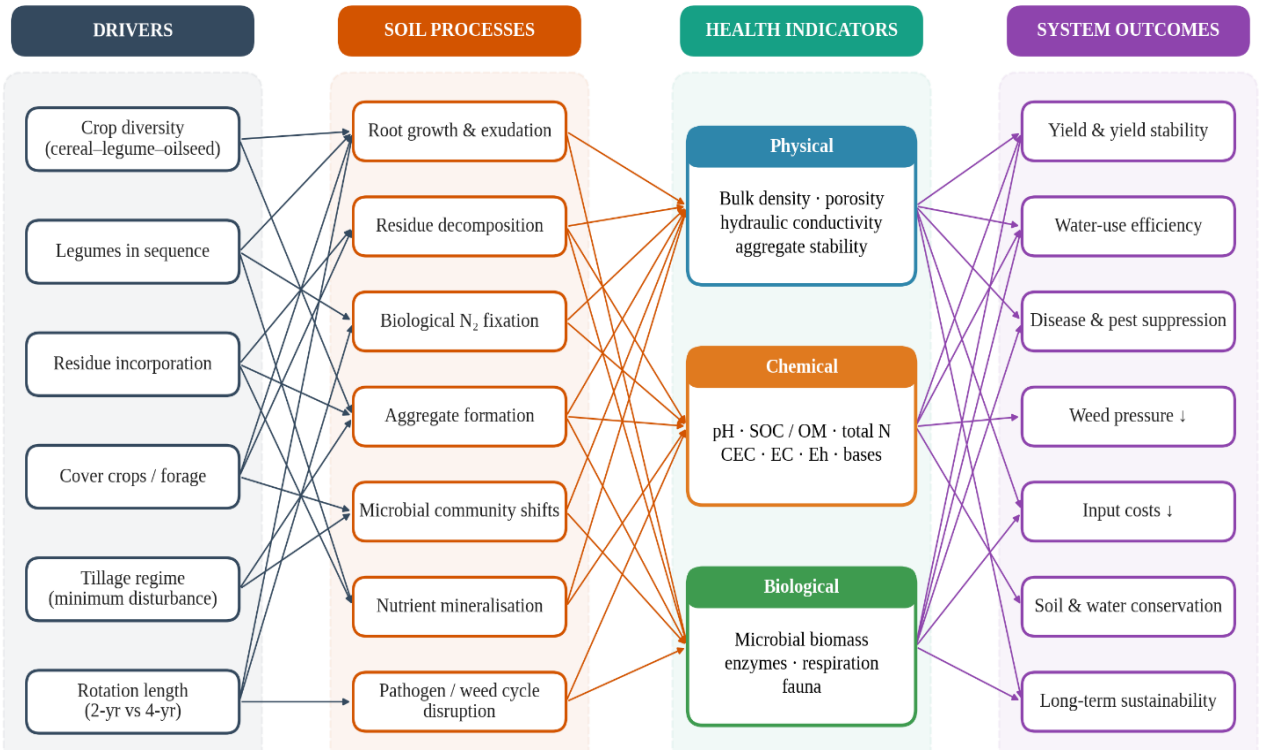

Fig 3: Effect of Crop rotation drivers on soil and overall system productivity

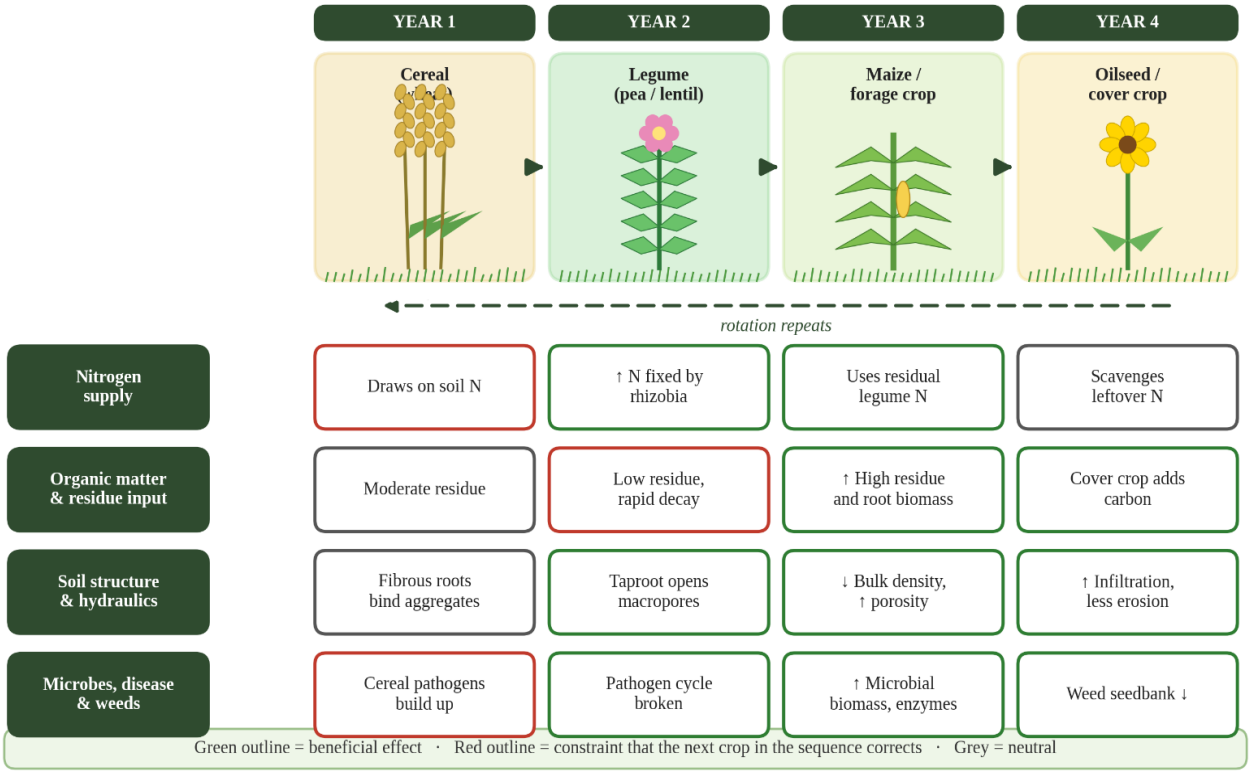

Fig. 4: Effect of crop rotation on soil nutrient, organic matter, hydraulic conductivity and disease management



Fig 5: Crop groups, feeding level and role in rotation. Crops are grouped by family and by how they affect the soil. Each colored card lists the main crops in one group: cereals (gold), legumes (green), brassicas and oilseeds (purple), the potato family (red), roots and alliums (orange), leafy crops and cucurbits (teal), and cover crops and fallow (olive). Each card also gives the group's feeding level (how much it takes from the soil) and its role in the rotation. Legumes make their own nitrogen and leave some in the soil for the next crop. Brassicas and the potato family are heavy feeders and need rich soil. Roots and alliums are light to medium feeders and prefer settled soil. Cereals break disease cycles, leafy crops and cucurbits fit into any gap, and cover crops protect and feed the soil. The golden rules summarize how to order the groups: never repeat a crop family, put legumes before heavy feeders, follow heavy feeders with light ones, alternate cereals and broadleaf crops, and wait 3 to 4 years before pest-prone crops return.

Rotations that include legumes, cover crops or diverse species generally improve soil carbon, nitrogen and cation exchange capacity. Cereal-dominated sequences with carbon-rich straw tend to immobilise N and show weaker nutrient gains. Nutrient responses vary with crop identity, residue quality and management, so rotations should be designed around legumes with high N fixation and residues that decompose at a moderate rate.

Soil pH

Haruna and Nkongolo (2019) reported different pH levels in different cropping systems: continuous corn (6.86), continuous soybean (6.84), corn–soybean rotation (6.74) and soybean–corn rotation (6.85). Similarly, Godsey *et al.* (2007) found that soil OM and pH were significantly influenced by rotation, especially at the soil surface (2.5 cm). In contrast, Xu *et al.* (2002) observed pH variations under wheat–lupin rotation in the 0–10 cm depth increment during a 14-year study. Wei *et al.* (2020) confirmed that soil pH under lentil–wheat–maize (8.42) was lower than under wheat–maize–potato (8.50) during 20 years of rotation. Soil pH under the lentil–wheat–maize system first decreased and then increased with soil depth, but Wei *et al.* (2020) found no significant differences among soil layers. They suggested that the lower water requirement of lentil and wheat stabilised soil pH, whereas pH under wheat–maize–potato increased with depth. Similar findings were reported by Godsey *et al.* (2007). Under wheat–potato–lentil and wheat–flax–pea rotations, soil pH also first decreased and then increased with depth, reaching minimum values of 8.28 and 8.27, respectively, in the 0.1–0.2 m layer (Wei *et al.* 2020). This is consistent with Hong *et al.* (2018), who noted that lentil, pea, flax, wheat and potato have shallow roots that effectively reduce rhizosphere pH by releasing H^+ ions. Wei *et al.* (2020) further observed that soil pH in shallow layers was lower than in deeper layers across four CRs, which was related to the incorporation of aboveground plant residues: these contribute organic acids to the topsoil, which break down before they can acidify the deeper layers, resulting in a relatively higher pH at depth (Chen *et al.* 2016).

In contrast, Degu *et al.* (2019) found that continuous maize resulted in a high pH (5.43), which they attributed to a local ploughing practice ("madager"/"shlshalo"). Exchangeable acidity ranged from 2.02 $cmol_c\ kg^{-1}$ under continuous maize to 4.12 $cmol_c\ kg^{-1}$ under maize–wheat–wheat. Kwiatkowski *et al.* (2020) reported a higher pH in soil under sugar beet (6.5) and the lowest under oat (6.2). Ding *et al.* (2020) showed that soil pH varied over three years of experimentation with garlic rotation, indicating that garlic rotation had greater potential to slow soil alkalisation.

Soil pH responses to crop rotation are real but generally modest, and they depend on the crops involved, the soil depth sampled and local management. Rotations with shallow-rooted crops such as lentil, pea, flax, wheat and potato tended to lower rhizosphere pH through H^+ release, and pH was typically lower in the topsoil than at depth because decomposing surface residues supply organic acids. Differences between rotations at a given depth were often small, whereas management practices such as local ploughing (as with continuous maize) and crop-specific effects (sugar beet versus oat) could shift pH more strongly. Some rotations, such as garlic, may help slow soil alkalisation. Rotation can therefore be used to moderate pH, but its effect should be interpreted alongside soil depth, residue inputs and tillage.

Soil electrical conductivity and redox potential

Bohrerova *et al.* (2004) measured significant differences in redox potential (Eh) among cropping systems in the surface horizon (0–30 cm) of an anaerobic soil, with a lower Eh under sugar beet–barley than under alfalfa–wheat rotation. In addition, soil electrical conductivity (EC) changed significantly during the growing season over three years; in the last two years, for instance, EC decreased with cucumber and increased after garlic (Ding *et al.* 2020). Nocco *et al.* (2019) combined evapotranspiration and soil apparent electrical conductivity (ECa) mapping to identify potential precision irrigation benefits. Variable-rate irrigation based on ECa mapping may lead to higher productivity and water conservation in sweet corn and potato than in field corn. They further deduced that sweet corn and potato had stronger ECa and higher evapotranspiration rates than field corn and, from all six field experiments, recommended precision irrigation based on ECa and evapotranspiration under CR. Apanovich and Lenssen (2018) compared EC across five cropping systems: banana–coffee, coffee-dominant, banana-dominant, annual CR and annual no-CR. EC was highest under the annual rotation system, followed by banana-dominant, banana–coffee, annual no-CR and coffee-dominant systems.

Crop rotation influences soil redox potential and electrical conductivity (EC), but the direction of the effect depends on the crops and the season. Redox potential in the surface horizon was lower under sugar beet-barley than under alfalfa-wheat, and EC shifted within and between growing seasons according to the preceding crop, falling after cucumber and rising after garlic. EC also differed among cropping systems, being highest under annual rotation and lowest under coffee-dominant systems. Because EC mapping reflects differences in crop water use and soil properties, it can support precision irrigation in rotations, with potential gains in productivity and water conservation. Rotation effects on these properties should therefore be interpreted alongside crop identity, sampling time and local management.

Soil cation exchange capacity

Degu *et al.* (2019) reported that cation exchange capacity (CEC) varied from 45.17 to 49.47 $cmol_c\ kg^{-1}$. They noted

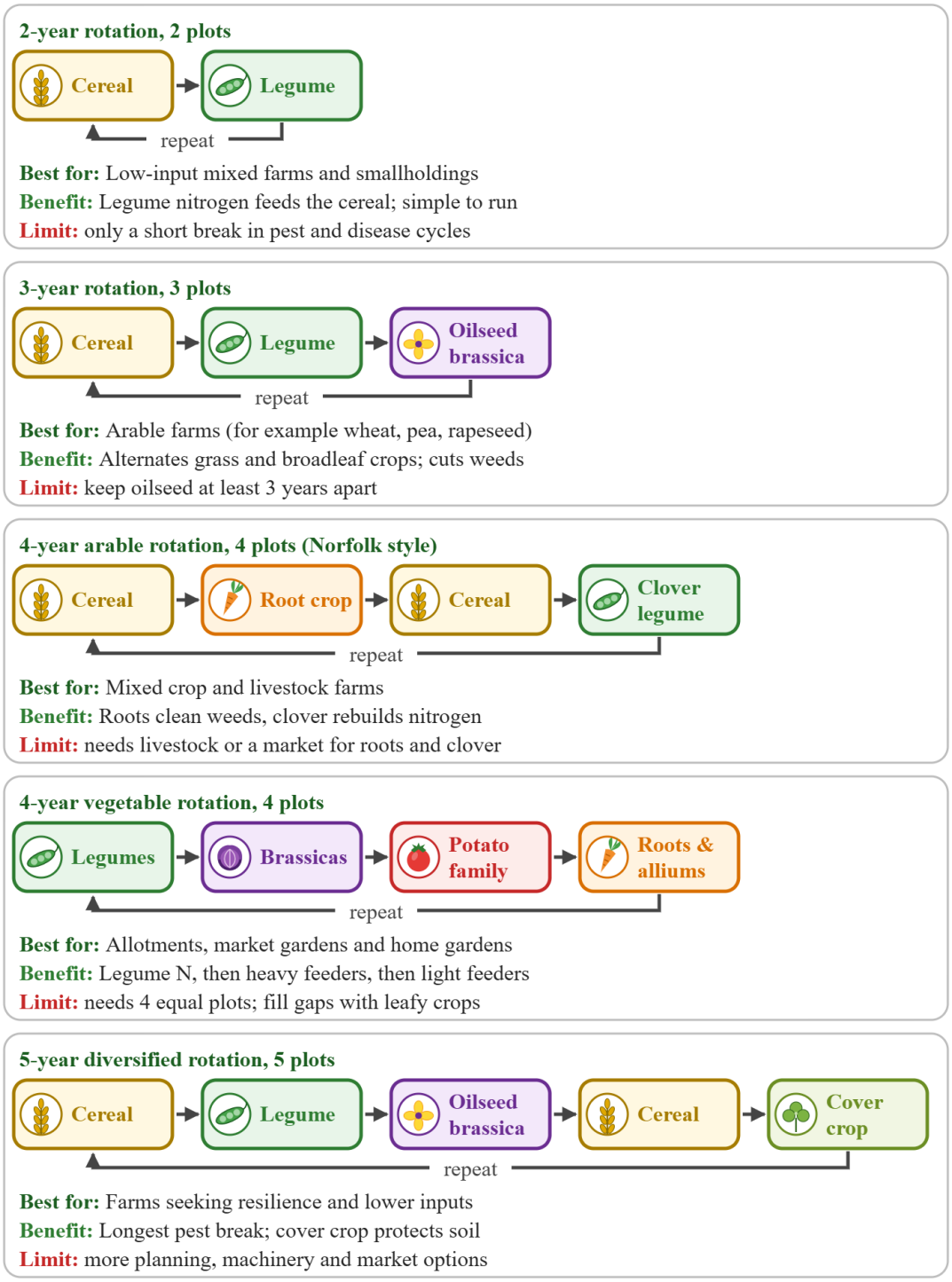

Fig 6: Five crop rotation options, from 2 to 5 years. Each row shows one rotation. The coloured boxes are crop groups: cereals (gold), legumes (green), brassicas and oilseeds (purple), the potato family (red), roots and alliums (orange), and cover crops (olive). Arrows show the order in which the groups follow one another on the same plot, and the return arrow shows that the cycle repeats. The number of plots equals the length of the rotation, so each plot grows a different group every year. The 2-year and 3-year options suit low-input and arable farms. The 4-year arable option (Norfolk style) suits mixed crop and livestock farms. The 4-year vegetable option suits allotments and market gardens, and the 5-year option adds a cover crop for a longer break from pests and disease.

mean CEC values of 44.05 $cmol_c\ kg^{-1}$ under maize–wheat–wheat, 48.57 $cmol_c\ kg^{-1}$ under maize–wheat–faba bean and 49.47 $cmol_c\ kg^{-1}$ under maize–faba bean–pepper. According to Apanovich and Lenssen (2018), CEC was highest in the annual rotation system, followed by banana-dominant, annual no-CR, banana–coffee and coffee-dominant systems.

Rotation design influenced CEC, with higher values under diversified sequences that included legumes or a broader mix of crops, and lower values under cereal-dominated or coffee-dominant systems. Rotations that add legumes and greater crop diversity may therefore improve the soil's capacity to retain nutrients.

Soil exchangeable bases

Exchangeable base cations were generally richer under rotation than under monocropping. Metson (1961) rated Ca^{2+} and Mg^{2+} as high and Na^{+} and K^{+} as moderate to high and found that cropping sequences including rotation held greater quantities of all the exchangeable bases than monocropped land.

Calcium showed the clearest response. Degu *et al.* (2019) recorded exchangeable Ca^{2+} of 10.29 cmolc kg^{-1} under continuous maize, compared with 14.22 under maize-wheat-faba bean and 15.28 under maize-faba bean-pepper. They attributed the higher value under maize-wheat-faba bean to the formation of stable complexes between Al^{3+} and organic acids released by faba bean, a process that raises soil acidity and in turn increases exchangeable Ca^{2+} in the soil layer. Magnesium was also higher on rotated land in Metson's (1961) work, although the values reported by Degu *et al.* (2019) were similar across systems, at 6.48 cmolc kg^{-1} under continuous maize and 6.00 under maize-wheat-maize.

Potassium and sodium responded differently. Exchangeable K^{+} was greatest under maize-wheat-wheat (2.03 cmolc kg^{-1}) and least under continuous maize (0.36) (Degu *et al.* 2019), whereas Metson (1961) classed it as moderate. Mean exchangeable Na^{+} was 0.45 cmolc kg^{-1} under continuous maize and peaked at 0.68 under maize-pepper-pepper, but it was lower (0.2) in all rotations managed with conservation practices than on land without them (Degu *et al.* 2019).

Taken together, these results suggest that rotation, and especially legume inclusion, improves the base cation status of soil. Degu *et al.* (2019) therefore advised rotating maize with other crops, particularly legumes and vegetables, to reduce heavy reliance on mineral fertilization.
(Degu *et al.* 2019).

Rotation generally increased exchangeable base cations relative to monocropping, although the response varied by cation and crop sequence. Calcium was higher under rotations that included faba bean, likely because organic acids from this crop form stable complexes with Al^{3+}, whereas magnesium, potassium and sodium showed more variable responses. Conservation practices were associated with lower exchangeable sodium. Maize fields should therefore be rotated with other crops, particularly legumes and vegetables, to improve base cation status and reduce reliance on mineral fertilisation.

CROP ROTATION AND SOIL BIOLOGICAL CHARACTERISTICS

Soil enzymes

Protease and dehydrogenase activities are higher under CR than under monoculture (Balota *et al.* 2004; Gianfreda *et al.* 2005). Kwiatkowski *et al.* (2020) reported that land rotated with red clover and sugar beet had the most beneficial effect on soil enzyme activity, followed by oat. Balota *et al.* (2004) further found that amylase activity at 5–10 and 10–20 cm depth was 20% higher under maize–wheat than under soybean–wheat and 11% higher than under cotton–wheat rotation. Arylsulfatase activity was influenced at 5–10 cm: maize–wheat had 37% and 27% higher activity than sugar beet–wheat and cotton–wheat rotations, respectively. Moreover, acid phosphatase activity was 6% and 10% higher under maize–wheat than under sugar beet–wheat and cotton–wheat, respectively, whereas alkaline phosphatase activity was lower under cotton–wheat than under the other rotations.

Borase *et al.* (2020) found that pigeon pea–wheat, maize–wheat–mung bean and maize–wheat–maize–chickpea had higher activities of protease (5–51%), dehydrogenase (52–79%), alkaline phosphatase (20–80%), β-glucosidase (9–16%) and arylsulfatase (16–35%) than maize–wheat. Ding *et al.* (2020) reported that soil invertase and catalase activities increased with onion and garlic rotation.

Soil enzyme activities were generally higher under diversified rotations than under monoculture or simple two-crop systems. Activities of protease, dehydrogenase and phosphatases increased where legumes, cover crops or alliums were included, and rotations with red clover and sugar beet had particularly beneficial effects. The response varied with crop identity and soil depth, however, as maize-wheat gave higher amylase, arylsulfatase and acid phosphatase activity than some other two-crop sequences. Rotations that add legumes and a broader range of crops can therefore enhance biological activity and nutrient cycling in soil.

Rotation generally enhances soil enzyme activity, particularly where legumes, cover crops or alliums are included. The magnitude of the response varies with crop identity and soil depth, so rotations that combine legumes with a broader range of crops are likely to improve microbial function and nutrient cycling most effectively.

Soil microbial communities

Table 1: Quantitative effects of crop rotation on soil properties, weeds, disease and system productivity in the reviewed studies

Parameter	Rotation (treatment)	Comparator	Reported values	Δ (%)	Reference
Soil water content	Lentil–wheat–maize	Wheat–maize–potato	9.81 vs 8.43%	+16.4†	Wei *et al.* 2020
Bulk density	Maize–soybean	Continuous maize	1.29 vs 1.40 g cm^{-3}	−7.9†	Nebo *et al.* 2020
Bulk density	Lentil–wheat–maize	Wheat–maize–potato	1.19 vs 1.16 Mg m^{-3}	+2.6†	Wei *et al.* 2020
Macroporosity (X-ray CT)	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	↑ pore number, coarse mesopores (226–1000 μm), macropores (>1000 μm)	—	Singh *et al.* 2020
Soil organic carbon	Pigeon pea–wheat; maize–wheat–mung bean	Maize–wheat	—	+22; +12	Borase *et al.* 2020
Soil organic carbon	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	—	+16	Singh *et al.* 2020
Soil organic carbon	Maize–pepper–pepper	Continuous maize	2.97 vs 2.63%	+12.9†	Degu *et al.* 2019
Soil organic carbon	Corn–soybean (short)	Continuous corn	Lower (not quantified)	↓	Coulter *et al.* 2009; Benjamin *et al.* 2010
Soil organic carbon	20-yr lentil–wheat–maize	Wheat–maize–potato	6.81 vs 6.91 g kg^{-1}	−1.4† (n.s.)	Wei *et al.* 2020
Total nitrogen	4-yr maize–soybean–oat–winter wheat	2-yr maize–soybean	—	+14	Singh *et al.* 2020
Total nitrogen	Soybean–lentil; soybean–pea	Soybean–wheat	—	+19; +21	Bhattacharyya *et al.* 2009
Exchangeable Ca^{2+}	Maize–faba bean–pepper	Continuous maize	15.28 vs 10.29 cmolc kg^{-1}	+48.5†	Degu *et al.* 2019
Exchangeable K^{+}	Maize–wheat–wheat	Continuous maize	2.03 vs 0.36 cmolc kg^{-1}	+464†	Degu *et al.* 2019
Cation exchange capacity	Maize–faba bean–pepper	Maize–wheat–wheat	49.47 vs 44.05 cmolc kg^{-1}	+12.3†	Degu *et al.* 2019
Available P	Maize–wheat–wheat	Continuous maize	6.09 vs 10.21 ppm	−40.4†	Degu *et al.* 2019
Dehydrogenase	Pigeon pea–wheat; maize–wheat–mung bean; maize–wheat–maize–chickpea	Maize–wheat	—	+52 to +79	Borase *et al.* 2020
Protease Alkaline phosphatase β-Glucosidase Arylsulfatase	As above	Maize–wheat	—	+5 to +51 +20 to +80 +9 to +16 +16 to +35	Borase *et al.* 2020
Soil respiration	Pigeon pea–wheat	Maize–wheat	—	+15	Borase *et al.* 2020
Disease-suppressive pmD gene	Corn–soybean–wheat + two cover crops	Monoculture	—	+9	Peralta *et al.* 2018
Weed cover	6-yr corn–soybean–wheat–hay	2-yr corn–soybean	20 vs 40%	−50†	Teasdale *et al.* 2018
Weed seedbank variance	Preceding three-year crop sequence	—	> 80% explained	—	Bohan *et al.* 2011
Herbicide use	Cereal–break-crop rotation with targeted weed control	Standard herbicide programme	—	−50	Jordan and Donaldson 1996
Potato soil-borne disease	Rapeseed in potato rotation	Without rapeseed	Incidence ↓ 10–52%	−10 to −52	Bernard *et al.* 2014
Oilseed rape yield	Two-year break	Continuous rape	3.36 vs 2.79 t ha^{-1}	+20.4†	Stobart 2011
System robustness	Most diverse 3-yr chickpea rotations	Less diverse rotations	—	+14	Li *et al.* 2019

Δ, relative change in the rotation (treatment) compared with the comparator. † Calculated from the reported means as (treatment − comparator) / comparator × 100; all other values are as reported in the source study. Semicolons separate values for the treatments listed in the same order. n.s., not significant; ↑/↓, increase/decrease; —, not reported.

Microbes can protect hosts from disease, but the mechanisms underlying their function in complex agroecosystems remain unresolved.

For instance, Zuber *et al.* (2018) found no differences in microbial activities among continuous soybean, corn–soybean and corn–soybean–wheat rotations. In another study, Wright *et al.* (2015) investigated six CRs (three potato-focused and three onion-focused) in a 10-year trial. Soils from the three potato-focused rotations had the same microbial biomass but different microbial activity parameters. Peralta *et al.* (2018) reported that CR increases microbial diversity and disease-suppressive capacity, either by influencing soil bacterial composition and plant diversity or by enhancing disease-suppressive microorganisms (Table 1).

Rotation effects on soil microbial communities are inconsistent and depend on the cropping system and the microbial parameter measured. Even so, diversified rotations

can enhance microbial diversity and disease suppression, although the underlying mechanisms need further investigation.

Overall, rotation effects on soil microbial communities are inconsistent and depend on both the cropping system and the microbial parameter measured. Diversified rotations nonetheless appear to enhance microbial diversity and disease suppression, although the underlying mechanisms require further investigation.

CROP ROTATION AND SYSTEM PRODUCTIVITY

Crop yield

Yield is probably the outcome of rotation that producers and researchers care about most. It is also a system-level result, since it reflects the combined state of the soil's physical, chemical and biological condition. As climate change adds pressure to farming systems, a further benefit of diverse rotations is drawing interest: they can make production more stable and better able to absorb shocks. Several studies illustrate this. Stobart (2011) compared oilseed rape grown in different sequences and found a clear penalty for repeating the crop. Rape sown on land that had never carried it produced 3.9 t ha^{-1}, while continuous rape managed just 2.79 t ha^{-1}. Growing it every second year gave 3.13 t ha^{-1}, and leaving a two-year gap raised this to 3.36 t ha^{-1}. In southern Sweden, Persson *et al.* (2008) followed arable rotations at three sites for 21 years, including a two-year ley phase of either pure grass or a grass–legume mix. At one of the sites, winter wheat did better when the ley

contained legumes. Wright *et al.* (2017) worked with potato and onion systems that ranged from monocultures to alternating potato–onion sequences and four-year rotations. Potatoes yielded more when they did not follow potatoes, and the four-crop rotation gave the best potato yield. Onions performed worst under continuous onion production. More recently, Li *et al.* (2019) ran three-year rotations through two full cycles, all centered on chickpea. The treatments paired chickpea with three different crops, with only one other crop, or grew it continuously. The most diverse rotations coped best with both abiotic and biotic stress, kept productivity steadier from one cycle to the next, and raised system robustness by 14%. Continuous chickpea, by contrast, ended in complete crop failure. So, across crops and environments, diversified and longer rotations raised yield and improved its stability, whereas continuous cropping consistently incurred yield penalties and, in the extreme case, crop failure.

Weed management

Crop rotation was widely regarded as an effective weed management tool even at the onset of the herbicide era, and subsequent research has largely supported this view. In an 18-year experiment comparing a two-year corn-soybean rotation, a three-year corn-soybean-wheat rotation and a six-year corn-soybean-wheat-hay rotation, mean weed cover declined with increasing rotation length, at 40%, 27% and 20%, respectively (Teasdale *et al.* 2018).

Rotation also structures weed communities in systems where herbicides are applied. Using national-scale arable datasets from the UK, Smith *et al.* (2008) reported that the composition of weed species and functional types was strongly associated with the current crop, with variation in weed assemblages between crops exceeding that within crops. They further demonstrated that contemporary weed assemblages could be predicted from the crops grown in the preceding three years, with sowing season, crop type and the weed species targeted by herbicide application identified as the principal determinants. In a factorial investigation of crop sequence, cultivar, sowing date and nitrogen supply, Froud-Williams *et al.* (1996) found that weed biomass was influenced most strongly by the two preceding crops and their interaction. For example, weed biomass in the second rotational year was greater in rape than in wheat, and greater in wheat-rape than in wheat-wheat sequences. Consistent with these findings, Bohan *et al.* (2011) analyzed farmland seedbank datasets and found that the crop sequence of the previous three years accounted for more than 80% of the variation in weed seedbanks.

Rotation can also be deployed strategically to mitigate weed problems associated with other management practices. Non-inversion tillage frequently promotes the proliferation of grass weeds. Jordan and Donaldson (1996) limited this build-up through an active rotational strategy in which cereals were alternated with break crops. Grass weeds were targeted in broad-leaved crops and broadleaf weeds in cereals, using herbicides supplemented with mechanical control. This approach achieved effective weed control while reducing herbicide use by 50% relative to a standard herbicide program. A similar approach was adopted by Jordan and Hutchinson (1996) within the LIFE project (less-intensive integrated production systems). Specific weeds were targeted in crops that permitted the use of the most effective herbicides, whereas the same weeds were tolerated in crops with fewer effective herbicide options. This improved weed management while reducing herbicide inputs. The authors also reported that the sowing date of the current crop influenced weed biomass, whereas wheat cultivar had no detectable effect.

In conclusion, rotation length and crop sequence are major determinants of weed abundance and community composition, and designing sequences around weed and herbicide options can improve control with lower herbicide inputs.

Disease management

Altering the crop sequence is among the oldest cultural practices for managing plant disease, and it remains the most effective means of controlling take-all of cereals, caused by

Gaeumannomyces graminis var. *tritici* (Kwak and Weller 2013). Chemical control of soil-borne pathogens is generally impractical, because the soil matrix physically shields the pathogens and can bind or degrade agrichemicals before they act. Rotation therefore remains one of the most effective strategies for managing soil-borne pests.

Evidence from potato and onion systems supports this. Over four years, Wright *et al.* (2017) observed that black scurf of potato (*Rhizoctonia solani*) was most severe in potato and onion monocultures and lower in potato-onion rotations. Read (1996) reported a comparable result, with double cropping of potato increasing disease symptoms caused by *R. solani*. Incorporating rapeseed (Brassica napus) into a potato rotation reduced the incidence of *R. solani*, silver scurf (*Helminthosporium solani*) and common scab (*Streptomyces scabiei*) by 10-52% in at least one year at both experimental sites (Bernard *et al.* 2014). On the basis of these outcomes, Wright *et al.* (2015) recommended four-year rotations in intensive onion and potato production to limit soil-borne disease and sustain yield.

CR is the most important practice for reducing the carry-over of biotrophic pathogens, which require living hosts and cannot survive saprophytically (Peters *et al.* 2003). It is less effective against pathogens such as *Spongospora subterranea*, *Sclerotinia* spp., *Pythium* spp. and *Fusarium* spp., which have long-term survival structures and broad host ranges (Krupinsky *et al.* 2002), and against pathogens with high population densities (Peters *et al.* 2003). However, some pathogens, such as *Pectobacterium carotovorum*, can be effectively reduced through CR (Hopkins *et al.* 2004).

Murphy (1997) reported that corn grown in rotation with potato gave excellent control of Verticillium wilt, a soil-borne disease that drastically reduces potato yield. Schwartz (2012) indicated that CR helps to overcome pathogen-infested soil and suggested that onion should be grown in a field no more than once every five years. He recommended barley as an alternative crop to onion, which not only improves organic matter but also reduces the risk of Fusarium basal rot and pink root. It is noteworthy that infestation of onion with *Phoma terrestris* and *Fusarium oxysporum* f. sp. *cepae* was reduced by rotating with non-susceptible crops for four years (Havey 1995; Sumner 1995). Peralta *et al.* (2018) determined that soil diversity under monoculture was 4% higher than under diverse CR (corn–soybean–wheat plus two cover crops). According to their findings, crop diversity increased the pmD gene (a disease-suppressive functional group) under diverse rotation by about 9% compared with monoculture. Lyu *et al.* (2020) found that fungal richness in Chinese cabbage rotation was significantly lower than in other CRs, while fungal diversity was highest under tomato cropping. They confirmed that celery rotation increased fungal richness and diversity. In contrast, Ding *et al.* (2020) found that fungal activity increased dramatically with garlic CR in an onion field (Fig. 5–6).

In summary, Rotation suppresses soil-borne disease most reliably for pathogens that depend on living hosts, and it can also enrich disease-suppressive microbial functions. Its effect is weaker against pathogens with persistent survival structures or wide host ranges, so rotation should be designed around the specific pathogens and crops involved.

CONCLUSION

Crop rotation influences soil health across its physical, chemical and biological dimensions. Diversified rotations that include legumes, forage crops or cereals generally reduced bulk density, improved porosity, hydraulic conductivity and water retention, and increased soil organic carbon, nitrogen and other nutrients, although responses varied among soils, rotations and durations: short-term trials found little effect on macroporosity, and some studies found no difference in organic carbon or microbial activity. Legume-based rotations were associated with higher N availability, exchangeable bases and enzyme activities. Longer, more diverse rotations also suppressed weeds (average weed cover of 20% under a six-year rotation compared with 40% under a two-year rotation) and soil-borne diseases, and they improved the stability of crop yields (a 14% increase in system robustness). Future research should focus on long-term, multi-site experiments that compare rotation sequences under contrasting soils and climates, and on resolving the microbial mechanisms through which rotations suppress disease and regulate nutrient cycling.

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NOVELTY STATEMENT

- Integrates the effects of crop rotation on soil physical, chemical and biological properties and on system productivity in a single review
- Compares contrasting rotation sequences using

quantitative values reported from long-term field studies

- Identifies legume- and diversity-based rotations as consistently beneficial for soil organic carbon, nitrogen and enzyme activity
- Links rotation-driven weed and disease suppression to reduced herbicide use and greater yield stability
- Highlights inconsistent responses and unresolved microbial mechanisms as priorities for future

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AUTHOR CONTRIBUTIONS

TA conceptualized the review and prepared the original draft. MN contributed to literature collection, analysis, and interpretation. YR contributed to critical review, editing, and final approval of the manuscript. All authors read and approved the final manuscript.

CONFLICT OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY

No new data were generated in this review. All data discussed are available in the cited publications.

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