

Peer Reviewed Article

Integrating Soil Functions for Sustainable Agriculture: Addressing Food Security, Climate Change, Biofuels, Water Resources, and Waste Management

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Abstract

This review investigates the pivotal role of soil functions in the context of sustainable agriculture and its multifaceted impacts on food security, climate change mitigation, biofuel production, water resources, and waste management. Soil, a cornerstone of agricultural systems, serves as a nexus for numerous critical functions including nutrient cycling, water retention, carbon sequestration, and waste degradation. Understanding and harnessing these functions are paramount in addressing pressing global challenges. The paper explores how sustainable soil management practices directly influence food security by enhancing crop yield and quality. Furthermore, it delves into the pivotal role of soil in climate change mitigation by elucidating its carbon sequestration capabilities and its potential to reduce greenhouse gas emissions. Additionally, it examines the intricate relationship between biofuel production and soil health, emphasizing sustainable approaches that prioritize soil preservation. The discussion extends to the vital role of soils in water resource management, focusing on their ability to retain, purify, and conserve water. Moreover, it highlights the significance of soil in waste management practices such as composting and waste bioremediation, contributing to both waste reduction and soil fertility improvement. Throughout the review, challenges in implementing sustainable soil management practices are addressed, presenting opportunities for innovation and policy development.

Keywords: Soil functions, food security, sustainable agriculture, biofuels, climate change, waste management.

Introduction

During the 19th century and the first half of the 20th century, soil management goals primarily aimed at sustaining agronomic productivity to meet the food requirements of a global population significantly smaller than today's. However, the demands placed on soil resources have drastically evolved in the densely populated and rapidly industrializing world of the 21st century. In contrast to the past, contemporary societies exhibit insatiable needs for energy, water, timber, and expansive land areas essential for urbanization, infrastructure, and effective waste disposal. There is an urgent need to address rural poverty and improve living standards for subsistence farmers. At the same time, critical environmental issues like climate change, water contamination, and biodiversity loss require immediate action.

The management of soil resources has been a cornerstone of agricultural practices throughout history, adapting in response to evolving societal needs and environmental challenges. During the 19th century and the first half of the 20th century, the primary focus of soil management was directed towards meeting the food demands of a global population significantly smaller than the present-day numbers. Agronomic techniques aimed at sustaining productivity were pivotal in ensuring adequate food supplies for a world that was less densely populated and had yet to witness the rapid industrialization and urban expansion characteristic of the 21st century.

However, the current era stands witness to an unprecedented surge in global population, technological advancements, urbanization, and an increasingly intricate web of interconnected challenges. The demands placed on soil resources have transcended the realm of mere food production to encompass a spectrum of societal, environmental, and economic requisites. Today, soils are expected to support not only burgeoning food needs but also serve as the bedrock for energy production.

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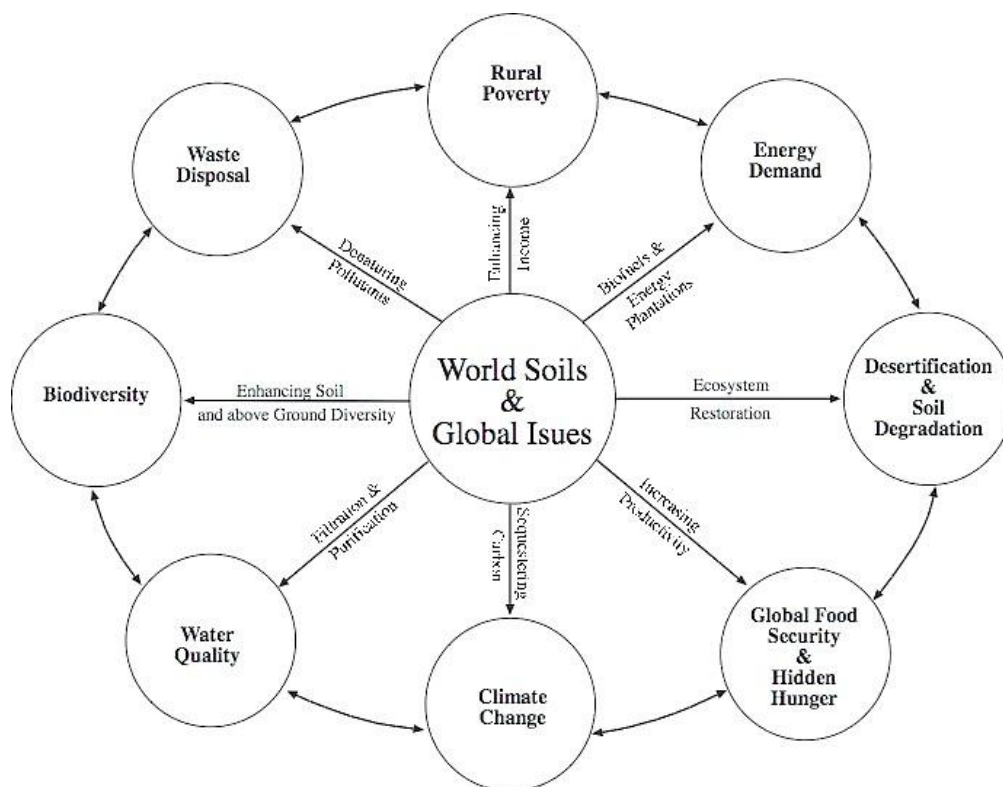


Figure 1. World soils and global issues of 21st century

In this rapidly changing landscape, the traditional goals of soil management have undergone a profound transformation. The demands on soil resources are no longer limited to agricultural productivity alone but encompass a multitude of challenges. Contemporary societies grapple with the imperative to simultaneously address rural poverty, elevate the standards of living for subsistence farming communities, and confront an array of environmental crises. The need to mitigate climate change, combat eutrophication and water contamination, arrest land degradation and desertification, and halt the alarming loss of biodiversity has reached a critical juncture. In the face of these multifaceted challenges, the importance of sustainable soil management emerges as an imperative solution. It becomes increasingly evident that the solutions to these complex issues are intrinsically linked to the judicious and sustainable management of the world's soil resources. This comprehensive review endeavors to navigate through the historical trajectories of soil management, juxtaposing past goals with the contemporary challenges of the 21st century. It aims to shed light on the critical role of sustainable soil management practices in addressing the pressing needs of a rapidly changing world, emphasizing the necessity of integrating cutting-edge scientific advancements into agricultural practices for a sustainable and resilient future.

Advancing Food Security

The global population, which stood at a mere 0.2 billion in ancient times, grew by only 0.11 billion (reaching 0.31 billion) over the course of the following millennium

until 1000 AD. However, in the subsequent 1000 years leading up to 2000 AD, this number surged dramatically by 20-fold, hitting 6 billion. Projections estimate a further increase to 9.4 billion by 2050 and a subsequent rise to 10 billion by 2100 (Fischer and Heilig, 1997; Cohen, 2003). A noteworthy trend in future population dynamics is that the entire anticipated growth of approximately 3.5 billion people is anticipated in developing regions of Asia (mainly South Asia) and Africa (largely sub-Saharan Africa). These areas face challenges due to limited soil resources per capita, susceptibility to both natural and human-induced disruptions, and the looming risks posed by projected climate changes and increased demographic pressures. Consequently, any future advancements in agricultural and food production must primarily focus on enhancing productivity per unit of land, time, and input (such as nutrients, water, and energy) already dedicated to agriculture. Within this framework, the development and identification of innovative soil management methods become pivotal in ensuring the sustenance of a global population of 10 billion. These methods need to minimize losses by efficiently delivering nutrients and water directly to plant roots during critical crop growth stages.

Rehabilitating degraded and desertified soils is crucial, involving strategies to enrich the soil organic matter (SOM) pool, establish a balanced elemental supply of all essential nutrients, effectively combat soil erosion caused by water and wind, rebuild soil structure and quality through biological activity, and promote diversity among soil fauna and flora species. Soil man-

agement techniques must be chosen to ensure: (i) liberal use of crop residues, animal dung and other biosolids, (ii) minimal disturbance of soil surface to provide a continuous cover of a plant canopy or residue mulch, (iii) judicious use of sub-soil fertigation techniques to maintain adequate level of nutrient and water supply required for optimal growth, (iv) an adequate level of microbial activity in the rhizosphere for organic matter turnover and elemental cycling, and (v) use of complex cropping/farming systems which strengthen nutrient cycling and enhance use efficiency of input. Identification, development and validation of such innovations must be based on modern technologies such as GIS, remote sensing, genetic manipulations of crops and rhizospheric organisms, soil-specific management, and slow/time release formulations of fertilizers. Increase in crop yields must occur in rainfed/dry farming systems which account for more than 80% of world's croplands. Breaking the agrarian stagnation/deceleration in sub-Saharan Africa must be given the highest priority by soil scientists and agronomists from around the world. While expanding irrigated agriculture is important, crop yields have to be improved on rainfed agriculture in Asia and Africa, by conserving or recycling every drop of rain, and by not taking soils for granted.

Biofuels

When viewed through the lens of future generations beyond 2100 AD, the period from 1750 to 2050, known as the industrial era, will likely be remembered as the Carbon Age or Carbon Civilization, in stark comparison to the Stone Age or Bronze Age. The pervasive use of fossil fuels since the onset of the industrial revolution in 1750 has significantly disrupted the global carbon cycle, leading to consequential impacts on climate change, escalating temperatures, and shifts in rainfall patterns. Presently, our civilization heavily relies on carbon, necessitating substantial rehabilitation efforts.

To break free from this carbon dependency, the development of carbon-neutral or non-carbon fuel sources becomes imperative, and both soil science and agronomy emerge as pivotal players in this pursuit. Efficient utilization of recommended agricultural practices (such as fertilizers, pesticides, tillage methods, and irrigation) is essential. Furthermore, meeting future energy demands will inevitably involve transitioning to non-carbon fuels, with hydrogen standing as a promising candidate. Hydrogen production from biomass generated through appropriate land utilization and thoughtful cropping/farming systems is a plausible avenue. In the interim, modern biofuels like ethanol and biodiesel can significantly mitigate greenhouse gas emissions, curbing the rise in atmospheric CO₂ concentrations (Brown, 1999; Cassman et al., 2006). However, the conversion of grains, such as corn, into ethanol is deemed inefficient in terms of energy production. Given the high demand for grains as

essential human food staples and livestock/poultry feed, this inefficiency poses challenges and necessitates alternative strategies.

Crop residues are also being considered as a source of energy (Somerville, 2006; Service, 2007). Indeed, one Mg (1t) of lignocellulosic residues is equivalent to 250–300 L of ethanol, 15–18 GJ of energy, 16 106 kcal or 2 barrels of diesel (Lal, 2005; Weisz, 2004). The energy return on investment (EROI) for grain-based ethanol is low. Furthermore, crop residues (of corn, wheat, barley, millet, rice) must be used as soil amendment/mulch to control erosion, conserve water and replenish the depleted SOM pool through soil C sequestration, and restore degraded soils and ecosystems (Wilhelm et al., 2004). Crop residues must not be considered a waste, because they have multifarious but competing uses including conservation of soil and water, cycling of nutrients, enhancement of the use efficiency of fertilizers and irrigation water, and above all, as a food of soil organisms which are essential to making soil a living entity. Using crop residues for production of biofuels is “robbing Peter to pay Paul” and all that glitters is not gold, not even the green gold. The price of harvesting crop residues (such as from the U.S. Corn Belt) will be severe soil and environmental degradation (dust bowl), because there is no such thing as a free lunch. It is, thus, important to identify dedicated crops which can be grown to establish biofuel plantations (Tab. I). Furthermore, new lands (agriculturally marginal/surplus soils; and degraded, disturbed and polluted soils) must be identified to establish appropriate biofuel plantations. In addition to providing the lignocellulosic biomass for conversion to ethanol, establishment of biofuel plantations on degraded soils would also lead to soil C sequestration and enhance soil quality and the ecosystem services that it would provide. The EORI of biofuel production system must be carefully assessed through a comprehensive life cycle analysis. In addition to establishing managed biofuel plantations, lignocellulosic biomass can also be harvested from natural vegetation growth on abandoned/set aside or fallowed land (Tilman et al., 2006). The issue of using crop residues for cellulosic ethanol production must not be resolved on the basis of short-term economic gains. The rational decision must be based on the long-term sustainable use of natural resources (Figs. 2, 3). Indeed, the immediate needs for fuel must not override the urgency to achieve global food security, especially for almost 1 billion food-insecure people in Africa and Asia. If the crop residues harvested for ethanol production are not returned as compost (with enhanced plant nutrients such as N, P, K), the long-term adverse impacts on soil quality (such as has been the case in severely degraded soils of sub-Saharan Africa and South Asia due to perpetual removal of crop residues) will jeopardize global food security and set-in-motion the soil degradation spiral with the attendant impact on social unrest and political instability (Fig. 4).

Table I. Species for establishing biofuel plantations.

English Name	Botanical Name
Warm Season Grasses	
1. Switch grass	<i>Panicum virgutum</i> L.
• Big blue stem	<i>Andropogan gerardi</i> , Vitnam
• Indian grass	<i>Sorghastrum nuttans</i> L. Nas
• Blue giant grass	<i>Calanagrostis Canadensis</i> Michx Bean L.
• Guines grass	<i>Panicum Maximum</i> L.
• Elephant grass	<i>Pennisetum perpereum</i> schm.
• Kallar/Karnal grass	<i>Leptochloa frscha</i> L.
• Molasses grass	<i>Melinis minutiflona</i>
• Reed canary grass	<i>Phalaris arundinacae</i> L.
• Cord grass	<i>Spartina pectinata</i> Link.
2. Short Rotation Woody Crops	
• Popalar spp	<i>Populus</i> spp.
• Willow spp	<i>Salix</i> spp.
• Mesquite (Velayti Babul)	<i>Prosopis juliflora</i>
• Miscanthus	<i>Miscanthus</i> spp.
• Black locus	<i>Robinia pseudoacacia</i> L.
• Birch	<i>Onopordum nervosum</i>
3. Halophytes	
• Pickle weed	<i>Salicornia bigelovii</i>
• Salt grass	<i>Distichlis palmeri</i>
• Salt brushes	<i>Atriplex</i> spp.
• Algae	<i>Spirulina geitleri</i>
4. Drought Tolerant Trees	
• Gum tree	<i>Eucalyptus</i> spp.
• Leucaena (Subabul)	<i>Leucaena leucocephala</i>
• Casurinas	<i>Casurina equisetifolia</i>
• Acacia	<i>Acacia</i> spp.
• Teak	<i>Tectona grandis</i>
• Cassia	<i>Casia siamea</i>

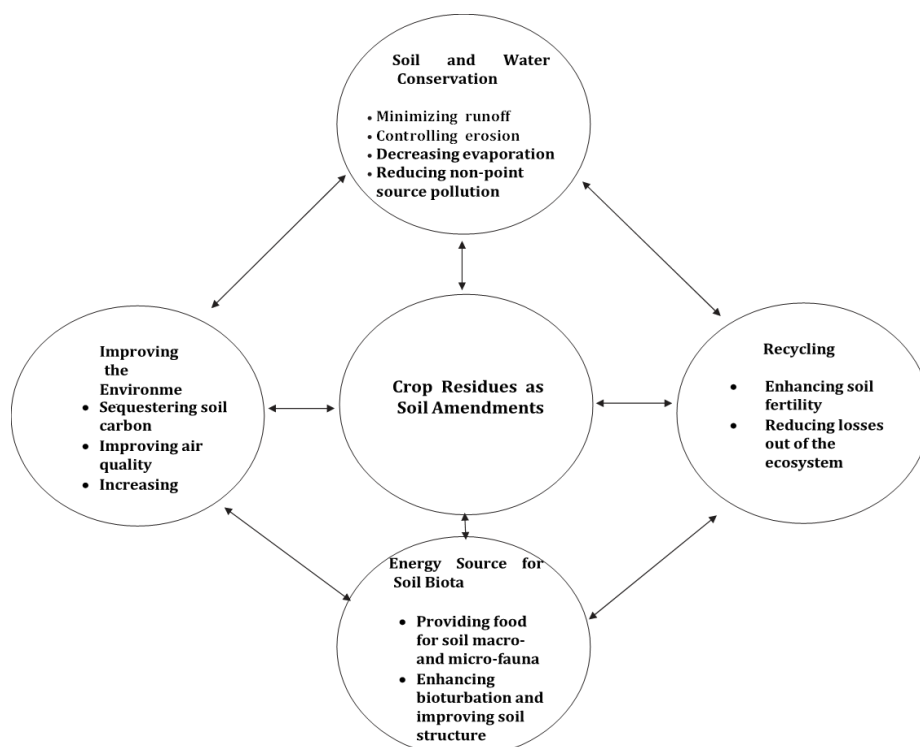


Figure 2. Site and eco-system specific effects of crop residue management on soil and environment quality must be assessed in relation to improvement in soil quality and sustainable use of natural resources

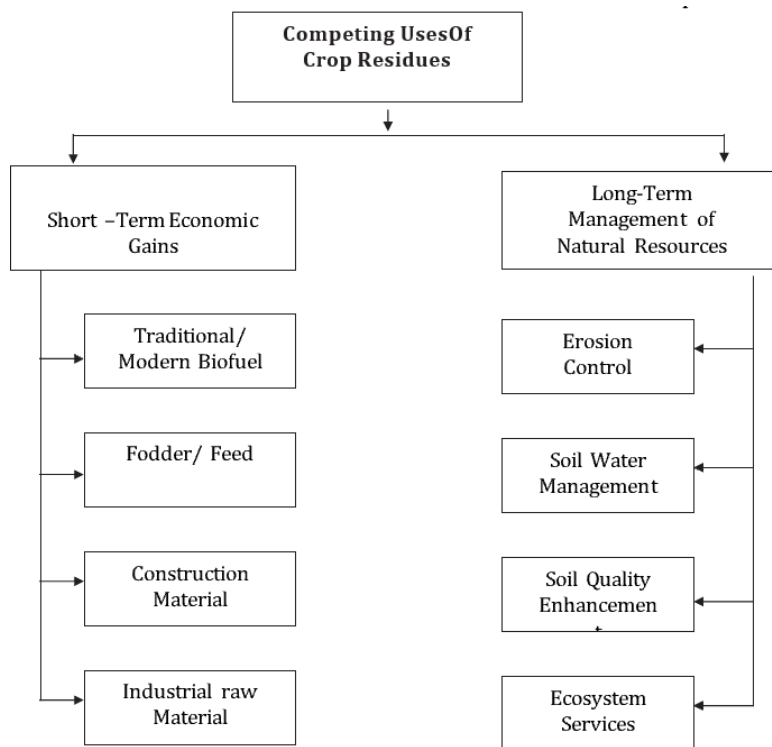


Figure 3. An objective assessment of short-term economic gains versus long-term and sustainable use of natural resources important to the decision-making process for competing uses of crop residues

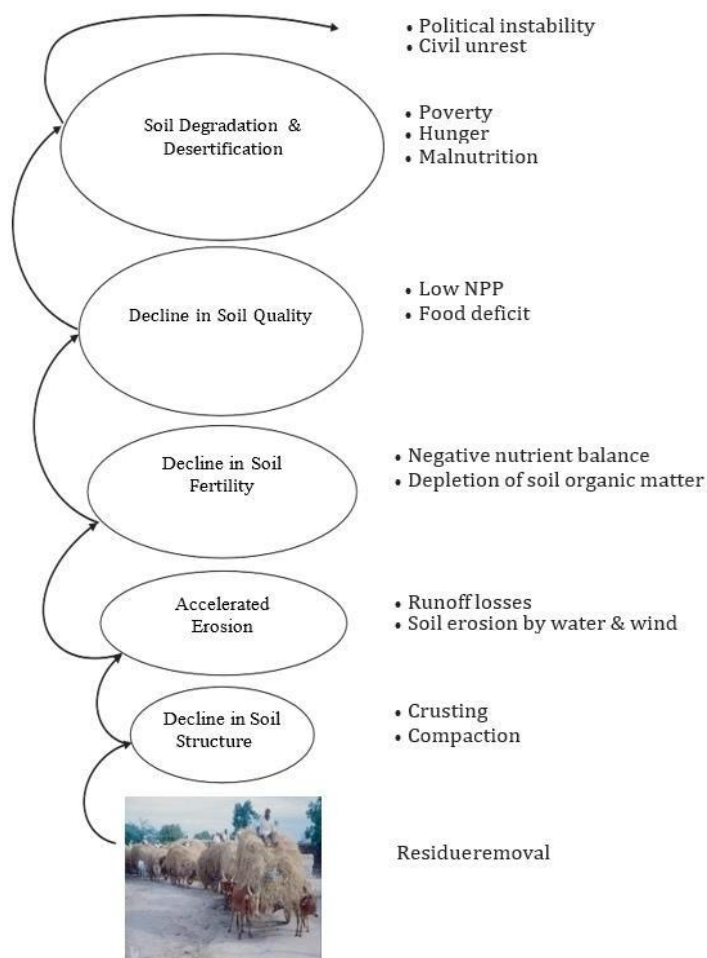


Figure 4. The Classic Collapse

Waste disposal

Waste disposal is a critical aspect of maintaining environmental health and sustainability. In a world where consumption is inevitable, the responsible management of waste is essential to mitigate its adverse effects on our surroundings. From household trash to industrial byproducts, the proper disposal of waste is a multifaceted challenge that demands a comprehensive approach. Firstly, understanding the types of waste is crucial in determining the appropriate disposal methods. Waste can be categorized into various types, such as solid, liquid, organic, hazardous, and recyclable materials. Each type requires distinct handling to ensure minimal impact on the environment. Solid waste, for instance, encompasses everyday items like paper, plastic, and food scraps. It necessitates sorting and recycling where possible to reduce the strain on landfills. Effective waste disposal involves a hierarchy of methods, commonly known as the waste management hierarchy. This framework prioritizes waste management strategies in a descending order of preference: prevention, reduction, reuse, recycling, energy recovery, and finally, disposal. Prevention and reduction stand at the top, emphasizing the importance of minimizing waste generation in the first place. This approach encourages sustainable practices, like using reusable products and reducing excess packaging, thereby lessening the amount of waste produced. Reuse and recycling play pivotal roles in waste disposal by extending the lifespan of materials. Reusing items or recycling materials conserves resources and diminishes the need for new raw materials. Recycling processes convert waste into new products, significantly reducing the burden on landfills and lowering energy consumption required for manufacturing. Furthermore, hazardous waste disposal demands specialized handling due to its potential to pose risks to human health and the environment. Proper containment, treatment, and disposal methods are imperative for materials such as chemicals, batteries, and electronic waste to prevent contamination and environmental degradation. Efficient waste disposal requires the collaboration of individuals, industries, and governments. Public awareness campaigns and educational initiatives play a crucial role in encouraging responsible waste disposal practices. Communities benefit from clear guidelines on waste segregation, recycling programs, and the proper disposal of hazardous waste. Additionally, industries must adopt sustainable production methods and invest in eco-friendly technologies to minimize waste generation and optimize resource use.

Government policies and regulations play a pivotal role in waste management. Implementing laws that enforce responsible waste disposal practices, imposing penalties for illegal dumping, and incentivizing recycling and waste reduction initiatives are instrumental in fostering a culture of environmental

responsibility. Technology also contributes significantly to waste disposal advancements. Innovations in waste-to-energy processes, composting techniques, and advancements in recycling technology enhance the efficiency of waste management systems, offering viable alternatives to traditional disposal method.

In conclusion, waste disposal is an intricate issue that demands a holistic approach. By prioritizing waste reduction, promoting recycling and reuse, implementing stringent regulations, and leveraging technological innovations, we can work towards a more sustainable future. A concerted effort from individuals, industries, and governments is essential to address the challenges posed by waste disposal and pave the way for a cleaner, healthier planet.

Farming Carbon

Farming carbon, also known as carbon farming or carbon sequestration, represents a crucial strategy in mitigating climate change by capturing atmospheric carbon dioxide and storing it in soils, plants, and trees. This approach acknowledges the significant role agriculture can play in reducing greenhouse gas emissions and enhancing carbon sinks. At its core, carbon farming revolves around implementing agricultural practices that enhance carbon sequestration while promoting sustainable land management. One of the primary methods involves increasing soil organic matter by adopting regenerative agriculture techniques. Practices like cover cropping, no-till farming, and crop rotation can enhance soil health, fostering increased carbon storage in the ground. Cover crops, for instance, not only protect the soil from erosion but also contribute organic matter upon decomposition, enriching soil carbon content. Another impactful method is agroforestry, which integrates trees and shrubs into farming systems. Trees act as carbon sinks, absorbing carbon dioxide during photosynthesis and storing it in their biomass and soils. Agroforestry practices not only sequester carbon but also offer additional benefits like improved biodiversity, enhanced soil fertility, and increased resilience to climate change-induced stresses. Additionally, reforestation and afforestation efforts play a vital role in farming carbon. Planting trees in areas that were previously devoid of forest cover or restoring degraded ecosystems contributes significantly to carbon sequestration. These efforts not only absorb carbon dioxide but also provide habitats for diverse flora and fauna, combat soil erosion, and mitigate the impacts of extreme weather events.

Livestock management also plays a part in carbon farming. Implementing rotational grazing systems and adjusting animal diets can reduce methane emissions from livestock, thereby curbing their carbon footprint. Techniques such as silvopasture, where livestock graze in wooded areas, contribute to both carbon sequestration and sustainable animal husbandry. Moreover, biochar, a type of charcoal produced from

organic materials, presents an innovative approach to carbon farming. Incorporating biochar into soils not only enhances fertility but also sequesters carbon for hundreds or thousands of years, aiding in long-term carbon storage.

Policy incentives and financial mechanisms are instrumental in encouraging farmers to adopt carbon farming practices. Subsidies, tax credits, and carbon offset programs provide economic incentives for farmers to implement sustainable land management practices that promote carbon sequestration. These initiatives not only benefit individual farmers but also contribute to national and global efforts to combat climate change. Education and outreach are also vital components of promoting carbon farming. Providing farmers with knowledge about the benefits of sustainable practices, offering training on implementation techniques, and sharing success stories can encourage widespread adoption of these methods.

In conclusion, farming carbon presents a multifaceted approach to mitigating climate change through agricultural practices that enhance carbon sequestration. By integrating regenerative agriculture, agroforestry, reforestation, and innovative techniques like biochar incorporation, we can transform farming into a proactive solution for reducing atmospheric carbon dioxide levels. Encouraging widespread adoption of these practices through supportive policies and education is crucial in transitioning towards a more sustainable and resilient agricultural system.

Water resources

In addition to concerns about fertility and nutrient provision, agricultural productivity faces significant constraints due to dwindling water resources, further compounded by the increasingly frequent and severe droughts anticipated with projected climate change. Agriculture, the largest consumer of water, contends with mounting competition from industrial and urban sectors due to burgeoning demographic pressures and rapid industrialization (Gleick, 2003; Kondratyev, 2003; Johnson et al., 2001). The scarcity of fresh water is exacerbated by both non-point and point source pollutions, intensifying the challenges faced (Tilman et al., 2006). Moreover, this scarcity is poised to escalate, particularly in developing economies like China and India, as dietary trends shift from plant-based to animal-based products (Clay, 2004). Given these circumstances, a profound understanding of soils and agronomic processes that enhance water use efficiency becomes paramount and exceptionally critical.

Collaboration among soil scientists, agronomists, plant breeders, and irrigation engineers is imperative. It necessitates the development of genetically engineered plants with heightened productivity per unit water consumption. This collaborative effort aims to curtail water losses during conveyance and delivery, minimize soil evaporation through micro-meteorological

interventions, and economically recycle water drained into sub-soil or groundwater.

Furthermore, partnership with large urban centers' municipal bodies is vital to explore and implement techniques for recycling wastewater, effectively repurposing it for irrigation and aquifer replenishment. Prioritizing the replacement of flood irrigation with techniques such as subirrigation or drip irrigation emerges as a pressing need in this context. This transition holds the promise of conserving water resources and significantly enhancing agricultural sustainability in the face of mounting water scarcity and competing demands.

Addressing these multifaceted challenges demands a comprehensive approach that integrates scientific research, technological innovation, and collaborative strategies among various disciplines and sectors. It is pivotal to not only mitigate.

Reaching out

Reaching out is the foundational cornerstone of human connection and progress. It's an act that transcends boundaries, fostering understanding, empathy, and collaboration among individuals, communities, and societies. Whether through a simple gesture of kindness, an extended hand in support, or a concerted effort to bridge divides, reaching out is the catalyst for meaningful change and growth.

At its essence, reaching out embodies the spirit of empathy and compassion. It's about extending a helping hand to those in need, offering support without judgment, and acknowledging the shared human experience. It's a recognition that we are all part of a larger tapestry, where each thread, each individual, contributes to the richness and diversity of the whole. In a world where differences often fuel division, reaching out becomes a powerful tool for building bridges. It's about embracing diversity, engaging in dialogue, and seeking common ground amidst varying perspectives. By reaching across cultural, ideological, or geographical divides, we pave the way for understanding, tolerance, and unity.

Moreover, reaching out encompasses the courage to ask for help when needed. It's acknowledging vulnerability and recognizing that no one navigates life's journey alone. By seeking support and guidance, whether from friends, family, or professionals, we foster resilience and create stronger, more connected communities. Technology has transformed the way we reach out, enabling connections across continents in an instant. Social media, online communities, and digital platforms serve as avenues for reaching out, transcending physical boundaries and allowing for global solidarity. However, amidst the digital landscape, the essence of genuine human connection remains paramount. Behind every message or post, there's a person seeking understanding, validation, or support.

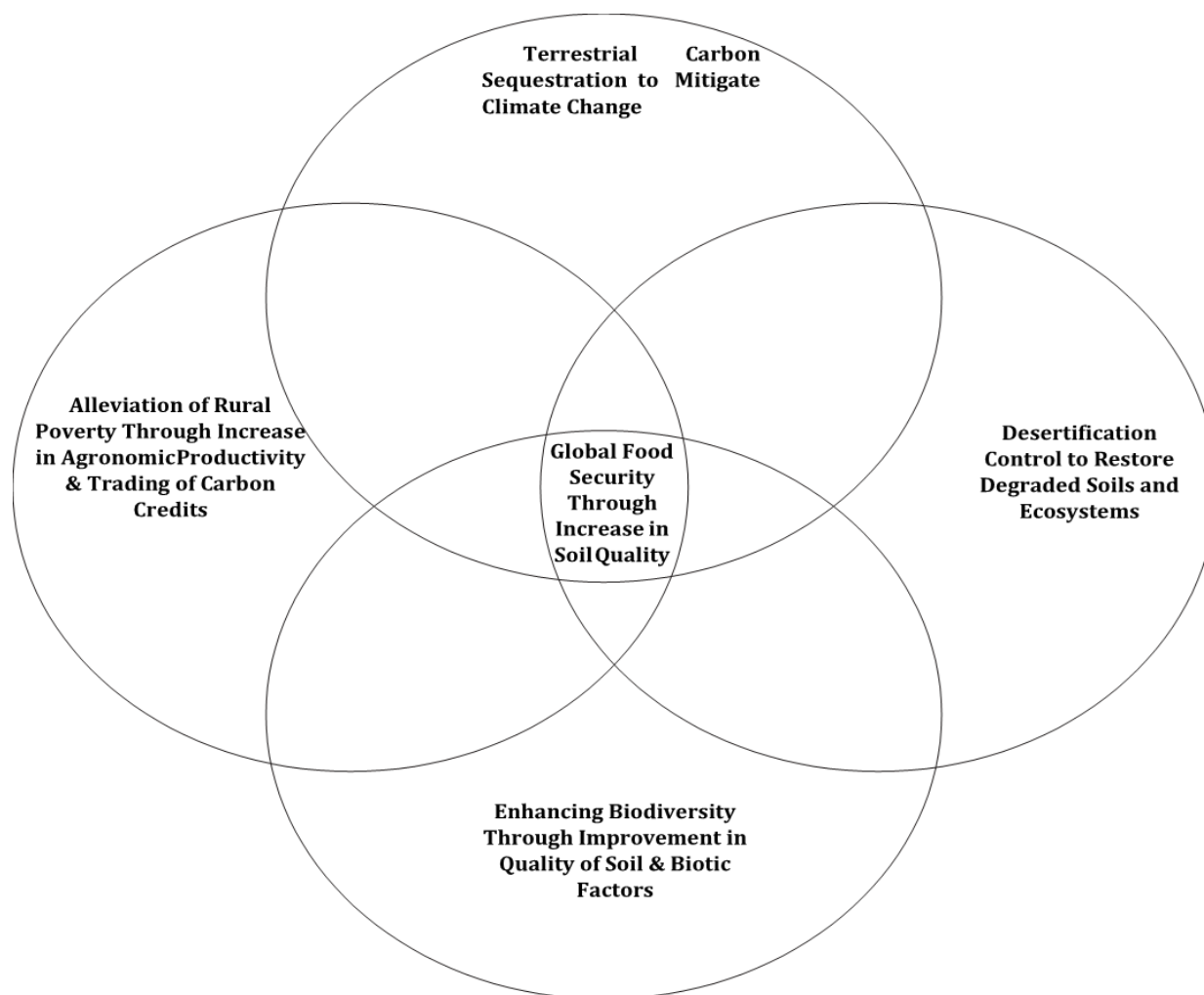


Figure 5. A positive and synergistic interaction between desertification control, biodiversity improvement, climate change mitigation, and food security. The latter is improved through improvement in soil quality, increase in availability of water resources, strengthening of elemental cycling, and enhancement of bioturbation in the rhizosphere. Soil scientists and agronomists must be actively pursuing quantification of these synergistic effects.

Reaching out also plays a pivotal role in addressing societal issues. It's the catalyst for activism, community organizing, and driving positive change. From advocating for human rights to environmental conservation efforts, the act of reaching out brings individuals together, amplifying their collective voices and creating a ripple effect of impact. Education and awareness form integral components of effective outreach. By informing, educating, and empowering individuals, communities can address misconceptions, break down barriers, and foster a culture of inclusivity and understanding.

In essence, reaching out transcends mere communication; it's about forging meaningful connections that nurture empathy, understanding, and solidarity. It's about recognizing our shared humanity, embracing diversity, and striving for a more compassionate and interconnected world. Ultimately, the act of reaching out is a testament to the strength of the human spirit. It's about fostering connections, building bridges, and creating a world where empathy and understanding prevail. Each outreach, no matter how small, contributes to the collective tapestry of

human experiences, weaving together a fabric of compassion and unity that transcends boundaries and enriches the lives of all involved.

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