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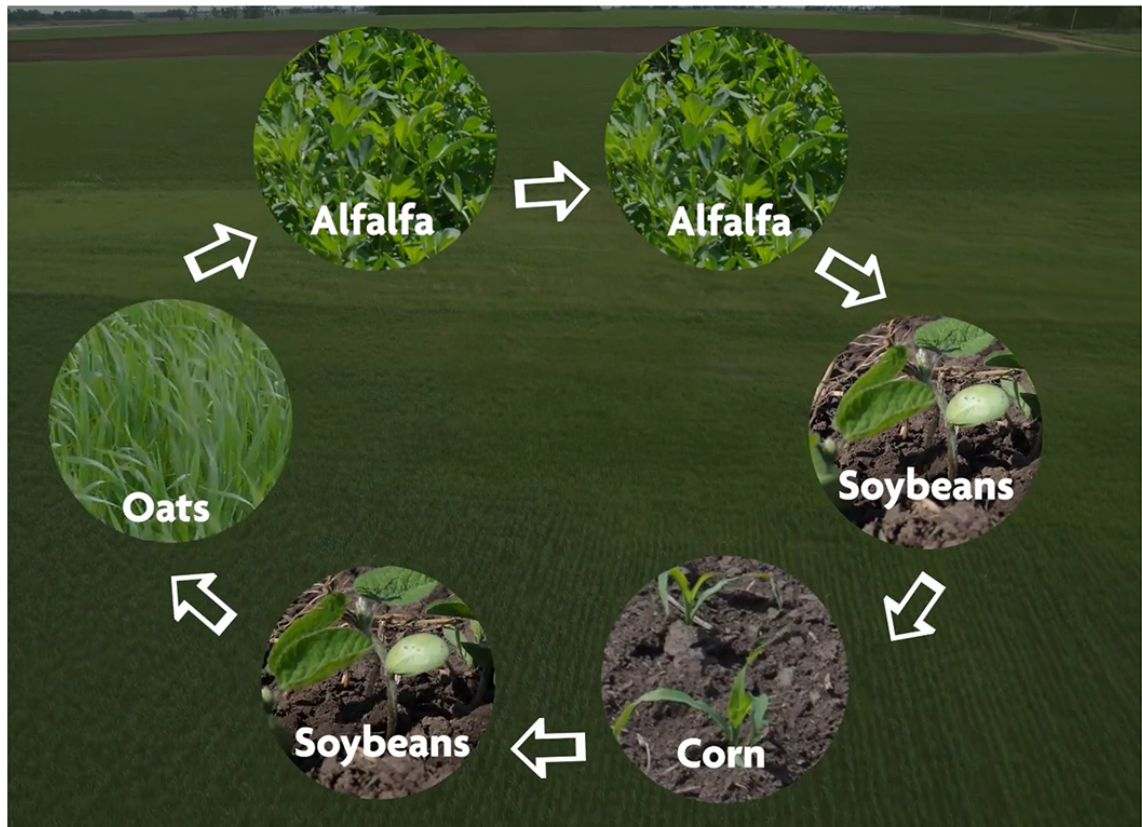
Diversified and environment-based crop rotation

A sustainable approach to enhance soil health and crop productivity

By Sumita Sen, Bala Subramanyam Sivarathri, Gustavo A. Roa, and Jovani

Demarco

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Screenshot from a video, “Managing Weeds on Your Farm,” produced by the Sustainable Agriculture Research and Education (SARE). It can be viewed at <https://youtu.be/IATeH46nQ7M>.

A diversified and environment-based crop rotation is gaining popularity as one of the best strategies in sustainable agriculture. This offers a realistic pathway to balance crop-environment interactions while improving crop productivity. Based on input requirements and microclimatic conditions such as localized topography, soil type, vegetation, and environment, diversified rotations can contribute to broader environmental benefits apart

from stabilizing crop yield for a growing global population.

In this article, we will explore why we need to investigate an environment-based diversified crop rotation, the impact on soil health with a specific focus on the plant–nutrient relationship, crop yield under diversified cropping systems, and finally, the challenges associated with developing microclimate-based diversified cropping patterns and the future of such system.

A diversified environment-based crop rotation is an integrated sustainable crop management practice for improving farm efficiency involving multiple crop species grown in the same field over time depending on soil type, climate, and ecological factors. The benefits of crop rotations are well known in long-established sustainable agricultural systems (Liu et al., 2023).

However, to harness the maximum long-term potential of crop rotations, recent research on “diversified and environment-based” cropping systems has gained momentum. A study conducted in southern Brazil revealed that, on average, farm profitability increased by 37% with species diversification compared with “double-cropped corn–soybean rotation” (Volsi et al., 2022). Factors associated with designing diversified cropping systems include climate, field size, and properties such as soil carbon (C) sequestration, soil pH, soil texture, crops grown in nearby fields, production costs, and marketability (Yang et al., 2024; Schöning et al., 2023; Liu et al., 2022;

Rosenberg et al., 2022). Diversified crop rotations enhance soil health, promote biodiversity, and increase carbon sequestration, ultimately improving crop growth and yields in the long term.

Despite these benefits, environment-based diversified crop rotations have received less attention due to multiple barriers, particularly an emphasis on a limited number of commercial crops. However, due to increasing concerns about changing climate patterns, interest in developing site-specific crop rotation strategies aligning with environmental impacts and crop productivity goals is growing.

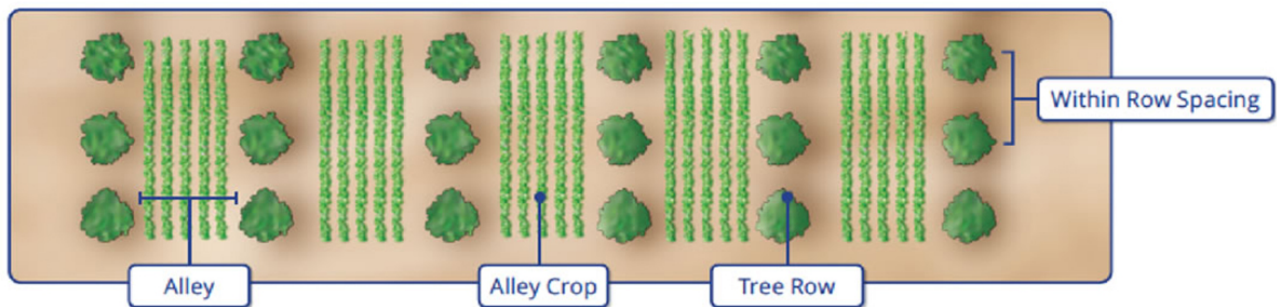
Sustainable agriculture and crop rotation

Increasing crop production for growing global population while maintaining environmental balance is challenging. For instance, in the past seven decades (from 1948 to 2021), agricultural productivity in the USA has increased nearly 188% (Wang et al., 2024) whereas the application of three major chemical fertilizer nutrients (nitrogen, phosphorus, and potassium) has increased at least 215% (USDA-ERS, 2025). According to FAO (2025), global inorganic fertilizer production in the past two decades alone increased at least 40% with nitrogen fertilizer at the top among all nutrients produced. This intensive agricultural system has emitted large amounts of greenhouse gases along with several other environmental issues such as soil health degradation, water pollution, and ecosystem damage.

Cropping system and management practices vary from region to region depending on the climatic conditions. Moreover, intensive corn and soybean cultivation throughout the central U.S. and approximately 30% of only corn or soybean monocropping for a minimum of two repeated years have led to soil degradation and water pollution (Bowles et al., 2020). Most of agriculture in the Western and Southern U.S. depends heavily on irrigation, whereas majority of the Eastern and Northern United States is

rained (Gonçalves et al., 2026).

Simulation results from rice-based systems in California show that, over time, diversified systems (such as rice–tomato or rice–legume rotations) have higher mean net present value and greater risk diversification (Rosenberg et al., 2025). While crop rotations in the Midwestern United States often focus on corn–soybean or corn–soybean–wheat systems, Ile et al. (2023) show that integrating short-rotation woody crops—such as American sycamore, eucalyptus, loblolly pine, poplar, and sweetgum—into agricultural systems can improve agroecosystem performance in the Southeastern United States, while also enhancing carbon sequestration and profitability through wood pellet markets.



Integrating short-rotation woody crops into agricultural systems has been shown to improve agroecosystem performance while enhancing carbon sequestration and profitability. Illustration courtesy of the USDA National Agroforestry Center.

Crop rotations not only balance soil nutrient dynamics, but also improve crop nutrient accessibility. In the North China Plain, candidate crops were selected based on input–output data, and local agronomists were consulted to determine rotation length; the resulting socio-economic and environmental analysis (ROTAT) formed the basis for a new crop rotation design framework (Liang et al., 2023). In Eastern Europe, similar findings have been observed, which conclude that that uniform crop rotation

strategies are insufficient for sustainability (Moldavan et al., 2024).

Soil health and nutrient dynamics

Crop rotation can influence soil health through changes in residue input, nutrient dynamics, and biological activity in the soil. Compared with monocropping, crop rotation usually provides more diverse plant residues and root growth patterns, which can improve organic matter dynamics, soil carbon storage, and nutrient cycling while supporting a more active and diverse microbial community. A global meta-analysis showed that adding one or more crops to a monoculture increased total soil C by 3.6% and total N by 5.3%, while rotations increased microbial biomass C by about 20.7% and microbial biomass N by 26.1%. When rotations included cover crops, gains were larger (McDaniel et al., 2014). These processes are closely linked since organic matter is both a product of crop residue inputs and also a driver of nutrient storage, microbial activity, and nutrient availability to plants. These interacting processes are summarized conceptually in Figure 1 (Yang et al. 2024).

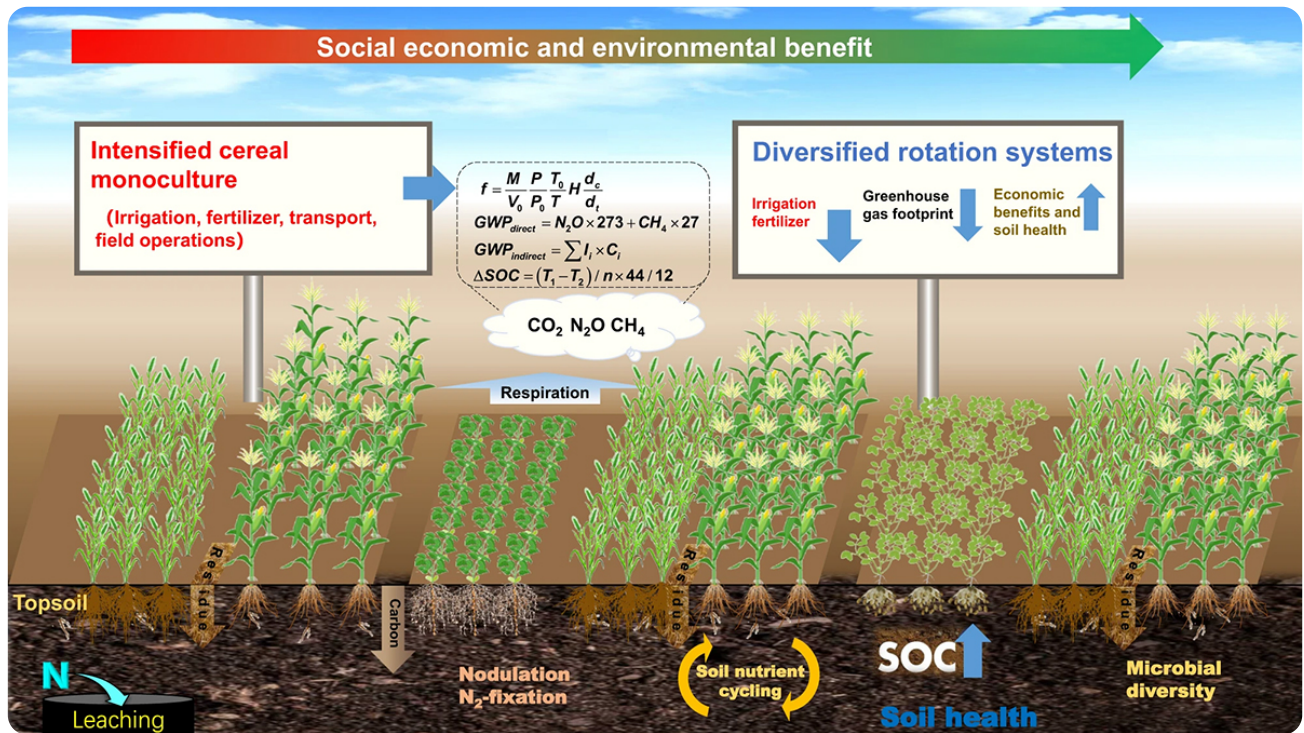


Figure 1. Conceptual diagram illustrating how diversified crop rotations influence soil health and nutrient dynamics through residue inputs, nitrogen fixation, microbial activity, and soil carbon processes. Republished from Yang et al., (2024) CC BY 4.0.

One of the main ways crop rotations affect soil health is through the quantity and quality of crop residues returned to the soil. Different crops produce residues that vary in biomass, rooting depth, carbon-to-nitrogen ratio, and decomposition rate. This increase in both the amount and diversity of plant-derived inputs has been shown to enhance soil aggregation and carbon storage. A global meta-analysis by Li et al. (2024) reported that crop diversification increased mean weight diameter (an indicator of aggregate stability) by 7.5% and bulk soil carbon by 3.3%, while macroaggregate-associated carbon increased by 12.5%. Over time, this can help maintain or increase soil organic matter, improve aggregation, reduce erosion risk, and support better water retention and soil structure.

Residue type also matters for how quickly nutrients are released back into the soil. Legume residues generally decompose faster and contribute nitrogen more rapidly, while high-carbon residues from grasses or cereals tend to decompose more slowly and can contribute to longer-term organic matter formation. For example, after one year, high C:N residues such as corn retained about 82% of their mass, whereas lower C:N residues such as sugar beet retained only about 17%, indicating much faster decomposition of low C:N materials (Chatterjee & Acharya, 2020). Because of this, diversified rotations can create a better balance between short-term nutrient supply and long-term soil carbon accumulation.

Different crops explore different parts of the soil profile and use nutrients differently. This can reduce nutrient mining from a single zone of the soil and improve overall nutrient use efficiency. Rotations that include legumes are especially important because biological N fixation can add nitrogen to the system and reduce dependence on synthetic nitrogen fertilizer. In addition, more intensive crop rotations can reduce nutrient losses since early growth of a crop can recover nutrients left behind by the previous crop, lowering the risk of nitrate leaching and improving recycling within the system. Residues also act as temporary nutrient reservoirs because as they decompose, nutrients are mineralized and become available for the next crop.



Rotations that include legumes are especially important because biological N fixation can add nitrogen to the system and reduce dependence on synthetic nitrogen fertilizer. Photo courtesy of Adobe Stock/zhang yongxin.

Crop rotation also improves nutrient availability by creating better conditions for soil biological activity. When different crops are grown in sequence, they return different residues to the soil and produce different root exudates, which helps support a more active and diverse soil community. In fact, the most diverse rotation showed significantly higher microbial activity and metabolic diversity than less diverse rotations (D'Acunto et al., 2018). This can strengthen residue decomposition, nutrient mineralization, soil structure, and overall nutrient cycling.

Impact on yield in rotational cropping system

Considering global population growth, the demand for food production has increased tremendously. To produce enough food, there is a need to reshape agricultural practices from monocropping to crop rotation, which could increase crop diversity and improve crop production. In general, a yield advantage is observed when a main crop is grown after a different crop rather than after itself, and this phenomenon is known as the “rotation effect.” Yield benefits under crop rotation may result from improved soil nutrition and biological activity; increased microbial diversity; reduced pest, disease, and weed pressure; and enhanced water-use efficiency and drought resilience.



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*Photo by Colette Kessler, USDA
NRCS South Dakota.*

Crop rotation will also benefit in enhancing the landscape utilization by growing more crops in the same landscape. This system also helps in increasing the functional diversity of agricultural land use by growing the crops in a sequential manner by

introducing annual or perennial crops, cereals, and legumes. Moreover, crop rotation helps not only to boost soil organic matter and total soil carbon, but also enhances soil water-holding capacity and water use efficiency. Furthermore, it also aids in increasing yields and yield stability. In the United States, most growers follow corn–soybean, corn–corn–soybean, and soybean–soybean–corn rotation systems (Burchfield et al., 2024).

Corn–soybean rotations are one of the most prominent crop rotation systems adopted by the growers to utilize applied nitrogen in an efficient way. This system is known to consistently boost yields compared with monocultures, especially corn. A yield benefit of 10 to 22% was observed when corn was grown in rotation with soybeans compared with monocropping of corn (Porter et al., 1997; Reidell et al., 2009; Stanger & Lauer, 2008; Wilhelm & Wortmann, 2004).

Similarly, soybean yields increased by 8–10% under crop rotation with corn compared with monocropping (Porter et al., 1997; Pederson and Lauer, 2004; Wilhelm and Wortmann, 2004). Corn rotated with soybeans has been shown to be a prominent crop rotation system compared with continuous corn. In contrast, a corn–corn rotation could yield 5 to 15% less in second-year corn compared with first-year corn (Sexton, 2019).

This may be explained by yield stabilization occurring after the third year of continuous corn. Yan et al. (2024) identified that corn yield was increased by 4.76 to 79.92% in combination with fertilizer applications and crop rotation compared with monocropping. Yuan et al. (2022) observed that corn yield was improved by 5.4% in corn–soybean–corn rotations. Similarly, soybean yield was increased by 9.7% in soybean–corn–corn rotations compared with monocultures. Beyond the traditional cropping patterns and crop rotations, there is a need to adopt/select the crops in crop rotations based on the prevailing environment to enhance the crop productivity.

Environment-based effective crop rotation

Understanding interactions among crop management practices, input optimization, and crop diversification is essential for developing location-specific, climate-resilient agricultural strategies, particularly under low-input farming systems (Kumar et al., 2026). This becomes even more relevant in modern agro-ecosystems where specialization and simplification of farming systems have led to environmental degradation (Lemaire et al., 2015). Researchers often suggest choosing multi-criteria-based methods to evaluate and select a suitable cropping plan (Dury et al., 2012).

For example, weather plays a big role while deciding crop rotations. In the Midwestern United States, corn and soybean rotation is predominant, whereas in Southeast Asia, a rice–legume rotation is common (Al-Musawi et al., 2025). Incidence of pests and diseases and soil properties of a particular region are to be taken into consideration while assessing existing cropping systems compared with the novel cropping system (Bachinger & Zander, 2007). Farmers with lower farm sizes prefer monocropping, whereas farmers with higher farm sizes tend to diversify crops, reducing both agricultural risks and production cost in general (Ghazali et al., 2016). A study in China found that crop rotations are a strategy to mitigate heavy metal concentrations in

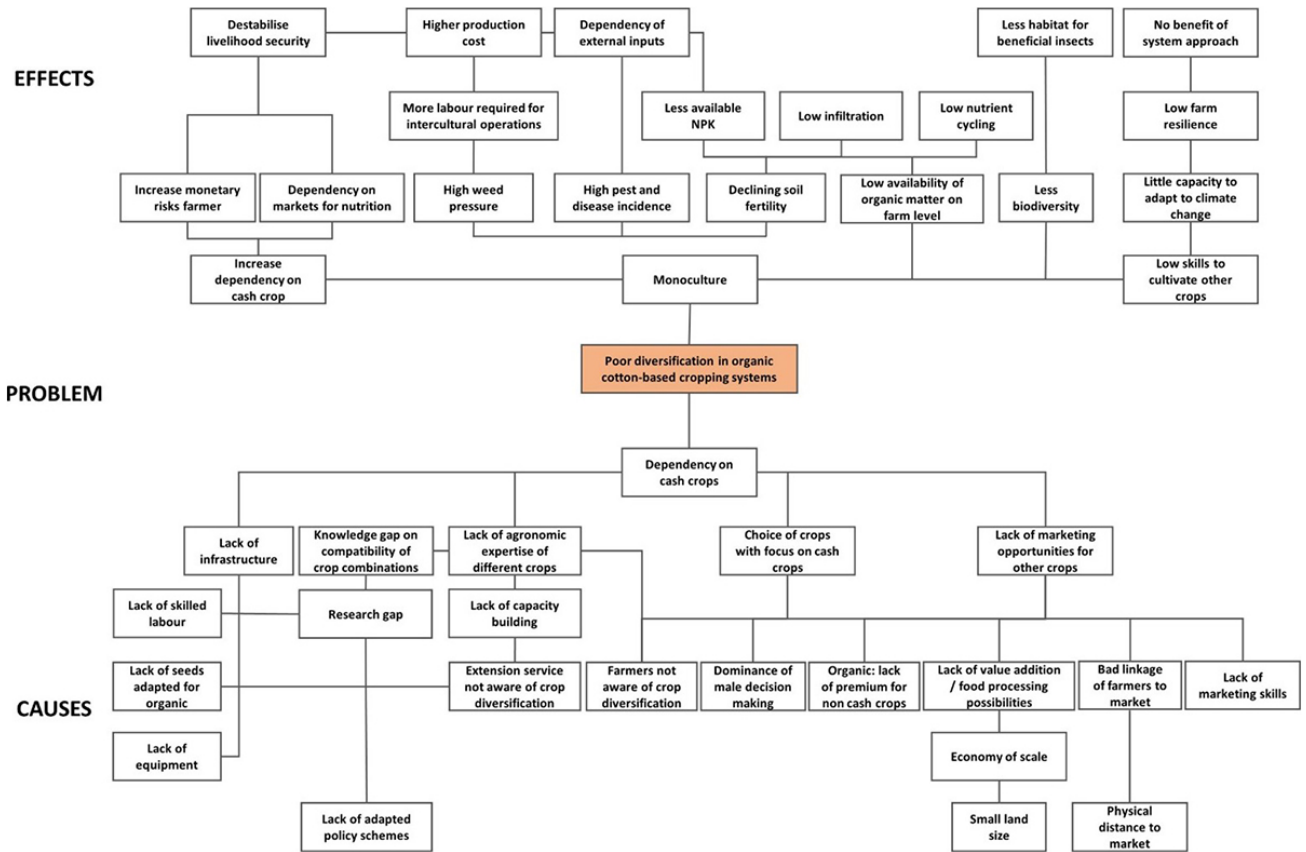
soils; a potato–rice rotation was the most effective system compared with continuous rice monocropping, which had the highest heavy metal buildup (He et al., 2021).

Moreover, the rotation system impacts micro–ecosystem and field physical properties in addition to crop productivity (Thenail et al., 2009).

Challenges and future prospects

Despite the evidence for positive benefits, adoption of diversified cropping systems is relatively low in the United States due to private–sector incentives, policies for supporting commodity crops, higher research on specific crops, and market availability for a few crops (Mortensen & Smith, 2020). Dominance of the corn–soybean system, particularly in the Midwest, is supported by strong supply chains, crop insurance policies, and federal benefits.

Moreover, farmers look for processing infrastructure and stable markets for small grains, forage crops, or other crops to diversify. Indirect effects such as improving the ecosystem of the surroundings rather than instant and direct benefits to the farmers may be another reason for slow adoption (Carlisle et al., 2026). Economic barriers in terms of higher initial costs for site–specific management and late and slow return may further complicate the adoption of diversified crop rotations.



Cause–effect framework of lower diversification rate in organic cotton-based cropping systems. Figured republished from Keller et al., (2024). [CC BY 4.0](#).

However, the prospects for diversified and environment-based crop rotations are strong. Advances in digital technologies—precision agriculture, digital decision-support tools, and research in this area—are helping to design site-specific crop rotation systems. Multi-seasonal crop planning is computationally complex; however, using integer linear programming and network-based model approaches can generate optimal cropping strategies (Benini et al., 2023).

Incentivizing practices such as cover cropping is getting popular as part of regenerative agriculture systems. The role of diversification for food production stability for climate-resilient agriculture is slowly being highlighted. These shifts

suggest that, with ongoing agricultural reforms, diversified crop rotations can play a significant role in promoting sustainable and resilient agriculture.

Conclusions

Researchers indicate that incorporation of multiple crops in a well-designed cropping system improves soil health, nutrient cycling, crop yield, and cropping system resilience while reducing external chemical inputs. Biological nitrogen fixation, pest and disease suppression, improvements in soil organic matter, and increased microbial diversity over time collectively offer a viable pathway toward sustainable agroecosystems. However, adoption of diversified rotations faces barriers through economic risks, current research gaps, and market availability. The future of environment-based diversified crop rotations depends on addressing these barriers through policy support, market availability, and research and extension services. Overall, in modern farming systems, diversified and environment-based crop rotations have the potential to be integrated as an important component to improve environmental health along with sustainability and resource efficiency.

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