*Front. Agr. Sci. Eng.*
https://doi.org/10.15302/J-FASE-2020336 Available online at http://journal.hep.com.cn/fase

PERSPECTIVE

# Soil biodiversity and crop diversification are vital components of healthy soils and agricultural sustainability

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The fast-growing world population exerts great pressure on the land to produce enough nutritious food. It is projected that global population will be 50% greater than at present by 2050 and the demand for global grain will have doubled[1]. The pressure further intensifies with the stresses resulting from climate change, associated extreme weather[2], and expansion of urbanization. Humanity has already transgressed three of the nine interlinked planetary boundaries, and agriculture is the major driving force behind this development[3]. The agricultural system must be transformed to simultaneously provide global food security and environmental integrity[4]. To address these challenges, sustainability in agriculture must be enhanced[3,5]. This is particularly true for rapidly developing countries such as China. While intensive, industrial agriculture achieved enormous successes, such as feeding 20% of the global population by producing 25% of the world's grain with less than 10% of world arable land, these achievements came at the expense of low resource use efficiency and environmental problems such as air pollution[6], water pollution[7], and soil acidification[8]. Agriculture in China is facing unprecedented challenges.

In 2017, the Chinese government proposed Agriculture Green Development (AGD) as "a national strategy of sustainable development; pursuing green development", in line with the call of the United Nations Sustainable Development Goals AGD, emphasizing the development of a more sustainable agriculture and a greener eco-environment and food industry. To realize the goals of AGD and to alleviate the deleterious effects of intensive agriculture, excessive use of external resource inputs, e.g., mineral fertilizers and agrochemicals, must be reduced and internal regulatory ecosystem processes must be promoted (Fig. 1). Ecological intensification is the strategy of choice to achieve these goals, as it focuses on managing and promoting ecosystem service-providing organisms and processes that make a quantifiable direct or indirect contribution to agricultural production[9]. The benefits of ecologically intensifying agriculture are achieved through greater reliance on biodiversity and ecosystem services[10], including the management of soils and their biota[11]. The regulation of internal soil ecosystem process has been compared to the operation and relevance of the gut microbiome in the human body[12]. Soils provide habitat to a wealth and diversity of organisms, including microbes, invertebrates and vertebrates, adding up to several thousands of species per cubic meter of soil making it one of the most biodiverse habitats on earth[13]. Plant roots, the associated microbiome, and soil microbiota interact in a multitude of ways and collectively perform multiple functions, such as the enhancement of nutrient availability, prevention of pests and diseases, carbon storage, and improvement of soil structure and water holding capacity[14]. Soil health, by definition, is the capacity of a living soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health[15]. Understanding the composition, traits and functions of soil organisms, as well as their ecological interactions, is vital for creating and maintaining healthy soils.

While it has become clear that many agricultural management practices, such as intensive tillage, fertilization, and pesticide use, lead to reductions in soil biodiversity[16,17], the resulting, potential negative effects on ecosystem

Received May 1, 2020

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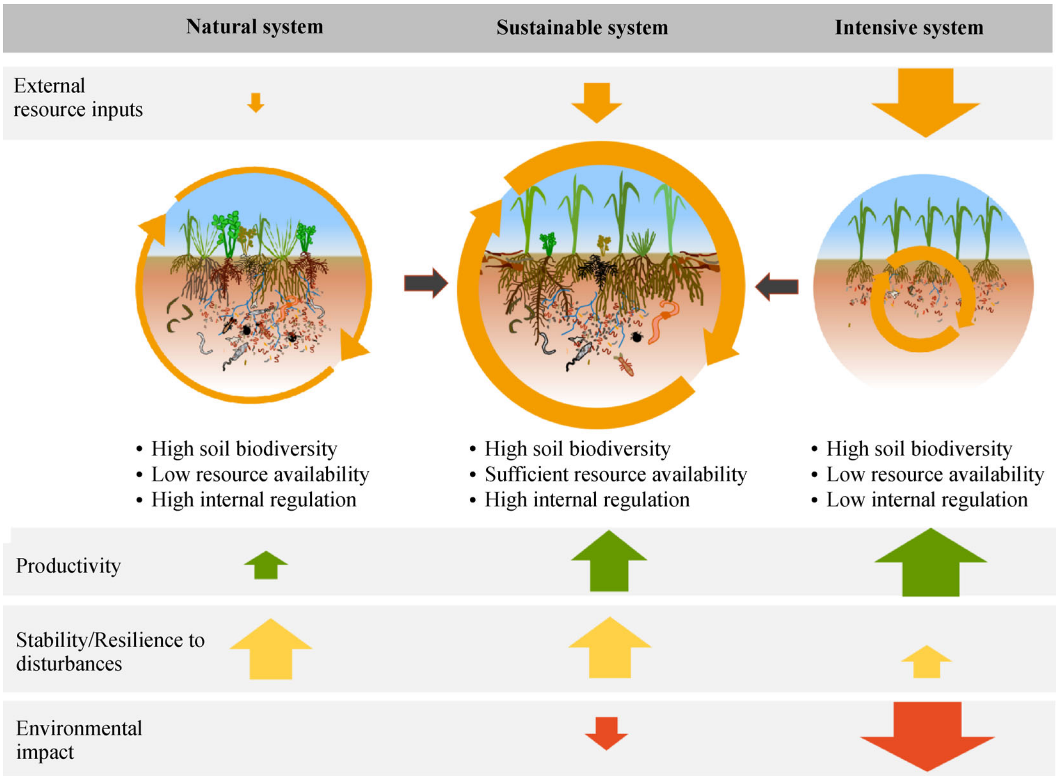


**Fig. 1** Conceptualization of a sustainable cropping system combining features of natural ecosystems (high biodiversity and high level of internal regulatory processes) with features of intensive cropping systems (high productivity) to meet the challenge of producing sufficient yields of high quality with high resilience to disturbances (e.g., climate extremes, pest outbreaks), low external resource inputs and low environmental impact.

function and service provisioning are more difficult to assess and quantify. Evidence is increasing that the functional redundancy of soil microorganisms (meaning that different microbes perform similar functions and the loss of certain taxa can be compensated by other groups) is limited and that changes in soil microbial community composition and the loss of specific species can potentially result in a loss of certain functions[18]. By using dilution and addition approaches, experimental results have demonstrated the importance of soil biodiversity per se and/or community composition for crucial ecosystem functions, such as mediating plant nutrition and growth, decomposition, nutrient mineralization and nutrient retention[19–21].

Large-scale, genetically-uniform, intensive monoculture production systems favor strong outbreaks and epidemics of pests and pathogens in agroecosystems[22] with adverse effects on food security[23]. Higher biodiversity at several levels, including soils, has been shown to reduce the emergence and damage of such pests and diseases[24–26]. Manipulation of plant microbiomes (e.g., through breeding for specific plant traits or by introducing potentially beneficial rhizosphere microbial species or species communities) could be a viable approach for reducing diseases by improving microbe-mediated pathogen suppression[27] and the plant immune system[28].

Soil communities are extremely complex and diverse, performing a myriad of functions[13]. Soil biodiversity showed stronger links with ecosystem functioning at relatively lower soil biodiversity levels and community composition showed stronger effects compared with species richness[29]. It is, therefore, suggested that a basic toolbox of organisms with certain functional traits may be sufficient to provide a basic level of internal (agro-)ecosystem regulatory processes[11]. However, due to constantly changing environmental conditions and increased emergence of extreme weather or other disturbance events, additional levels of biodiversity and functional redundancy will be required to provide species pools that can assure a biodiversity insurance effect to increase biodiversity-supported ecosystem resilience[30,31]. The level of complexity and connectedness of soil communities are important features to maintain ecosystem functioning. The connectedness of the entire soil community was shown to correspond with increased efficiency of carbon uptake by the soil food web[32]. In a recent study, soil community network complexity was positively related to several ecosystem functions simultaneously[33].

With rapid technological advances in the detection and quantification of soil organisms, the ability to fully uncover their structure, diversity and functional potential within the complex interactions between plants, soil and soil microbiota at spatial and temporal scales under natural field conditions increases. A meaningful functional characterization of soil biological communities in realistic agricultural scenarios, however, remains challenging. While molecular approaches can provide information about the taxonomic and functional potential of soil biological communities, these measures often show little direct links with actual process measurements. This is most likely related to the vast variety of biological, chemical and physical factors simultaneously acting at multiple levels[34]. Enhancing ecosystem services in high-input farming systems can be challenging and it will require novel design of the systems, both in concept and in practice. For example, through the implementation of an integrated soil-crop management framework termed the Science and Technology Backyard in China[35], approximately 21 million farmers adopted improved management practices that resulted in a 15% to 18% reduction in nitrogen fertilizer use, while yields, on average, increased by 11%.

Bender et al.[11] proposed the strategy of soil ecological engineering, a targeted manipulation of soil biological communities at different levels, from broad-scale approaches that create conditions serving to enhance overall soil biodiversity to specific manipulation of organisms, or communities with known benefits for ecosystem service provisioning to increase the sustainable intensification of cropping systems. Broad-scale approaches include adjusting soil management, crop choice, crop rotations, and spatial and temporal designs of agroecosystems (Fig. 2). This can comprise established strategies, such as conservation agriculture[36], or less well explored, but promising options, such as planting genetically diverse cultivars of the same crop in one field[24]. By increasing the spatial, temporal or genetic levels of heterogeneity in agroecosystems, such approaches will increase biological niche variations and therefore provide conditions conducive for sustaining diverse and active soil biological communities[37]. While higher soil biodiversity can enhance ecosystem stability and resilience among other benefits, approaches that are more specific might become necessary to serve the specific needs of agricultural crop production, such as high plant productivity, efficient nutrient use and low susceptibility, and/or high resistance to pests and diseases. Potential ways for more specific manipulation are the integration of plant breeding, rhizosphere microbiome engineering[38,39], and the application of biofertilizers and biocontrol. A range of biological products to enhance crop performance, such as arbuscular mycorrhizal fungi, N fixing bacteria, *Trichoderma*, among others,

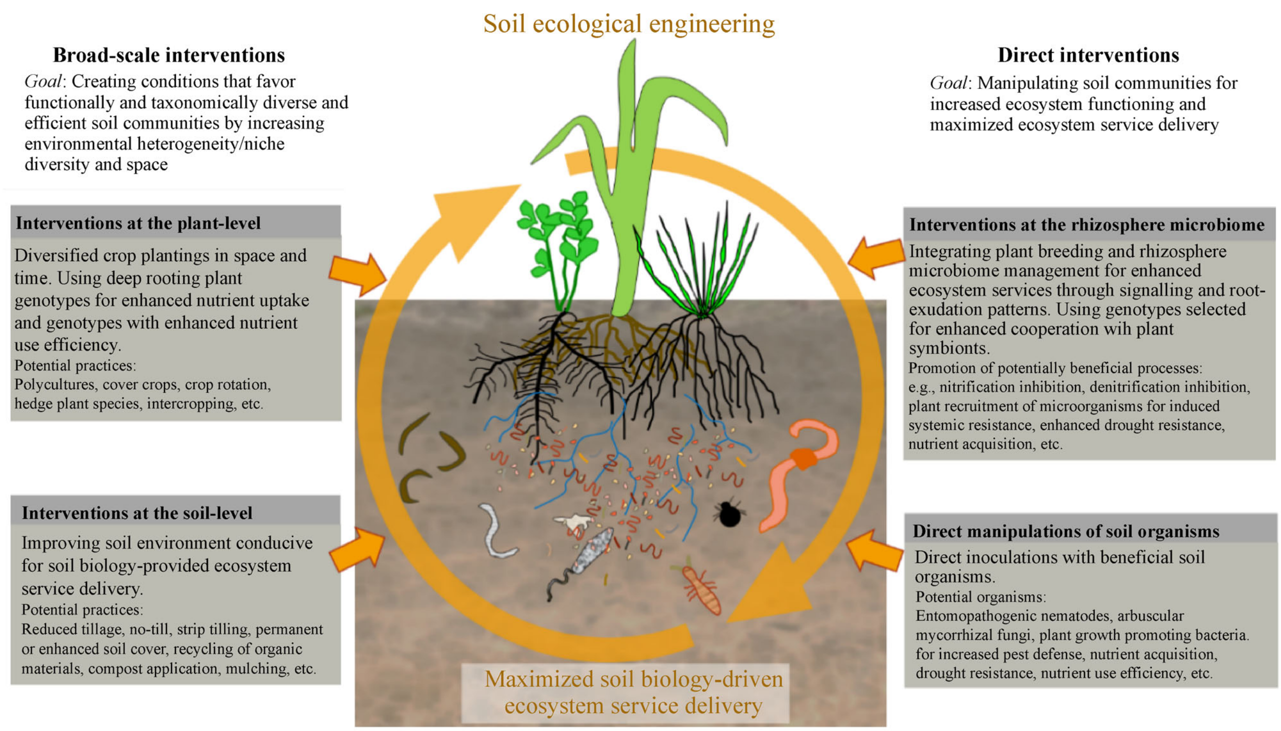


**Fig. 2** The concept of soil ecological engineering aims at maximizing soil biodiversity-driven ecosystem service delivery in cropping systems. Broad-scale interventions aim at creating conditions allowing abundant and diverse soil biological communities to thrive. Direct interventions aim at directly manipulating soil microbiomes or specific organisms in a targeted way to achieve the provisioning of certain desired functions and services.

have great potential to enhance sustainability in agriculture[40]. The specific conditions under which such products provide the desired benefits often remain elusive. Also, there is a lack of independent control of the quality and efficiency of biological products on the market. To fully unfold the potential of soil ecological engineering, specific research areas require further attention. These include an increased understanding of the mechanisms by which crops communicate with and recruit soil biological communities, and how these mechanisms can be used to enhance crop performance, as well as an increased understanding of the conditions under which targeted applications of biological inoculants can provide the desired benefits and risk assessment of their effects on native biological communities.

In addition to incorporating the strategies of soil ecological engineering, a successful implementation of the AGD framework requires attention to further specific issues. While many of the approaches proposed here focus on plant health and production, the impact on food quality needs more attention to ensure balanced and healthy nutrition of the population. The integration of livestock in crop production systems can potentially provide efficient nutrient recycling on the farm level, while the separation of animal and crop production can cause environmental pollution and increase the risk of disease transfer. Applying composted livestock manure can increase soil organic matter content and enhance the activities of soil microorganisms. Strategies for successful integration of combined livestock-crop production systems need to be developed. Table 1 summarizes specific recommendations to enhance agricultural sustainability that are directly applicable by farmers, as well as recommendations for future research and novel application strategies that require further attention. Practicality and acceptance by farmers are important for successful implementation of such management practices. These measures often increase short-term costs for farmers, while benefits may only be realized in the long term. Policy measures have to provide incentives for farmers to assure that they do not face economic hardship while converting to more sustainable management practices. For the implementation of science and technology innovations, such socioeconomic aspects have to be taken into account.

Intensified research efforts are required to be able to provide context specific recommendations and solutions to assure productive, agricultural production systems with a high level of internal, biodiversity-supported regulatory processes, little external resource inputs, and minimal environmental impact. Until the required level of

**Table 1** Specific recommendations to improve sustainability while keeping high productivity

| Specific measures for enhanced agricultural sustainability that are already known and can be applied directly by farmers | Enhancement of ecosystem services | References |
|---|---|---|
| Moderate reduction of fertiliser use and increase in manure application | Increase nutrient use efficiency, reduce nutrient loss, promoting soil fertility | [35] |
| Promotion of crop rotation | Combat the environmental costs of mono-cropping and reduce the external costs of intensive agriculture | [41–43] |
| Increased use of nitrogen fixing crops (beans, legumes) in rotations and crop mixtures | Reduce fertiliser use and reduce the footprint of fertilisation | [44]<br>[45] |
| Sowing of cultivar mixtures instead of a single genotype | Increase crop quality; enhance yield stability and resilience toward climate change, pests and weather extremes | [24] |
| Improve soil biodiversity, soil carbon storage and soil quality (reduced tillage, cover crops etc) | Promote soil health and soil multiple functioning | [36]<br>[46] |

| Recommendations for future research and implementation into practice | Facilitation of the delivery of ecosystem services by technological innovations |
|---|---|
| Addition of beneficials (e.g., mycorrhizal fungi, disease suppressive microbes, nitrogen fixing bacteria) and integration of novel biological crop protection | Reduce the reliance on pesticides and fertilisers |
| Breeding for crop cultivars with reduced nutrient requirements, e.g., deep rooting cultivars; cultivars efficient in association with mycorrhizal fungi and nitrogen fixing bacteria | Reduce the reliance on pesticides and fertilisers |
| Producing mineral nitrogen fertilisers with the help of solar panels and sun energy instead of fossil fuels; improve the ability to separate nitrogen (ammonium and nitrate) from manure | Increase energy use efficiency and minimize nutrient loss during the production process |
| Novel below-ground and above-group detection sensors; development of non-destructive measurement; potable and cheap equipment for *in situ* measurement | Precision agriculture |
| Design of genetically modified crops for disease resistance, nitrogen fixation, improved product quality | Provision of nutritious food, reduce the reliance on pesticides and fertilizers |
| Combined efforts of scientists and farmers for systematic investigation on strategies to cope with context specificity in agroecosystems[47] | Successful adaptation of practices across a variety of conditions |

understanding is achieved, scientists, politicians and farmers should refer to the increasing theoretical understanding resulting from convincing model studies, as well as the traditional and local farmers' knowledge and experiences. All necessary steps to prevent a further loss of soil biodiversity need to be taken before its enormous potential to regulate agricultural systems, as well as global ecosystem functioning, may get lost forever.

**Acknowledgements** This work was funded by the National Natural Science Foundation of China (31872182), the National Key Research and Development Program of China (2016YFE0101100), and the Swiss National Science Foundation through the 2015-2016 BiodivERsA COFUND call (31BD30-172466 and 31003A-166079).

**Compliance with ethics guidelines** Junling Zhang, Marcel G. A. van der Heijden, Fusuo Zhang, and S. Franz Bender declare that they have no conflicts of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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