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Soil Health in the Age of Conservation Agriculture

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Soil health is essential for sustainable agriculture, but intensive cultivation, excessive tillage, residue removal, and poor nutrient management can degrade soil quality. This paper highlights the role of Conservation Agriculture (CA) and agroforestry in improving soil health. The three CA principles i.e., minimum soil disturbance, permanent soil cover, and crop diversification, helps to improve soil structure, conserve moisture, reduce erosion, increase organic carbon, and support beneficial soil organisms. Agroforestry further improves soil health through litter addition, root turnover, nutrient recycling, and enhanced biological activity. Integrated nutrient management can strengthen these benefits. The relevance of these practices to Odisha is also discussed, particularly in addressing soil erosion, moisture stress, low organic matter, and nutrient imbalance. Overall, sustainable soil management requires long-term and locally adapted practices to maintain soil health and agricultural productivity.

Introduction

Soil is a living and dynamic natural resource essential for agriculture, biodiversity, and environmental sustainability. Healthy soil provides plants with nutrients and water, supports diverse soil organisms, stores carbon, and helps protect the environment. However, intensive cultivation, excessive tillage, crop-residue removal or burning, imbalanced fertilizer use, and poor land management have contributed to soil degradation in many agricultural regions. Although modern agriculture has greatly increased food production, intensive farming practices can negatively affect soil health. Frequent tillage can disturb soil structure, accelerate organic matter decomposition, and increase erosion, while bare soil is more exposed to rainfall and sunlight. In this context, Conservation Agriculture (CA) provides an important approach to sustainable soil management. By minimizing soil disturbance, maintaining soil cover, and diversifying crops, CA works with natural soil processes to improve soil health, conserve resources, and support the long-term sustainability of agricultural systems.

What is Soil Health?

Soil health can be described as the continued capacity of soil to function as a living ecosystem that sustains plants, animals and humans. A healthy soil is productive, biologically active and environmentally resilient. The ultimate goal of soil health management is to maintain a balance among these three components systems. A healthy Soil should have-

- **Good water infiltration:** Water can enter the soil easily rather than flowing away from the surface.
- **Good water-holding capacity:** The soil can store enough water and make it available to plants when needed.
- **Resistance to erosion:** Healthy soil is better able to resist being washed away by rain or carried away by wind.

Soil health consists of-

1. Chemical Health

Chemically healthy soil contains adequate organic matter to support fertility and nutrient availability, balanced concentrations of essential nutrients such as nitrogen, phosphorus, and potassium, low levels of pollutants or toxic substances, and a soil pH suited to efficient nutrient uptake.

2. Biological Health

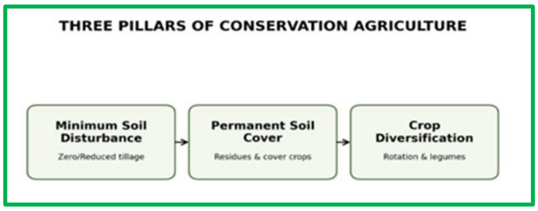
Biological health reflects the abundance and diversity of soil organisms — bacteria, fungi, earthworms, and other soil life — that drive nutrient cycling and decompose organic residues into plant-available forms. An active, diverse biological community sustains soil fertility, supports plant growth, and improves the soil's resilience to disturbance and stress.

3. Physical Health

Physical health encompasses soil texture, structure, bulk density, porosity, aggregation, and water-holding capacity. A physically healthy soil permits unrestricted root growth and efficient movement of water and air through the profile.

Principles of Conservation Agriculture

A. Minimum Mechanical Soil Disturbance



Frequent ploughing and excessive tillage can disturb the soil and break down its natural structure. It may also speed up the loss of organic matter. Practices such as minimum or zero tillage help keep the soil structure intact and allow natural soil processes to continue. These practices can also reduce the use of labour and fuel and help protect the soil surface from erosion.

B. Permanent Organic Soil Cover

Crop residues, mulch and cover crops act as a protective blanket over the soil. They reduce the impact of raindrops, lower evaporation, moderate soil temperature and gradually contribute organic materials as they decompose

C. Crop Diversification

Crop rotation and diversification improve nutrient cycling and reduce the risks associated with continuous monocropping. Including legumes can support biological nitrogen fixation and enhance the diversity of soil organisms.

How Conservation Agriculture Builds Healthy Soil

1. Building Soil Organic Carbon:

Soil organic carbon is a key indicator of soil health, as it improves soil structure, water-holding capacity, nutrient retention, and biological activity. Frequent tillage and crop-residue removal can reduce soil carbon, while conservation agriculture helps rebuild it through reduced soil disturbance and residue retention. These benefits increase gradually with continued adoption, showing that soil restoration is a long-term process. Improved soil carbon also supports crop productivity by helping the soil retain water and nutrients and providing energy for soil organisms.

2. Improving Soil Structure and Water Movement

Minimum soil disturbance and continuous residue cover allow soil aggregates to form and stabilize rather than being repeatedly broken apart by tillage. Root channels, earthworm burrows, and other biopores remain intact under conservation agriculture, creating a more porous soil structure that supports better water infiltration and internal drainage. Over time, this improved structure reduces surface crusting and runoff, allows rainfall to penetrate more effectively, and enhances the soil's capacity to store and transmit water to plant roots, benefits that develop gradually as soil aggregation and biological activity increase with sustained CA adoption.

3. Conserving Soil Moisture

Surface residue retention reduces evaporative water loss and buffers the soil from excessive heating. Combined with higher organic matter and improved infiltration, this increases water availability during short dry spells, a benefit that is especially valuable in rainfed systems, where crop growth depends on uneven or unpredictable rainfall.

4. Protecting the Soil from Erosion

Bare soil is easily affected by wind and water erosion. When the soil surface is covered with crop residues, the residues help absorb the force of raindrops and slow down the movement of water across the field. In this way, conservation agriculture helps prevent the loss of valuable topsoil and nutrients and keeps them available for crop growth.

The Hidden Workforce: Soil Biology

Healthy soil contains many organisms, including bacteria, fungi, actinomycetes, and earthworms. These organisms decompose residues, recycle nutrients, improve soil structure, and support plant growth. Reduced soil disturbance and regular residue addition create favourable conditions for their activity, helping maintain soil fertility and productivity.

Soil Health and Agroforestry Systems

Major Agroforestry Systems and Their Effect on Soil Health

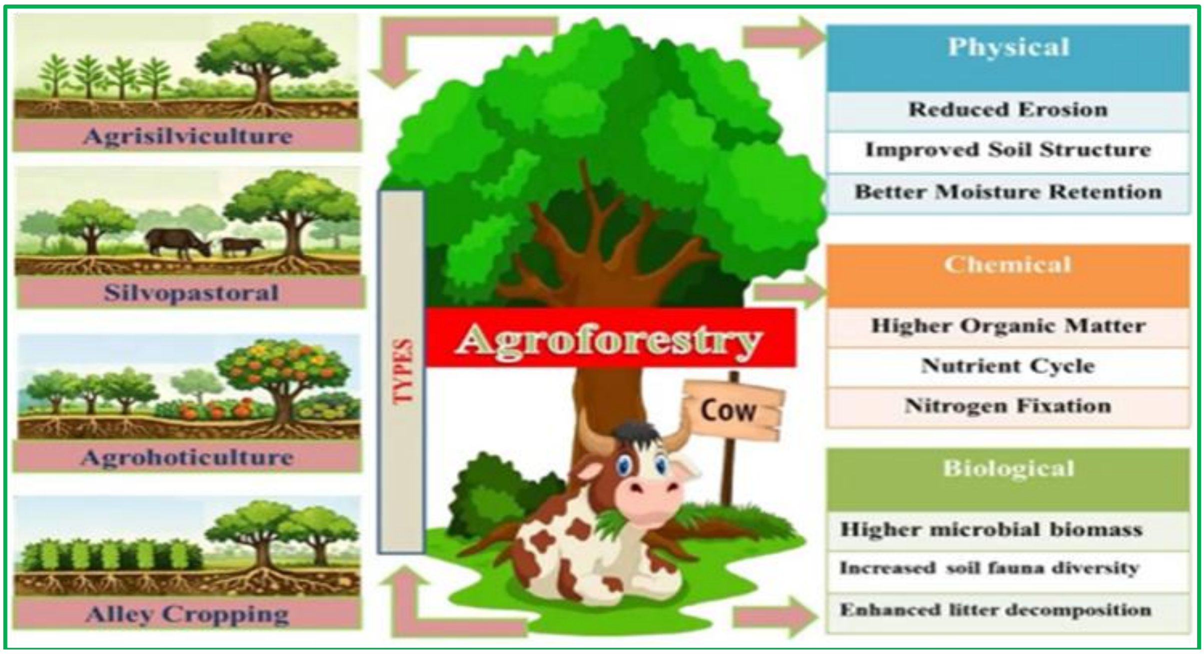
Different agroforestry systems influence soil health through similar underlying ecological processes, though the specific combination of trees, crops, and livestock determines how organic matter, nutrients, and water are managed.

Agrisilviculture integrates trees with agricultural crops. Regular inputs of leaf litter, root residues, and root exudates raise soil organic carbon (SOC), which over time improves aggregation, supports nutrient cycling, and stimulates beneficial soil microbial activity (Montagnini & del Fierro, 2022; Lorenz & Lal, 2014).

Silvopastoral systems combine trees, forage, and livestock. Leaf litter and manure supply organic matter that improves soil structure, water infiltration, and erosion resistance, while tree biomass and root inputs add further nutrient reserves (Nair, 1993).

Agrihorticultural systems pair perennial horticultural trees with annual crops. Because trees remain in place for many years, they provide a continuous supply of leaf and root residues that build soil organic matter and carbon storage while supporting nutrient cycling.

Collectively, these systems sustain higher plant diversity and more continuous organic inputs than conventional monocropping, resulting in improved soil structure, enhanced nutrient cycling, greater microbial activity, and stronger long-term soil productivity (Jose, 2009).

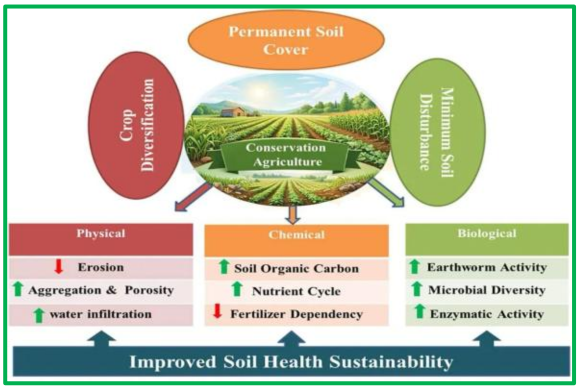


Nutrient Management: Feed the Soil as well as the Crop

Conservation Agriculture does not mean avoiding fertilizers altogether. Instead, it emphasizes efficient, need-based nutrient use alongside strengthening the soil's own capacity to recycle and supply nutrients. Integrated nutrient management, guided by regular soil testing, is therefore central to sustaining both crop productivity and long-term soil health (Vanlauwe *et al.*, 2010). Practical elements of this approach include: applying fertilizers based on soil-test results and crop-specific recommendations to avoid both deficiency and over-application; retaining or appropriately incorporating crop residues rather than removing them, so that organic matter and nutrients are returned to the soil (Turmel *et al.*, 2015); supplementing with organic sources such as compost, farmyard manure, and green manure; and using biofertilizers or beneficial microorganisms where appropriate to enhance nutrient availability and biological activity (Vessey, 2003). Incorporating legumes into cropping systems further supports nutrient cycling through biological nitrogen fixation while adding to crop diversity and overall soil ecosystem health (Giller, 2001).

Soil Health and Climate Resilience

Agriculture is increasingly exposed to droughts, intense rainfall and temperature extremes. Healthy soils act as a buffer against these stresses. A well-structured soil with adequate organic matter can absorb rainfall more effectively, store water for longer periods and resist erosion. Reduced tillage can also lower the number of field operations required for crop establishment.



Why it Matters for Odisha?

Odisha's undulating terrain and high-intensity monsoon rainfall make it particularly vulnerable to soil erosion, with studies estimating annual soil loss of over 40 $t\ ha^{-1}$ in parts of the Eastern Ghats region and erosion-prone hotspots covering more than 32,000 km^2 of agricultural and hilly land (Dandapat *et al.*, 2024). This is compounded by low soil organic carbon, moisture stress, and nutrient imbalance across much of the state (Lenka *et al.*, 2014). By reducing tillage, retaining residues, and diversifying cropping systems, Conservation Agriculture directly addresses these constraints, making it a locally relevant strategy for sustaining soil health and productivity in Odisha.

Challenges and the Way Forward

Conservation Agriculture faces challenges such as residue availability, weed management, limited machinery, and slow, often invisible improvements in soil health, all of which can discourage sustained adoption by farmers (Araya *et al.*, 2024). Competing demands for crop residues as fodder or fuel further limit surface retention in many smallholder systems. Addressing these constraints requires farmer training, continued local research, and location-specific solutions tailored to soil, climate, and socio-economic conditions. Because soil restoration unfolds gradually, CA should be viewed as a long-term strategy, where small, consistently applied changes accumulate over time to build healthier, more resilient, and more productive agricultural soils.

Conclusion

The future of agriculture depends on healthy soil. Conservation Agriculture helps protect and restore soil through minimum disturbance, permanent soil cover, and crop diversification. These practices improve soil structure, conserve moisture, support soil organisms, and enhance nutrient cycling. Combined with balanced nutrient management, they can promote productive and resilient farming systems. Since soil health improves gradually, its management requires continuous care to maintain physical, chemical, and biological balance for future agricultural productivity.

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