System approach for enhancing soil health and food security- emphasizing integrated strategies for long term agricultural sustainability

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A robust approach to achieving long-term agricultural sustainability and food security involves integrating system-level strategies that enhance soil health. These strategies aim to balance productivity with environmental protection and social well-being, crucial for feeding a growing global population.

The Interconnectedness of Soil Health and Food Security

Soil is a fundamental natural resource for food production, providing approximately 95% of the food we consume. Healthy soil forms the cornerstone of sustainable agro-ecosystems, impacting agricultural production, environmental sustainability and human health. Despite producing enough food globally to feed the population, around 925 million people remained food insecure in 2010. Soil degradation, which affects about one-third of the ice-free land, exacerbates human malnutrition, impacting over 2 billion people, or about 25% of the total population. The quality of food, in terms of both quantity and nutritional value, is directly determined by soil quality. Protecting the physical, chemical and biological integrity of soil is therefore critical for safeguarding global food security. The concept of soil health encompasses its status as a dynamic process with normal ecological structure and function, including physical, nutrient, biological, environmental and ecosystem health. Anthropogenic activities, such as intensive land use and farming techniques, significantly influence soil processes, necessitating a thorough understanding of soil health. In the past, soil health assessments primarily focused on non-biological characteristics like nutrients and soil structure, but it is now recognized that soil microbes play a vital role in maintaining soil health. There is a perceived link between the health of soil, plants and humans and the cultural context also influences how soil health and food security are understood. Soil degradation, whether through erosion, salinization, or nutrient depletion, has historically led to the collapse of thriving civilizations.

System Approaches for Enhancing Soil Health

Given the complexity of agricultural systems and the need to achieve multiple objectives, system approaches and multidisciplinary assessments are essential for enhancing soil health. These methods use scientific models and information from knowledgeable stakeholders to consider the temporal and geographical aspects of agronomic systems. By integrating stakeholders, including farmers, residents and policymakers, systems approaches can improve research and implementation.

Agroecology

Agroecology is a system approach that seeks to improve soil health while reducing the reliance on synthetic inputs. This is achieved by encouraging beneficial soil organisms, recycling organic matter and increasing biodiversity. This strategy is considered an effective way to address climate change, hunger and the economic viability of rural communities. Agroecology emphasizes using local resources for soil fertility and biological control over expensive external inputs like chemical fertilizers and pesticides. It is gaining political momentum globally through the active involvement of farmer movements.

Integrated Farming Systems (IFS)

Integrated farming systems (IFS) represent a holistic approach that combines diverse cropping systems with other agricultural enterprises. This creates a stable and sustainable production system that efficiently recycles waste and crop residues, generating additional income sources for farmers. IFS activities involve interdependent production systems based on crops, animals and related ancillary professions. This approach enhances species diversity, which improves soil health, particularly organic carbon content and optimizes ecological conditions necessary for long-term production system sustainability. Furthermore, IFS helps to prevent the spread of pests and improves soil nutrient cycling. When crops and livestock are integrated, they create a synergy where recycling maximizes the use of available resources. For example, manure can be used to improve crop production and crop residues can feed animals, supplementing feed supplies and improving animal nutrition. This intensification of nutrients through livestock and by product production can enhance agricultural productivity and reduce the need for chemical fertilizers.

Conservation Agriculture (CA)

Conservation agriculture (CA) is a sustainable approach for improving soil health and food security. It includes practices like no-till farming, residue mulching and cover cropping. CA has been shown to restore soil carbon in marginal lands and improve soil properties. The adoption of CA practices can enhance soil water retention and crop productivity, contributing to household food and income security and supporting sustainable development goals. Despite its benefits, the adoption of no-till farming has been limited due to various biophysical, social and economic factors, including competing uses for crop residues.

Integrated Soil Fertility Management (ISFM)

Integrated soil fertility management (ISFM) is a crucial component of sustainable agricultural development. It involves managing soil fertility and nutrient cycles, often through the use of fertilizer trees in southern Africa and biological soil fertility management in tree-crop agroforestry. ISFM can also include green manure/cover crops to recuperate soils and maintain fertility in tropical regions and the use of compost and vermicompost as soil amendments. Balanced fertilization, combining mineral and organic fertilizers, significantly improves soil microbial diversity, community stability and functional resilience against environmental stressors. This dual approach can enhance soil structure, boost water and nutrient retention capacity and increase microbial biomass by 20-30%, fostering long-term soil fertility. Field trials have demonstrated yield increases of 25-40% in crops like rice and maize with combined fertilization, along with enhanced soil organic carbon (110.6%) and nitrogen content (59.2%). Replacing 20-40% of mineral fertilizers with organic alternatives can mitigate environmental risks such as greenhouse gas emissions and nutrient leaching while sustaining crop yields.

Integrated Strategies for Long-Term Agricultural Sustainability

Long-term agricultural sustainability requires an integrated system of plant and animal production practices that are site-specific and aim to satisfy human food and fiber needs over the long term. These practices are designed to protect the environment, expand the Earth's natural resource base and maintain and improve soil fertility. Sustainable agriculture involves balancing farm profit over the long term with the needs for healthy soil, clean water and a safe environment.

Crop Diversification and Rotation

Crop diversification and rotation are essential for sustainable land use

Including grain legumes in rice-wheat cropping systems, for instance, can improve soil organic carbon pools over time. Crop rotations reduce soil fungal diversity, which can impact the proportion of fungal pathotrophs in semi-arid agroecosystems. Long-term observations of crop-pasture rotations have shown their impact on chemical soil properties. Diverse cropping sequences can influence wheat yield and protein in semi-arid regions.

Agroforestry and Cover Cropping

Agroforestry systems contribute to soil health improvement and maintenance. They can restore degraded pasture lands through agroforestry practices. Agroforestry and grass buffers can also positively affect water quality in grazed pastures. Cover crops are another vital strategy, enhancing no-till potential for improving soil physical properties. They can also mitigate and adapt to climate change and reduce soil and nutrient runoff losses during and after corn silage production when interseeded. Cover crops play a role in improving soil and row crop productivity and increasing soil microbial diversity.

Efficient Resource Management

Efficient resource management is a key component of sustainable agriculture. This includes optimizing the use of water and land resources. Sustainable agricultural practices aim to maximize crop yield under environmentally sustainable conditions through nutrient management, site-specific nutrient management and sustainable water management. Reducing the consumption of chemicals like fertilizers and pesticides, along with improving agricultural input use efficiency, can minimize greenhouse gas emissions and protect the environment.

Integrated Pest Management (IPM)

Integrated pest management (IPM) is another crucial integrated strategy for long-term agricultural sustainability. IPM aims for optimal pesticide use, complementary weed control strategies and alternative cultural and biological controls. Implementing IPM programs can lead to economic benefits, including improvements in water quality, food safety, pesticide application safety and the long-term sustainability of pest management systems.

Challenges and Future Directions

The current food systems face significant limitations, including their failure to end hunger and malnutrition, provide sufficient nutritious food, reverse degrading environmental trends and alleviate poverty. Climate change poses an additional challenge, affecting crops, livestock, soil, water resources and agricultural workers. Soil salinization, a growing problem, further threatens ecosystems, soil health and global food security. Despite these challenges, scientific advancements since the 1960s offer innovative solutions. These include restoring soil and biophysical environments, adopting nutrition-sensitive agriculture, sequestering atmospheric carbon dioxide in soil and vegetation, using supplemental irrigation, recycling nutrients from biowaste and improving the efficiency of fertilizer and water use. The adoption of practices such as conservation agriculture, mulch farming and the integration of crops with trees and livestock (agroforestry) can lead to reduced chemical inputs, promotion of a bio-circular economy and benefits from digital innovations like precision agriculture. Future research should focus on refining fertilization frameworks through interdisciplinary approaches, addressing complex soil-crop-climate interactions and scaling sustainable practices to diverse agroecosystems. Aligning agricultural policies with ecological principles is crucial to safeguard soil health and ensure resilient food systems for future generations. Long-term agroecosystem experiments are vital for understanding and assessing agricultural sustainability and global change, providing a resource for evaluating biological, biogeochemical and environmental dimensions of sustainability. These experiments also aid in predicting future global changes and validating model performance. An international network coordinating data collection across sites would facilitate more precise predictions for agroecosystem sustainability and future global change.

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