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Research · December 2024

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Indian Journal of Agronomy **69** (Global Soils Conference Special issue): S173–S184 (2024)

Designing conservation tillage cum nutrient management model for different agro-ecosystems

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ABSTRACT

Modern agricultural practices, such as conventional tillage and excessive fertilizer use, have led to severe environmental challenges, including soil erosion, loss of organic carbon, nutrient imbalances, and eutrophication of water bodies. These issues have not only threatened long-term food security but also contributed to greenhouse gas (GHG) emissions and raise the environmental issues. Sustainable agricultural practices, such as conservation agriculture (CA), aim to counteract these effects by promoting minimal soil disturbance, residue retention, and efficient crop diversification. The CA practices are recognized for improving soil health, enhancing water retention, and increasing nutrient use efficiency (NUE), making them important for mitigating soil degradation and reducing the environmental footprint. In addition to CA, innovative and efficient nutrient management strategies, including integrated nutrient management (INM), ecological nutrient management, and precision agriculture, offer solutions to optimize fertilizer application and minimize environmental impacts. Precision agriculture, for example, uses real-time data and variable rate technology (VRT) to apply nutrients site-specifically, reduces wastage, and improves NUE. Similarly, INM combines organic and inorganic nutrient sources, optimizing plant nutrition and reducing the reliance on inorganic/chemical inputs. The adoption of these practices not only improves crop productivity but also lowers GHG emissions and reduces nutrient application losses. However, the effectiveness of these sustainable practices is highly dependent on specific agro-ecosystems, as soil types, climate conditions, and cropping systems vary widely across the globe. As a result, a "one-size-fits-all" approach to sustainable tillage and nutrient management is insufficient. Therefore, emphasis must be given to developing ecosystem-specific models that customize agricultural practices to local environmental conditions. Studies from different temperate, tropical, and arid regions validate the advantages of such models, including enhanced carbon sequestration, improved biodiversity, increased soil organic matter, and better crop productivity. For example, no-till combined with crop rotations in temperate regions, residue retention in arid regions, and agroforestry in tropical systems have shown significant benefits. Further research is necessary to address region-specific challenges and enhance decision-support systems for farmers. Promoting the adoption of ecosystem-specific models will be critical for achieving cleaner agricultural production and ensuring the resilience of global food systems in the face of climate change. These approaches are essential for optimizing resource use, protecting soil health, and supporting long-term agricultural sustainability.

Key words: Carbon sequestration, Conservation agriculture, Ecological nutrient management, Government policies, Soil health, Sustainability

Soil is the structural base of our civilization which sustains the world in food production and is regarded as a vital option for terrestrial carbon sequestration. Being a significant carbon sink, it helps in the reduction of atmospheric CO_2 concentration, which subsequently alleviates the negative effects of global warming and climate change. In addition, soil offers vital ecosystem services and hosts a number of microorganisms and fauna, which play a critical role in the soil food web, nutrient recycling, pest-disease regulation, pollution remediation, etc. Therefore, it is explicit that the significance of soil extends far beyond food security. However, modern agricultural practices have led to various environmental challenges that are affecting soil health. Issues such as soil erosion, depletion of soil organic carbon, and various forms of physical and chemical degradation are all taking a toll on soil health. However, the methods employed in modern agricultural have led to several environmental issues that are affecting soil health. Particularly problems like soil erosion, loss of

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soil organic carbon, different kinds of physical and chemical degradation etc. significantly affect soil health. Among the many factors contributing to soil degradation, conventional tillage (CT) and inefficient nutrient management are especially important. Globally, CT practices have been predominantly adopted that involve intensive deep plowing of soil for the seedbed preparation. Though these practices are effective in opening the soil and breaking up the hard pan for better planting and crop establishment, they have several adverse effects on soil health. Out of them, soil erosion is a significant consequence of CT, where the mechanical disturbance of soil exposes the surface soil to wind and water erosion, leading to the loss of fertile topsoil. Additionally, this practice disrupts soil structure, decreases organic matter content, and negatively impacts the microbial and soil faunal communities vital for nutrient cycling and soil fertility (Lal, 2015a; Montgomery, 2007).

The intensification of agriculture aiming crop yield maximization has further aggravated these issues. Excessive reliance on synthetic fertilizers, indiscriminate fertilizer application, crop residue removal, and the absence of organic sources of plant nutrition have led to nutrient imbalance and mining, chemical runoff, changes in soil pH, heavy metal contamination, poor biological health of soil, etc. The excessive use of chemical inputs has also contributed to the contamination of surface water bodies, groundwater and the emission of GHGs, particularly nitrous oxide (N_2O), a potent GHG with a global warming potential 298 times that of CO_2 (Foley *et al.,* 2011). The cumulative effect of these practices has been the degradation of vast tracts of agricultural land, threatening long-term food security and the sustainability of agricultural systems. In response to these challenges, there has been a growing recognition of the need for sustainable tillage and nutrient management options that will lead to a lower environmental footprint.

Sustainable agriculture seeks to balance the need for food production with the conservation of natural resources and the preservation of ecosystem services. Practices such as minimum or zero tillage, crop rotation, and residue retention have been shown to improve soil structure, enhance water retention, and reduce nutrient losses (Giller *et al.,* 2009a). These practices, collectively known as conservation agriculture (CA), are increasingly seen as essential for achieving sustainable agriculture (Parihar *et al.,* 2017). Other than CA-based management options, many situation-specific potential alternative tillage strategies can be useful for cleaner agricultural production. Similarly, nutrient management is also equally important for maintaining soil health. There are several practices like ecological nutrient management (Drinkwater and Snapp, 2022) integrated nutrient management (INM), site-specific nutrient management (SSNM), use of organic amendments, and precision nutrient management, etc. which can help in reducing the environmental footprint associate with nutrient management. These technologies reduce the environmental losses, improve the use efficiency along with increasing the productivity of crops.

Although, researchers have identified a number of cleaner tillage and nutrient management options, but in most of the cases, they are unlikely to be effective universally across all agro-ecosystems. That's why the main challenge lies in identifying the location and situation specificity in implementing these cleaner tillage and nutrient management practices. Here comes the importance of formulating ecosystem-specific models that integrate location and situation-specific recommendations resulting in a cleaner production system. While these resource conservation technologies (RCTs) provide a general framework for sustainable agriculture, their application must be tailored to the specific characteristics of different agro-ecosystems. Agricultural ecosystems are diverse, with variations in soil types, climatic conditions, topography, and biological activity. For example, practices that work well in temperate regions may not be suitable for tropical or arid regions, where soils and climatic conditions are markedly different. Therefore, it is critical to develop ecosystem-specific models that take into account the unique characteristics and needs of different agricultural landscapes. Such models would provide a framework for designing and implementing tillage and nutrient management practices that are both effective and sustainable within specific ecosystems. These models should consider factors such as soil type, climate, crop type, and the availability of resources, and should be flexible enough to accommodate changes in these variables over time. By tailoring practices to local conditions, ecosystem-specific models can help optimize agricultural productivity while minimizing environmental impacts, thereby contributing to the overall sustainability of agricultural systems (Verhulst *et al.,* 2011).

Need of conservation tillage and integrated nutrient management approaches

The primary objective of this review is to explore the current state of tillage and nutrient management practices, identify gaps and challenges, and propose comprehensive framework models that are environmentally clean and tailored to specific agroecosystems. These models aim to address the environmental impacts associated with conventional agricultural practices, such as soil degradation, nutrient runoff, and greenhouse gas emissions while improving soil health, nutrient use efficiency (NUE), and promoting climate change mitigation. By integrating cleaner tillage and nutrient management practices with ecosystem-specific considerations, these models seek to provide a holistic approach to sustainable soil management (DeGraaff *et al.,* 2011).

Current state of tillage and nutrient management practices

Conventional agriculture-based practices

The CT practices have been a dominant approach for seedbed formation in agriculture for long. These practices typically involve the use of plows, harrows, and other mechanical implements to break up soil, bury crop residues, and prepare seedbeds. While CT has been effective in creating favorable conditions for seed germination and early plant growth, its drawbacks have become increasingly apparent over time (Kassam *et al.,* 2009). One of the primary issues with CT is its impact on soil structure. The mechanical disturbance of soil disrupts its natural aggregation, leading to a breakdown of soil particles and a loss of soil organic matter. This, in turn, reduces the ability of soil to retain water and nutrients, making it more prone to erosion and nutrient leaching. Additionally, conventional tillage often involves the removal of crop residues from the soil surface, leaving the soil exposed to wind and water erosion. Over time, these practices can lead to soil degradation, reducing the land's productivity and resilience to environmental stresses. A study conducted by Parihar *et al.* (2016) reported that CT-based practices resulted in significantly higher bulk density and penetration resistance, along with lower water-stable aggregates (16.1-32.5%), soil organic carbon (23.6-35.3%), soil microbial biomass carbon (45-48.9%) in 0-30 topsoil compared to CA-based zero tillage and permanent bed plots in maize-based cropping systems of north-west India.

In the case of nutrient management in conventional agriculture, it has traditionally relied on the blanket application of synthetic fertilizers to meet the nutrient demands of crops. While synthetic fertilizers are effective in providing readily available nutrients, their overuse has led to several environmental problems. Sapkota *et al.* (2021) found that farmers' practice-based conventional nutrient management resulted in 2.5% higher global warming potential (GWP) in rice and 12-20% higher GWP in wheat over nutrient expert-based fertilizer management across 1594 side-by-side comparison trials in Indo-Gangetic plains (IGP). Similarly, Nayak *et al.* (2022) also showed how conventional nutrient management-based practices can cause lower yields compared to the 4R nutrient stewardship-based nitrogen management option in maize.

CAand nutrient management practices

Contrary to conventional practice, there are several alternatives in the form of CA and nutrient management practices as they lower the emissions, improve the input use efficiency, and, improve soil health along with sustaining or improving the productivity. One such major example is CA-based practices which exclude tilling the land. It has three basic pillars: minimal soil disturbance, residue retention, and efficient crop diversification (Fig. 1). Under minimal soil disturbance, there is a reduction or elimination of mechanical soil disturbance, such as plowing or tilling. Instead, seeds are directly sown into the soil with minimal disruption to the soil structure. This approach conserves soil moisture, improves soil structure, and promotes biological activity in the soil, leading to increased soil organic matter and improved water infiltration (Derpsch *et al.,* 2010). The second principle is residue retention or permanent soil cover which maintains a permanent or semi-permanent organic cover on the soil surface, using crop residues or cover crops. This organic cover protects the soil from erosion, reduces evaporation, and provides a habitat for beneficial soil organisms. Besides it also contributes to nutrient cycling by slowly decomposing and releasing nutrients back into the soil (Giller *et al.,* 2009b). The third principle is efficient crop diversification which includes crop rotation and intercropping. By rotating crops with different rooting depth/ lateral spread and nutrient requirements, CA-based practices will reduce the risk of soil degradation and pest buildup while improving soil fertility. Crop diversification enhances above and below-ground biodiversity, crucial for maintaining a resilient agroecosystem. Other alternative CA options are minimum tillage, strip tillage, ridge tillage, control trafficking, etc. These practices do not disturb the entire land area, rather localized row zone tilling is done. In the hilly-regions contour tillage is practiced across the slope to check soil erosion.

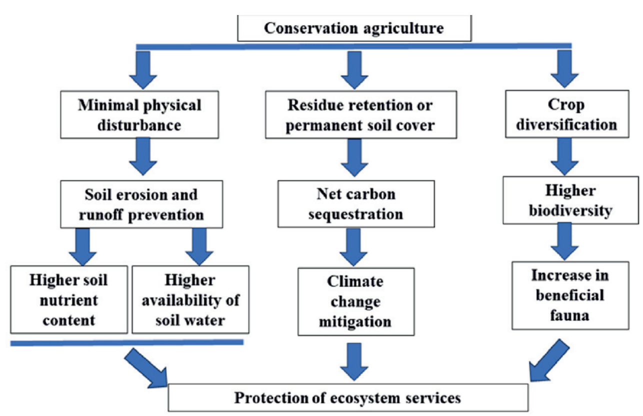


Fig. 1. Principles of CA and its benefits.

The adoption of these CA practices offers numerous benefits for soil health, carbon sequestration, and nutrient use efficiency.

a) *Soil health:* CA improves soil health by increasing organic matter content, enhancing soil structure, and promoting biological diversity. The reduced soil disturbance allows the development of a stable soil structure with improved porosity and water-holding capacity, which supports robust root growth and microbial activity (Table 1).

b) *Carbon sequestration:* CA has a prominent role in mitigating climate change by sequestering carbon in the soil. The retention of crop residues and minimal soil disturbance reduces the oxidation of organic matter, allowing more carbon to be stored in the soil (Table 2) CA helps in the physical protection of organic carbon by improving the soil structure, clay-mediated chemical stabilization, and microbe-mediated biological stabilization as recalcitrant organic carbon fraction. This not only enhances soil fertility but also reduces greenhouse gas emissions from agriculture (Fig. 2).

Nutrient use efficiency (NUE): CA practices improve NUE by promoting efficient nutrient cycling within the soil. The retention of organic residues and diversified

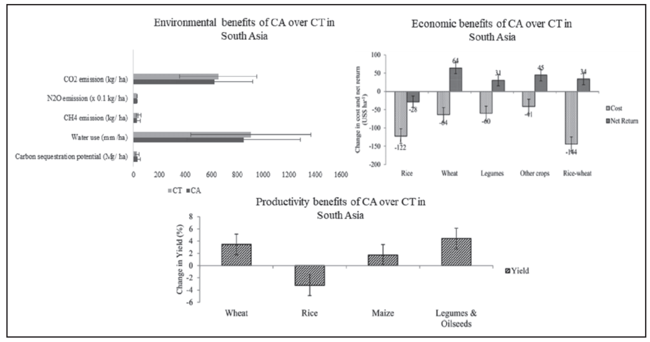


Fig. 2. Meta-analysis of benefits of conservation agriculture in South Asia (Kumara *et al.,* 2020)

cropping systems reduce the need for synthetic fertilizers, leading to lower nutrient runoff and leaching. Additionally, the enhanced biological activity in CA systems helps in the mineralization of nutrients, making them more available to plants (Powlson *et al.,* 2011). Several researchers' have shown the potential of CA in improving nitrogen use efficiency significantly across various agroecologies (Rana *et al.,* 2023).

Along with tillage, cleaner nutrient management is also

Table 1. Increase in soil microbial biomass carbon (MBC) in conventional agricultural systems compared to those incorporating CA practices

Location	Time period (years)	Cropping system	MBC conventional system (μg/g)	MBC conservation system (μg/g⁻)	Average change in MBC (%)	References
Australia	17	Wheat, lupins, canola	215	538	+154	Pankhurst *et al.,* 2002
Mexico	25	Wheat-wheat, wheat-sorghum-soybean	290	564	+94	González-Chávez *et al.,* 2010
India	3	Soybean, wheat	336	650	+15	Somasundaram *et al.,* 2019
		Soybean-cotton	299	385	+14	
		Soybean-fallow	285	297	+4	
		Soybean-pigeon pea	420	431	+3	
		Soybean-fallow	296	321	+8	
		Maize-chickpea	322	408	+27	
China	7	Maize	171	205	+20	Zhang *et al.,* 2012

Source: Page *et al.* (2020)

Table 2. Worldwide estimates of SOC change following the incorporation of CA practices

Study location	Cropping system	Depth considered (m)	Time since management change (years)	SOC change (Mg ha/year)	References
Sub-Saharan Africa	Maize based cropping	0.12–0.6	2-16	+0.37	Powlson *et al.,* 2016
Indo-Gangetic Plains	Wheat-rice	0.05–1.05	2–26	+0.54	Powlson *et al.,* 2016
Southeastern USA	Mainly cereal, corn and cotton based	0.15–0.3	3–25	+0.45	Franzluebbers, 2010
Mediterranean regions	Cereal, corn, and legume rotations.	0.15–0.4	6–72	+0.3	Francaviglia *et al.,* 2017
Worldwide	Various	0.15–1.2	3–43	Tropical +0.86 Temperate +0.17 World: +0.52	Mangalassery *et al.,* 2015

Source: Page *et al.* (2020)

important for an overall cleaner production system. Cleaner nutrient management is an umbrella term, that includes several management strategies for improving their use efficiency and reducing the environmental footprints. These practices mainly focus on 5R nutrient stewardship principles, i.e., right source, right form, right rate, right time, and right place. Nutrient management practices like site-specific nutrient management, integrated nutrient management, ecological nutrient management, precision nutrient management, etc. are considered cleaner strategies compared to conventional nutrient management practices.

a) *Right source:* Kumar *et al.* (2024a, 2024b) have reported the superiority of urea super granules over conventional nitrogen management practices in CA-based maize-wheat cropping systems in terms of lower nutrient loss, environmental footprint, and higher productivity.
b) *Right place and time:* Nayak *et al.* (2022) have reported the superiority of point placement of nitrogen at the late vegetative stage in CA-based maize over conventional surface application regarding nitrogen use efficiency and productivity.

Other than this, the potential of INM, ecological nutrient management (Drinkwater and Snapp, 2022), precision nitrogen management has been highlighted by various researchers across the world.

Need for integrated models that consider ecosystem variability

Despite the multiple benefits, the adoption of CA and nutrient management practices faces several challenges, particularly across different ecosystems due to soil type and climate variability. CA-based practices may not be universally applicable due to the diverse range of soil types and climatic conditions. For example, in heavy clay soils, reduced tillage may lead to waterlogging and poor crop establishment. Similarly, in arid regions, maintaining soil cover can be challenging due to limited biomass production (Giller *et al.,* 2009b). Moreover, the optimum timing of nitrogen application also depends upon specific soil and climatic types of any location, as these factors affect the growth pattern of crops. So, the generalized recommendation of applying fertilizer after certain days of sowing may not always be beneficial. Apart from this, yield reduction in the initial years in CA (Kassam *et al.,* 2009) as well as in organic nutrient management, poor knowledge-guided extension services (Montgomery, 2007) etc. are some of the other reasons hindering the adaptation of clean tillage and nutrient management practices. These highlight the significance of formulating agro-ecosystem specific situation dependent clean tillage and nutrient management practices. This will not only help in sustaining the yield and improve the use efficiency of inputs, but also will lead to a lower environmental footprint. Such models should be adaptable to different soil types, climates, and cropping systems, providing farmers with tailored recommendations for CA and nutrient management practices. These models should also incorporate socio-economic factors, ensuring that the proposed practices are not only environmentally sustainable but also economically viable for farmers (Smith *et al.,* 2016a).

Designing environmentally clean tillage models for different agroecosystems

Developing an environmentally clean tillage model requires adhering to principles that prioritize soil health, enhance carbon sequestration, and control erosion while also being adaptable to diverse ecosystems.

a) *Low soil disturbance*: The model should prioritize minimal soil disturbance to maintain soil structure and biological activity. Techniques such as reduced tillage or strip-till should be promoted, as they limit the disruption of soil life and structure (Derpsch *et al.,* 2010).
b) *Carbon sequestration:* A key focus of the model should be on enhancing carbon sequestration by integrating practices that retain crop residues and promote the buildup of organic matter in the soil. This can be achieved through the adoption of zero tillage, minimum tillage, use of deep-rooted crops, and integration of crops that produce more leaf litter to maximize carbon inputs into the soil (Lal, 2015b).
c) *Erosion control:* The model must incorporate strategies to prevent soil erosion, such as maintaining soil cover, using contour farming in hilly areas, and implementing buffer strips. These practices not only prevent the loss of topsoil but also reduce sedimentation in waterways (Verhulst *et al.,* 2010).
d) *Compatibility with diverse soil types and climatic conditions*: The model must be versatile, with adjustable parameters that can be fine-tuned to fit the specific needs of different ecosystems. This requires a deep understanding of local conditions and the development of decision-support tools that can guide farmers in choosing the most appropriate practices for their specific context (Paustian *et al.,* 2000).

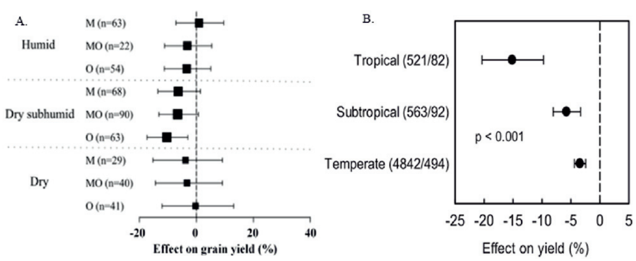
Case studies on environmentally clean tillage model

Successful implementation of reduced or no-tillage practices in various ecosystems demonstrates the potential of environmentally clean tillage models.

a) *Temperate ecosystems:* In temperate regions, no-tillage practices combined with cover cropping have been shown to significantly enhance soil health and reduce greenhouse gas emissions. For instance, in the U.S. Midwest, no-till combined with crop rotations has led to increased soil organic carbon levels and improved water retention (Powlson *et al.,* 2011). A meta-analysis based study (Fig. 3), also confirmed that no till-based approach is most suitable for temperate region agroecosystems compared to tropical and sub-tropical agroecosystems (Pittelkow *et al.,* 2015).

b) *Tropical ecosystems:* In tropical regions, conservation tillage with agroforestry practices has been effective in enhancing soil fertility and reducing erosion. In Brazil, for example, integrating no-till with nitrogen-fixing cover crops has improved nutrient cycling and resulted in higher crop yields (Lal, 2015b).

c) *Arid ecosystems:* In arid regions, reduced tillage combined with residue retention has been crucial in conserving soil moisture and preventing wind erosion. In Australia, adopting reduced tillage practices has helped maintain crop productivity in the face of increasing drought conditions (Verhulst *et al.,* 2010).



In addition to these, various tools and supporting techniques, such as decision support systems and remote sensing and GIS technologies, are crucial for developing and optimizing location- and situation-specific environmentally sustainable tillage models. Decision support systems (DSS) tools such as DSSAT (Decision Support System for Agrotechnology Transfer), APSIM (Agricultural Production Systems Simulator), EPIC (Environmental Policy Integrated Climate) models are invaluable in developing and validating tillage modules. These systems allow for the simulation of different tillage practices under varying climatic and soil conditions (Fig. 4), helping researchers and practitioners to identify the most effective strategies (Zhang *et al.,* 2022). Besides this, remote sensing and Geographic Information Systems (GIS) can also play a crucial role in monitoring and optimizing tillage practices. These technologies enable the assessment of soil health, erosion risk, and carbon sequestration potential across large landscapes, providing valuable data for fine-tuning tillage models. For example, remote sensing can be used to monitor crop residue cover, while GIS can help in mapping erosion-prone areas and planning conservation measures accordingly.

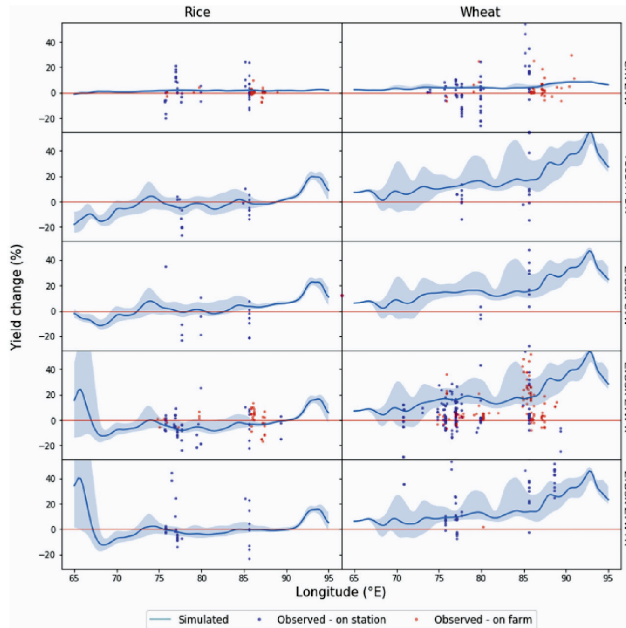


Fig. 4. EPIC simulated yield response in rice and wheat shows more response of CA based practices in eastern part of South Asia. The response is more in wheat compared to rice. CTR–ZTW: CTR followed by zero tilled wheat; PBDSR-PBW: direct seeded rice followed by wheat both on permanent beds; ZTDSR–CTW: zero-till direct seeded rice followed by CTW; ZTDSR–ZTW-R: ZTDSR followed by ZTW without residues; ZTDSR–ZTW+ R: ZTDSR followed by ZTW with residues. (Zhang *et al.,* 2022)

Designing environmentally clean nutrient management models for different agroecosystems

Cleaner nutrient management is crucial for enhancing crop productivity while minimizing environmental impacts. Tailoring nutrient management to specific agroecosystem characteristics ensures that crops receive the right amount of nutrients at the right time, at the right place, from the right source, reducing wastage and environmental pollution. In temperate regions with abundant organic matter, nutrient management typically focuses on maintaining a balanced supply of nitrogen, phosphorus, and potassium (Table 3). In contrast, tropical soils, often low in organic matter, may require higher inputs of organic amendments to improve soil fertility and structure (Vitousek *et al.,* 2010). Innovative approaches to nutrient management can further enhance nutrient use efficiency with lower environmental impacts:

a) *Precision nutrient management for targeted nutrient application*: Precision agriculture involves the use of technology to apply nutrients in precise amounts and locations based on real-time data. Techniques such as

Table 3. Some practical tips that can be considered for cleaner nutrient management.

Nutrient	Specific considerations
Nitrogen	• Do not apply urea as surface broadcasting under residue retained condition. • Sub-surface placement, band placement or point placement of urea is advisable depending upon the crop. • Split the N dose according to the crop need and soil condition. • Coated fertiliser or slow-release fertiliser can be a better option for reducing the loss of N. • Apply N just before rain or irrigate after fertilization to reduce volatilization loss. • Facilitate better drainage in the field or avoid water stagnation. For crops like rice in the CA system, alternate wetting and drying-based irrigation strategies should be followed. • Under residue retained condition, give preference to NO_3 fertilisers instead of NH_4-based fertiliser. • Include a legume component in the crop rotation. • If there is heavy weed pressure, do not apply N fertiliser. First, manage the weeds, then only go in for fertiliser application.
Phosphorus	• Residual contribution of P through mineralization • Sub-surface placement-based approach of P fertilization • Designing the crop rotation prioritizing mycotrophic plants like legume and maize, favouring the establishment of AM fungi • Maintaining favourable moisture regime in soil.
Potassium and other essential nutrients	• Apply only after assessing the nutrient supplying capacity of the soil and the crop requirement. • Ensure favorable soil moisture regime and good microbial activity.

Source: Sharma *et al.* (2023).

variable rate technology (VRT) allow for the site-specific application of fertilizers, reducing wastage and ensuring that crops receive the nutrients they require. Sapkota *et al.* (2021) reported that implementing Nutrient Expert-based fertilizer recommendation practices across all rice and wheat acreage in India could lead to an increase of 13.92 million tonnes in rice and wheat production, reduce nitrogen fertilizer use by 1.44 million tonnes, and decrease greenhouse gas emissions by 5.34 million tonnes of CO_2 equivalent annually compared to current farmer practices. This approach not only improves nutrient use efficiency (NUE) but also lowers the risk of environmental pollution.

b) *INM-based approach for optimized yield emission trade-offs*: Integrated nutrient management-based options not only improve the yield but also help in lowering the environmental footprint. Mohanty *et al.* (2020) reported that INM led to an 11–24 % reduction in N_2O emissions from lowland rice.

c) *Ecological nutrient management*: Ecological nutrient management (ENM) is an agroecological approach focused on managing the biogeochemical cycles that regulate soil ecosystem services and maintain soil fertility. The portfolio of ecological nutrient management (ENM) strategies goes beyond the use of inorganic fertilizers and is based on five key principles *i.e.,* build soil organic matter and other nutrient reserves, minimize the size of nitrogen (N) and phosphorus (P) pools that are most vulnerable to losses, maximize the agroecosystem's capacity to utilize soluble inorganic nitrogen and phosphorus, utilize functional and phylogenetic biodiversity and construct mass balances at both the agroecosystem and field scales to monitor net nutrient flows. A core tactic of ENM involves strategically increasing spatial and temporal plant species diversity. A few classic examples of this approach include the "*Push-pull polyculture*" system in sub-Saharan Africa and the "*Parkland agroforestry*" practice in West Africa. These systems enhance diversification by incorporating semi-perennial legumes like pigeon pea and groundnut, contributing to improved soil health, pest management, and overall sustainability.

Model framework for integrated tillage cum nutrient management strategy

Developing a conceptual framework for integrating tillage and nutrient management requires a thorough assessment of ecosystem-specific factors and the broader implications for climate change adaptation and mitigation. An effective model should integrate tillage and nutrient management based on principles that promote soil health, carbon sequestration, and nutrient efficiency. it must be adaptable enough to different ecosystems, enabling customization of practices based on local soil and climatic conditions (Fig. 5). The key considerations for developing these integrated models include:

a) *Considerations for different ecosystems like temperate, tropical, arid, and wetland ecosystems*

The model should account for the unique characteristics of different ecosystems (Table 4). For example, in

Table 4. Some examples of integrated tillage cum nutrient models across different agro-ecosystems.

Agro-ecological condition	Tillage management	Nutrient management	Benefits	Constraints
Humid tropics	Reduced tillage, strip tillage	Integrated nutrient management (INM), site-specific nutrient management (SSNM)	Reduced soil erosion, improved soil fertility, enhanced water retention	Weed management challenges, initial cost of implementation
Arid and Semi-Arid Regions nutrients	Zero tillage with mulching, strip tillage, contour tillage	Micro-dosing of fertilizers, fertigation, foliar spray etc.	Water conservation, reduced erosion, optimized nutrient use	High initial cost for equipment, need for careful management of water and
Temperate regions	Strip tillage, rotational tillage	Slow-release fertilizers, cover cropping with legumes, deep placement of fertilizers etc.	Improved soil health, reduced nutrient leaching, enhanced crop yields	Requires careful management to balance tillage and cover cropping, possible higher labor costs.
High rainfall regions	Contour farming with minimum tillage, raised bed planting	Controlled-release fertilizers, split application of fertilizers, slow-release fertilizers.	Reduced runoff, improved nutrient use efficiency, better soil structure.	Risk of soil compaction, higher costs for controlled-release fertilizers
Mountain and hilly regions	Terracing with minimal tillage, contour bunding	Organic manures, vermicompost, nutrient recycling with crop residues, legume integration in system, etc.	Erosion control, improved soil structure, enhanced nutrient cycling	High labor and cost for terracing, limited access to organic manure in some areas
Clay soils (heavy soils)	Subsurface tillage, raised bed farming, etc.	Deep placement of fertilizers, organic matter amendments, foliar spray, etc.	Improved drainage, enhanced soil structure, better nutrient uptake	Potential for soil compaction, high initial cost for specialized equipment
Sandy soils (light soils)	Minimal tillage with organic mulching, strip tillage	Frequent, low-dose fertilization, slow-release fertilizers, foliar spray, organic amendments application	Improved moisture retention, reduced nutrient leaching, enhanced soil structure	Need for frequent applications, poten tially higher costs for slow-release fertilizers.
Organic farming systems	No-till with organic mulching, cover cropping	Compost and manure application, crop rotation with legumes	Improved soil health, sustainable nutrient cycling, reduced reliance on synthetic inputs	Higher labor requirements, pest management
Areas prone to soil degradation	Minimum tillage with cover crops, reduced tillage etc.	Agroforestry with nutrient-rich trees, inclusion of legume in system, application of organic amendments etc.	Enhanced soil fertility, reduced degradation, improved carbon sequestration.	Initial investment in biochar and agroforestry systems.

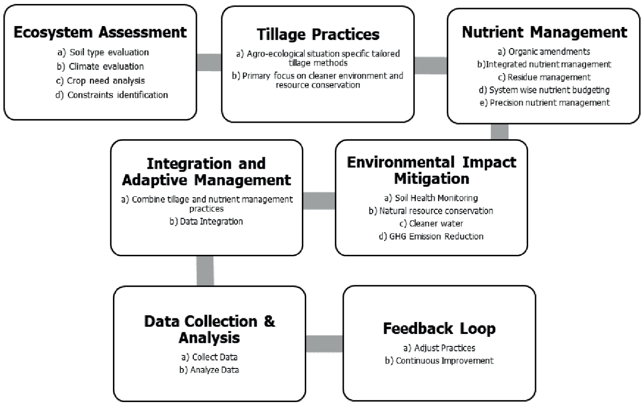


Fig. 5. Framework for integrated tillage cum nutrient management strategy.

temperate ecosystems, the model might emphasize the integration of cover crops and crop rotations to maintain soil organic matter and nutrient cycling. In tropical ecosystems, where soil degradation is a significant concern, the model might focus on agroforestry practices and the use of organic amendments to restore soil fertility. In arid ecosystems, the model might prioritize water conservation practices, such as mulching and reduced tillage, to enhance moisture retention and nutrient availability (Lal, 2015a).

b) *Consideration of crops and their specific management practices*

While designing the framework, significant consideration should be given to specific crops or cropping systems being addressed. For example, earthing up is an important management practice for crops like maize, potato, and sugarcane. It is advised to apply nitrogen as top dressing near to the crop plant as band or localized placement and then go for earthing up, which is helpful for increasing the use efficiency of nitrogen. Similarly, if the crop is rice, brown manuring with *Sesbania* can be an effective practice, that adds biologically fixed nitrogen to the soil, helps prevent soil erosion, and improves nutrient use efficiency.

c) *Role of climate change adaptation and mitigation in model design*

The model should also consider the impacts of climate change on soil health and nutrient availability. Practices that promote soil carbon sequestration, such as reduced tillage and the use of cover crops, can aid in climate change mitigation by lowering greenhouse gas emissions. Additionally, the model should incorporate adaptive strategies to help farmers cope with changing climatic conditions, such as adopting drought-resistant crop varieties and employing water-efficient irrigation techniques (Smith *et al.,* 2016b).

Environmental and socio-economic impacts of CAand nutrient management

Environmental benefits

Adopting environmentally clean tillage and nutrient management practices offers numerous environmental benefits, which contribute to overall sustainability and resiliency in agriculture.

a) *Potential for reducing greenhouse gas emissions:* Environmentally clean tillage practices, such as no-till or reduced tillage, can significantly reduce greenhouse gas emissions. These practices help maintain soil organic carbon levels by minimizing soil disturbance, and reducing carbon dioxide (CO_2) release from soil organic matter. Additionally, reduced tillage decreases nitrous oxide (N_2O) emissions by minimal soil disturbance and curtails fertilizer application which is a primary source of N_2O. Studies have shown that conservation tillage can reduce CO_2 emissions by up to 50% compared to conventional tillage (Powlson *et al.,* 2011). Furthermore, improved nutrient management practices can reduce methane (CH_4) emissions, particularly in puddled transplanted rice, by optimizing the timing and dose of fertilizer applications.

b) *Enhancing biodiversity and ecosystem services*: Environmentally clean tillage and nutrient management practices contribute to enriched biodiversity and ecosystem services. Practices such as maintaining ground cover and involving diverse crop rotations create habitats for a wide range of plants and animals, enhancing biodiversity. For example, cover crops can foster beneficial insects and soil organisms, contributing to greater ecosystem resilience. Furthermore, the improved soil health resulting from these practices enhances ecosystem services such as water filtration, erosion prevention, and nutrient cycling. This, in turn, supports the overall health of agroecosystems and their ability to provide essential services to agriculture and surrounding environments (Giller *et al.,* 2009b).

Socio-economic benefits

Understanding the economic implications of adopting clean tillage and nutrient management models is key to promoting their widespread use and ensuring long-term sustainability. A comprehensive cost-benefit analysis is essential to evaluate the economic feasibility of adopting clean tillage and nutrient management practices. While initial costs may involve investments in new equipment like no-till drills or precision agriculture tools, along with farmer training, these costs can be mitigated by long-term advantages such as decreased input costs (e.g., reduced fertilizer and fuel consumption), improved crop yields, and better soil health. Economic evaluations have shown that, despite high initial costs, long-term savings and productivity gains often result in a positive return on investment (Powlson *et al.,* 2011). Besides, in the long term, adopting environmentally clean practices increases resiliency to climatic variability, such as droughts or heavy rainfall. Communities also benefit from reduced environmental pollution, enhanced ecosystem services, and improved food security. These long-term advantages can contribute to the overall economic sustainability of agricultural systems and rural communities (Smith *et al.,* 2016b).

Policy implications

Policies play a crucial role in supporting the adoption and implementation of sustainable agricultural practices. Policymakers may prioritize creating a supportive framework for adopting clean tillage and nutrient management practices. This includes developing policies that promote research and development, provide technical support and extension services, and facilitate knowledge exchange among farmers. Additionally, policies could promote the integration of sustainable practices into agricultural programs and curricula, ensuring that farmers are equipped with the knowledge and skills needed for successful implementation (Montgomery, 2007). Financial incentives, such as subsidies or cost-sharing programs, can help offset the upfront costs of adopting innovative/new practices and encourage widespread implementation. Additionally. regulations that limit the use of harmful inputs or promote natural resources conservation practices can also drive significant change. For example, subsidies for cover crops or no-till equipment can make these practices more accessible to farmers, while regulations mandating nutrient management plans can help reduce environmental impacts (Lal, 2015b; Smith *et al.,* 2016b).

Research gaps, challenges, and future prospects

To advance sustainable agricultural practices, it's essential to address research gaps and implementation challenges. Research should focus on understanding the long-term impacts of clean tillage and nutrient management on soil health, crop productivity, and environment, as well as tailoring practices to specific regional conditions, such as soil type, climate, and cropping systems. Additionally, understanding the socio-economic impacts and barriers to adoption, like knowledge gaps, high initial costs, and inadequate infrastructure, is crucial for effectively supporting farmers. To overcome these barriers, access to financial support, technical assistance, and education on sustainable practices is needed. Emerging technologies, such as artificial intelligence (AI) and the Internet of Things (IoT), offer new opportunities for optimizing nutrient management and tillage through enhanced decision-making and real-time monitoring. Scaling up successful models will require collaboration among researchers, practitioners, and policymakers to promote best practices and adapt solutions to various contexts. By building networks, sharing resources, and leveraging technological advancements can facilitate broader adoption of these sustainable practices, ultimately improving resource use efficiency and agricultural sustainability.

CONCLUSIONS

This review underscores the critical need for ecosystem-specific tillage and nutrient management models to advance sustainable agriculture. By tailoring practices to diverse ecosystems, these models can enhance soil health, improve nutrient use efficiency, and mitigate environmental impacts. Researchers are urged to focus on long-term impacts, regional specificity, and emerging technologies, and also to implement and adapt sustainable practices tailored to local conditions. Policymakers must support these efforts through incentives, regulations, and technical support. Global collaboration is essential to share knowledge and best practices, overcome adoption barriers, and drive progress toward a sustainable agricultural system. The urgency of climate change and the need for food security amplify the importance of these efforts, emphasizing the need for a coordinated global approach to enhance agricultural sustainability and ensure the health and productivity of soils for future generations.

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