



# Carbon–Nitrogen Coupling in Agroecosystems under Elevated CO<sub>2</sub> Scenarios: A Review

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## Authors' contributions

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## ABSTRACT

Plants assimilate carbon mostly by the process of photosynthesis, fixing atmospheric CO<sub>2</sub> into organic materials like carbohydrates. These materials not only form the structural components of plant biomass but also substrates that energize soil microbial populations. Carbon–nitrogen (C–N) coupling is a key element controlling agroecosystem productivity, soil fertility, and the earth's climate. Elevated atmospheric CO<sub>2</sub> levels (eCO<sub>2</sub>) promote photosynthesis and biomass production, while augmenting nitrogen (N) requirement in a way that tends to trigger nutrient dilution effects and decreased nutritional quality of crops. This review compiles conceptual foundations, empirical reactions, management practices, and issues underpinning C–N coupling under eCO<sub>2</sub>. It emphasizes the dual function of eCO<sub>2</sub> to stimulate plant growth while amplifying N limitation, modifying belowground processes, and impacting greenhouse gas (GHG) processes. Management practices like integrated nutrient management, conservation tillage, legume integration, and microbial interventions hold potential for augmenting C–N balance. Yet, there are uncertainties arising from soil heterogeneity, climate interactions, and limitations of existing models. Future work should focus on long-term multifactor experiments, advanced modeling structures, and innovations in breeding to balance productivity, nutritional value, and environmental stability. Enhancing C–N coupling in eCO<sub>2</sub> is critical for sustainable agriculture, mitigation of climate change, and food security at the global level. Weak coupling of carbon and nitrogen cycles can contribute to nutrient dilution in crops, loss of soil fertility, and enhanced nitrous oxide (N<sub>2</sub>O) emissions, which could reduce otherwise expected climate change mitigation.

*Keywords: Food security; climate change; Carbon–nitrogen (C–N) coupling; metabolism.*

## 1. INTRODUCTION

Elevated carbon dioxide (eCO<sub>2</sub>) affects the translocation of photosynthesized carbon (C) from plants to soil, which is predominantly executed by soil microorganisms. However, the response strategy and mediation of the bacterial community on photosynthesized C allocation belowground remains elusive under eCO<sub>2</sub> coupled with nitrogen (N) availability. The interaction of eCO<sub>2</sub> and N availability affects photosynthesized C sequestration in soil through the microbial response is still an open question, although this question has ramifications for the fertilization strategy and sustainability of agroecosystems under the scenario of global change (Jia et al., 2023). The highly interdependent carbon (C) and nitrogen (N) cycles, tightly coupled together, provide the basis for agroecosystems that underpin world food production (Shah, et al., 2019). Carbon supplies the framework as well as a source of energy for plant development, whereas nitrogen is a central component in the synthesis of amino acids, proteins, nucleic acids, chlorophyll, and enzymes necessary in plant productivity and metabolism (Nunes-Nesi et al., 2010). The equilibrium

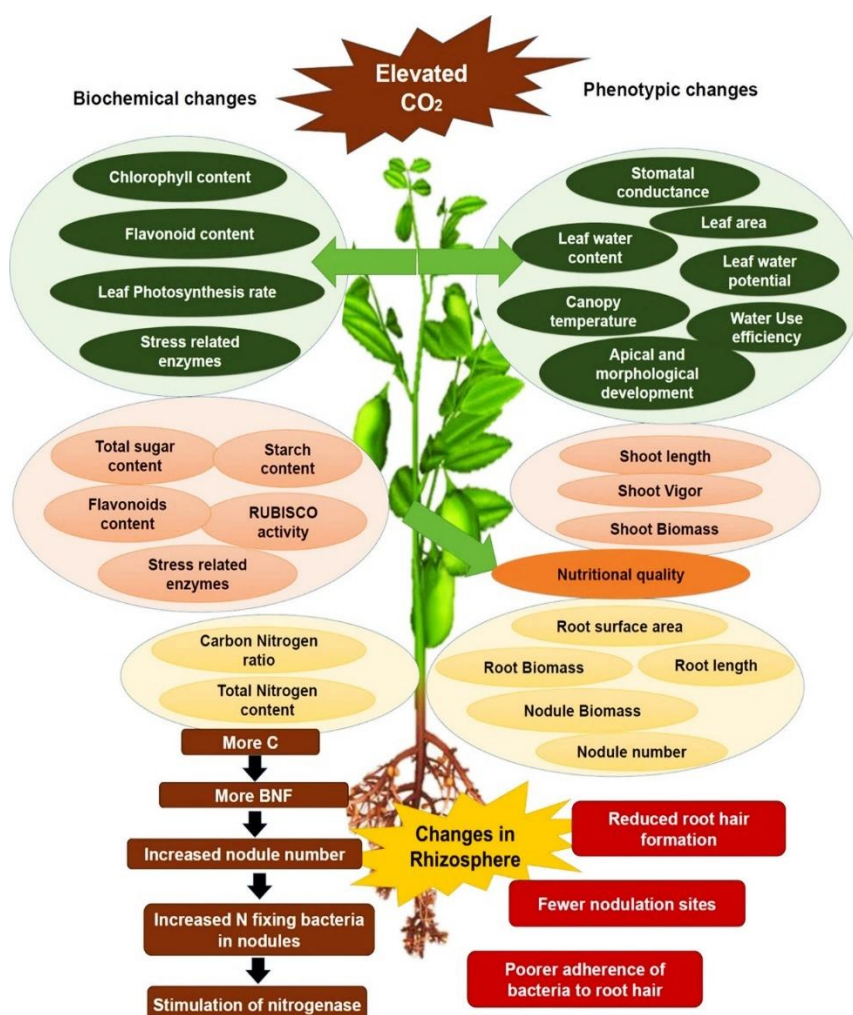
between these two cycles guarantees not only maximum crop production but also soil health, microbial metabolism, and ecosystem stability in the long run. Soil microorganisms play a crucial role in facilitating nutrient cycling, enhancing plant nutrient absorption, and maintaining soil health through the decomposition of organic matter. An inoculation with N<sub>2</sub>-fixing bacteria can consequently improve N uptake and faba bean growth. In response to environmental changes such as increasing CO<sub>2</sub> concentrations, soil microorganisms may adapt by modifying their metabolic pathways and community structures, thereby influencing plant growth and soil fertility. It has been observed that eCO<sub>2</sub> can lead to a significant reduction in soil NO<sub>3</sub><sup>-</sup>-N, possibly due to increased plant uptake or losses to groundwater and the atmosphere (Dong et al., 2024).

Plants assimilate carbon mostly by the process of photosynthesis, fixing atmospheric CO<sub>2</sub> into organic materials like carbohydrates (Raines, 2011). These materials not only form the structural components of plant biomass but also substrates that energize soil microbial populations. Concurrently, nitrogen is obtained

primarily from the soil in mineral forms like ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ), which become part of organic molecules to fuel plant physiological processes (Shukla et al., 2021). Soil microbes via processes like mineralization, nitrification, and denitrification also control nitrogen availability, thus connecting soil nutrient cycling with plant development.

Biochemical and phenotypic changes in legumes exposed to high  $\text{CO}_2$  (left) and to the combined effect of high  $\text{CO}_2$  and temperature (right). The major biochemical and phenotypic parameters are discussed in Section 1 of this review (Adireddy, et al., 2024). The lower panel shows sequential changes occurring in the rhizosphere, where high  $\text{CO}_2$  increases carbon availability, thus impacting biological nitrogen fixation (BNF) and subsequently affecting root nodulation (Schaedel, et al., 2023).

The continued increase in atmospheric concentrations of  $\text{CO}_2$  ( $e\text{CO}_2$ ), which is largely anthropogenically driven, has significant ramifications for both carbon and nitrogen cycling within agroecosystems (Shah, et al., 2019). Increased  $\text{CO}_2$  generally increases plant photosynthesis (the so-called "CO<sub>2</sub> fertilization effect"), with increased assimilation of carbon and biomass production. Yet, this additional carbon input comes at the price of increased nitrogen demand, as additional proteins, enzymes, and metabolic compounds are necessary to maintain elevated growth rates (Erickson, 1993). This discrepancy can lead to an effect referred to as the dilution effect, where elevated plant biomass under  $e\text{CO}_2$  can have comparatively lower nitrogen content, lowering crop nutritional value in general.



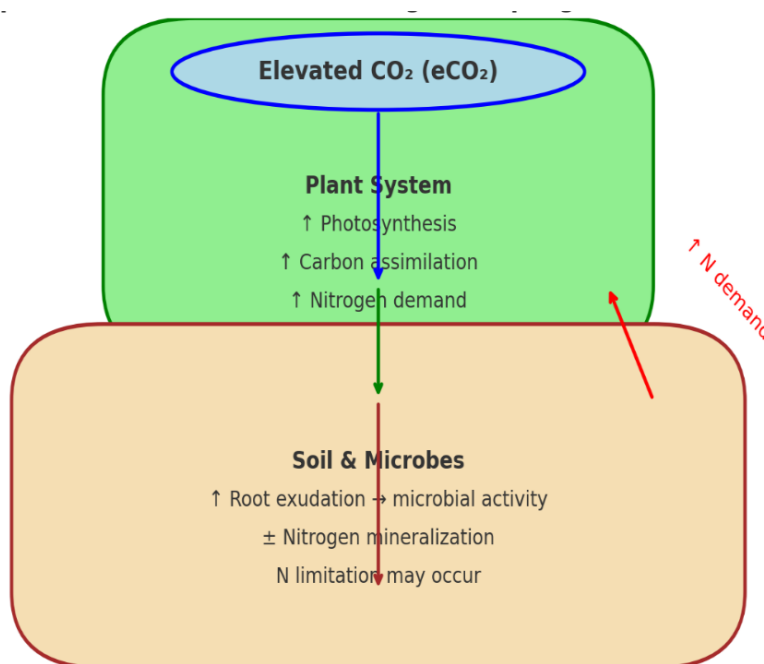
**Fig. 1. Key physiological characteristics affected by increased  $\text{CO}_2$  and temperature**  
(Source, Palit, et al., 2020)

Additionally,  $e\text{CO}_2$  modifies soil-microbe-plant interactions, affecting root exudation, microbial decomposition, and processes of nitrogen mineralization. Carbon addition to the soil can drive microbial activity, but it may hasten or retard nitrogen availability depending on soil status, quality of organic matter, and microbial community structure (Wang, et al., 2019). Nitrogen limitation in  $e\text{CO}_2$  could limit the beneficial effects of increased photosynthesis, resulting in a disconnection of the carbon and nitrogen cycles in some instances.

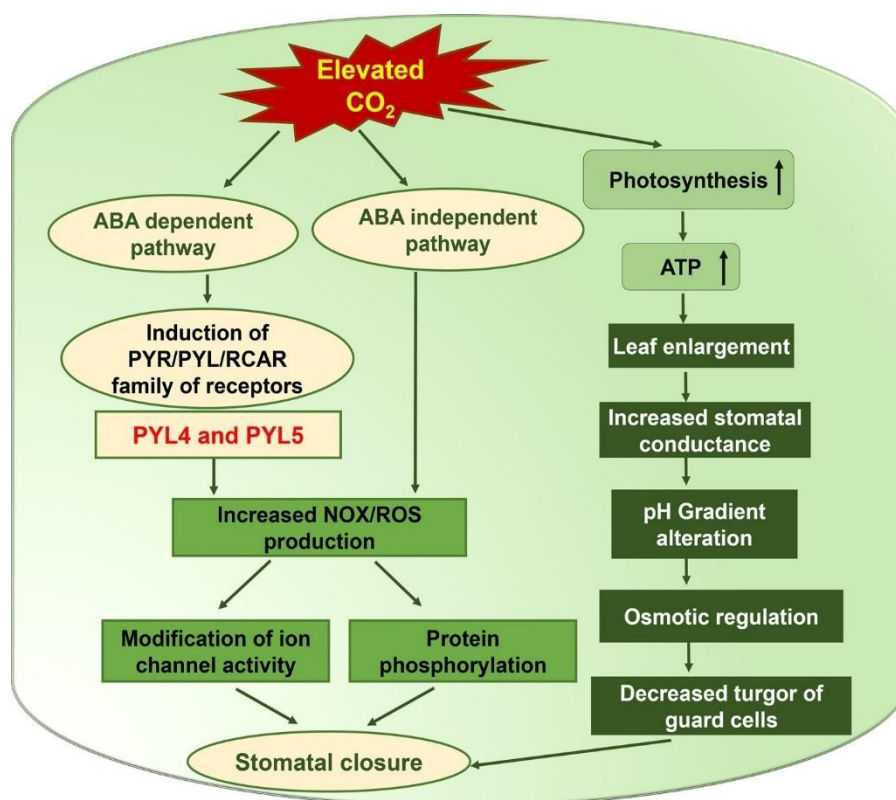
Characterizing these intricate interactions under  $e\text{CO}_2$  conditions is of profound significance in the framework of global food security, climate change mitigation, and sustainable agriculture (Thakur, et al., 2024). With a growing world population posed to face uncertain climatic conditions, information on carbon–nitrogen coupling gives useful direction to devise adaptive measures like integrated nutrient management, crop breeding to enhance nitrogen-use efficiency, and managed soil microbial engineering. It will be critical to this knowledge to provide resilient and productive agroecosystems in the future (Walker, et al., 2021).

Nutrient cycling is an important factor in controlling the terrestrial biosphere's carbon uptake and considerably affects how the carbon cycle reacts to temperature and

precipitation changes (Luo, 2007). Yet, global coupled carbon–climate models mostly ignore nutrient dynamics. Our research indicates that, including nutrient cycling specifically, the tight coupling between carbon and nitrogen within the terrestrial biogeochemistry module of a coupled climate system model radically alters the behavior of a number of important feedback mechanisms connecting terrestrial ecosystems to the global climate (Zaehle and Dalmonech, 2011). When interactions between carbon and nitrogen are accounted for, the globally averaged terrestrial carbon uptake response to increasing atmospheric  $\text{CO}_2$  is decreased by 74% relative to a carbon-only model. Furthermore, net land carbon exchange sensitivity to temperature and precipitation changes is greatly reduced by carbon–nitrogen coupling (Jain, et al., 2019). At increasing atmospheric  $\text{CO}_2$ , carbon cycle responses to temperature and precipitation are weaker in the coupled model, but stronger in the carbon-only model. These results imply that previous carbon-only models most probably exaggerated the terrestrial ecosystems' ability to reduce atmospheric  $\text{CO}_2$  through direct fertilization effects. So, the next generations of coupled climate–biogeochemistry models ought to represent explicitly and dynamically terrestrial carbon–nitrogen interactions in order to enhance projections of atmospheric  $\text{CO}_2$  concentration and climate change (Ciais, et al., 2014).



**Fig. 2. Conceptual framework: Carbon-nitrogen coupling under elevated  $\text{CO}_2$**



**Fig. 3. Cumulative effects of elevated CO<sub>2</sub> and drought on stomatal behavior.**  
(Source, Palit, et al., 2020)

Increased CO<sub>2</sub> controls OPEN STOMATA1 (OST1) by both ABA-dependent and ABA-independent mechanisms with increased NOX activity, production of reactive oxygen species (ROS), and regulation of the activities of ion channels. These modulate osmotic balance, pH, protein phosphorylation, and turgor pressure in guard cells. Besides, increased photosynthetic rate and ATP production additively affect leaf growth and canopy temperature control.

At the molecular level, high CO<sub>2</sub> causes stomatal closure and diminishes stomatal density mainly through the generation of ROS. The signaling pathway branches through ABA and the PYR/RCAR family of ABA receptors in the guard cell ABA signal network. The mechanism is mediated by the loop involving CO<sub>2</sub>-induced ABA accretion, which in turn increases sensitivity to CO<sub>2</sub> by the system. The ABA–OST1/SnRK2.6 signaling cascade illustrating basal ABA signaling and OST1/SnRK2.6 activity is required for CO<sub>2</sub> responsiveness in stomata clearly shows that the CO<sub>2</sub>-specific response, in particular, requires PYL4 and PYL5, despite ABA and high CO<sub>2</sub> stimulating PYR/PYL/RCAR receptors independently.

## 2. CONCEPTUAL UNDERPINNINGS OF C–N COUPLING UNDER ECO<sub>2</sub>

Carbon (C) and nitrogen (N) cycle coupling is the backbone of ecosystem functioning, especially in agroecosystems where plant productivity and soil fertility are strongly interconnected. Increased atmospheric CO<sub>2</sub> (eCO<sub>2</sub>) alters the carbon and nitrogen pathways, reorganizing plant–soil–microbe interactions and regulating nutrient processes. A mechanistic understanding of these conceptual underpinnings offers a basis to anticipate ecosystem responses and develop adaptive management approaches (Peng, et al., 2023).

### 2.1 CO<sub>2</sub> Fertilization and Nitrogen Constraints

The CO<sub>2</sub> fertilization effect is a highly documented fact in which eCO<sub>2</sub> promotes photosynthetic carbon fixation through enhanced carboxylation efficiency and diminished photorespiration losses in C<sub>3</sub> plants. It usually results in increased biomass accumulation and yield potential. Yet, the magnitude of yield improvement is highly modulated by nitrogen

availability. When nitrogen is in short supply, stimulation of photosynthesis under eCO<sub>2</sub> cannot be maximized, resulting in decreasing returns in crop yields (Kant, et al., 2012). Additionally, promoted growth is often accompanied by a nutrient dilution effect, such that plant tissues have more carbon per unit nitrogen, lowering protein content and, by extension, nutritional value of the crops. This disparity highlights the key function of nitrogen to modulate the size of the CO<sub>2</sub> fertilization response (Reich, and Hobbie, 2013).

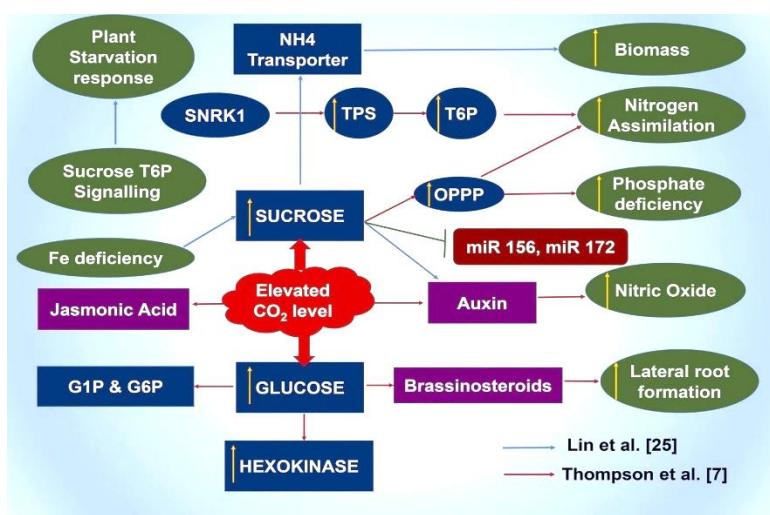
## 2.2 Shifts in Allocation and Rhizosphere Processes

In eCO<sub>2</sub> conditions, plants tend to have changed patterns of carbon allocation, with a higher

fraction of assimilated carbon directed below ground. This is reflected in elevated root growth, rhizodeposition, and exudation of organic compounds like phenolics, amino acids, and organic acids. These additions serve as energy substrates for soil microbial populations, thus activating microbial activity and altering nutrient turnover (Goswami, and Deka, 2022). Notably, the impact of boosted root exudation on nitrogen cycling is situation-specific: whereas it can increase nitrogen mineralization and make nutrients more accessible, it can also enhance microbial nitrogen immobilization, resulting in temporary conflict between microbes and plants. The overall result is thus largely contingent on both the quality of root-derived carbon inputs and the initial nitrogen status of the soil (Deb, et al., 2023).

**Table 1. Comparative responses of cropping systems to elevated CO<sub>2</sub> (eCO<sub>2</sub>)**

Level / Process	Positive Outcomes	Negative Outcomes	Conditional / Context-dependent Outcomes
Plant Growth, Yield & Quality	↑ Biomass accumulation and photosynthesis in C <sub>3</sub> crops; yield gains under adequate N supply	↓ Grain protein, Fe, Zn → nutritional dilution in cereals	Yield response highly dependent on N availability; C <sub>4</sub> crops less responsive to eCO <sub>2</sub>
Belowground C Inputs & SOC	↑ Root growth, rhizodeposition, and soil C inputs under eCO <sub>2</sub>	In low-N soils, microbial immobilization & priming dominate → SOC gains limited	In high-N soils, greater SOC stabilization through organo-mineral associations
Nitrogen Cycling	In legumes with N supply: ↑ BNF and nifH gene abundance (up to 2x)	eCO <sub>2</sub> alone does not consistently enhance BNF across systems	N fertilization boosts plant growth but can also ↑ N <sub>2</sub> O emissions, offsetting C benefits



**Fig. 4. Probable model on elevated CO<sub>2</sub>-mediated response in sugar signaling crosstalk.**  
(Source, Palit, et al., 2020)

The graph illustrates how high CO<sub>2</sub> raises sucrose and glucose, which are energy sources and also signaling molecules. These sugars interact with nutrient assimilation, stress signaling, phytohormones, and microRNAs in controlling biomass buildup, root development, and responses to nutritional deficiencies in plants.

### 2.3 Soil Moderators

The reaction of the carbon–nitrogen coupling under eCO<sub>2</sub> is not consistent but strongly moderated by soil characteristics and climatic conditions. Soil texture, organic matter content, and mineral composition determine SOC stabilization, whereas moisture and temperature regimes influence microbial process activity and nutrient conversion (Harrison-Kirk, et al., 2014). For example, finer-textured soils with elevated clay contents have a tendency to favor SOC stabilization by organo-mineral associations, while sandy soils tend to have reduced stabilization capacity. Furthermore, eCO<sub>2</sub>-induced alterations in aeration of the soil and microbial activity can affect nitrous oxide (N<sub>2</sub>O) emissions, an important greenhouse gas. Even though studies on these moderators are still less extensive, available evidence suggests that the interactions among eCO<sub>2</sub>, soil properties, and climate actually decide whether or not carbon gains are maintained or balanced out by nitrogen limitation and loss of greenhouse gases (Reich et al., 2014).

## 3. EMPIRICAL RESPONSES IN CROPPING SYSTEMS

Experiments conducted in the field and in controlled environments offer key information on the response of agroecosystems to rising CO<sub>2</sub> (eCO<sub>2</sub>). Although a general stimulation of plant growth is noted, the responses of yield, soil organic carbon (SOC), and nitrogen cycling are more complex and vary with crop type, nitrogen management, and soil properties (Kahiluoto et al., 2014).

### 3.1 Growth, Yield, and Quality

In various cropping systems, eCO<sub>2</sub> increases vegetative growth and biomass production, especially in C<sub>3</sub> cereals like rice, wheat, and soybean. Yield responses depend on nitrogen status. In conditions of high nitrogen, crops exhibit substantial increases in grain yield, whereas under conditions of nitrogen stress,

improvements in yield are usually small or non-existent even when biomass is increased (Ekele, et al., 2025). Of major concern is the quality of the harvestable product. Many studies report a reduction in protein, iron, and zinc content in grains produced under eCO<sub>2</sub>. Nutrient dilution through this effect threatens human nutrition, especially in areas that rely on cereals as staples. Therefore, although eCO<sub>2</sub> will promote plant growth, it also presents food-quality and nutritional-security issues.

### 3.2 Belowground Carbon Inputs and SOC

eCO<sub>2</sub> tends to enhance root biomass and rhizodeposition, adding more carbon to the ground. But these additions don't always equate to increased SOC stocks. The impact is heavily influenced by nitrogen status:

**Low-N systems:** More root-derived carbon tends to increase microbial activity, resulting in increased nitrogen immobilization and priming of soil organic matter decomposition. This can counteract SOC gains and even enhance carbon loss (Cheng, and Kuzyakov, 2005).

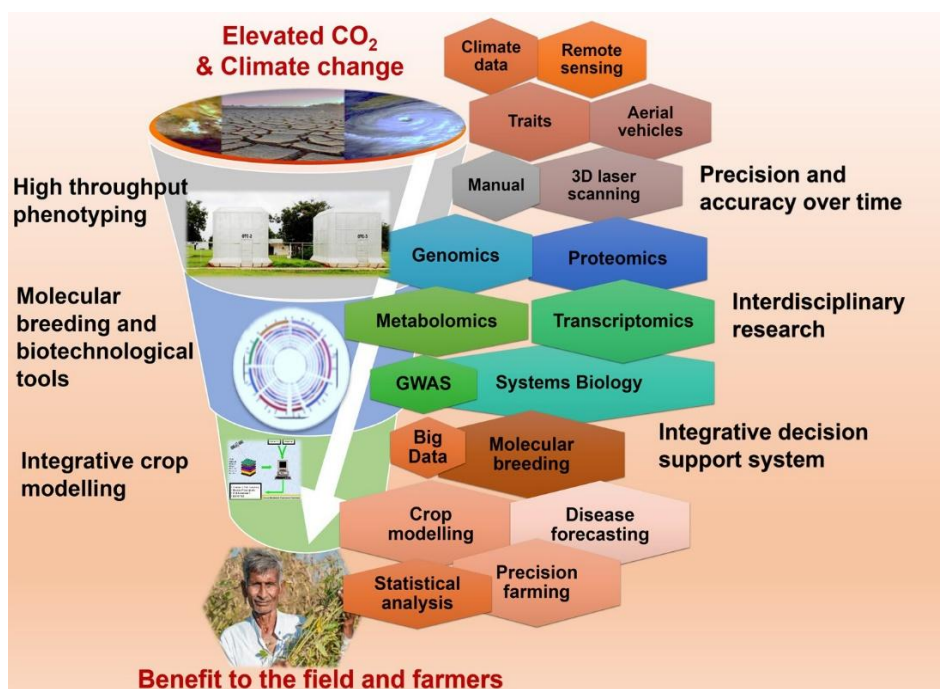
In high-N systems, microbial nitrogen demand is satisfied, enabling root-derived carbon to more effectively stabilize SOC, thus increasing soil carbon sequestration (Fitch, et al., 2024).

These divergent effects emphasize the necessity of integrated nutrient management to achieve the potential of eCO<sub>2</sub>-driven belowground carbon inputs in long-term soil fertility and climate mitigation.

### 3.3 Nitrogen Cycling

The influence of eCO<sub>2</sub> on nitrogen cycling is variable. The range of CO<sub>2</sub> by itself does not always promote biological nitrogen fixation (BNF) in all cropping systems. In legumes with adequate soil nitrogen, however, eCO<sub>2</sub> stimulates BNF, doubling nifH gene abundance a molecular marker for nitrogen-fixing microorganisms (Nag, et al., 2020). This demonstrates synergistic action of eCO<sub>2</sub> and added nitrogen in enhancing plant nitrogen uptake.

At the system level, nitrogen addition increases plant productivity under eCO<sub>2</sub> but has mixed effects on soil carbon capture and greenhouse gas (GHG) emissions (Yang, et al., 2022). For instance, nitrogen fertilization can increase crop yields while also promoting N<sub>2</sub>O emission, a



**Fig. 5. Prospective strategy for climate change research in legumes**  
(Source, Palit, et al., 2020)

powerful greenhouse gas, thus making eCO<sub>2</sub> climate benefits more complicated. These discrepancies reflect the intricacy of C–N coupling in managed systems, where the interaction between management regime, crop species, and microbial reaction is context-dependent.

The diagram shows a funnel framework where climate stress challenges like higher CO<sub>2</sub> and climate change constitute the initiating point at the top. These challenges are tackled in the middle using multi-scale tools like high-throughput phenotyping, molecular breeding, omics technologies, big data, and crop modeling. At the bottom, these combined methods find expression as usable outputs for farmers, which result in precision farming, improvement of better crop varieties, and increased resilience to climate change (Lobell, and Gourdjji, 2012).

The figure illustrates a funnel approach in which climate stress challenges, such as elevated CO<sub>2</sub> and climate change, form the starting point at the top. These challenges are addressed in the middle through multi-scale tools, including high-throughput phenotyping, molecular breeding, omics technologies, big data, and crop modeling. At the bottom, these integrated approaches translate into actionable outputs for farmers, leading to precision farming, the development of

improved crop varieties, and enhanced resilience to climate change.

#### 4. MANAGEMENT STRATEGIES

The challenges of maintaining carbon–nitrogen (C–N) balance under elevated CO<sub>2</sub> (eCO<sub>2</sub>) necessitate adaptive management practices that optimize productivity while minimizing environmental trade-offs (Shi, et al., 2025). Several evidence-based strategies are promising:

##### 4.1 4R Nutrient Stewardship

The system of "4R Nutrient Stewardship" situating the right nutrient source, at the right rate, at the right time, and in the right location, continues to be at the forefront of enhancing nitrogen use efficiency (NUE). Such a method reduces losses of nitrogen by leaching and denitrification and consequently lowers nitrous oxide (N<sub>2</sub>O) emissions, a key climate issue under amplified CO<sub>2</sub>–N interactions (Hassan, et al., 2022).

##### 4.2 Legume and Cover Crop Integration

Integration of legumes in crop rotations and cover crops in farming systems augments BNF, hence the use of synthetic fertilizers is

minimized. This not only protects cropping systems against nitrogen deficit under eCO<sub>2</sub> but also improves soil fertility, biodiversity, and system resilience (Cui, et al., 2023).

### 4.3 Residue Retention and Conservation Tillage

Practices like keeping crop residues, reduced tillage, or conservation tillage maintain soil organic carbon (SOC) pools and stabilize nitrogen cycling. Residue cover supplies substrates for microbial activity, minimizes soil erosion, and maximizes soil moisture storage (Li, et al., 2020). These practices complement eCO<sub>2</sub>-induced increases in root-derived carbon to enhance long-term soil fertility and carbon sequestration.

### 4.4 Integrated Nutrient–Water–Carbon Management

With the interconnected nature of water availability and nutrient dynamics, management strategies integrated across fertilization with a balance, optimized irrigation, and enhancement of organic matter in the soil are imperative. These reduce crop dilution risk from nutrients, stabilize yields, and enhance adaptability to climate variability.

## 5. RESEARCH GAPS AND NEXT STEPS

A great deal of progress has been made notwithstanding, there are still key knowledge gaps in understanding and managing C–N coupling under eCO<sub>2</sub>. A research focus for the future should include the following directions:

### 5.1 Long-Term Field Experiments

There are requirements for additional long-term Free-Air CO<sub>2</sub> Enrichment (FACE) experiments on various soil types, climatic regions, and crop systems. These would give sound evidence concerning the persistence and variation of C–N response in field conditions (Ainsworth and Long 2021).

### 5.2 Multifactorial Experiments

In addition to CO<sub>2</sub> enrichment per se, all future experiments should include CO<sub>2</sub> × N × P × water × microbial manipulations to constrain the range of possibilities regarding agroecosystem response complexity. This integrated treatment is

necessary since nutrient interactions and water supply frequently co-limit eCO<sub>2</sub> plant productivity.

### 5.3 Advanced C–N Modeling Frameworks

Current models need to be refined for improved representation of processes like priming effects, microbial nitrogen immobilization, stoichiometric flexibility of microbes and plants, and mycorrhizal pathways of nutrient exchange. These processes would add predictive ability and guide sustainable management strategies.

### 5.4 Productivity–Quality Trade-offs

An important research area is the balance between greater productivity and reduced nutritional value of crops under eCO<sub>2</sub>. Experiments that bridge crop physiology, nutrient biochemistry, and human nutrition consequences are essential to evaluate long-term effects on food security and public health.

### 5.5 Socioeconomic and Policy Dimensions

In addition to biophysical studies, there must be consideration of the socioeconomic effects and policy structures that guide nutrient management across shifting CO<sub>2</sub> regimes. These involve farmer adoption options, costs of interventions, and coordination with climate-smart agriculture policy.

## 6. CHALLENGES UNDER ECO<sub>2</sub> SCENARIOS

Even though the potential of higher CO<sub>2</sub> (eCO<sub>2</sub>) to enhance plant growth and sequester carbon exists, several challenges limit the long-term feasibility of such advantages. Carbon–nitrogen (C–N) coupling interactions add uncertainties that need to be overcome for efficient management.

### 6.1 Nitrogen Limitation

The CO<sub>2</sub> fertilization effect is also highly sensitive to sufficient nitrogen supply. Nitrogen supply in most cropping systems is already a limiting factor, and eCO<sub>2</sub> increases plant nitrogen requirement. Without added inputs or biological nitrogen fixation, the long-term sustainability of yield increases is doubtful. This poses a major challenge in resource-poor farming systems in which fertilizer availability is restricted.

## 6.2 Soil Organic Matter Dynamics

Whereas eCO<sub>2</sub> boosts belowground carbon inputs, it also initiates microbial breakdown of SOM. This tends to speed up nitrogen mineralization but at the same time enhances nitrogen losses by leaching and denitrification. Consequently, short-term gains in productivity may be at the expense of long-term soil fertility and ecosystem stability.

## 6.3 Greenhouse Gas Trade-offs

One of the most important issues at hand is the risk of enhanced nitrous oxide (N<sub>2</sub>O) emissions, which is a greenhouse gas with approximately 300 times the global warming potential of CO<sub>2</sub>. High nitrogen cycling in eCO<sub>2</sub> may inadvertently increase N<sub>2</sub>O fluxes, which could counteract the climate change mitigation potential of increased carbon sequestration. This trade-off makes it more challenging for agroecosystems to play a positive role in climate change mitigation efforts.

## 6.4 Management Gaps

Traditional fertilizer application regimes do not completely resonate with the changed nutrient dynamics under eCO<sub>2</sub>. Over-reliance on blanket nitrogen recommendations can cause either deficiency or excess, both of which disempower productivity and environmental benefits. Improved nutrient strategies, such as site-specific and adaptive management, are yet to be properly developed in most areas.

## 6.5 Model Uncertainty

Existing crop and ecosystem models have a tendency to oversimplify C–N coupling, tending to omit processes like microbial nitrogen immobilization, priming effects, and plant–

microbe competition. These omissions decrease the validity of long-term predictions, making it challenging to accurately determine the resilience of agroecosystems to future CO<sub>2</sub> scenarios.

**These problems demand a multifaceted approach:**

**Integrated Nutrient Management (INM):** The integration of organic and inorganic sources of nutrients can improve nitrogen use efficiency while preserving soil health.

**Breeding and Biotechnology:** breeding crop plants for enhanced nitrogen-use efficiency, root structure, and symbiotic relationships with beneficial microbes can optimize C–N coupling under eCO<sub>2</sub>.

**Microbial Interventions:** applications of plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, and constructed microbial consortia can enhance soil–plant interactions and SOM stabilization.

**Advanced Modeling and Monitoring:** Coupled carbon–nitrogen models, integrated with remote sensing and big data analytics, are essential to forecast system-level responses under future climate conditions and inform adaptive management practices.

In the long term, enhancing C–N coupling at high CO<sub>2</sub> is not only a technical but also a policy and governance problem. Interdisciplinary collaboration between soil scientists, plant breeders, ecologists, and climate scientists, as well as farmer-focused researchers extension approaches, is necessary to overcome knowledge-to-practice gaps.

**Table 2. Effects of elevated CO<sub>2</sub> on carbon and nitrogen processes in agroecosystems**

Level	Positive Outcomes	Negative Outcomes	Conditional Outcomes
Plant	↑ Biomass, ↑ photosynthesis, ↑ water-use efficiency	↓ Grain protein, ↓ micronutrients	Yield response depends on N availability
Soil	↑ Root exudates and rhizodeposition, potential SOC storage	Enhanced SOM decomposition, ↑ N losses via leaching/denitrification	SOC stabilization occurs mainly under high-N systems
Microbial	↑ Rhizosphere activity, stimulation of nifH genes in legumes under eCO <sub>2</sub> + N supply	Potential priming effect, N immobilization reduces plant uptake	N fixation response depends on legume presence and soil fertility

**Table 3. Challenges and opportunities for managing C–N coupling under eCO<sub>2</sub> scenarios**

Aspect	Challenges	Opportunities
Nitrogen availability	N limitation constrains CO <sub>2</sub> fertilization effect	Integrated Nutrient Management (INM), balanced organic–inorganic fertilization
Soil Organic Matter (SOM)	Enhanced decomposition, N loss through leaching/denitrification	Residue retention, conservation tillage, SOC stabilization
Greenhouse gases (GHG)	↑ N <sub>2</sub> O emissions may offset C gains	Climate-smart practices (agroforestry, cover crops) reduce net GHG footprint
Genetic & microbial innovations	Lack of varieties adapted to eCO <sub>2</sub> and low-N conditions	Breeding for NUE, microbial inoculants (mycorrhizae, diazotrophs)
Modeling & prediction	Crop models oversimplify C–N coupling	Advanced multi-factor models (CO <sub>2</sub> × N × water × microbes)

Finally, stabilizing carbon–nitrogen bonds is central to maintaining sustainable intensification of agriculture, reducing the impact of climate change, preserving ecosystem services, and promoting global food and nutritional security. In the direction where the world is heading toward net-zero emission commitments, C–N coupling science and its real-world application will be instrumental in reconciling agricultural productivity and environmental sustainability.

## 7. CONCLUSION

Carbon–nitrogen (C–N) coupling is the keystone of functioning agroecosystems, having direct effects on plant productivity, soil fertility, and environmental sustainability. At elevated CO<sub>2</sub> (eCO<sub>2</sub>) levels, crops tend to show increased photosynthetic performance and biomass production, implying potential for enhanced yields. Yet, these advantages are not assured, as nitrogen (N) availability, SOM dynamics, and greenhouse gas (GHG) emissions represent critical limiting and regulatory factors. Weak coupling of carbon and nitrogen cycles can contribute to nutrient dilution in crops, loss of soil fertility, and enhanced nitrous oxide (N<sub>2</sub>O) emissions, which could reduce otherwise expected climate change mitigation.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of this manuscript. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input

prompts provided to the generative AI technology.

## Details of the AI usage are given below:

1. ChatGpt

## COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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