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Review

Managing Carbon in Agroecosystems: The Roles of Fertilizers and Crop Management

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Abstract

Agriculture faces the dual challenge of reducing greenhouse-gas emissions while maintaining food production under increasing climatic stress. This review examines fertilizer and crop management strategies to reducing production-related emissions and restoring carbon stocks in agroecosystems. It links fertilizer-related emissions, plant carbon inputs, and nutrient cycling to assess soil carbon sequestration in relation to both climate mitigation and soil fertility. Mineral nitrogen fertilizers often account for the largest share of the carbon footprint of crop production, but an adequate nitrogen supply is also required for photosynthesis, net primary production, root growth, crop yield, and plant-derived carbon inputs to soil. Carbon management should therefore optimize fertilizer production and use rather than simply restrict nitrogen inputs. Relevant measures include lower-emission fertilizer manufacture, improved nutrient-use efficiency, mineral–organic fertilization, manure and residue recycling, increased use of legumes and cover crops, and regulation of carbon–nitrogen interactions during organic-matter decomposition. Mineral fertilizers generally produce modest increases in soil organic carbon (SOC), whereas organic amendments produce larger gains. However, finite carbon-storage capacity, declining sequestration rates, reversibility, limited biomass and nutrient resources, and measurement uncertainty substantially restrict the contribution of soil sequestration to global climate-change mitigation. The most realistic objective of agroecosystem recarbonization is therefore to restore soil fertility, support stable food production, and increase resilience to climatic extremes.

Keywords: carbon footprint; soil carbon sequestration; nitrogen fertilizers; organic amendments; soil fertility; climate-change mitigation

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1. Introduction

Disruption of the biogeochemical carbon cycle through fossil-fuel combustion, deforestation, land conversion, and other human activities has increased atmospheric carbon dioxide (CO_2). In 2023, its global mean concentration reached 420 ppm, or 151% of the pre-industrial level [1]. Soils are a major natural source and sink of CO_2 [2,3], and agriculture contributes substantially to anthropogenic greenhouse gas emissions [4].

Rising concentrations of CO_2 and other greenhouse gases warm the planet and increase the frequency and duration of extreme weather events [5–7]. Climate change contributes to soil degradation, biodiversity loss, ecosystem desertification, food shortages, and freshwater scarcity [8,9]. This further aggravates the problem of food security, particularly

because global food demand is expected to increase by 30–62% between 2010 and 2050 [10]. Climatic extremes profoundly alter biological processes and element cycling in the soil–microorganism–plant system [11–13].

Modern agroecosystems face interconnected challenges that threaten productivity and soil health. Agricultural intensification has increased food production, but poorly managed systems can deplete soil organic carbon (SOC), reduce nutrient-use efficiency, and increase nutrient losses and greenhouse gas emissions. Crop residue burning and excessive or inefficient agrochemical use further aggravate these problems. Changes in temperature and rainfall, together with more frequent extreme events, affect crop growth, water availability, and nutrient cycling. Sustainable soil management must therefore maintain crop productivity, restore SOC stocks, and improve resilience while limiting emissions [13–17].

Elevated atmospheric CO_2 can also stimulate plant growth. This biological phenomenon is known as the CO_2 fertilization effect [18]. Higher CO_2 concentrations increase substrate availability for photosynthesis and can reduce leaf transpiration, improving carbon assimilation, water-use efficiency, and biomass production [13]. The CO_2 fertilization effect occurs in approximately 90% of C_3 plants, including wheat, rice, soybean, and forest trees, and to a lesser extent in C_4 plants, including maize and sorghum; the magnitude of the response also depends on the cultivar [19]. An increase in CO_2 concentration of 1 ppm has been reported to increase the yields of maize, soybean, and wheat by 0.5%, 0.6%, and 0.8%, respectively [20]. Retrospective calculations by these authors attributed 10%, 30%, and 40% of the yield increases in these three crops since 1940 to increasing CO_2 emissions. An increase in atmospheric CO_2 concentration of 100 ppm may increase crop productivity by 5–17% on average among regions, by 0–33% among crops within the same region, and by 1–21% among individual countries [21]. Other estimates suggest that the yield increase associated with elevated atmospheric CO_2 may range from approximately 10% to 50% depending on the region, with a mean of approximately 26% [22,23]. However, nutrient limitation, particularly nitrogen deficiency, water shortage, extreme temperatures, and the metabolic acclimation of plants to elevated atmospheric CO_2 over time may weaken or completely eliminate the fertilization effect [24,25]. C_3 plants are more sensitive to temperature stress than C_4 plants [13]. In addition, the CO_2 fertilization effect entails such risks as reduced nutritional quality of some staple crops through lower protein and mineral concentrations [24].

The CO_2 fertilization effect may partly offset climate-related yield losses, but its benefits appear smaller than previously expected. The response will differ among regions. At high latitudes, the expected increases in temperature and CO_2 concentration may positively affect yields, but more frequent extreme weather events will constrain sustainable production [13]. Crop production at lower latitudes may, in turn, be severely affected by climate change, especially for crops with the C_4 photosynthetic pathway, such as maize. Thus, CO_2 fertilization should not be assumed to outweigh the adverse effects of climate change on agriculture.

Agricultural technologies and fertilization systems should both reduce greenhouse gas emissions from production and restore depleted carbon stocks in agroecosystems. Decarbonization requires identifying direct and indirect emissions throughout production and selecting measures that improve energy efficiency and reduce carbon and nitrogen losses. Agroecosystem recarbonization aims to replenish soil organic matter (SOM) and improve conditions for plant growth. It brings together practices that increase crop carbon inputs, reduce mineralization and erosion losses, and improve the use of mineral and organic fertilizers. These complementary objectives underpin carbon agrochemistry [26,27], which seeks to manage carbon cycling in the soil–plant–atmosphere system while sustaining food production under increasing climatic stress.

This review evaluates fertilizer and crop management strategies to restoring SOC stocks and managing soil carbon sequestration. It examines how mineral and organic fertilizers affect carbon cycling in the soil–microorganism–plant system, nutrient-use efficiency, and crop productivity. It also assesses the limitations of sequestration as a climate mitigation strategy and identifies practices that support soil fertility, stable food production, and climate resilience.

2. Carbon Footprint of Agricultural Production and Priorities for Decarbonizing Agriculture

The carbon footprint is the total amount of greenhouse gases emitted directly or indirectly into the atmosphere over a defined life cycle, from production to disposal, expressed as carbon dioxide equivalents (CO_2-eq). The principal agricultural sources of greenhouse gases are emissions from grazing livestock (16.1% of agricultural emissions), mineral-fertilizer use (12.6%), rice production (10%), manure processing and storage (6.7%), and the application of crop residues and manure (6.5%) [28]. The carbon footprint of mineral nitrogen, phosphorus, and potassium fertilizers differs depending on their composition, production technology, and application. The mean carbon footprint of nitrogen fertilizers is estimated at 3–8 t CO_2-eq per tonne of nutrient (Table 1). This high footprint reflects the high energy demand of production, particularly the manufacture of ammonia from natural gas. The production of 1 t of mineral nitrogen fertilizer, including ammonia, ammonium nitrate, or urea, releases approximately 1.8–2.2 t CO_2. Nitrous oxide (N_2O) emissions following fertilizer application further increase the total carbon footprint because its global warming potential on a 100-year time horizon is more than 250 times that of CO_2. N_2O also contributes to stratospheric ozone depletion [29]. Phosphorus and potassium fertilizers have substantially smaller carbon footprints than nitrogen fertilizers (Table 1).

Table 1. Indicative carbon footprints of selected agricultural inputs and operations reported in the literature.

Category	Material or Process	Reported Footprint	Functional Unit	References
Pesticide	Herbicide	6.2–46.2	kg CO_2-eq kg^{-1} product	[30,31]
	Insecticide	4.4–29.7		
	Fungicide	4.4–29.3		
Mineral fertilizer	Ammonium nitrate	4–6	kg CO_2-eq kg^{-1} nutrient	[28,30–38]
	Urea	5–8		
	Ammonium sulfate	3–4		
	Single superphosphate	0.6–1.0		
	Double superphosphate	0.9–1.3		
	Potassium chloride	0.3–0.5		
	Potassium sulfate	0.4–0.6		
	Compound fertilizer 15:15:15	0.80–1.02		
Organic fertilizer	Liquid manure, direct application	24.4	kg CO_2-eq t^{-1} manure	[39]
	Liquid manure, aerobic treatment	37.9	kg CO_2-eq t^{-1} manure	[39]
	Lagoon storage	45.3	kg CO_2-eq t^{-1} manure	[39]
	Digested cattle manure	0.14 ± 0.06	kg CO_2-eq kg^{-1} live-weight gain	[40]
	Undigested cattle manure	0.19 ± 0.07	kg CO_2-eq kg^{-1} live-weight gain	[40]

Table 1. *Cont.*

Category	Material or Process	Reported Footprint	Functional Unit	References
Fuel	Diesel	2.68–2.75	kg CO_2-eq L^{-1}	[30,31,41]
	Gasoline	2.31	kg CO_2-eq L^{-1}	
	Liquefied petroleum gas	1.51	kg CO_2-eq L^{-1}	
	Natural gas (methane)	2.75	kg CO_2-eq m^{-3}	
	Biodiesel	0.5–1.0	kg CO_2-eq L^{-1}	

Note: Values are literature estimates and are not directly comparable because system boundaries, energy sources, allocation procedures, and functional units differ among studies. Pesticide ranges also reflect differences among active ingredients and manufacturing processes; they should not be interpreted as uncertainty bounds for a single product.

The carbon footprint of mineral fertilizers depends on the energy source, manufacturing process, fertilizer formulation, application method, soil and climate conditions, crop, and N_2O emissions after application. Electrolytic ammonia produced using renewable and nuclear energy had the lowest carbon footprint, at 0.59–1.05 t CO_2-eq t^{-1} NH_3, while a 15% increase in synthesis efficiency reduced the carbon footprint by 12.5% [42]. It has been proposed that a net carbon footprint should be calculated by including the CO_2 consumed during photosynthesis and assimilation, which may substantially reduce the estimated fertilizer footprint [28,32]. The contribution of nitrogen fertilizer can be illustrated using an emission factor of 5.6 kg CO_2-eq kg^{-1} N reported in [28]. At 170 kg N ha^{-1} and a grain yield of 8 t ha^{-1}, this factor gives 952 kg CO_2-eq ha^{-1}, or 0.119 kg CO_2-eq kg^{-1} grain. This calculation represents only the contribution associated with the fertilizer emission factor, not the full carbon footprint of cereal production.

Calculations of the carbon footprint of organic fertilizers account for emissions from livestock production and manure collection; CO_2, CH_4, and N_2O emissions during manure processing, composting, and storage; the distance and mode of manure transport to the field; CO_2 losses and CH_4 and N_2O emissions in the field; and reductions or increases in emissions per unit of product when manure or compost is used as fertilizer. Estimated carbon footprints for different manure-storage methods are presented in Table 1. The energy source used for processing raw manure has a major influence on the footprint. For example, replacing fossil energy with renewable energy during aerobic treatment reduced the manure footprint from 37.9 to 29.5 kg CO_2-eq t^{-1} fresh material [39]. In most cases, the source data are reported as carbon loss (%) or emissions (kg C t^{-1} feedstock) rather than as a carbon footprint (kg CO_2-eq kg^{-1}). Moreover, consistent estimates covering organic fertilizer production, application, and subsequent effects on SOM are scarce. These limitations complicate carbon-footprint calculations for livestock and crop production.

The carbon footprints of biofertilizers derived from composts and sewage sludge are 0.8 kg CO_2-eq kg^{-1} N and 1.8 kg CO_2-eq kg^{-1} P, whereas the corresponding footprints of mineral fertilizers are 1.9–7.8 and 2.3–4.5 kg CO_2-eq kg^{-1} N and P, respectively [37]. Biological nitrogen fixation in legumes can provide nitrogen with a low carbon footprint. Its carbon footprint arises from the fuel used to grow legume crops. When field operations are included, the carbon footprint of 1 kg of biologically fixed nitrogen does not exceed 0.5–2 kg CO_2-eq, which is 1.5–16 times lower than that of industrial nitrogen. The carbon footprint of a crop rotation receiving low nitrogen inputs was 40–60% lower than that of a rotation receiving high nitrogen inputs, and unfertilized pure legume stands had the smallest footprint [43].

Emissions of CO_2 and other fuel-combustion products from tractors, harvesters, pumps, and other agricultural machinery are direct components of the carbon footprint of farming. The footprint of different fuels is estimated at 0.5–2.68 kg CO_2-eq L^{-1} (Table 1). Fuel use is approximately 60–90 L ha^{-1} for wheat, 70–100 L ha^{-1} for maize, 50–80 L ha^{-1} for

sunflower, 120–180 L ha^{-1} for potato, and 40–70 L ha^{-1} for soybean. Consequently, direct CO_2 emissions from fuel combustion range from 110 kg ha^{-1} for soybean to 480 kg ha^{-1} for potato. Reducing the number of tillage operations and using direct seeding can save fuel and limit CO_2 emissions [41,44].

Different crop species require different tillage practices, crop management, fertilization, and plant-protection systems, which are modified according to soil and environmental conditions. Therefore, their carbon footprints differ. According to aggregated data, the product carbon footprint is 0.12–1.2 kg CO_2-eq kg^{-1} for cereals, including wheat, barley, and maize; 1.2–4.5 for rice; 0.5–1.2 for sunflower; 0.1–0.3 for potato; and 0.1–0.4 for sugar beet [45–49]. Regional variation is illustrated by wheat footprints of 0.55, 0.30, and 0.39 kg CO_2-eq kg^{-1} grain in China, the United States, and Canada, respectively, and rice footprints of 0.80 and 1.35 kg CO_2-eq kg^{-1} in China and India, respectively [31]. Residue placement also affects carbon mineralization. In an incubation study, incorporating rice and maize residues generally increased cumulative carbon mineralization compared with surface placement, although the response depended on residue and soil type [50]. These results concern decomposition losses and do not, by themselves, establish the net life-cycle carbon footprint of either practice.

There are many practical examples of reductions in the carbon footprint of crop production. A transition from conventional tillage to direct seeding reduced the footprint two- to fourfold, to 0.217–0.224 kg CO_2-eq kg^{-1} grain for wheat and 0.533 kg CO_2-eq kg^{-1} grain for sorghum [44]. The carbon footprint of fertilization systems containing different proportions of mineral and organic fertilizers ranged from 0.16 to 0.39 kg CO_2-eq kg^{-1} grain; replacing mineral fertilizer with manure reduced the footprint by 18–58% [48]. According to these authors, high yield and a low footprint were achieved when manure replaced 50% of the mineral fertilizer. At the same yield and economic return, manure and straw application reduced the carbon footprint of crop production by 59–85% relative to nitrogen fertilizer alone, whereas replacing a mineral system with an organic system in semiarid regions was a practical solution for increasing agricultural productivity and reducing carbon emissions [51]. Energy consumption is lower in organic agriculture because mineral fertilizers are excluded and only a narrow range of plant-protection products is permitted [52,53].

Overall, mineral nitrogen fertilizer application accounted for nearly 75% of the carbon footprint on the farms assessed [52]. The other inputs and operations contributed less. In that assessment, their contributions decreased in the following order: nitrogen fertilizer > manure > ploughing > herbicides > phosphorus fertilizer > potassium fertilizer > fungicides > crop management and harvest > mechanical tillage. The carbon footprints of crops decreased in the following order: potato > winter oilseed rape > winter cereals > spring cereals > legumes.

Reduced or no tillage, more catch crops and legumes in rotations, combined mineral–organic fertilization, and suitable organic-farming practices can reduce greenhouse gas emissions. Carbon-footprint assessments should account for changes in SOC stocks and the eventual fate of harvested biomass. Gross photosynthetic CO_2 uptake should not be treated as a permanent offset if that carbon is subsequently re-emitted. Mineral nitrogen fertilizers are a priority for emissions reduction, but reducing their use without maintaining an adequate crop nitrogen supply can lower yields. The practical objective is therefore to reduce emissions per unit of production through efficient fertilizer manufacture and use, biological nitrogen fixation, and nutrient recycling [28,32,43,52].

Agroecosystem recarbonization complements efforts to reduce production-related emissions. It aims to restore SOC stocks depleted by agriculture and sustain carbon cycling in the soil–microorganism–plant system, supporting crop production, biodiversity, and

climate adaptation [54]. Soil carbon sequestration is an important pathway toward this objective, although its potential depends on local conditions and management.

3. Soil Carbon Sequestration

Soil carbon sequestration is the net transfer of atmospheric CO_2 into SOM through plant production and subsequent stabilization of plant-derived carbon and microbial residues [55]. It involves photosynthetic CO_2 uptake, plant carbon inputs to soil, microbial transformation, and the retention of part of this carbon in SOM. Sequestration is a process, whereas carbon storage describes the amount retained in soil; an increase in storage is not necessarily equivalent to atmospheric carbon removal. Several accounting principles are therefore essential [55–58].

First, sequestration must increase SOC stocks relative to a defined baseline over a specified period, and its climate benefit must be assessed using the net greenhouse gas balance. Second, the accounting boundary must be explicit, for example, a plot, field, farm, or landscape. Carbon imported in manure, compost, or eroded sediment can increase SOC at the receiving site, but this transfer alone does not establish additional removal of CO_2 from the atmosphere. Such removal may occur through additional plant growth and soil carbon inputs, provided that losses and emissions elsewhere in the system are included. Third, carbon residence time matters: retention can range from short-lived accumulation to long-term storage. Greater persistence strengthens the climate benefit, but neither a fixed residence time nor a particular soil depth alone defines sequestration [57,58].

The global mean sequestration rate in agroecosystems ranges from 0.05 to 1 t C ha^{-1} $year^{-1}$ [14] and, according to other aggregated data, from 0.05 to 1.84 t C ha^{-1} $year^{-1}$ [55]. A literature synthesis compared changes in topsoil carbon stocks under different practices, primarily over periods of at least 20 years [59]. It reported relatively high carbon accumulation under biochar application, agroforestry, lignocellulosic crops, and compost application, but responses varied widely. Because the underlying studies differ in climate, soil, duration, and accounting boundaries, these results should not be interpreted as a universal ranking or as evidence that agroforestry and lignocellulosic crops have identical sequestration potentials [14,15,59]. Published changes in SOC stocks indicate that sequestration rates may range from negative values to 0.40 t C ha^{-1} $year^{-1}$ under mineral nitrogen fertilization and from 0.03 to 0.63 t C ha^{-1} $year^{-1}$ under manure application [55]. Mineral fertilization generally produces a larger crop-yield increase than organic fertilization, whereas organic fertilizers are considered more favorable for agroecosystems and produce a larger increase in SOC. Consequently, the carbon-sequestration efficiency of practices and inputs should be evaluated using at least two parameters simultaneously: the yield increase and the increase in SOC [56]. Nevertheless, most current estimates of the sequestration potential of agricultural technologies are based on their effects on SOC contents and stocks.

Manure, composts, and crop residues applied separately or together with mineral fertilizers produce several effects: they promote soil recarbonization; improve soil structure and water-related physical properties; provide plants with a prolonged nutrient supply; increase the taxonomic diversity of the microbial community and soil biological activity; and balance nitrogen and phosphorus mineralization–immobilization transformations. Their net climate benefit nevertheless depends on the full greenhouse gas balance, resource availability, and local conditions [15,59].

4. Agrochemical Approaches to Managing Soil Carbon Sequestration in Agroecosystems

By supplying plants with nutrients, affecting nutrient cycling, and modifying the biological and physicochemical properties of soil, mineral and organic fertilizers affect

several stages of carbon cycling, from plant uptake of CO_2 during photosynthesis to the mineralization of organic matter and the emission of CO_2 to the atmosphere. Consequently, fertilizers and other natural or chemically synthesized products can optimize plant production, reduce the adverse effects of weather on plant growth, and control the incorporation of crop residues into SOM.

4.1. Optimization of Photosynthesis and Crop Production Through Fertilization

Fertilizers can increase crop carbon inputs by improving photosynthesis and plant growth. Soil carbon sequestration is limited more strongly by photosynthesis and the amount of net primary production (NPP) than by soil processes and properties [60]. The present amount of biomass synthesized through photosynthesis effectively constrains annual global carbon sequestration in agricultural soils. The photosynthetic efficiencies of C_3 and C_4 plants, defined as the ratio of energy converted into biomass to total incident solar energy, are substantially lower than the theoretical maximum of 11–26%, amounting to only approximately 4.6% and 6%, respectively, and to less than one-third of these values under field conditions [61].

Leaf nitrogen is divided among four functional pools: respiratory, photosynthetic, structural, and storage nitrogen [62]. Its allocation among these pools differs among plant species, resulting in marked differences in the net photosynthetic rate and photosynthetic nitrogen-use efficiency. More than half of the nitrogen in C_3 leaves is incorporated into the photosynthetic system. Photosynthetic nitrogen is, in turn, allocated to carboxylation, electron transport, and light-harvesting systems. Optimization of nitrogen allocation among the components of the photosynthetic apparatus can increase photosynthetic capacity by 60% and improve nitrogen-use efficiency without additional nitrogen input [61].

An adequate nitrogen supply supports photosynthesis through several physiological and biochemical processes [62–64]. Nitrogen fertilizers improve the nitrogen supply of the photosynthetic system, stimulate the synthesis of chlorophyll and other photosynthetic pigments, and increase leaf area. Greater nitrogen availability increases chlorophyll a and b concentrations and thereby improves the capacity of plants to absorb light energy for photosynthesis. Nitrogen supply increases stomatal conductance, promoting CO_2 uptake and gas exchange and further enhancing photosynthesis. Optimal nitrogen nutrition has beneficial effects on carboxylation and the electron-transport chain and thereby increases photosynthetic capacity. Nitrogen promotes the translocation of carbohydrates from vegetative organs to the ears after flowering in cereal crops. It is also required to increase plant stress resistance. Management of plant nitrogen nutrition with fertilizers can mitigate the negative effects of high temperatures on plant growth and development. Excessive nitrogen supply, however, can impair plant physiology and photosynthetic function [64].

On average, crops assimilate 4.5 t C ha^{-1} $year^{-1}$ from the atmosphere, with values ranging from 1.7 t C ha^{-1} $year^{-1}$ for barley to 5.2 t C ha^{-1} $year^{-1}$ for maize [65]. According to these authors, 61% of assimilated carbon is contained in shoots, 20% in roots, and 7% in soil, while 12% is returned to the atmosphere through plant autotrophic respiration. Maize produced the largest accumulation of carbon in soil, at 1.00 t C ha^{-1} $year^{-1}$, followed by ryegrass at 0.95, wheat at 0.80, and rice at 0.70 t C ha^{-1} $year^{-1}$. However, wheat had the highest efficiency of soil enrichment with plant-derived carbon, at 23% of total assimilation, followed by rice at 20% and maize and ryegrass at 19% each. Thus, when applied optimally, nitrogen fertilizers substantially enhance photosynthesis, resulting in greater shoot and root growth and higher crop productivity.

4.2. Fertilizer Effects on Shoot-to-Root Biomass Allocation

A global meta-analysis showed that nitrogen, phosphorus, and combined nitrogen–phosphorus fertilization increased wheat grain yield by 95%, 14%, and 189%, respectively, relative to unfertilized soil, while increasing straw biomass by 80%, 18%, and 176%, respectively [66]. The amount of carbon entering soil following the sequestration of atmospheric CO_2 depends on the ratio of aboveground to belowground biomass. Roots account for an average of 18% of NPP in small-grain cereals, 23% in maize, 24% in soybean, and 51% in perennial forage crops [67]. In natural meadow-steppe ecosystems, the corresponding values range from 48–64% to 61–80% of NPP in mixed meadow ecosystems. In mature wheat, the ratio of shoot biomass to root biomass measured in the upper 0–30 cm was 5.9–7.7 [68]. Mean shoot-to-root ratios of grasses ranged from 0.6 at 0–15 cm to 0.4 at 0–120 cm, which differed substantially from the corresponding values for spring wheat, at 6.7 and 3.0 [69]. Based on aggregated Canadian experiments, mean aboveground biomass, including stems and leaves, to root biomass ratios were highest for small-grain cereals (7.4), followed by maize (5.6) and soybean (5.2), and lowest for forage crops (1.6) [67]. Compared with cereals, legumes have smaller ratios because of their nitrogen-fixing activity, whereas grasses have the largest root biomass.

Nitrogen fertilizer affects crop root biomass in a dose-dependent manner [70,71]. Moderate nitrogen application increases root length, surface area, volume, and total biomass relative to the nitrogen-free treatment. Low nitrogen availability generally stimulates root elongation but restricts shoot growth because plants allocate more growth to roots to acquire nutrients. Excessive nitrogen application, by contrast, decreases root biomass, lateral-root density, rooting depth, and enzyme activity, which may impede effective root-system development. The root-to-shoot mass ratio reflects biomass allocation in response to nutrient supply and stress. It varies with crop species, growth stage, environmental conditions, and nutrient availability [72]. A higher root-to-shoot mass ratio generally indicates a greater capacity to acquire nutrients and withstand stresses such as drought. Conversely, a lower ratio may correspond to nutrient-rich conditions in which a large root system is less important. A meta-analysis of 50 field experiments evaluated the effects of nitrogen, phosphorus, or potassium deficiency on root length and biomass and on root length per unit of aboveground shoot biomass [73]. Root length and biomass decreased by 9% and 7%, respectively, under nitrogen deficiency and by 14% and 25% under phosphorus deficiency. Root length per unit of shoot biomass increased by 33% in nitrogen-deficient soils and by 51% in phosphorus-deficient soils. Potassium had no significant effect on these morphological plant traits.

Thus, an optimal nitrogen supply that avoids both deficiency and excess is crucial for maximizing root growth, nitrogen-use efficiency, and plant productivity. Species with a larger proportion of root biomass and a larger mass of by-products and post-harvest residues are preferable for soil carbon sequestration.

4.3. Improving Plant Nutrient-Use Efficiency

Mineral fertilizers remain the principal factor supporting stable high crop yields [74,75]. At the global scale, cereal yields and nitrogen-fertilizer consumption have increased in an almost linear relationship over the past 40 years and are closely correlated. Across 467 experiments worldwide, nitrogen fertilizer increased cereal yield by an average of 62% relative to the control, from 3.10 to 5.16 t ha^{-1}, while decreasing interannual yield variability by 6 percentage points, from 34% to 28% [76]. The more efficiently crops use nutrients from soil and fertilizers, the greater the potential for biomass production and carbon inputs to soil. Greater crop nutrient-use efficiency can be achieved by selecting optimal fertilizer rates, forms, timing, and placement, by using different proportions of mineral and organic

fertilizers, and by applying other practices. Nitrogen-use efficiency (NUE) is determined using difference, isotopic, or balance methods [77]. The balance method often produces extremely high NUE values, reaching 125–323% [75,77]. Difference-based NUE exceeds isotope-based NUE by an average of 24.6 percentage points, at 66.5% versus 41.9% [78], or, according to other estimates, by 5.9 percentage points, at 48.3% versus 42.4% of the applied amount [79].

Difference-based NUE for cereal crops is 35%, 41%, 30%, and 21% globally, in the United States, China, and India, respectively [80]. For comparison, the global mean phosphorus-use efficiency (PUE) of fertilizer phosphorus is estimated at 12.4% [81]. In long-term field experiments in Russia, difference-based nitrogen recovery by cereals was estimated at 45.7% of the applied amount [78]. Balance-based NUE is estimated at 45–50% in China, 50–60% in Russia and the United States, and 60–65% in the European Union, whereas in countries with less developed agricultural practices it is below 40% of the nitrogen entering the soil. NUE decreases as the fertilizer rate increases, while residual mineral nitrogen accumulates in soil (Figure 1). Thus, a substantial fraction of nitrogen entering agroecosystems is not recovered in crop production.

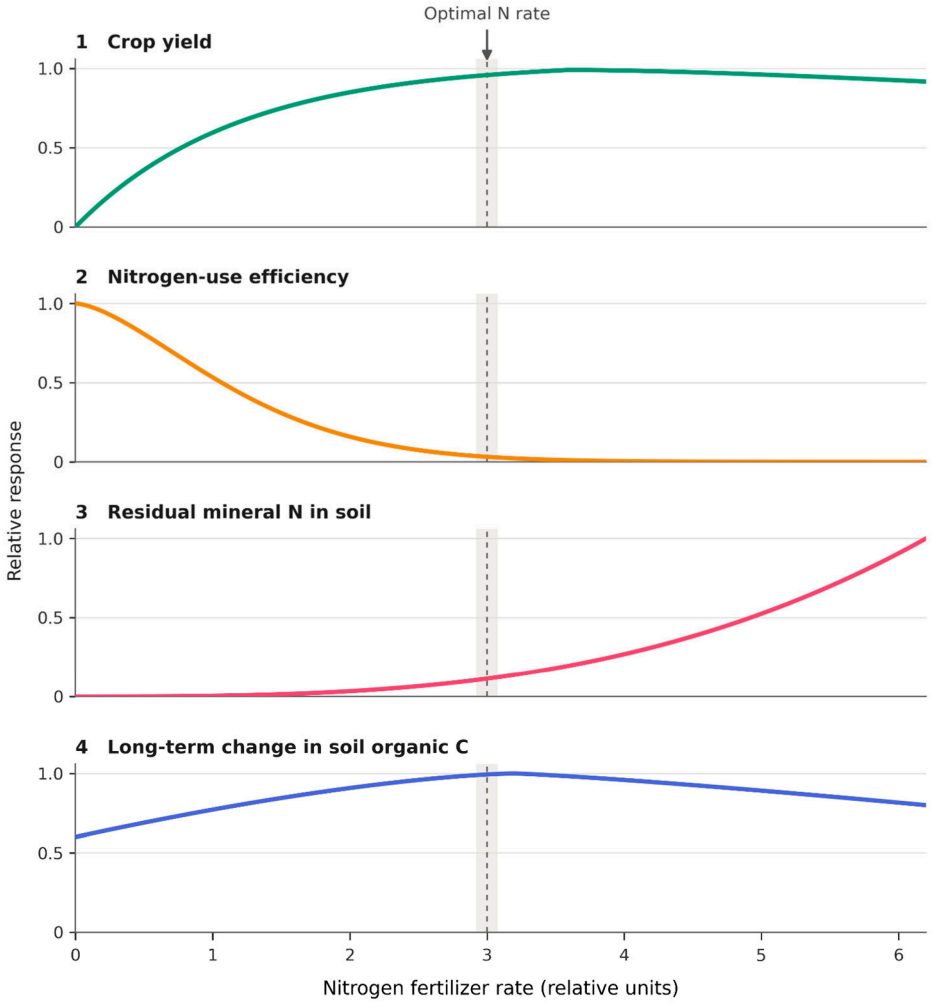

Figure 1. Conceptual relationships between nitrogen fertilizer rate and crop yield (**1**), nitrogen-use efficiency (**2**), residual mineral nitrogen in soil (**3**), and long-term change in SOC (**4**); a schematic based on [82,83], not a quantitative model fitted to a single experimental dataset.

Another indicator of the efficiency of crop nitrogen use is the agronomic efficiency of nitrogen fertilizer (AEN), which expresses the additional yield obtained per kilogram

of fertilizer nitrogen applied. AEN varies with crop species, fertilizer rate, soil nutrient availability, and environmental conditions. Global AEN for wheat commonly ranges from 12 to 25 kg grain kg^{-1} applied N, although it may exceed 30 kg kg^{-1} N at low nitrogen rates and low soil mineral-nitrogen stocks. High nitrogen application rates reduce AEN. According to Russian sources, the agronomic efficiency of nitrogen fertilizers for cereal crops is 7.1 ± 4.6 kg kg^{-1} N, with a range of 0.4–21.3; the corresponding values for phosphorus and potassium fertilizers are 4.3 ± 3.4 kg kg^{-1} P_2O_5, with a range of 0.1–15, and 2.6 ± 3.0 kg kg^{-1} K_2O, with a range of 0.3–15.6 [84]. These data show that increasing plant nutrient-use efficiency can substantially improve crop productivity and thereby increase the amount of plant biomass entering the soil.

4.4. Regulating Carbon–Nitrogen Interactions in Soil

Balanced carbon and nitrogen cycles are a fundamental requirement for stable agroecosystem functioning [17,85]. Because carbon and nitrogen cycling are closely coupled, carbon sources can be used to control the transformation of nitrogen fertilizers in soil, while nitrogen application can regulate the rate of crop-residue decomposition and mineralization. Nitrogen addition accelerates the decomposition of readily degradable compounds, including sugars, cellulose, hemicellulose, and proteins, during the initial stage of decomposition [86], promoting microbial biomass accumulation and the formation of CO_2 and mineral nitrogen and phosphorus. Conversion of residue carbon into microbial biomass can promote the formation of microbial necromass and its association with soil minerals, thereby contributing to carbon stabilization [87]. At later stages of decomposition, soil nitrogen suppresses the degradation of resistant compounds such as lignin [86]. This increases the proportion of slowly decomposing material and its residence time in soil and therefore also promotes soil carbon sequestration. Nitrogen supply can therefore influence the pathways through which both readily and slowly decomposing inputs contribute to SOM.

The addition of organic carbon to soil as crop residues or manure promotes microbial biomass growth and increases enzyme activity. Microorganisms obtain nitrogen from decomposing material or immobilize mineral nitrogen from soil. Depending on the carbon-to-nitrogen ratio, either organic-nitrogen mineralization or mineral-nitrogen immobilization predominates. Mineralization increases nitrogen availability to plants, positively affecting plant productivity and atmospheric CO_2 fixation. Immobilization may temporarily decrease nitrogen availability to plants, but it enriches SOM with nitrogen and reduces nitrogen losses from soil. As a general guide, substrates with a C:N ratio below 20 or a nitrogen concentration above 1.5% tend to undergo net nitrogen mineralization, whereas those with a C:N ratio above 30 or a low nitrogen concentration tend to promote immobilization. These thresholds vary with substrate composition and soil conditions [17,85].

4.5. Restoring Depleted Soil Organic Carbon Stocks with Mineral and Organic Fertilizers

Mineral nitrogen fertilizers have sometimes been considered to deplete SOM by stimulating carbon mineralization. More recent evidence, including studies using the stable carbon isotope ^{13}C, shows that their effects are more complex. Nitrogen fertilization increases the amount of new carbon entering soil with crop residues and slows the loss of old carbon [88]. Nitrogen fertilizer increased the activity of hydrolytic enzymes responsible for converting crop residues into labile SOM, while decreasing oxidase activity associated with the decomposition of native SOM [86,89]. This is supported by meta-analyses showing that mineral fertilization increases both labile particulate organic matter (POM) and stable mineral-associated organic matter (MAOM) [90,91]. Overall, the large increases in aboveground biomass, roots, and crop residues induced by mineral nitrogen fertilizer are accompanied by a relatively modest increase in SOC stocks [92,93]. The relative responses

to mineral fertilization summarized in Table 2 have an unweighted mean of approximately 9.4%, although both gains and losses were reported. This is a descriptive summary of heterogeneous literature estimates, not a pooled effect from a new meta-analysis. Increased root and residue inputs, microbial biomass and necromass formation, and mineral association help explain positive SOC responses, while their relative importance varies among sites [86–91].

In the cited meta-analysis, urea produced a larger SOC increase than other nitrogen fertilizers, with the greatest response reported at about 100 kg N ha^{-1} over a 10-year period [94]. Application of mineral nitrogen at agronomically optimal rates increases net primary productivity and thereby increases the production of both aboveground and belowground plant biomass, which in turn increases SOM [82]. Agronomically optimal nitrogen rates are therefore crucial for maintaining or increasing SOC in arable soils, whereas low or excessively high rates either fail to increase SOC or lead to its decline (Figure 1). Long-term field experiments indicate that 1 kg ha^{-1} of applied nitrogen can produce 1–2 kg C ha^{-1} $year^{-1}$ in SOM [95,96]. Long-term phosphorus, nitrogen, and combined NP fertilization increased SOC by 10%, 22%, and 28%, respectively [66].

Table 2. Reported changes in SOC under mineral, organic, and combined fertilization relative to unfertilized controls.

Study	Mineral Fertilizers (%)	Organic Fertilizers (%)	Combined Mineral and Organic Fertilizers (%)	Reference
1	6	—	—	[97]
2	6	—	18	[98]
3	−11	—	—	[98]
4	7	—	—	[94]
5	9	20	51	[99]
6	19	—	—	[100]
7	6	—	—	[101]
8	6	—	—	[88]
9	5	—	—	[102]
10	8	—	—	[90]
11	28	—	—	[90]
12	22	—	—	[66]
13	8	—	—	[89]
14	11	—	—	[86]
15	7	30	—	[103]
16	—	19	—	[104]
17	10	—	36	[105]
18	15	—	20	[105]
19	8	37	29	[106]
20	9	29	34	[107]
21	—	29–49	—	[108]
22	—	8–29	—	[109]
23	12	32	27	[110]
24	10	30	46	[111]
25	9	20	18	[112]
26	6	59	—	[91]
27	0.06–0.08 †	0.17–0.25 †	0.09–0.20 †	[113]

Note: Values without † are relative changes (%) in SOC concentration or stocks compared with the unfertilized control; they are not percentage-point changes in SOC concentration. —, not reported. † Absolute differences in SOC concentration, expressed in percentage points of soil mass. Fertilizer formulations, rates, and organic materials are those used in the cited studies and are not standardized across rows. Estimates differ in study design, duration, and outcome; they are presented as a descriptive synthesis rather than a new meta-analysis.

When manure is applied, soil is enriched with the organic matter of the manure itself and with crop residues. Consequently, repeated manure application produces a stable and significant increase in SOC contents and stocks relative both to unfertilized soil and to mineral fertilization [106,114,115]. For example, manure applied together with mineral fertilizers increased grain yield by 6–19% and SOC by 9–39% relative to mineral fertilizers alone [93]. According to the meta-analyses and reviews summarized in Table 2, manure application increases SOC by approximately 30% relative to unfertilized controls in the literature summarized here.

Because mineral fertilizers are applied primarily to crops from which a substantial proportion of production is removed from the agroecosystem, the increase in SOC resulting from fertilization is small and the actual sequestration effect is lower than its potential value. Organic fertilizers can substantially increase SOC, but imported organic carbon must be distinguished from additional atmospheric carbon removal. Yield increases and associated plant carbon inputs can contribute to sequestration; their net effect depends on the accounting boundary and the full carbon balance [58].

4.6. Cultivation of Nitrogen-Fixing Crops to Improve Nitrogen Supply

Legumes can supply nitrogen with a low carbon footprint and promote SOM accumulation, making them useful components of carbon management. Their capacity to convert atmospheric N_2 into plant-available forms through root nodules containing diazotrophs gives legumes substantial advantages in nitrogen-poor soils. In addition to satisfying their own requirements, legumes can supply nitrogen to neighboring species and promote their growth. Depending on soil and environmental conditions and crop management, nitrogen-fixing legumes may have positive, negative, or neutral effects on SOC stocks [75,116].

Positive effects of legumes on SOM stocks arise because nitrogen-fixing species enrich soil with nitrogen-rich crop residues and rhizodeposits, which may increase gross primary productivity and consequently belowground biomass and promote SOC accumulation. Negative effects may result from enhanced SOM decomposition through a priming effect caused by increased inputs of fresh litter with a narrow C:N ratio. A global meta-analysis comprising 385 observations from 136 studies found that nitrogen-fixing species increased SOC stocks by 16% relative to non-fixing species [116]. This increase in SOC was accompanied by an increase in soil nitrogen, with a mean accumulation of 7.8 g C per gram of additional soil N. Legumes had the largest effect on SOC accumulation in dry and warm regions. The ratio of additional soil carbon to nitrogen, 7.8:1, is consistent with the accumulation of nitrogen-rich organic matter, which may contribute to soil fertility and nutrient supply.

5. Restoring Soil Fertility Is a More Attainable Goal of Soil Carbon Sequestration than Climate Change Mitigation

The climate-mitigation role of soil carbon sequestration has been critically reassessed in recent years [55,117–121], and the Four per 1000 initiative should be considered in light of its opportunities and practical limitations [122]. Increasing SOC cannot fully offset fossil-fuel CO_2 emissions at current levels of crop productivity. Considering the net carbon input to soil from net photosynthetic production, the proportion of biomass removed for economic use, and carbon losses during decomposition of biomass and SOM, one assessment estimated the attainable offset at approximately 1.5% of global fossil-fuel emissions [54]. Several factors limit the practical implementation of the Four per 1000 initiative and the climate-mitigation efficiency of soil carbon sequestration. First, sequestration rates in agroecosystems vary widely with environmental conditions and management practices, not all of which consistently increase crop yield or SOC each year. Biochar application can increase

soil carbon stocks, but its effect on yield depends on the soil, feedstock, application rate, and management. Yield increases have been reported, including for rice receiving rice husk biochar under particular irrigation regimes [123]. Second, sequestration rates may decline as soils approach a new equilibrium or, for mineral-associated carbon, saturation [119,120]. Third, SOC accumulation is finite and depends on soil texture and mineralogical properties, which control the capacity of the mineral matrix to stabilize organic matter, and on the initial soil carbon level [120]. Fourth, the proportion of sequestered carbon retained in soil rarely exceeds 10% of the carbon entering with plant biomass, while SOC can be lost more rapidly than it accumulates; therefore, carbon-sequestering practices must be maintained continuously over the long term [55,119]. Fifth, current crop productivity and organic-fertilizer production are insufficient to restore previously depleted SOC stocks [60,119]. Sixth, increasing plant-biomass inputs under carbon-sequestering technologies will require additional fertilizer nitrogen to support biomass production and organic matter formation, with associated emissions from fertilizer production and use [17]. Seventh, slowly decomposing organic matter with low CO_2 production is preferable for reducing emissions and retaining sequestered carbon, whereas rapidly decomposing, potentially mineralizable organic matter that supplies N, P, K, S, and other nutrients is more important for soil fertility. Climate mitigation and nutrient supply can therefore involve trade-offs, although microbial processing can also promote persistent SOM formation [87,118]. Eighth, spatial soil heterogeneity, small annual changes in SOC, labor-intensive and costly conventional soil sampling and analysis, and the insufficient accuracy of remote monitoring and modeling complicate the selection of optimal measures and increase uncertainty in estimates of their effectiveness [58]. Ninth, widespread adoption of minimum or no tillage, cover crops, agroforestry, and organic-matter return will require structural changes on farms and investment in equipment and may entail risks of temporary yield decline [15,59,122].

Limits to carbon storage, declining sequestration rates, reversibility, restricted biomass and nitrogen supplies, and measurement uncertainty constrain climate mitigation benefits. Despite the uncertain contribution of soil carbon sequestration to climate-change mitigation, the recarbonization of soils and agroecosystems is highly promising for maintaining soil fertility and sustainable food production (Figure 2). Carbon is not only a natural climate regulator but also the basic constituent of SOM, which serves as a source of mineral nutrients and a key edaphic factor for plants. SOM indirectly affects crop yield by creating and maintaining soil conditions that support plant growth, development, mineral nutrition, and production. It is therefore more realistic to advance approaches and practices that increase SOC and improve soil quality and functioning, because even a small increase in SOC may produce a substantial agronomic benefit, although it does not necessarily lead to a rapid increase in yield under specific conditions [119].

The relationship between SOC and crop yield is often nonlinear: crop yield increases only up to a certain SOC level, above which the yield response remains unchanged or even declines [56,74,124–127]. Estimates of threshold SOC concentrations associated with optimally high cereal yields are 1.27–1.34% [127], 1.4% [126], or 2% [125]. Above 2% SOC, yield did not increase significantly, but nitrogen-fertilizer efficiency increased [126]. In medium- and heavy-textured forest-steppe Chernozems, a critical SOC concentration for crop productivity is 2.0–2.3% [124]. The SOC concentrations associated with the maximum reported maize and rice grain yields are 4.32–4.39% and 3.12–3.24%, respectively [126]. The cereal-yield response to SOC depends not only on its total concentration but also on SOM quality [126].

Within the range of 0.1–2.0% SOC, soil carbon concentration correlates with wheat and maize yield irrespective of mineral-fertilizer application. Above 2% SOC, yield did not increase significantly, but the effect of nitrogen fertilizer increased. For croplands below

2% SOC, raising concentrations toward this level was estimated to increase maize and wheat yields by about 10% and 23%, respectively, corresponding to approximately 5% and 10% of global annual production [125]. Thus, fertilizer-induced soil carbon sequestration provides a dual benefit: it supports additional food production and increases the resilience of agroecosystems to climatic disruption. Economic feasibility also affects adoption. Management costs, yield responses, access to organic inputs, and the costs of measuring and verifying SOC changes can determine whether a practice is attractive to farmers [15,59,122]. Carbon-credit schemes additionally require credible baselines, evidence of additional carbon removal, and provisions for reversals and double counting [58]. These requirements should be considered alongside agronomic benefits; a full comparison of carbon markets and jurisdiction-specific certification rules is beyond the scope of this agrochemical review.

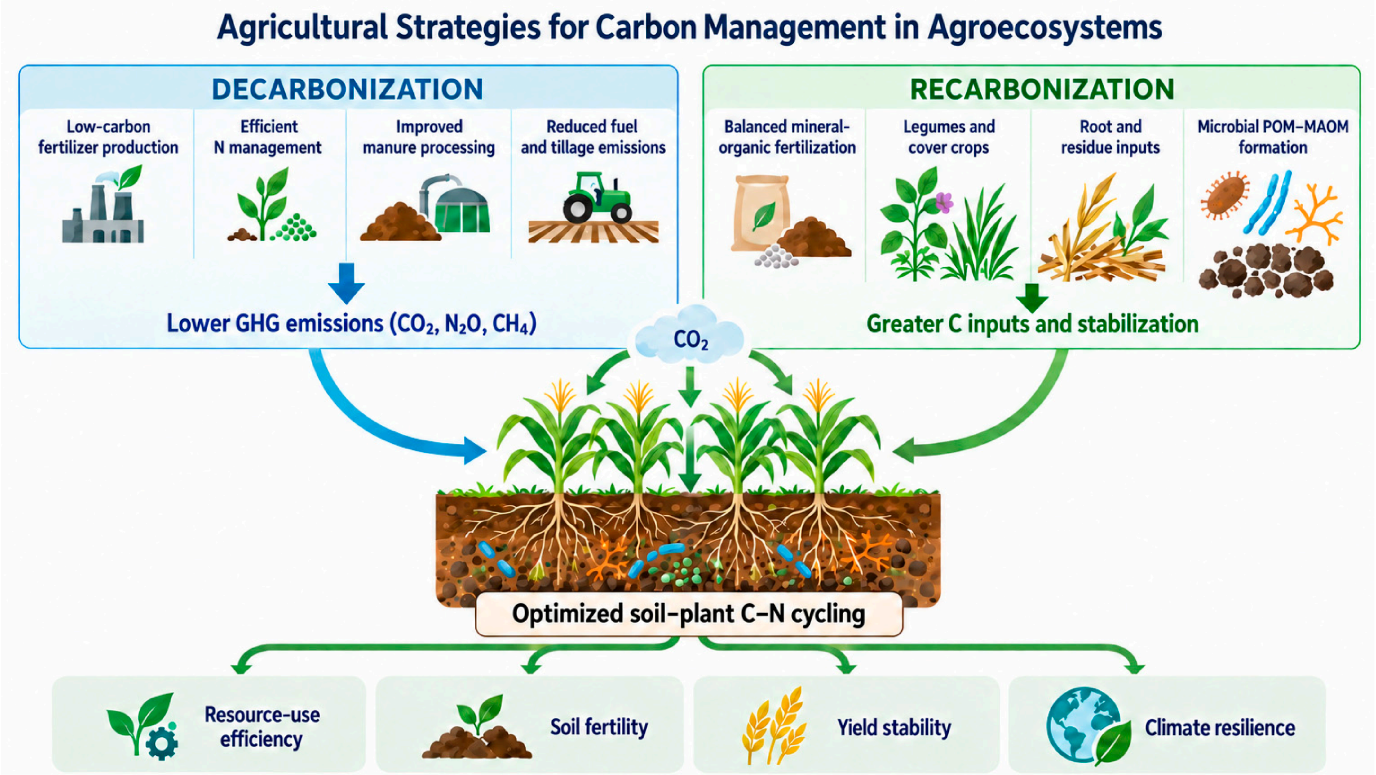

Figure 2. Agricultural strategies linking lower emissions and soil recarbonization to resource-use efficiency, soil fertility, yield stability, and climate resilience.

6. Conclusions

Maintaining food security while reducing greenhouse gas emissions is a central challenge for sustainable agriculture. The technological pathways for addressing these challenges are the decarbonization of agriculture by reducing the carbon footprint of materials and technologies and the recarbonization of agroecosystems through soil carbon sequestration.

Mineral nitrogen fertilizers account for the largest share of the carbon footprint of agricultural production and are therefore the primary target of measures to decarbonize agriculture. At the same time, optimal nitrogen supply is essential for increasing photosynthetic activity, net primary production, biomass accumulation, and consequently the input of organic carbon to soil. Although the increase in SOM under mineral fertilization is relatively small, the contribution of mineral fertilizers to SOM replenishment should not be underestimated. Organic fertilizers introduce substantial amounts of exogenous carbon to soil and produce a larger increase in SOC; however, transferring this carbon between sites is

not itself evidence of additional atmospheric CO_2 removal. Additional plant carbon inputs and the net system-wide greenhouse gas balance must also be considered.

The most realistic and important objective of carbon agrochemistry is not global climate-change mitigation but the maintenance and improvement in soil fertility, efficient resource use in agroecosystems, and the adaptation of agriculture to intensifying climatic extremes. These objectives are supported by management practices that combine optimized mineral nutrition, an increased proportion of legumes, mineral–organic fertilization systems, a greater proportion of catch and cover crops with a large belowground biomass fraction, and regulation of carbon–nitrogen interactions in agroecosystems. From a policy perspective, nitrogen fertilizer application should be optimized according to crop requirements, soil nutrient status, and expected yield to improve nitrogen-use efficiency while minimizing excess nitrogen inputs and associated greenhouse gas emissions. Agricultural policies should also encourage the inclusion of leguminous crops in crop rotations and the wider adoption of cover crops to enhance biological nitrogen fixation, increase organic matter inputs to soil, and support long-term soil fertility.

Slowing the decomposition of SOM to retain sequestered and native soil carbon for longer periods solely to increase carbon storage may be counterproductive. Carbon in soil should not merely be stored; it should function. Rapid transformation of fresh organic matter and its incorporation into SOM are prerequisites both for stabilizing and retaining carbon in soil and for maintaining biological activity in the soil–fertilizer–plant system. Carbon management should maintain or increase SOC stocks while sustaining crop production and nutrient cycling. Future work should quantify these outcomes together with N_2O emissions, carbon persistence, and the costs of maintaining management practices.

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Abbreviations

AEN	Agronomic efficiency of nitrogen fertilizer
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
MAOM	Mineral-associated organic matter
N_2O	Nitrous oxide
NPP	Net primary production

NUE	Nitrogen-use efficiency
POM	Particulate organic matter
PUE	Phosphorus-use efficiency
SOC	Soil organic carbon

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