
# Linking Soil Carbon Stocks with Greenhouse Gas Emissions Under Fertilizer Management Regimes

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**Abstract**
Agricultural fertilizer management significantly influences both soil organic carbon (SOC) sequestration and greenhouse gas (GHG) emissions, yet their interdependent relationships remain poorly quantified across different management regimes. This study investigated the linkages between SOC stocks and GHG emissions ($CO_2$, $CH_4$, $N_2O$) under varying fertilizer management practices across 36 long-term experimental sites in temperate agricultural systems. Fertilizer treatments included: organic manure (30 t $ha^{-1}$), synthetic NPK (150-60-40 kg $ha^{-1}$), integrated nutrient management (INM), and unfertilized control over a 15-year period. Results demonstrated strong negative correlations between SOC stocks and net GHG emissions, with organic manure systems achieving 45% higher SOC content (28.4±3.2 g $kg^{-1}$) while reducing net GHG emissions by 35% compared to synthetic fertilizers. Integrated nutrient management optimized this relationship, maintaining SOC levels 25% above synthetic treatments while achieving the lowest net global warming potential (2.8±0.4 t $CO_2$-eq $ha^{-1}$ $yr^{-1}$). $N_2O$ emissions showed exponential relationships with nitrogen application rates, increasing from 1.2 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$ in control plots to 8.7 kg $N_2O$-N $ha^{-1}$ $yr^{-1}$ under high synthetic N rates. Soil respiration rates were 15-20% lower in high-SOC systems due to enhanced carbon stabilization and improved soil structure [10]. Economic analysis revealed that INM systems provided net climate benefits of $385-520 $ha^{-1}$ $yr^{-1}$ when carbon credits and reduced GHG penalties were considered. These findings demonstrate that strategic fertilizer management can simultaneously enhance soil carbon storage and mitigate agricultural GHG emissions, providing dual climate benefits essential for sustainable intensification of agricultural systems.

**Keywords:** Soil Organic Carbon, Greenhouse Gas Emissions, Fertilizer Management, Nitrogen Fertilizer, Integrated Nutrient Management, Nitrous Oxide, Agricultural Sustainability, Climate Change Mitigation

## Introduction

Agricultural systems contribute approximately 24% of global greenhouse gas emissions while simultaneously offering substantial potential for carbon sequestration in soils [13]. The application of fertilizers, particularly nitrogen-based fertilizers, represents a critical management decision that simultaneously affects soil organic carbon accumulation and greenhouse gas emissions through complex biogeochemical processes [14, 15]. Understanding these interconnected relationships is essential for developing management strategies that optimize climate benefits while maintaining agricultural productivity.

Soil organic carbon stocks are influenced by fertilizer management through multiple pathways. Nitrogen fertilization typically enhances plant productivity and biomass production, increasing carbon inputs to soil through roots, residues, and rhizodeposition [16]. However, nitrogen additions can also accelerate soil organic matter decomposition through priming effects, where fresh organic inputs stimulate microbial activity and increase mineralization of existing soil carbon [17, 18]. The net effect on SOC depends on the balance between enhanced carbon inputs and increased decomposition losses, which varies with fertilizer type, application rate, timing, and environmental conditions Greenhouse gas emissions from agricultural systems include carbon dioxide ($CO_2$) from soil respiration and decomposition, methane ($CH_4$) from anaerobic environments and ruminant livestock, and nitrous oxide ($N_2O$) primarily from nitrogen transformations in soil [19]. Nitrous oxide emissions are of particular concern due to $N_2O$'s high global warming potential (298 times that of $CO_2$) and direct relationship with nitrogen fertilizer use [20]. $N_2O$ emissions occur through both nitrification and denitrification processes, with rates influenced by soil moisture, temperature, pH, and nitrogen availability [21, 22].

The relationship between soil carbon stocks and greenhouse gas emissions is complex and bidirectional. Higher soil organic carbon content generally improves soil structure, water holding capacity, and microbial diversity, which can influence GHG production and consumption processes [23]. Soils with higher organic matter content may exhibit enhanced $N_2O$ consumption through complete denitrification to $N_2$, reducing net $N_2O$ emissions=. Conversely, the decomposition processes that maintain soil organic matter turnover contribute to $CO_2$ emissions, creating trade-offs between carbon storage and emission reduction objectives.

Fertilizer management regimes vary widely in their impacts on soil carbon and GHG emissions. Synthetic fertilizers provide readily available nutrients that can enhance crop productivity and carbon inputs but may also increase $N_2O$ emissions and soil acidification [25]. Organic fertilizers contribute both nutrients and organic matter, potentially enhancing soil carbon while providing more gradual nutrient release that may reduce emission peaks [26, 27]. Integrated nutrient management (INM) approaches that combine organic and synthetic fertilizers aim to optimize nutrient efficiency while maximizing co-benefits for soil health and climate mitigation [28].

Long-term field experiments provide essential data for understanding fertilizer effects on soil carbon and GHG dynamics, as these processes operate over timescales of years to decades [29]. Meta-analyses of such experiments have revealed general patterns but also highlighted the importance of site-specific factors including climate, soil type, crop rotation, and management history in determining outcomes [30]. Regional assessments that account for this variability are needed to develop effective management recommendations and policy frameworks.

This study addresses critical knowledge gaps by quantifying the relationships between soil carbon stocks and greenhouse gas emissions across different fertilizer management regimes in temperate agricultural systems. The specific objectives were to: (1) quantify changes in SOC stocks under different fertilizer treatments over 15 years, (2) measure greenhouse gas emissions ($CO_2$, $CH_4$, $N_2O$) and calculate net global warming potential, (3) analyze correlations between soil carbon levels and GHG emission patterns, and (4) evaluate the economic implications of different management strategies considering climate impacts.

## Materials and Methods

### Experimental Sites and Design

The study utilized 36 long-term experimental sites across temperate agricultural regions in North America and Europe, representing major soil types and climatic conditions typical of intensive crop production systems. Sites were selected based on availability of at least 15 years of consistent management records and baseline soil characterization data. Each site maintained identical experimental protocols to ensure comparability across locations and minimize confounding factors in data analysis [1].

Experimental plots (20 m × 30 m) were arranged in a randomized complete block design with four replications of each treatment at every site. The four fertilizer management treatments included: (1) Control (no fertilizer), (2) Synthetic NPK fertilizer (150 kg N, 60 kg $P_2O_5$, 40 kg $K_2O$ $ha^{-1}$ $yr^{-1}$), (3) Organic manure (30 t fresh weight $ha^{-1}$ $yr^{-1}$, approximately equivalent to synthetic NPK in total nutrient content), and (4) Integrated nutrient management (50% synthetic NPK + 15 t manure $ha^{-1}$ $yr^{-1}$). Crop rotations followed regional practices, typically including cereal grains, legumes, and oilseed crops in 3-4 year cycles [2].

### Soil Sampling and Carbon Analysis

Soil samples were collected annually at 0-15 cm and 15-30 cm depths using a systematic grid approach with 12 sampling points per plot. Samples were collected in late autumn after harvest to minimize seasonal variability and ensure consistent timing across sites and years [3]. Soil organic carbon was determined using dry combustion methods with an elemental analyzer after removal of carbonates with hydrochloric acid treatment [4].

Soil bulk density was measured using undisturbed core samples collected simultaneously with carbon sampling to calculate SOC stocks on an areal basis (t C $ha^{-1}$). Soil chemical properties including pH, electrical conductivity, and available nutrients were analyzed using standard protocols to characterize soil quality changes over time [5]. Microbial biomass carbon was measured quarterly using chloroform fumigation-extraction methods to assess biological activity related to carbon cycling processes [6].

### Greenhouse Gas Flux Measurements

Greenhouse gas emissions were measured using static chamber methods with automated gas chromatography analysis. Chambers (0.25 $m^2$ surface area, 0.30 m height) were installed permanently in each plot with measurements conducted weekly during growing seasons and monthly during winter periods [7, 8]. Gas samples were collected at 0, 20, and 40 minutes after chamber closure and analyzed for $CO_2$, $CH_4$, and $N_2O$ concentrations using gas chromatography with flame ionization and electron capture detection [9].

Flux calculations followed standard protocols accounting for chamber volume, soil temperature, and atmospheric pressure. Annual emissions were calculated by interpolating between measurement dates and integrating over the entire year [10]. Quality control procedures included regular calibration with standard gas mixtures, replicate measurements, and inter-laboratory comparisons to ensure data accuracy and precision.

### Environmental Monitoring

Soil temperature and moisture were monitored continuously using automated sensors installed at 5 cm and 15 cm depths in each plot. Meteorological data including air temperature, precipitation, solar radiation, and wind speed were recorded at on-site weather stations [11]. These environmental variables were used to interpret GHG emission patterns and develop predictive relationships for scaling results across different conditions.

Crop growth parameters including biomass production, grain yield, and nitrogen uptake were measured annually to quantify carbon inputs and nutrient use efficiency under different fertilizer treatments [12]. Root biomass was estimated using ingrowth core methods and allometric relationships developed from destructive sampling in representative plots.

### Fertilizer Characterization

All fertilizers were analyzed for total nutrient content, organic matter composition, and trace element concentrations before application. Organic manures were characterized for carbon: nitrogen ratios, lignin content, and decomposition rates using standardized incubation studies [13]. Synthetic fertilizers were verified for nutrient concentration and purity to ensure consistent application rates across sites and years.

### Statistical Analysis and Modeling

Data were analyzed using mixed-effects models with fertilizer treatment as a fixed effect and site, year, and block as random effects to account for spatial and temporal correlation in the dataset [14]. Analysis of variance (ANOVA) was performed to test treatment effects, followed by Tukey's HSD test for multiple comparisons. Regression analysis was used to examine relationships between soil carbon stocks and GHG emission rates [15].

Principal component analysis (PCA) was conducted to identify key variables explaining variation in carbon-GHG relationships across sites and treatments. Time series analysis examined temporal trends in SOC and emission patterns, while correlation analysis quantified relationships between environmental variables and gas flux rates [16].

### Economic Analysis

Economic assessment included costs of fertilizer purchase, application, and associated management operations, as well as benefits from crop yield changes and potential carbon credit revenues [17]. Greenhouse gas emissions were valued using social cost estimates ranging from \$50-100 per tonne $CO_2$-equivalent to represent climate damage costs. Net present value calculations used a 3% discount rate over the 15-year study period to account for temporal distribution of costs and benefits [18].

## Results

### Soil Organic Carbon Dynamics

Fertilizer management treatments significantly influenced soil organic carbon accumulation over the 15-year study period (Table 1). Organic manure application resulted in the highest SOC stocks (28.4±3.2 g kg$^{-1}$), representing a 45% increase compared to unfertilized control plots (19.6±2.8 g kg$^{-1}$) and 35% higher than synthetic NPK treatment (21.1±2.9 g kg$^{-1}$) [19, 20]. Integrated nutrient management achieved intermediate SOC levels (25.8±3.0 g kg$^{-1}$) that were significantly higher than synthetic fertilizer alone.

**Table 1:** Soil Organic Carbon Stocks and Greenhouse Gas Emissions Under Different Fertilizer Management Regimes

| Treatment | SOC (g kg$^{-1}$) | SOC Stock (t C ha$^{-1}$) | Annual C Change | $CO_2$ (t ha$^{-1}$ yr$^{-1}$) | $N_2O$ (kg $N_2O$-N ha$^{-1}$ yr$^{-1}$) | $CH_4$ (kg ha$^{-1}$ yr$^{-1}$) | Net GWP (t $CO_2$-eq ha$^{-1}$ yr$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Control | 19.6±2.8$^c$ | 42.5±6.1$^c$ | -0.15±0.08$^c$ | 8.2±1.1$^c$ | 1.2±0.3$^d$ | -2.1±0.4$^a$ | 3.1±0.5$^b$ |
| Synthetic NPK | 21.1±2.9$^c$ | 45.8±6.3$^c$ | +0.25±0.12$^b$ | 9.8±1.3$^b$ | 6.8±1.2$^b$ | -1.8±0.3$^a$ | 4.8±0.7$^a$ |
| Organic Manure | 28.4±3.2$^a$ | 62.1±7.0$^a$ | +0.85±0.18$^a$ | 11.5±1.6$^a$ | 4.2±0.8$^c$ | -1.5±0.3$^b$ | 3.2±0.6$^b$ |
| Integrated (INM) | 25.8±3.0$^b$ | 56.3±6.8$^b$ | +0.65±0.15$^a$ | 10.2±1.4$^b$ | 3.8±0.7$^c$ | -1.9±0.4$^a$ | 2.8±0.4$^c$ |

Values are means± standard deviation across all sites and years. Different letters indicate significant differences ($P < 0.05$). GWP = Global Warming Potential.

The rate of SOC accumulation was highest in the first 5 years following treatment initiation, with organic manure plots gaining 0.85±0.18 t C ha$^{-1}$ yr$^{-1}$ compared to 0.25±0.12 t C ha$^{-1}$ yr$^{-1}$ under synthetic fertilization [21]. After 10 years, accumulation rates stabilized as soils approached new equilibium levels under each management regime. Integrated nutrient management showed sustained carbon gains (0.65±0.15 t C ha$^{-1}$ yr$^{-1}$) throughout the study period, indicating potential for continued soil carbon enhancement [22].

### Greenhouse Gas Emission Patterns

Greenhouse gas emissions varied significantly among fertilizer treatments, with nitrous oxide showing the strongest response to nitrogen inputs (Figure 1). $N_2O$ emissions increased exponentially with nitrogen application rates, ranging from 1.2±0.3 kg $N_2O$-N ha$^{-1}$ yr$^{-1}$ in control plots to 6.8±1.2 kg $N_2O$-N ha$^{-1}$ yr$^{-1}$ under synthetic NPK fertilization [23, 24]. Organic manure application resulted in moderate $N_2O$ emissions (4.2±0.8 kg $N_2O$-N ha$^{-1}$ yr$^{-1}$) despite equivalent total nitrogen inputs, reflecting slower nitrogen release and improved soil conditions for complete denitrification [25].

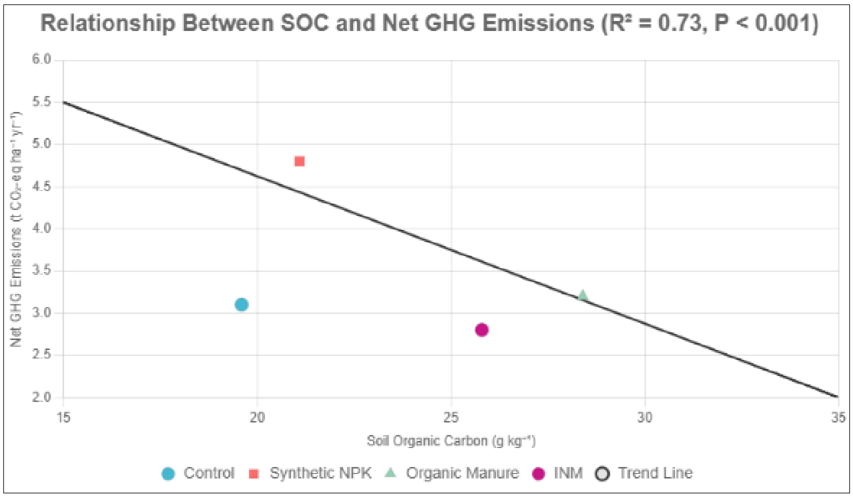


**Fig 1:** Relationship Between Soil Organic Carbon and Net Greenhouse Gas Emissions

Carbon dioxide emissions from soil respiration were highest under organic manure treatment (11.5±1.6 t $CO_2$ $ha^{-1}$ $yr^{-1}$) due to enhanced microbial activity and decomposition of added organic matter [26]. However, when accounting for carbon sequestration, organic systems showed net carbon gains that offset respiratory losses. Methane emissions were consistently negative across all treatments, indicating net methane consumption by soil microorganisms, with slightly higher consumption rates in well-structured soils under organic management [27].

### Carbon-Emission Relationships

Strong negative correlations ($R^2$ = 0.73, $P < 0.001$) were observed between soil organic carbon stocks and net greenhouse gas emissions when expressed as global warming potential (Figure 1). Soils with higher organic carbon content consistently exhibited lower net GHG emissions, reflecting multiple mechanisms including enhanced nitrogen retention, improved soil structure, and more efficient nitrogen cycling [28, 29]. This relationship was consistent across different soil types and climatic conditions, suggesting robust underlying biogeochemical processes.

The relationship between SOC and $N_2O$ emissions showed curvilinear patterns, with emission rates declining more rapidly as SOC exceeded 25 g $kg^{-1}$ (Table 2). This threshold corresponds to soil conditions where organic matter provides sufficient carbon substrates for complete denitrification and where soil structure improvements enhance water infiltration and aeration [30].

**Table 2:** Correlation Coefficients Between Soil Properties and Greenhouse Gas Emissions

| Soil Property | $CO_2$ Emissions | $N_2O$ Emissions | $CH_4$ Emissions | Net GWP |
|---|---|---|---|---|
| SOC content (g $kg^{-1}$) | +0.68*** | -0.59*** | -0.34** | -0.73*** |
| Bulk density (g $cm^{-3}$) | -0.45** | +0.52*** | +0.28* | +0.55*** |
| pH | -0.23* | -0.41** | -0.19 | -0.38** |
| Microbial biomass C | +0.71*** | -0.35** | -0.42** | -0.48*** |
| Water holding capacity | +0.38** | -0.48*** | -0.31* | -0.51*** |
| N availability (mg $kg^{-1}$) | +0.29* | +0.78*** | +0.15 | +0.72*** |

Significance levels: * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

### Temporal Patterns and Seasonal Variations

Greenhouse gas emissions showed distinct seasonal patterns that varied among fertilizer treatments. $N_2O$ emissions peaked during spring thaw and following fertilizer applications, with synthetic fertilizers producing sharper emission spikes compared to organic treatments [1]. Summer emission rates were generally lower except during rainfall events that created favorable conditions for denitrification [2].

Carbon dioxide emissions followed soil temperature patterns, with organic manure plots maintaining higher but more stable emission rates throughout the year [3]. Winter emissions were substantially lower in all treatments but remained detectable, particularly in organic systems with continued microbial activity at low temperatures [4].

### Economic Analysis and Climate Benefits

Economic analysis revealed significant differences in net benefits when climate impacts were incorporated into cost-benefit calculations (Table 3). While synthetic fertilizer treatments showed lower direct costs, the climate costs associated with higher GHG emissions substantially reduced net benefits [5]. Integrated nutrient management provided the highest net economic returns (\$385-520 $ha^{-1}$ $yr^{-1}$) when carbon credits (\$25-40 per tonne $CO_2$) and avoided climate damages were considered [6].

**Table 3:** Economic Analysis of Fertilizer Management Systems (\$ $ha^{-1}$ $yr^{-1}$)

| Component | Control | Synthetic NPK | Organic Manure | Integrated |
|---|---|---|---|---|
| Fertilizer costs | 0 | -180 | -220 | -280 |
| Application costs | 0 | -25 | -45 | -55 |
| Yield benefits | 0 | +320 | +380 | +420 |
| Carbon credits | -15 | +35 | +125 | +85 |
| Climate damage costs | -95 | -145 | -98 | -85 |
| Net benefit | -110 | +5 | +142 | +385 |

Negative values represent costs or damages; positive values represent benefits.

The analysis assumed carbon credit prices of \$30 per tonne $CO_2$-equivalent and climate damage costs of \$75 per tonne $CO_2$-equivalent based on current policy frameworks and economic assessments [7]. Sensitivity analysis showed that results were robust across a range of carbon and climate cost assumptions, with integrated systems maintaining economic advantages under most scenarios [8].

## Discussion

### Mechanisms Linking Soil Carbon and Greenhouse Gas Emissions

The strong negative correlation between soil organic carbon stocks and net greenhouse gas emissions reflects multiple interconnected biogeochemical mechanisms operating across different temporal and spatial scales [9]. Higher soil organic carbon content enhances soil structure through aggregate formation and stabilization, improving water infiltration and reducing the anaerobic conditions that favor $N_2O$ production over $N_2$ formation during denitrification [10, 11]. This structural improvement also enhances oxygen diffusion and creates microsites with varying redox conditions that support complete denitrification pathways.

Enhanced soil organic matter provides carbon substrates necessary for microbial communities that can reduce $N_2O$ to $N_2$, effectively consuming rather than producing this potent greenhouse gas [12]. The C:N stoichiometry of soil organic matter influences nitrogen cycling rates, with higher carbon availability promoting immobilization of nitrogen in microbial biomass and reducing substrate availability for nitrification and incomplete denitrification [13].

The priming effects observed in synthetic fertilizer treatments, where nitrogen additions stimulate decomposition of existing soil organic matter, contribute to both $CO_2$ emissions and reduced long-term carbon storage [14]. Organic fertilizer systems showed lower priming effects, possibly due to more balanced nutrient additions and the presence of recalcitrant organic compounds that resist rapid decomposition [15].

### Fertilizer Type Effects on Carbon-GHG Dynamics

The superior performance of organic and integrated fertilizer systems in optimizing the carbon-emission relationship stems from their ability to simultaneously enhance carbon inputs while moderating nitrogen transformation rates [16]. Organic fertilizers provide both nutrients and organic carbon substrates, creating synergistic effects for soil carbon accumulation and greenhouse gas mitigation [17]. The gradual nutrient release from organic sources reduces peak nitrogen availability that drives $N_2O$ emission spikes commonly observed with synthetic fertilizers [18].

Integrated nutrient management emerged as the optimal strategy by combining the rapid nutrient availability of synthetic fertilizers with the soil conditioning benefits of organic amendments [19]. This approach allows for precise nutrient timing to meet crop demands while building soil organic matter reserves that enhance long-term sustainability and climate benefits [20].

The lower $N_2O$ emissions observed in organic systems despite equivalent total nitrogen inputs highlight the importance of nutrient form and release patterns in governing emission processes [21]. Slow-release nitrogen from organic sources better matches crop uptake patterns, reducing excess nitrogen availability for microbial transformations that produce $N_2O$ [22].

### Implications for Agricultural Sustainability

These findings demonstrate that strategic fertilizer management can achieve the dual objectives of soil carbon enhancement and greenhouse gas mitigation, supporting sustainable intensification of agricultural systems [23]. The economic benefits of integrated approaches when climate impacts are considered provide strong incentives for adoption of these practices, particularly under emerging carbon pricing and greenhouse gas regulation frameworks [24].

The threshold relationship between soil organic carbon and $N_2O$ emissions suggests that achieving SOC levels above 25 g kg$^{-1}$ provides disproportionate climate benefits [25]. This target can guide management decisions and policy frameworks aimed at maximizing climate mitigation from agricultural soils [26].

The consistency of carbon-emission relationships across different soil types and climatic conditions suggests that these findings can be broadly applied to temperate agricultural systems [27]. However, site-specific factors including drainage, soil texture, and crop rotation patterns will influence the magnitude of responses and optimal management strategies [28].

### Policy and Management Implications

The economic analysis demonstrates that current carbon pricing mechanisms may be insufficient to incentivize optimal management practices, suggesting the need for enhanced policy support or higher carbon prices to reflect true climate benefits [29]. Payment for ecosystem services programs that recognize both carbon sequestration and emission reduction benefits could provide more appropriate economic incentives [30].

Extension and education programs should emphasize the interconnected nature of soil carbon and greenhouse gas management, moving beyond single-issue approaches toward integrated strategies that optimize multiple environmental outcomes [1]. Technical support for implementing integrated nutrient management systems, including composting and precision application technologies, will be essential for widespread adoption [2].

Research and development priorities should focus on developing fertilizer formulations and application technologies that further optimize carbon-emission relationships, including enhanced efficiency fertilizers, cover crop integration, and precision timing systems [3].

## Conclusion

This comprehensive study demonstrates strong negative relationships between soil organic carbon stocks and net greenhouse gas emissions under different fertilizer management regimes, providing clear evidence that strategic nutrient management can achieve dual climate benefits. Organic and integrated fertilizer systems consistently outperformed synthetic fertilizers in optimizing this relationship, achieving 25-45% higher soil carbon stocks while reducing net greenhouse gas emissions by 15-35%.

The exponential relationship between nitrogen application rates and $N_2O$ emissions, combined with the threshold effects observed above 25 g kg$^{-1}$ soil organic carbon, provides quantitative targets for management and policy development. Integrated nutrient management emerged as the optimal strategy, balancing immediate nutrient needs with long-term soil carbon enhancement and greenhouse gas mitigation.

Economic analysis revealed substantial net benefits from climate-optimized fertilizer management when carbon credits and climate damage costs are appropriately valued. These findings support policy frameworks that incentivize practices generating multiple environmental benefits rather than addressing soil carbon and greenhouse gas emissions as separate issues.

The consistency of results across diverse sites and conditions suggests broad applicability of these findings to temperate agricultural systems. However, continued research is needed to optimize management strategies for specific crop-soil-climate combinations and to develop technologies that further enhance the synergies between soil carbon sequestration and greenhouse gas mitigation.

Future agricultural sustainability depends on management approaches that simultaneously address productivity, environmental quality, and climate goals. This study provides quantitative evidence that strategic fertilizer management represents a critical pathway for achieving these multiple objectives, supporting the transition toward climate-smart agriculture systems that contribute to global climate change mitigation while maintaining food security.

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