Trends in Ecology & Evolution

Review

An Underground Revolution: Biodiversity and Soil Ecological Engineering for Agricultural Sustainability

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Soil organisms are an integral component of ecosystems, but their activities receive little recognition in agricultural management strategies. Here we synthesize the potential of soil organisms to enhance ecosystem service delivery and demonstrate that soil biodiversity promotes multiple ecosystem functions simultaneously (i.e., ecosystem multifunctionality). We apply the concept of ecological intensification to soils and we develop strategies for targeted exploitation of soil biological traits. We compile promising approaches to enhance agricultural sustainability through the promotion of soil biodiversity and targeted management of soil community composition. We present soil ecological engineering as a concept to generate human land-use systems, which can serve immediate human needs while minimizing environmental impacts.

Trends

Recent evidence showed that soil biodiversity supports several ecosystem functions simultaneously, underpinning its crucial role in ecosystems worldwide.

To enable the proper functioning of ecosystems, soil biodiversity has to be enhanced and maintained.

Our analysis indicates that the sustainability of agricultural ecosystems can be restored by stimulating soil life and internally regulated ecosystem processes.

To face the immense global problems related to a growing human population and deterioration of the global biosphere, targeted manipulations of soil organisms become necessary in addition to promoting soil biodiversity.

Targeted approaches through soil ecological engineering to maximize the contribution of soil biological processes to sustainable ecosystem functioning can help to provide food security while minimizing negative environmental impacts.

Soils and Ecological Intensification

Soils are among the most biologically diverse habitats on Earth. It has been estimated that 1 g of soil contains up to 1 billion bacteria cells comprising tens of thousands of taxa, up to 200 m fungal hyphae, and a wide range of nematodes, earthworms, and arthropods [1]. Land-use intensity is constantly increasing on a global scale, with adverse effects on soil ecosystems. One quarter of soils worldwide face degradation [2] and an increasing number of studies have shown that intensive land use threatens **soil biodiversity** (see Glossary), with some groups of soil biota severely affected in very intensive systems [3,4]. Simultaneously, land-use intensification and associated reductions in soil biodiversity contribute to several environmental problems, such as the eutrophication of surface water, reduced aboveground biodiversity, and global warming [5], and can negatively affect human well-being [6]. To combat the negative consequences of human land use, **ecological intensification** has been proposed as an approach to integrate ecological processes into land-management strategies to enhance **ecosystem service** delivery and reduce anthropogenic inputs [7]. However, the role of belowground biodiversity in ecological intensification has been unclear.

In this review, we apply the concept of ecological intensification to soils (Figure 1, Key Figure) and we present soil biological engineering as a concept to enhance usage of internal ecosystem processes for sustainable soil management. We first highlight how soil organisms contribute to **ecosystem functioning**, especially in their capacity to enhance a multitude of ecosystem processes simultaneously. We demonstrate that enhanced soil biodiversity and specific changes in soil **community composition** can complement each other to increase overall

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Key Figure

Schematic Model Applying the Concept of Ecological Intensification [7] to Soils

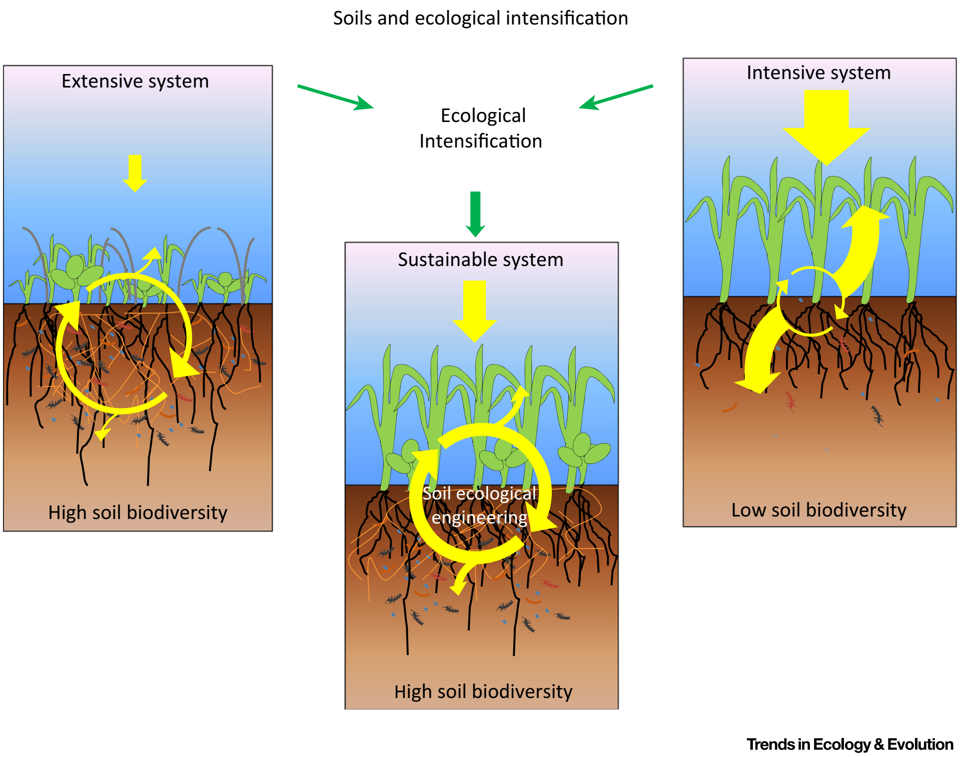

Figure 1. Yellow arrows show the relation of resource inputs, losses, and internal regulatory processes performed by soil biota (indicated by colored shapes in the soil) in relation to management intensity. The extensive system has a rich soil life and is characterized by low resource inputs and outputs, a high rate of internal regulatory processes, and low productivity. The intensive system has a depleted soil life, is characterized by high resource inputs, high losses, a low rate of internal regulatory processes, but high productivity. Ecological intensification ideally combines traits of both systems and leads to a sustainable system that has a rich soil life and is characterized by moderate resource inputs, a high rate of internal regulatory processes, low nutrient losses, and high productivity. Soil ecological engineering further optimizes the internal regulatory processes performed by soil biota to maximize ecosystem service delivery.

ecosystem sustainability and **ecosystem stability**, in terms of the long-term, environmental friendly delivery of crucial ecosystem services. Second, we show how current land-use practices and agricultural intensification affect belowground processes in positive and negative ways and, in most cases, ignore them. Finally, we present management options to foster soil biodiversity and engineer soil community composition in managed ecosystems (e.g., agricultural systems) to enhance and maintain ecosystem productivity, stability, and sustainability.

Soil Biota and Ecosystem Function

The role of soil organisms in ecosystem functioning has been long recognized and it is well known that soil biota are of pivotal importance for nutrient and carbon cycling in natural ecosystems (Figure 1). Soil fauna and **saprotrophic fungi** fragment and decompose organic matter, making organically bound nutrients available for further processing through the entire soil food web and for plant uptake [8,9]. Micropredators, such as nematodes or protozoans, further

Glossary

Arbuscular mycorrhizal fungi (AMF): soil fungi living in a mutualistic relation with most land plants and, in many cases, providing benefits to plants and ecosystems.
Community composition: proportion of different organisms relative to the total in a given habitat.
Ecological intensification: the attempt to integrate ecosystem services provided by biodiversity into crop production systems.
Ecosystem function or process: a biological, geochemical, or physical process occurring in an ecosystem.
Ecosystem multifunctionality: simultaneous performance of multiple ecosystem functions.
Ecosystem service: benefit that humans derive from ecosystems.
Ecosystem stability: the resistance and resilience of ecosystems to disturbance or stress, such as through environmental change.
Ecosystem sustainability: the ability of an ecosystem to maintain its potential for self-regulation in the long term.
Microbiome: the entity of microorganisms inhabiting a certain habitat, such as the soil or rhizosphere.
Saprotrophic fungi: fungi deriving their energy from nonliving organic material.
Soil biodiversity: the variety of living organisms inhabiting soil.
Soil microfauna: soil-inhabiting invertebrates with a maximum size of 0.1 mm.