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Soil Health Management and Sustainable Farming Practices

Dr. Rajat Meghwal

PhD (Environmental Science), CMJ University, Jorabat, Meghalaya

Abstract

Soil health management is the cornerstone of sustainable farming systems that ensure food security, ecological resilience, and environmental protection. Healthy soils integrate physical, chemical, and biological processes that regulate nutrient cycling, water retention, microbial activity, and overall agro-ecosystem stability. The paper emphasizes the importance of soil health as a determinant of agricultural productivity and ecological sustainability. It highlights indicators of soil health such as soil organic matter, microbial diversity, and nutrient availability, linking them to sustainable farming practices. Principles of sustainable farming including crop rotation, cover cropping, reduced tillage, organic amendments, integrated nutrient management, efficient water use, and integrated pest management are explored as vital strategies to restore and maintain soil quality. The study also analyzes conservation agriculture, agroforestry systems, soil erosion control, and policy frameworks supporting sustainable land use. Case studies demonstrate both successful and failed attempts at sustainable soil management, providing insights into socio-economic and ecological factors influencing outcomes. Future research directions focus on technological innovations such as precision agriculture, geospatial tools, and ecological intensification to enhance soil resilience. The findings underscore that soil health is not only central to sustainable agricultural production but also essential for biodiversity, climate resilience, and long-term human welfare.

Keywords- Soil Health; Sustainable Farming; Conservation Agriculture; Nutrient Management; Water Management; Crop Rotation; Cover Cropping; Organic Amendments; Agroforestry.

Introduction

The productivity of the land is an essential factor for the well-being and survival of the world's people. Greater productivity calls for a soil with a well-balanced supply and availability of nutrients. Nutrient imbalance can have an effect on activity of soil flora; nutrient deficiencies commonly reduce the rate of plant growth, activity of soil flora, and microbial population; nutrient toxicity or excesses may actually increase limited microbial populations or activity in the same manner as an organic substrate. "The ultimate determinant of soil quality and health is the land manager" and the "assessment of soil health will increasingly serve as a primary indicator of sustainable management". Interest in evaluating the quality and health of our soil resources has been stimulated by increasing awareness that soil is a critically important component of the earth's biosphere, functioning not only in the production of food and fiber but also in ecosystems function and the maintenance of local, regional, and global environmental quality. Soil health can change over time due to natural events or human impacts. It is enhanced by management and land-use decisions that address multiple soil functions and impaired by decisions focusing only on single functions like crop productivity. Indicators of soil quality relate to their utility in defining ecosystem processes, integrating physical, chemical, and biological properties, and their sensitivity to management and climatic variations. The ultimate determinant of soil quality and health is the land manager. The sun provides energy for photosynthesis, which fuels most life on earth. Most organisms utilize oxygen to metabolize food sources, capturing energy and recycling heat, CO_2 , and water, completing the cycle of life. Decomposition processes in soil play a key role in recycling nutrients and maintaining ecosystem health. Recent dramatic changes in agricultural development, natural resource use, and global environmental stability have increased awareness worldwide about ecosystem health and resource consumption. Meeting future food needs will require doubling crop yields due to limited new agricultural land.

Understanding Soil Health

Over the last ten years, a movement has emerged to improve soil quality and health. However, soil quality and soil health remain difficult to define, appreciate, and use because of the multitude of physical, chemical, and biological properties involved. The insight or concept of soil quality or health has been evident throughout the history of agriculture. Soil degradation often results from misguided land management practices and reflects a deterioration of soil health. In the biosphere, soils constitute a thin skin, the survival of which is essential to current and future generations, tightly linking soil management to sustainability.

Because sustainability, agriculture, and soil management are interdependent, indicators of soil quality and health should relate to ecosystem processes that the soil supports and integrate physical, chemical, and biological properties and functions. For example, soil productivity is a function of nutrient cycling; hence, an appropriate indicator would reflect important processes in nutrient cycling. Water quality provides an example that relates soil quality to food and fiber production, ecosystem function, and environmental quality. Researchers have explored relations between land management practices and surface- and ground-water quality, and the degree to which such practices appear to be demonstrably sustainable. Tillage, cropping pattern, pesticide, and fertilizer use all influence water quality, yet such practices constitute a subset of those needed to evaluate overall sustainability. Defining more comprehensive, sustainable agricultural management practices involves a holistic approach that: optimizes all soil functions; preserves and conserves water resources and biodiversity; promotes soil, air, and water quality; and encourages productivity, flexibility, and profitability. With this perspective, sustainable agricultural systems lead to improved soil quality.

The comparison of productivity on the Spodosol and Alfisol clearly demonstrated the relative advantages of raising SFS as a method of crop production on podzols compared with traditional farming techniques. Grass production was as much as 25 percent greater under SFS for individual years and a 5-year average for the two soils combined showed an increase of 50 percent in grass production over that produced under the conventional system. The SFS method produced roughly the same energy yield as that obtained from the continuous forest system except that the former system reached soil recovery by the third year whereas the latter soil was still recovering after 7 years of forest fallow.

Soil health plays a pivotal role in ecosystem function, agricultural sustainability, and the maintenance of environmental quality. Increasingly recognized as the capacity of a soil to function within ecosystem and land-use boundaries, it encompasses the productivity of the soil and the provision of needed ecosystem services. Maintaining soil in a healthy growing condition is central to achieving long-term sustainability goals in agriculture, since it serves as the interface between natural and managed ecosystems. Innovation in sustainable farming focuses on new strategies to manage key soil processes and the vegetation growing on the soil surface under a wide range of environmental and cultural conditions.

Sustainable agriculture requires practical, accessible indicators of soil health that producers can readily apply to evaluate and guide management decisions (W. Doran & R. Zeiss, 2000). A definition emphasizes strategies designed to optimize soil functions, conserve resources, and promote soil quality and health. These principles underpin efforts to maximize benefits from natural cycles, minimize reliance on non-renewable inputs, and support long-term productivity. Holistic approaches involve a framework of indicators—both qualitative and quantitative—that provide clear measures of soil condition and environmental sustainability. Partnerships with producers, as primary land stewards, are essential in developing effective assessment standards and translating science into practice (W. Doran, 2002). Because soil- and land-management practices largely determine soil quality and health, indicators for agricultural systems must therefore identify management priorities that accelerate progress toward sustainable production.

Soil Management Practices

Sustainable soil management is a key prerequisite for safeguarding food security and essential ecosystem services. Crop production and agricultural land management based on Conservation Agriculture principles—no-till seeding and weeding, maintaining soil mulch cover, and crop diversification—decisively improve the delivery of soil-mediated productivity and ecosystem services, including soil carbon sequestration and the efficient use of natural resources and external inputs, while maintaining or increasing productivity. Many conservation practices provide significant ancillary benefits as well, including protecting water quality through greater infiltration of rainfall; supporting longer-term farm productivity through increased soil organic matter and microbial activity; and reducing fuel and labor requirements by limiting tillage. Conservation Agriculture includes a range of conservation tillage strategies, including no-till, ridge-till, and mulch-till, and can be conducted successfully regardless of climate zone or crop selection. Soil management practices that maintain clean water and air require measures that keep soil in place and build soil quality; an approach based on Conservation Agriculture clearly meets these objectives as well.

Crop rotation, the practice of growing different crops on the same land in sequential seasons, has long been a cornerstone of sustainable agriculture due to its benefits for soil health. Conventional agriculture often relies on monocropping—planting the same crop repeatedly—but this practice can lead to depleted soil nutrients, increased soil-borne pathogens, and overall yield penalties. To compensate, growers depend heavily on external inputs, thereby interrupting the natural cycling of nutrients.

Cover cropping has attained a central role in sustainable agriculture worldwide. Cover crops fit into the context of crop rotation in the sequence of crops grown in a field either on a seasonal or a year-to-year basis. They are planted after the harvest of the cash crop or between rows of the main crop to cover the soil surface and resides in place to protect and improve the soil. Cover crops are typically inexpensive and non-competitive with the production of the main crop. They may be grown over a winter period or during some other period when the soil would otherwise be bare. Various legumes and small grains, such as vetch and rye, are the most common cover crops. Most farmers practice cover cropping on a small scale compared with other types of soil management. Technical information is widely available and defines optimal species, soil type and planting date, and seeding rate for maximum soil protection and nutrient benefits. Pesticides and fertilizer applications are generally minimal since these crops are rarely diseased or insect-infested. Cover crops provide a nutrient source to the following crop, reduce nitrate leaching and denitrification by holding nitrate in their biomass during the non-growing season, and protect the soil from erosion.

Reduced tillage practices can reduce expenses and environmental impacts caused by intensive tillage. Conventional tillage requires heavy machinery, increasing fuel, labor, and equipment costs, and can lead to nutrient and soil losses through runoff. Reduced tillage helps build soil structure and decrease erosion. Strip tillage cultivates a 4-6 inch strip along both sides of the row, allowing soil near the seed to dry and warm faster and till the soil deeper where the crop is planted. No-till practices use coulters to cut the soil and plant seed into the slot, with attachments to close the slot and promote seed contact. Vertical tillage lightly tills the top 2-3 inches of soil to prepare a smooth seedbed without creating tillage pans. Reduced tillage systems have been shown to improve soil health, nutrient cycling, drainage, and crop yields. At a larger scale, reduced tillage strongly influences soil organic carbon and soil bio-physicochemical properties. It also impacts greenhouse gas emissions and soil carbon stocks in cropping systems. No-tillage can stimulate carbon sequestration in agricultural soils; tillage intensity affects total SOC stocks mainly in topsoil, with long-term experiments highlighting effects on soil chemical properties. No-till soil management significantly increases microbial biomass and alters microbial community profiles. Linking macroaggregation to microbial communities and organic carbon accumulation reveals that different tillage and residue management practices influence soil structure and organic matter stabilization. Minimum soil tillage affects abiotic soil properties and microbial community composition, impacting enzyme activities and organic matter chemistry. Consequently, reduced tillage can benefit soil health and carbon sequestration. The adoption of non-inversion tillage systems also alters diesel and glyphosate expenditures, which unexpectedly improve conservation tillage economics. No-till management influences crop productivity and soil carbon sequestration, while additional organic material inputs can enhance soil carbon stocks. Socio-economic factors affect farmers' uptake of soil conservation practices in Europe. Tillage technologies considerably affect energy balance, costs, and CO2 emissions in maize cultivation. No-till practices face various challenges and offer opportunities across different European regions. Addressing soil degradation in European agriculture therefore requires appropriate practices and policies. Tillage systems additionally impact energy inputs and greenhouse gas emissions. Variation in tillage practices throughout England influences crop production systems. Soil tillage directly affects crop growth, with studies demonstrating yield responses under conservation agriculture. Comparative analyses reveal differences in profitability and performance among tillage methods. Farmer characteristics also correlate with improved farm business performance. Organic amendments involve the addition of plant or animal materials (e.g., crop residues, cover crop biomass, animal manures, composts, biosolids) to supply nutrients to soils and indirectly enhance nutrient cycling through increased microbial activity. The addition of fresh organic amendments and subsequent microbial decomposition release soil-available mineral nutrients such as ammonium, nitrate, and plant-available phosphorus (P) and sulfur (S). However, in situations where the amount of organic amendments added exceeds the microbial demand for N, ammonium and nitrate may accumulate in the soil, leading to increased nutrient loss through leaching, runoff, and gaseous emissions. Under such conditions, soil microorganisms compete intensively for other nutrients such as phosphate and micronutrients that are added in lower quantities with the amendments but are essential for microbial decomposition. This can lead to the immobilization of these nutrients until the microbial demand is satisfied. Organic amendments can be classified into mineralisable or stable amendments based on their mineral nutrients release potential.

Nutrient Management

Nutrients are the building blocks of a healthy soil and a key consideration for sustainable farming. They play a decisive role in shaping crop yield and the health of the ecosystem. Balanced nutrition under integrated nutrient management (INM) is a solution to the persistent problems of declining crop yield and multiple nutrient deficiencies in intensive cropping systems. The INM of organic and chemical nutrients on a sustainable basis is also helpful in maintaining long-term fertilizer use efficiency, soil fertility, crop productivity, and profitability without deteriorating the soil and environment. The concept of INM integrates all possible sources of plant nutrients to maintain soil fertility and to achieve sustained productivity at economical levels. Organic matter plays a central role in sustainable agriculture in terms of rebuilding degraded soils and minimizing the ill effects of excessive chemical use.

Enhancing nutrient use efficiencies may not be a new concept but its importance has been slowly realized in recent years, particularly after the introduction of precision nutrient management packages at crop and location-specific scales in rainfed production systems. Soil fertility is a growth-limiting factor in rainfed systems. Results of extensive soil fertility surveys have revealed the status of major secondary nutrients and micronutrients, and the role of fertilizer from organic sources in balanced nutrient management. The fertilizer recommendation system based on soil test has been evolved and practiced at the village cluster level by taking into consideration infrastructure, human resource, input and output market economics, farmers' field size, and above all, the associated risks, particularly for small farmers in marginal environments. The soil test-based balanced fertilizer recommendation indicates a full, half, or no dose of nutrients, depending upon the number of farms deficient in a given nutrient. The aim of fertilizer recommendations is to manage the risk by minimizing the fertilizer dose for a larger population of nutrient-sufficient farmers and enabling the nutrient-deficient farmers to harvest their optimal potential yields.

Soil is a key input in agricultural production and analysis. The adequacy of soil-plant-water management may be determined through soil testing and analysis. The goal of soil testing is to evaluate a soil's fertility and to determine the soil's limitations in order to provide recommendations for the best use of the soil. A soil sample should be representative of the field; typically, at least twenty-five to thirty samples are collected to form one composite sample. Indiscriminate sampling may cause the land manager to apply a uniform recommendation to a site that is inherently variable and, therefore, reduce crop yields or increase production costs. Routine sampling involves laboratory analysis of nutrients in soils that have been extracted with a chemical reagent solution. The extractable nutrient concentration correlates to the available (plant-usable) nutrient in the soil. A laboratory can perform quantitative analyses of primary nutrients (nitrogen, phosphorus, potassium) to determine soil nutrient status and fertility recommendations; select the optimum amount and type of fertiliser; ascertain the pH of the soil and help decide the need for liming; check secondary and micronutrient levels; and diagnose the specific nutrient deficiencies of the crops. Soil analysis on orchard sites often focuses on assessment of a few critical macronutrients and the supply of nitrogen.

Soil fertility management forms the foundation of sustainable agriculture and is a major factor limiting crop production and income in many tropical countries. Fertilizer use represents a significant investment, especially the use of improved seeds and agrochemicals. Low fertilizer-use efficiency is typical of most Ethiopian farming systems, a consequence of the complex interactions among soil erosion, crop management, and limited input use. Proper fertilizer management can increase crop and land productivity by improving the nutrient balance at field, farm, and watershed levels. Integrated soil fertility and plant nutrient management is an approach that aims to maximize fertilizer-use efficiency and optimize crop production in a sustainable manner. The key component of ISFM is the development of strategies to enhance fertilizer-use efficiency through factors affecting nutrient availability and use, such as crop varieties, soil moisture, and agronomic practices. Although the 'double green revolution' promises to address multiple constraints simultaneously, poor soil fertility remains a significant challenge. The central challenge for filling the yield gap among smallholder farmers lies in the right placement of appropriate technologies designed to help manage for maximum fertilizer-use efficiency under diverse farming systems.

The debate between organics and synthetics in agriculture has been framed largely by immediate effects and anecdotal assessments, often remaining inconclusive. Fertilizers are applied to meet the nutrient demand of crops, but a vast proportion can become lost in the environment through surface runoff and leaching, volatilization, and denitrification. Organic farming systems have a propensity to make greater use of fertilizers, at least in the transitory period from conventional to sustainable. The extensive use of organic amendments can be responsible for mineral nitrogen leaching, induced by nitrogen mineralization, excessive water supply, surface agriculture, and salinization of soils. Synthetic fertilizers are very soluble and dissolvable in water and can persist from a few hours to some months if the uptake of nitrogen by plants is not rapid enough, leading to considerable losses to the field. The surface soil layer can also affect nitrogen losses—typically, losses decrease as the soil texture gets heavier. Carbon mineralization produces nongaseous components that can fix nitrogen, sulfur, and phosphorus and make them unavailable to plants. Potentially, a combination of synthetic and organic fertilizers could decrease the amounts of nitrates leached during the transition period from conventional to organic.

Pest and Disease Management

Pest and disease management is an integral component of sustainable farming. Integrated Pest Management (IPM) and biological control techniques reduce reliance on chemical pesticides. Appropriate methods selected according to pest identity and severity of outbreak play a significant role in improving soil ecosystem health while reducing potential negative impacts of pesticide contamination.

Integrated Pest Management (IPM) minimizes the use of chemical pesticides through more environmentally sensitive approaches, benefiting the biological and economic functioning of the soil and reducing the potential development of harmful resistance among insect populations. Effective management of pests and diseases is imperative to sustainable agriculture and can be achieved through a variety of environmentally sound systems that employ both physical and biological controls. Sustaining the viability and efficiency of these controls requires minimizing the use of agrochemicals that would otherwise destroy beneficial species in the soil and on the surface of the crop plant or its fruit. "The objective of control is not to 'eliminate' but to keep the target organisms below thresholds of economic damage or social nuisance". An integrated pest-management strategy seeks to prevent outbreak of a pest or disease by carefully cultivating and maintaining a healthy soil and crop. It then combines biological controls, cultivation techniques, and informed, selective chemical applications to reduce the level of damage to one that is economically sustainable and socially acceptable.

With rising human population and awareness of the harmful effects of chemical pesticides, biological control strategies have gained increasing attention. Biological control is a non-chemical pest- and pathogen-management technique particularly suited for organic and sustainable cultivation. It is environmentally safe, sustainable, economically viable, and highly specific. Certain species of soil microbes can inhibit the growth of or kill various pests and pathogens, although an understanding of the interaction of the plant with the pathogen as well as environmental conditions—temperature, soil moisture, soil pH, microbe availability—is necessary before the practice is implemented. The ultimate aim of biological control is to reduce the abundance of harmful species, while simultaneously encouraging the growth of beneficial crops, insects, and microbes. Successful biological control revolves around interactions between plants and microbes in the rhizosphere and phyllosphere that minimize disease and control pests. Organisms capable of effective biocontrol are often sourced from the environment but may also be introduced from outside. The biocontrol of pathogens and pests is generally more effective when a consortium of microorganisms displaying collaborative properties is employed rather than a single organism. Besides the application of microbes, the use of plant extracts, biofertilizers, biopesticides, natural enemies of pests, and gene products from microorganisms and plants also plays a significant role in biological control.

Economic Aspects of Sustainable Farming

Increasing awareness of the challenges facing the agricultural sector has stimulated interest in sustainability and alternative farming systems. A comprehensive farm-level analysis must incorporate both agronomic and economic considerations in evaluating alternative systems. Successful adoption of sustainable finance requires a clear understanding of the associated costs and benefits. There are additional economic advantages to producing sustainable products, as indicated by reports of market premiums paid for sustainably produced goods.

In recent years, there has been increasing interest in the environmental benefits of Climate-Smart Agricultural (CSA) practices. A cost–benefit analysis of investments in CSA practices in Ghana over 2017–2027 was performed using the Economic Surplus Model (ESM). One key aspect of this modelling tool is the ability to estimate external effects from an increase in productivity, yield, or income. External effects of CSA practices include benefits on-farm biodiversity, soil biodiversity, carbon sequestration, and the reduction of soil erosion and greenhouse gas emissions. These externalities were valued by assessing changes due to CSA practices and applying shadow prices as proxies for societal willingness to pay. Various methods are employed to estimate shadow prices, depending on the external effect concerned. When shadow price ranges exhibit high uncertainty, Monte Carlo simulations are undertaken using Risk to account for risks and to identify optimal decisions.

External effects related to soil erosion, soil biodiversity, carbon sequestration, and social impact are linked to practices such as minimum tillage, mixed cropping, integrated nutrient management, crop rotation, and supplementary feeding. Minimum tillage enhances soil fertility and supports low soil loss. Mixed cropping and the presence of shrubs and trees within crop land contribute to increased plant diversity. Integrated nutrient management typically fulfills nutrient requirements without incurring excessive soil acidity. Crop rotation further bolsters soil fertility and increases plant diversity. Additional social impacts associated with these CSA practices include employment creation and the mitigation of greenhouse gases.

The market for sustainable products offers opportunities for the agri-food sectors. Sustainable production practices can sometimes entail a higher level of effort and care; however, farming at the lowest possible level of inputs does not serve the multiple purposes involved. Although the functional properties of a healthy soil are well understood, in practice it is easily overlooked what is necessary to achieve and sustain healthy agricultural soils. Crop production and agricultural land management based on the principles of Conservation Agriculture have proven to improve decisively the delivery of all soil-mediated productivity and ecosystem services, including soil carbon sequestration, the efficient use of natural resources and external inputs, and thus improved cost efficiency and profit, while maintaining or increasing productivity. Soil management for correcting fertility levels has also proved an effective technology to improve productivity levels and livelihoods.

Future Trends in Soil Health Management

Soil health will continue to be a major research topic in sustainable land management. Future efforts may expand current information networks on soil, human health and other sustainability factors; synthesize data to develop interpretive frameworks; and strengthen communication between researchers, educators and farmers. A new GAIA Center concept will continue to emphasize ecosystems as a framework for integrated land and water management, with soil at the core of terrestrial health and function. Broadening long-term comparative studies of traditional and new crops under organic and conventional practices—and linking them to native plant communities—will generate insights into how species and technologies shape restorative potential. The ability to measure multiple soil functions will improve the development and interpretation of site-specific soil quality indicators to guide practices. Building mechanistic understanding of linkages between soil properties, processes and ecosystem functions will play a major role in the sustainable intensification of production and the enhancement of soil and landscape biodiversity. Effective implementation of sustainable policies also requires improved educational outreach that translates current knowledge of soil-plant-animal-human interrelationships into practical land stewardship.

Innovations in technologies and processes explicitly designed to promote sustainability offer the most hopeful prospects for the future of sustainable agriculture. The term "sustainable intensification" indicates the existence and utility of such innovations. Several technical options are already widely available and potentially fruitful for improving the efficiency of resource use. These include precision guidance and steering systems, optical sensing, and computer modeling of variable rates of fertilizer application. On-board yield monitors combined with on-farm analysis of spatial data acquired through global positioning systems (GPS) provide feedback for calibrating enterprise budgets on a much finer degree of scale. The challenge for sustainable agriculture is to convert technological possibilities into practical realities and to ensure that increases in technical efficiency translate into enhancements of sustainability.

Research priorities addressing soil health and sustainable farming are diverse, encompassing educational outreach, vision, future research, and pilot ecosystem studies. Education goals include teaching about ecological interactions, human impacts, environmental restoration, and sustainable land use. Approaches comprise assembling resources on soil, health, and sustainability; synthesizing new information with social, economic, and environmental dimensions; and expanding information networks. An ecosystem-based framework guides research and land management, with soil providing the structural foundation. Comparative studies of traditional crops under various technologies and conditions, alongside natural areas, support a multifunctional strategy for monitoring and assessing soil ecosystems. Site-specific soil quality indicators and improved understanding of soil processes are critical for sustaining productivity, biodiversity, animal and human health, and environmental quality. There is a need to connect soil quality with societal health, environmental degradation, and ecological production systems, stabilize key soil attributes, and clarify their relationships to ecosystem functions at multiple scales. Translating knowledge into sustainable land-management practices and outreach through extension programs are essential elements.

Key areas for future exploration include maintenance of soil productivity and amelioration of physical and chemical constraints; measures to maintain biodiversity and promote disease suppression; and risk assessment of contaminants and their pathways into the environment. Sustainability assessments should be set in a global context, considering climate change, population growth, and increased demands on resources and technological capacities. Emerging technologies that deserve focused investigation encompass geospatial information systems (GIS), remote sensing, global positioning, metagenomics, stable isotopes, risk assessment and modeling, as well as decision-support systems integrating satellite and other data sources.

Conclusion

Society's best hope for a sustainable, abundant, nutritious, and economical food supply lies with the development of sustainable land management systems for Earth's limited resources. Practically, ecological, or sustainable agriculture relies on advances in agroecology that describe biological or physical processes operating in soil or plant and animal communities. Research with particular emphasis on soil biology, nutrient cycling, and plant–soil–water relations has identified sustainable approaches that optimize productivity, protect soil and water resources, and enhance economics and social equity. Field evaluations of reduced tillage, cover crops, diversified rotations, and efficient nutrient and water management demonstrate the value of ecological principles for both crop and animal production systems. Ecological approaches assist in dealing with increasingly complex uncertainties from regulatory, environmental, and social perspectives. Improvements in basic understanding underpin continuing development of sustainable systems and protect the integrity of terrestrial and aquatic ecosystems. A shift in emphasis from agricultural chemistry to agricultural ecology and a coupled increase in interdisciplinary and interinstitutional collaboration and long-term studies will speed development and implementation of sustainable systems.

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