

Review

Crossing the Nitrogen Line: Cropland Emissions, Planetary Boundaries, and the SDGs

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Abstract

Fertilised cropland systems are the dominant source of reactive nitrogen losses in the global environment, contributing most anthropogenic nitrous oxide emissions and driving agricultural nitrogen surplus to nearly three times the safe planetary boundary for nitrogen. This review advances a nitrogen-centred analytical framework that positions cropland nitrogen management as a greenhouse gas mitigation imperative, a planetary boundary challenge, and a cross-cutting lever for integrated Sustainable Development Goal progress. Unlike prior reviews that treat nitrous oxide emissions, nitrogen use efficiency, or Sustainable Development Goal linkages as separate concerns, this framework demonstrates that reducing reactive nitrogen losses from fertilised cropland is the single intervention space most likely to generate co-benefits across food security, clean water, climate action, life on land, and partnership goals, while helping restore the transgressed nitrogen boundary. The nitrogen cascade from fertilised croplands and associated livestock manure generates sequential damages across climate, water quality, human health, and terrestrial biodiversity that are mapped against their goal implications. Mitigation strategies including precision nitrogen management, nitrification inhibitors, biochar amendment, agroforestry, circular manure management, and emerging bio-technical innovations are evaluated against their co-benefits, adoption constraints, and potential to shift losses toward other nitrogen species. A financing gap of over one trillion dollars annually and the absence of binding global nitrogen governance are identified as the primary barriers to integrated action. Spatially explicit nitrogen redistribution and nitrogen use efficiency improvement are presented as design principles capable of reconciling planetary boundary recovery with food security equity across nitrogen surplus and nitrogen-deficit regions.



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1. Introduction

The nitrogen cycle is among the most severely disrupted of all Earth system processes. Richardson et al. confirmed that six of the nine planetary boundaries have now been transgressed, with the biogeochemical flow boundary for nitrogen among those most critically

exceeded [1]. Reactive nitrogen (Nr) released to the global environment currently stands at approximately 190 Tg per year, far above the estimated safe operating boundary of 62 to 82 Tg per year [1]. This 62 to 82 Tg per year figure refers to the revised global nitrogen fixation boundary reported in the Richardson planetary boundaries framework. It is conceptually distinct from the regional-aggregated agricultural nitrogen surplus boundary of 43 Tg N yr⁻¹ derived separately by Schulte-Uebbing et al. [2], which is introduced and compared against current agricultural nitrogen surplus in Section 3.1. This transgression is driven overwhelmingly by agricultural nitrogen management across the global food and land-use system [2]. Agriculture, forestry, and other land use (AFOLU) account for approximately one-third of total anthropogenic greenhouse gas (GHG) emissions [3]. Within this sector, nitrogen is the primary agent of non-CO₂ radiative forcing. AFOLU systems contribute approximately 81% of global anthropogenic nitrous oxide (N₂O) emissions, with agricultural soils responsible for approximately 96% of the AFOLU N₂O total [4]. The globally averaged atmospheric concentration of N₂O reached a record high of 338.0 ± 0.1 ppb in 2024, representing a 25% increase above pre-industrial levels [5]. N₂O is a potent and long-lived greenhouse gas with a global warming potential of 273 CO₂ equivalents over a 100-year horizon and an atmospheric lifetime of approximately 120 years [4]. Jones et al. further established that cumulative agricultural N₂O emissions have contributed measurably to historical radiative forcing since 1850 [6].

The nitrogen challenge in AFOLU extends beyond N₂O alone. Reactive nitrogen losses from agricultural systems cascade through the environment as ammonia (NH₃), nitrogen oxides (NO_x), and nitrate (NO₃⁻), each generating distinct but interconnected damages across terrestrial, aquatic, and atmospheric systems [7]. Agricultural Nr is estimated to contribute approximately 30% of fine particulate matter (PM_{2.5}) globally and to increase surface ozone concentrations in intensively fertilised regions by 15 to 37%, together causing approximately 1.88 million premature deaths annually worldwide [8]. This multi-pathway damage means that nitrogen mismanagement simultaneously threatens climate stability, human health, water quality, and biodiversity. These impacts do not fall on a single Sustainable Development Goal. Raghuram et al. established that reactive nitrogen affects all 17 SDGs to varying degrees [9]. A recent quantitative framework applied to China demonstrated that nitrogen use and losses affected 11 of the 17 SDGs in 2020, with substantial regional variation in the direction and magnitude of these effects [7]. Despite this cross-cutting reach, nitrogen is rarely treated as a unified SDG variable in the policy or scientific literature. Most existing reviews address N₂O emissions, NUE, or SDG linkages as separate concerns, without integrating them into a coherent analytical framework. Most of this evidence, and the majority of the evidence synthesised in this review, concerns fertilised cropland systems specifically, which remain the largest single source of agricultural Nr losses; pastures, forests, peatlands, and manure management are discussed but with comparatively less depth, consistent with the scope reflected in the title of this review.

This review addresses that gap. It advances a unified nitrogen-centred analytical framework that positions reactive nitrogen management in AFOLU systems simultaneously as a GHG mitigation imperative, a planetary boundary challenge, and a cross-cutting lever for integrated SDG progress. This framework demonstrates that reducing nitrogen losses from agricultural and land-use systems is the intervention space most likely to generate co-benefits across SDGs 2, 6, 13, 15, and 17, while contributing to the recovery of the transgressed biogeochemical flow planetary boundary. The specific conceptual advance offered here, beyond existing treatments of the nitrogen cascade, planetary boundaries, and nitrogen–SDG linkages individually, is the explicit linkage of all three into a single cross-referenced framework in which the same quantified Nr pathways are traced simultaneously through their climate, planetary-boundary, and SDG consequences, rather than being

assessed against each of these domains in isolation. The review synthesises evidence on Nr sources and mechanisms in AFOLU, maps the multi-SDG consequences of nitrogen losses, evaluates mitigation strategies with reference to their SDG co-benefits, and identifies the critical policy and governance gaps that currently prevent integrated nitrogen action at scale.

Scope and Review Approach

This review synthesises peer-reviewed literature published between 2020 and 2026, identified through Web of Science, Scopus, and Google Scholar. Search terms combined “reactive nitrogen,” “nitrous oxide,” “ammonia,” “nitrate,” “AFOLU” or “agriculture,” “planetary boundary,” and “Sustainable Development Goal” in varying combinations. Research from 2018 to 2019 was retained only where no directly comparable recent study existed for a specific claim. Pre-2018 sources were retained only where they represent foundational, irreplaceable evidence, including the original planetary boundaries framework published in 2009 and a 2017 synthesis of nitrogen deposition impacts across United States ecoregions, since no directly equivalent updated study covers these specific findings. Because the purpose of this review is to construct a novel cross-domain analytical framework linking the nitrogen cascade, planetary boundaries, and the SDGs, rather than to exhaustively enumerate all AFOLU nitrogen literature, the approach taken is a narrative review rather than a systematic review following the PRISMA protocol. A systematic search, screening, and study-selection flow diagram is therefore not reported. Evidence strength for the nitrogen-SDG interactions summarised in this review is assessed using three descriptive categories. Very strong evidence indicates multiple independent primary experimental and modelling studies with globally consistent findings. Strong evidence indicates several primary studies conducted across different regions with a broadly consistent direction of effect. Moderate evidence indicates primary modelling or synthetic studies for which field-level validation remains incomplete or context-specific. These categories are applied consistently throughout the review and are not intended to substitute for a formal systematic evidence-grading protocol. Readers should interpret the conclusions of this review as a synthesis of the best currently available evidence rather than as an exhaustive or fully reproducible systematic assessment.

2. The Nitrogen Problem in AFOLU: Sources, Magnitudes, and Mechanisms

2.1. The Reactive Nitrogen Cascade in Agricultural Systems

Reactive nitrogen (Nr) comprises all chemically active nitrogen species, including ammonia (NH_3), nitrogen oxides (NO_x), nitrous oxide (N_2O), and nitrate (NO_3^-), that are mobilised when nitrogen gas (N_2) is converted from its inert atmospheric form into biologically and chemically available compounds [8]. The Haber–Bosch process, which industrially fixes atmospheric N_2 into ammonia for synthetic fertiliser production, fundamentally transformed the global nitrogen cycle from the early twentieth century onward [10]. This process now underpins the food security of approximately half the global human population, yet it simultaneously drives the overloading of reactive nitrogen across terrestrial, aquatic, and atmospheric systems [9]. Once released into the environment, a single Nr molecule does not cause a single impact and then disappear. It cascades through successive environmental compartments, causing multiple sequential and compounding damages before being finally converted back to inert N_2 [8]. A molecule of NH_3 volatilised from a fertilised field may first acidify downwind soils, then contribute to fine particulate matter ($\text{PM}_{2.5}$) formation in the atmosphere and finally deposit onto aquatic ecosystems where it stimulates eutrophication. This cascade concept is foundational to understanding why nitrogen management in

AFOLU carries consequences that extend far beyond the field scale and across multiple SDG domains [7]. Global Nr losses from agricultural systems continue to increase. Land-use conversion from natural to managed ecosystems has been demonstrated to reduce soil net nitrogen mineralisation by approximately 7.5% while simultaneously increasing net nitrification by 150%, indicating that agricultural expansion structurally increases the Nr loss potential of soils at the landscape level [11]. These structural shifts make agricultural Nr management one of the most consequential levers available for simultaneously addressing GHG emissions, air quality, water quality, and biodiversity loss.

2.2. N_2O : Sources, Mechanisms, and Climate Forcing

N_2O is produced in agricultural soils through three microbially mediated pathways: nitrification, denitrification, and nitrifier denitrification. Nitrification releases N_2O as a by-product of ammonium oxidation, driven primarily by ammonia-oxidising bacteria (AOB) and archaea (AOA) [12]. Denitrification generates N_2O when the terminal reduction step, catalysed by nitrous oxide reductase encoded by the *nosZ* gene, is incomplete during the anaerobic reduction of nitrate to inert N_2 [13]. Nitrifier denitrification, in which AOB reduce nitrite to N_2O under partially aerobic conditions, can contribute substantially to emissions in soils with fluctuating moisture [12]. The relative dominance of these pathways depends on soil water-filled pore space (WFPS), with nitrification dominating below approximately 60% WFPS and denitrification above 70% [12]. Soil pH, temperature, organic carbon, and ammonium concentration further modulate emission rates, contributing to an estimated 60% uncertainty in agricultural N_2O emission factors that constrains accurate national inventory compilation [4].

Global cropland N_2O emissions quadrupled from approximately 0.3 Tg N_2O -N per year in 1961 to 1.2 Tg N_2O -N per year in 2020, driven primarily by the rapid expansion of synthetic nitrogen fertiliser use across major agricultural regions [14]. Agricultural activities contribute approximately half of all anthropogenic N_2O emissions globally, with fertilised cropland soils identified as the single largest anthropogenic source [14]. Over 80% of the global mitigation potential for cropland N_2O is concentrated in South Asia, China, the European Union, and Southeast Asia, reflecting the geographic concentration of nitrogen overuse in these regions [14]. The mitigation potential of 0.7 Tg N_2O -N per year without compromising crop production is substantial, with 86% of that potential achievable through optimising nitrogen fertilisation practices alone [14]. The sources, emission pathways, global magnitudes, and global warming potentials of N_2O and related Nr species from AFOLU systems are summarised in Table 1.

Table 1. Reactive nitrogen species from agriculture, forestry, and other land use (AFOLU) systems. Primary emission mechanisms, estimated global magnitudes, climate forcing contributions, and key environmental impacts relevant to Sustainable Development Goal linkages.

Nr Species	Primary AFOLU Sources	Key Emission Mechanism	Estimated Global Agricultural Magnitude	Climate Forcing	Primary Environmental Impacts	Key SDG Linkages
Nitrous oxide (N_2O)	Fertilised cropland soils, manure management, pasture	Nitrification (AOB/AOA-mediated NH_4^+ oxidation) and denitrification (<i>nosZ</i> -incomplete reduction of NO_3^-)	3.9 Tg N yr^{-1} direct agricultural emissions (2020); cropland emissions quadrupled from 0.3 to 1.2 Tg N_2O -N yr^{-1} over 1961–2020	$GWP_{100} = 273$ CO_2eq ; atmospheric lifetime ~120 years; contributes 6.4% of total enhanced radiative forcing	Stratospheric ozone depletion; long-term warming; persists in the atmosphere for approximately 120 years and continues to contribute to radiative forcing over multi-decadal timescales	SDG 13 (climate action); SDG 3 (health via ozone)

Table 1. Cont.

Nr Species	Primary AFOLU Sources	Key Emission Mechanism	Estimated Global Agricultural Magnitude	Climate Forcing	Primary Environmental Impacts	Key SDG Linkages
Ammonia (NH ₃)	Urea and ammonium fertiliser application, livestock manure volatilisation, manure storage	Urease-mediated hydrolysis of urea to NH ₄ ⁺ ; NH ₃ -NH ₄ ⁺ equilibrium shift under high pH and temperature	Global agricultural NH ₃ emissions reached ~60 Tg N yr ⁻¹ by 2018, a 78% increase since 1980; cropland NH ₃ ~28 Tg N yr ⁻¹	Net indirect cooling via secondary aerosol formation; cooling effect projected to weaken under future Nr emission controls	PM _{2.5} formation (~30% of global PM _{2.5}); soil and freshwater acidification; terrestrial nitrogen deposition and biodiversity loss	SDG 3 (air quality/health); SDG 6 (water quality); SDG 15 (biodiversity)
Nitrogen oxides (NO _x)	Nitrification and denitrification in agricultural soils, biomass burning from land clearing	Incomplete nitrification/denitrification; thermal and microbial combustion during burning	Poorly constrained globally; agricultural soils estimated to contribute 1–3 Tg N yr ⁻¹ ; land clearing fires contribute additional episodic pulses	Indirect warming via tropospheric ozone formation; also contributes to aerosol-mediated cooling	Tropospheric ozone formation damaging crop yields and human health; soil acidification via HNO ₃ deposition; contributes to Nr cascade	SDG 2 (crop yield losses); SDG 3 (respiratory health); SDG 15 (ecosystem acidification)
Nitrate (NO ₃ ⁻)	Leaching from fertilised croplands and manure-amended soils, runoff from agricultural land	Incomplete plant uptake of applied N; preferential flow and subsurface lateral transport under excess irrigation or rainfall	Global cropland nitrate leaching from synthetic fertilisers estimated at 12.9–15.4 Tg N yr ⁻¹ ; agriculture contributes 70–80% of total nitrate leaching globally	No direct radiative effect; drives indirect N ₂ O production from aquatic systems	Groundwater contamination threatening drinking water safety; freshwater and coastal eutrophication; hypoxic dead zones in coastal waters	SDG 6 (clean water); SDG 14 (life below water); SDG 2 (aquaculture/food system)
Reactive N cascade (cumulative)	All AFOLU Nr sources interacting sequentially across environmental compartments	Sequential transfer of Nr molecules through atmospheric, terrestrial, and aquatic systems without conversion back to N ₂	Global agricultural Nr surplus approximately 119 Tg N yr ⁻¹ in 2010–approximately 177% above (roughly 2.8 times) the aggregated safe planetary boundary of 43 Tg N yr ⁻¹ [see table note below]	Net direct radiative forcing of anthropogenic Nr estimated at −0.34 W m ⁻² (net cooling), though highly uncertain	Multi-domain: air quality, water quality, biodiversity, soil degradation, climate; each Nr molecule may cause damage in multiple compartments sequentially	SDG 2 (food security), 3 (health), 6 (water), 13 (climate), 14 (life below water), 15 (life on land), 17 (partnerships)

Note: The 119 Tg N yr⁻¹ and 43 Tg N yr⁻¹ figures both refer specifically to the agricultural nitrogen surplus indicator defined by Schulte-Uebbing et al. [2], which is distinct from the broader total anthropogenic Nr flux of approximately 190 Tg N yr⁻¹ reported by Richardson et al. [1] and discussed in Sections 1 and 3.1. These two indicators use different system boundaries and should not be compared directly to one another. SDG 14 is included in this row because nitrate-driven eutrophication cascades into marine and coastal systems. It is treated as a secondary, downstream linkage in this review rather than one of the five core SDGs (2, 6, 13, 15, 17) emphasised in the unified framework, since the primary evidence base for this review concerns terrestrial and freshwater rather than marine pathways. **Sources:** [2,7,11–17]. **Abbreviations:** AOB, ammonia-oxidising bacteria; AOA, ammonia-oxidising archaea; GWP₁₀₀, global warming potential over 100-year horizon; Nr, reactive nitrogen; PM_{2.5}, fine particulate matter with aerodynamic diameter below 2.5 micrometres; SDG, Sustainable Development Goal.

2.3. NH₃, NO_x, and Nitrate: The Non-GHG Reactive Nitrogen Losses

While N₂O exerts its primary impact on the climate, NH₃, NO_x, and NO₃⁻ complete the reactive nitrogen cascade through distinct but interconnected environmental damage pathways. NH₃ volatilisation from urea hydrolysis and manure decomposition represents the largest gaseous nitrogen loss pathway in many dryland cropping systems, with urease enzyme activity in soil accelerating the conversion of urea to NH₄⁺ and subsequent release to the atmosphere [8]. Volatilised NH₃ serves as the primary alkaline precursor to secondary inorganic aerosols and PM_{2.5} formation, contributing to approximately 30% of PM_{2.5} globally [8]. These aerosols exert an indirect net cooling effect on the climate through aerosol–radiation interactions. The overall direct radiative forcing of anthropogenic Nr is estimated to be approximately −0.34 W m⁻², representing a net cooling that partially offsets warming from N₂O, though this estimate carries substantial uncertainty [18]. This cooling effect is projected to weaken as Nr aerosol loadings decline under future emission control scenarios, potentially unmasking additional warming from N₂O that has accumulated in the atmosphere [18].

NO_x species, including nitric oxide (NO) and nitrogen dioxide (NO₂), are emitted from nitrification and denitrification processes in agricultural soils and from biomass burning associated with land clearing for agriculture [8]. NO_x contributes to tropospheric ozone

formation, which damages crop yields and human respiratory health, and its atmospheric deposition drives soil acidification through nitric acid (HNO_3) generation [11]. Nitrate leaching from fertilised soils to groundwater and surface waters drives eutrophication of aquatic ecosystems and the formation of hypoxic dead zones in coastal waters globally [2]. These non-GHG Nr losses from AFOLU generate damages spanning water quality, ecosystem integrity, and human health, all of which map directly onto multiple SDG targets examined in Section 4.

2.4. Land-Use Change as an Amplifier of Nitrogen Losses

Land-use change restructures soil nitrogen cycling in ways that amplify reactive nitrogen losses over extended time horizons, compounding the direct Nr emissions from fertiliser application. Forest conversion to cropland significantly increases soil net nitrification rates by stimulating the growth and activity of AOB and AOA populations, while simultaneously reducing the carbon-to-nitrogen ratio that otherwise supports conservative nitrogen cycling in intact native soils [17]. A global meta-analysis of 1782 paired observations confirmed that land-use conversion from natural to managed ecosystems increased net nitrification by 150%, documenting a structural shift from nitrogen-conservative to nitrogen-leaky soil systems that persists after conversion [11].

Tropical deforestation for agricultural expansion represents a particularly acute amplifier of Nr losses. Forest conversion to oil palm plantation in tropical peatlands substantially increases both CO_2 and N_2O emissions relative to pre-conversion forest land, with peat drainage lowering water tables and creating aerobic surface conditions that stimulate nitrification followed by denitrification-driven N_2O production in deeper anaerobic layers [19]. Forest disturbance due to fire reached its highest recorded levels since monitoring began in 2001 during 2023 and 2024, with the 2023 to 2024 average global fire disturbance area 2.2 times higher than the 2002 to 2022 average and over one quarter of all 2024 fire disturbance occurring in tropical forests [20]. Biomass burning from these fire events releases substantial Nr to the atmosphere as NO_x and NH_3 , amplifying the cascade of reactive nitrogen impacts across multiple systems [8]. The cross-cutting environmental impacts of these Nr loss pathways, mapped against their SDG relevance, are further detailed in Table 1.

3. Nitrogen and the Planetary Boundaries Framework

3.1. The Biogeochemical Flow Boundary and Its Status

The planetary boundaries framework, first proposed by Rockström et al., defines nine Earth system processes within which human societies can safely operate without triggering irreversible environmental change [21]. The framework set an initial safe boundary for industrial and agricultural nitrogen fixation at 35 Tg N yr^{-1} , acknowledging this figure as a first approximation requiring further refinement [21]. Subsequent work by Schulte-Uebbing et al. established a more spatially explicit and environmentally grounded set of regional nitrogen boundaries, deriving an aggregated global nitrogen surplus boundary of 43 Tg N yr^{-1} with respect to all environmental thresholds combined, including eutrophication of terrestrial and aquatic ecosystems and nitrate contamination of groundwater [2]. The 2023 comprehensive quantification by Richardson et al. confirmed that the biogeochemical flow boundary for nitrogen is among the six planetary boundaries now transgressed, with current anthropogenic nitrogen inputs to the environment standing at approximately 190 Tg N yr^{-1} [1].

These two figures, 190 Tg N yr^{-1} and 43 Tg N yr^{-1} , are not directly comparable and should not be read as competing estimates of the same quantity. The 190 Tg N yr^{-1} figure reported by Richardson et al. represents the total anthropogenic reactive nitrogen input

to the global environment across all sources and pathways, used as the control variable for the biogeochemical flow planetary boundary [1]. The 43 Tg N yr⁻¹ figure derived by Schulte-Uebbing et al. instead represents an aggregated regional boundary specifically for agricultural nitrogen surplus, defined as nitrogen inputs to cropland more than the nitrogen removed through harvest, and benchmarked against a narrower set of eutrophication and groundwater contamination thresholds [2]. Because these two indicators use different system boundaries and different units of analysis, the appropriate comparison for assessing agricultural boundary transgression is between the global agricultural nitrogen surplus itself and the 43 Tg N yr⁻¹ boundary, both derived using the same Schulte-Uebbing et al. methodology [2], as set out below.

This transgression is not uniform across the globe. Schulte-Uebbing et al. demonstrated substantial regional heterogeneity, with nitrogen surpluses exceeding critical environmental thresholds in intensive agricultural regions of East and South Asia, Western Europe, and parts of North America, while significant nitrogen deficits and associated yield gaps persist across sub-Saharan Africa and parts of South Asia [2]. This spatial divide means that the planetary boundary is transgressed at the global aggregate level even as hundreds of millions of people in nitrogen-deficient regions remain food-insecure [22]. The global agricultural nitrogen surplus in 2010 was approximately 119 Tg N yr⁻¹, approximately 177% above (roughly 2.8 times) the aggregated safe boundary derived by Schulte-Uebbing et al. [2], confirming that current AFOLU nitrogen management is operating well outside the safe operating space. The biogeochemical flow boundary does not operate in isolation from the other eight planetary boundaries. Excess nitrogen cascades through freshwater systems to coastal oceans, amplifying eutrophication that connects nitrogen transgression to the biosphere integrity boundary [1]. Atmospheric deposition of Nr from agricultural sources contributes to terrestrial ecosystem acidification and biodiversity loss, linking the nitrogen boundary directly to land-system change and biosphere integrity processes [8]. N₂O accumulation in the atmosphere compounds radiative forcing that drives the climate change boundary further into transgression [15]. These interconnections mean that failing to address the nitrogen boundary simultaneously accelerates the transgression of at least three other boundaries, creating compounding Earth system risks that no single-sector intervention can resolve.

3.2. *Why the Nitrogen Boundary Cannot Be Met Without AFOLU Reform*

Agriculture is the dominant driver of nitrogen boundary transgression and the only sector capable of restoring it within a timeframe relevant to the 2030 Agenda. The Haber-Bosch process, which is responsible for the majority of global anthropogenic nitrogen fixation, currently operates at a scale more than five times the original 35 Tg N yr⁻¹ boundary proposed by Rockström et al. [21]. While this boundary has since been revised upward based on more nuanced environmental and food security modelling, current global fixation still substantially exceeds even the most generous, revised estimates [2]. Reducing nitrogen inputs to within the planetary boundary while maintaining food production for a global population approaching 10 billion by 2050 is only achievable through a combination of dramatically improved NUE, redistribution of nitrogen inputs from surplus to deficit regions, dietary transitions, and reductions in food loss and waste [22].

The food security constraint on nitrogen reduction is acute and regionally asymmetric. In sub-Saharan Africa, average fertiliser application rates have stagnated between 13 and 20 kg of nutrient per hectare, compared with 120 kg per hectare in South Asia, producing yield gaps of 50 to over 90% for staple crops including rainfed rice and wheat [23]. Redistribution of current global nitrogen inputs to major cereals among countries, without any net increase in total global nitrogen use, could double food production in the

most food-insecure nations while simultaneously increasing global cereal production by 12%, demonstrating that spatial redistribution alone offers substantial synergies between food security and planetary boundary recovery [22]. This finding is central to the novel analytical framework advanced by this review. It demonstrates that returning toward the nitrogen planetary boundary and advancing SDG 2 are not inherently opposed objectives but become complementary when nitrogen governance is spatially explicit and equity centred.

The relationship between NUE improvement and boundary recovery deserves particular attention. Global average NUE in crop systems remains at approximately 55%, meaning that roughly 45% of applied nitrogen is lost to the environment as Nr [9]. This 55% figure refers to global average nitrogen use efficiency in crop systems as reported by Raghuram et al. [9]. Section 4.1 separately reports a global average nitrogen recovery efficiency of 48% from You et al. [24]. These are related but distinct metrics, calculated using different methodologies and reference datasets, and the approximately seven percentage point difference reflects methodological variation across studies rather than an inconsistency within this review. Modelling by Schulte-Uebbing et al. showed that increasing NUE to approximately 0.77 globally could be sufficient to meet minimum crop demand for the current global population without transgressing regional nitrogen boundaries, provided dietary patterns shift modestly toward plant-based foods [2]. These findings position NUE improvement not as a technical agronomic goal but as a planetary boundary governance priority with direct and simultaneous consequences for SDGs 2, 6, 13, and 15. Agricultural ammonia emissions, which have increased by 78% since 1980 and reached approximately 60 Tg N yr^{-1} by 2018, represent one of the most tractable entry points for reducing Nr losses at scale, given that their primary driver is excess fertiliser application rather than fundamental food production requirements [16]. Figure 1 illustrates the conceptual framework linking reactive nitrogen loss pathways from AFOLU systems through planetary boundary transgression to cross-SDG impacts, showing how N_2O connects to SDG 13, NH_3 connects to SDGs 3 and 15, NO_x connects to SDGs 2 and 3, and nitrate leaching connects to SDGs 6 and 15, and the overarching nitrogen surplus connects to the biogeochemical flow boundary whose recovery is a prerequisite for long-term SDG progress.

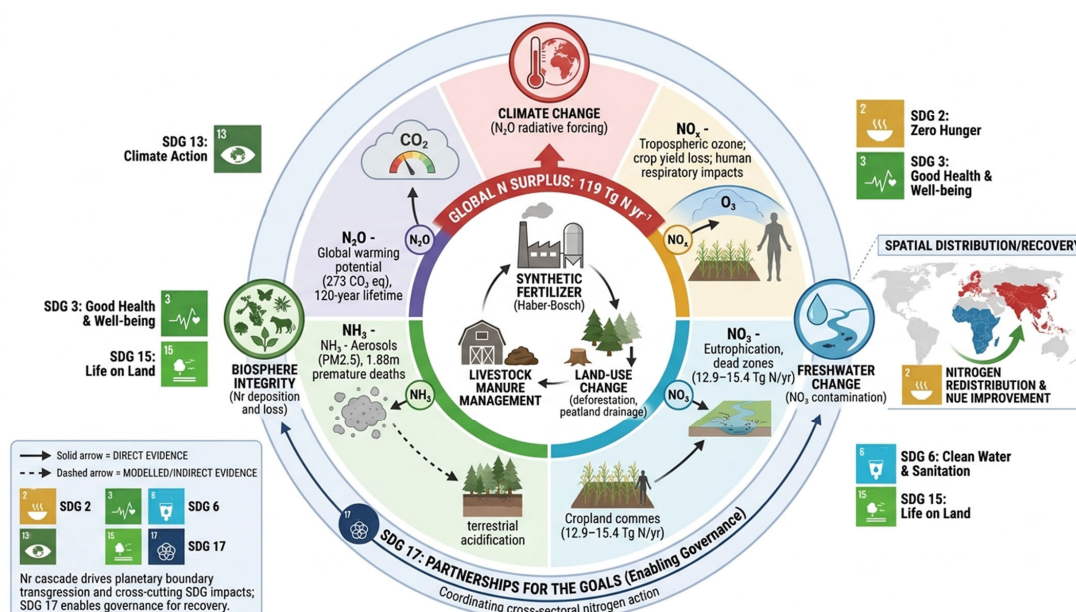


Figure 1. The reactive nitrogen cascade from fertilised cropland through planetary boundary transgression to cross-cutting SDG impacts. Nr originates from synthetic fertiliser application,

livestock manure management, and land-use change [11,12,21]. It cascades through four pathways. N_2O , contributing approximately 6.4% of enhanced radiative forcing and threatening SDG 13 [15]; NH_3 , forming $\text{PM}_{2.5}$ and threatening SDG 3 and SDG 15 [8]; NO_x , driving tropospheric ozone formation and threatening SDG 2 and SDG 3 [8]; and NO_3^- leaching, estimated at 12.9 to 15.4 Tg N yr^{-1} and threatening SDG 6 and SDG 15 [11]. The cumulative cascade drives the agricultural nitrogen surplus to approximately 119 Tg N yr^{-1} , approximately 177% above the 43 Tg N yr^{-1} boundary [2], cascading into the climate, biosphere integrity, and freshwater change boundaries [1]. Spatially explicit redistribution and NUE improvement can reconcile boundary recovery with SDG 2 progress across nitrogen-surplus and nitrogen-deficit regions [22]. The outer ring shows SDG 17 as the enabling governance framework. Solid arrows indicate direct primary evidence; dashed arrows indicate indirect or modelled evidence [25]. **Abbreviations:** GWP₁₀₀, global warming potential over 100-year horizon; Nr, reactive nitrogen; NUE, nitrogen use efficiency; $\text{PM}_{2.5}$, fine particulate matter with aerodynamic diameter below 2.5 micrometres; SDG, Sustainable Development Goal.

4. Cross-Cutting SDG Implications of Agricultural Nitrogen Losses

4.1. SDG 2 (Zero Hunger): The Productivity-Emissions Tension

Nitrogen is irreplaceable for global food production. Approximately half of the global human population is currently fed through crops supported by Haber–Bosch-derived synthetic nitrogen fertiliser [10]. Between 713 and 757 million people experienced hunger in 2023, representing approximately one in eleven people globally, with projections suggesting that without transformative action approximately 582 million people will remain chronically undernourished by 2030 [26]. This food security crisis creates a structural tension with nitrogen reduction goals. Reducing synthetic nitrogen inputs in food-insecure regions risks deepening yield gaps that are already severe, particularly in sub-Saharan Africa where average fertiliser application rates of 13 to 20 kg of nutrient per hectare produce yield gaps of 50 to over 90% for staple crops [23].

The tension between nitrogen reduction and food security is, however, fundamentally a problem of nitrogen misallocation rather than nitrogen scarcity at the global level. Global average nitrogen recovery efficiency in croplands currently stands at approximately 48%, meaning that more than half of applied nitrogen is lost before crop uptake [24]. A meta-regression analysis of 2436 paired observations from 407 primary studies demonstrated that optimal combinations of nutrient, crop, and soil management could increase global mean NUE by approximately 30%, from 48% to approximately 78%, with nutrient management practices contributing the largest share of this improvement at 27% [24]. Adoption of 11 key management measures identified from a synthesis of 1521 global field observations could simultaneously reduce nitrogen losses to air and water by 30 to 70% while increasing crop yield by 10 to 30% and NUE by 10 to 80%, demonstrating that SDG 2 and SDG 13 progress are compatible rather than opposed under improved management [27]. South Asian rice farmers provide a specific field-scale case study in which 55% of surveyed farmers overuse nitrogen fertiliser and could reduce application by 18 kg of nitrogen per hectare without compromising rice yield, demonstrating substantial scope for SDG 2 and SDG 13 co-benefits within existing food systems [28].

4.2. SDG 6 (Clean Water and Sanitation): Nitrogen Legacy and Hydrological Contamination

Agricultural nitrogen losses to freshwater systems represent one of the most pervasive and persistent threats to SDG 6 progress globally. Nitrate contamination of groundwater and surface waters drives eutrophication, hypoxic dead zones, and direct health risks, with nitrate concentrations above the WHO safe drinking water threshold of 50 mg L^{-1} (measured as NO_3^-). This is equivalent to approximately 11.3 mg L^{-1} expressed as NO_3^- -N, associated with methemoglobinemia in infants, thyroid disorders, and increased cancer risk [11]. Global cropland nitrate leaching from synthetic fertilisers is estimated

at 12.9 to 15.4 Tg N yr⁻¹, with agriculture contributing 70 to 80% of total nitrate leaching globally [11]. The Rhine and Mississippi river basins have accumulated legacy nitrogen since the 1950s, and despite decades of regulatory effort, groundwater nitrogen reservoirs persist due to hydrological time lags that can delay water quality improvement by 9 to over 35 years depending on basin characteristics [29]. This legacy effect means that current nitrogen management decisions will determine water quality outcomes for multiple decades into the future, embedding SDG 6 progress firmly within the trajectory of AFOLU nitrogen governance.

The challenge for SDG 6 is compounded by the interaction between atmospheric Nr deposition and aquatic systems. NH₃ volatilised from agricultural fields deposits onto surface waters, contributing additional dissolved inorganic nitrogen loads that exacerbate eutrophication particularly in regions downwind of intensive livestock and cropping systems [8]. These atmospheric nitrogen inputs to water bodies are often excluded from agricultural nitrogen management frameworks focused solely on direct leaching, creating a governance gap that may undermine water quality improvements even where direct leaching is controlled [16]. Addressing SDG 6 targets for clean water therefore requires integrated management of both direct nitrate losses from soils and indirect atmospheric nitrogen deposition pathways.

4.3. SDG 13 (Climate Action): N₂O as the Defining Agricultural Ghg

N₂O is now recognised as the third most important long-lived greenhouse gas contributing to anthropogenic warming and is the dominant ozone-depleting substance currently emitted by human activities [30]. Direct agricultural N₂O emissions reached 3.9 Tg N yr⁻¹ in 2020, representing the largest single anthropogenic N₂O source category globally [15]. The 2024 Global Nitrous Oxide Assessment, launched at COP29 in Baku, confirmed that N₂O emissions are rising faster than projected under all IPCC scenarios and identified opportunities to reduce emissions by over 40% primarily through changes in food systems and fertiliser management, with ambitious action potentially preventing up to 20 million premature deaths globally by 2050 through air quality co-benefits [30]. This combined mitigation and health benefit makes AFOLU nitrogen management one of the most impactful near-term levers available for simultaneous SDG 13 and SDG 3 progress.

Despite this potential, N₂O mitigation remains severely underrepresented in nationally determined contributions. Most NDCs treat agricultural GHG mitigation as a secondary priority relative to energy system decarbonisation, and specific targets for N₂O reduction from fertiliser use are rare among submitted NDCs from both developed and developing nations [4]. The cropland N₂O mitigation potential of 0.7 Tg N₂O-N per year, achievable without compromising food production and with 86% realised through nitrogen fertilisation optimisation alone, remains largely unclaimed by current policy frameworks [14]. Bridging the gap between this technical mitigation potential and actual NDC implementation requires targeted agricultural climate finance, strong monitoring and verification systems for N₂O from soils, and integration of nitrogen efficiency targets into national climate planning processes.

4.4. SDG 15 (Life on Land): Nitrogen Deposition and Ecosystem Degradation

Atmospheric Nr deposition from AFOLU systems drives terrestrial ecosystem degradation through a cascade of mechanisms that directly threaten SDG 15 targets on biodiversity conservation and land degradation neutrality. Nr deposition acidifies soils, alters nutrient balance, and shifts plant community composition toward nitrophilous species, reducing species richness in nitrogen-sensitive habitats including heathlands, grasslands, and forest understories. A synthesis of nitrogen deposition impacts across five US ecoregions identi-

fied 21 critical load thresholds triggered by Nr deposition, ranging from 2 to 39 kg N ha⁻¹ yr⁻¹, which cascaded through 582 individual pathways to affect 66 categories of final ecosystem goods and services and 198 distinct regional human beneficiary types [31]. High-ambition nitrogen policy interventions under moderate climate scenarios could reduce terrestrial ecosystem areas with Nr deposition exceeding critical loads by 260 million hectares by 2030 and 420 million hectares by 2050, equivalent to a 43% and 69% reduction respectively in critical load exceedance areas relative to 2015 levels [32]. These figures illustrate that Nr mitigation and SDG 15 biodiversity protection are strongly synergistic when nitrogen governance is sufficiently ambitious.

The interaction between nitrogen deposition and land-use change compounds ecosystem damage in ways that are not captured by examining either driver alone. Forest conversion to agriculture amplifies soil Nr losses through increased net nitrification rates, while simultaneously removing the forest canopy that otherwise intercepts and buffers atmospheric Nr deposition before it reaches sensitive ground-level vegetation [17]. In tropical biomes where deforestation rates remain high, this compound effect of direct Nr losses from newly converted agricultural land and reduced buffering capacity creates localised nitrogen deposition hotspots that drive rapid biodiversity loss [20]. These dynamics reinforce the case for treating AFOLU nitrogen management and forest conservation as complementary rather than competing priorities within SDG 15 implementation.

4.5. SDG 3, SDG 7, and SDG 17: Secondary and Cross-Sectoral Linkages

Reactive nitrogen from AFOLU systems affects SDG 3 (Good Health and Well-Being) through two primary atmospheric pathways. NH₃ is a leading precursor to PM_{2.5} aerosol formation and contributes to approximately 30% of global PM_{2.5} concentrations, contributing to a share of the approximately 1.88 million combined premature deaths annually from agricultural Nr-related PM_{2.5} and ozone exposure [8]. NO_x from agricultural soils and biomass burning separately contributes to tropospheric ozone formation, estimated to cause approximately 1.04 to 1.23 million premature deaths globally due to respiratory disease exposure, with the two pathways together accounting for the 1.88 million total cited in Section 1. High-ambition Nr mitigation scenarios could prevent up to 20 million premature deaths globally by 2050 through improvements in air quality [30], establishing integrated nitrogen management as a major public health intervention with direct SDG 3 relevance.

The SDG 7 (Affordable and Clean Energy) linkage operates through the Haber–Bosch process, which consumes approximately 1 to 2% of global energy supply and generates approximately 300 million metric tonnes of CO₂ annually [10]. Transitioning ammonia production to green hydrogen-based processes represents a critical intersection between the energy transition and nitrogen governance, with the potential to simultaneously reduce energy-related GHG emissions and the total carbon cost of global food production. A structured evidence-based review of Nr use across all 17 SDGs and 169 targets found that Nr use can enable the accomplishment of 76 targets while potentially hindering 36 targets, confirming the cross-cutting nature of nitrogen governance across the entire 2030 Agenda [33].

SDG 17 (Partnerships for the Goals) represents the enabling governance framework without which cross-sectoral nitrogen progress is unlikely to be achieved. Mitigation measures targeting one specific Nr pollution pathway often generate trade-offs among other SDG targets, emphasising the need for integrated Nr management across sectors and regions to achieve SDG synergies rather than isolated progress [33]. A global nitrogen agreement analogous to the Paris Agreement for carbon does not yet exist, leaving nitrogen governance fragmented across the UNECE Geneva Convention on Long-range

Transboundary Air Pollution, the Convention on Biological Diversity, and individual NDC frameworks, none of which provides the integrated cross-sectoral mandate that the scale of the nitrogen challenge requires. The implications of this governance gap are examined in Section 6. Table 2 summarises the SDG-nitrogen interaction matrix across SDGs 2, 3, 6, 7, 13, 15, and 17, identifying the direction of each interaction as synergy or trade-off, the strength of evidence, and the primary AFOLU nitrogen pathway responsible.

Table 2. Nitrogen-SDG interaction matrix for agriculture, forestry, and other land use systems, showing the primary reactive nitrogen (Nr) pathway, direction of interaction, strength of evidence, key quantitative indicator, and primary research sources for each Sustainable Development Goal linkage.

SDG	SDG Title	Primary Nr Pathway from AFOLU	Interaction Direction	Evidence Strength	Key Quantitative Indicator	Primary Research Sources
SDG 2	Zero Hunger	Synthetic N fertiliser overuse and spatial misallocation	Trade-off under current management. Synergy under improved NUE and spatial redistribution	Strong-multiple primary field and modelling studies across regions	Global mean NUE = 48%; optimal management can increase NUE by 30% to 78%; redistribution of current N inputs could double food production in most food-insecure nations with 12% global cereal increase	[22–24,27,28]
SDG 3	Good Health and Well-Being	NH ₃ volatilisation forming PM _{2.5} ; NO _x and HONO from nitrification, denitrification, and biomass burning forming tropospheric ozone	Trade-off-Nr losses generate 1.88 million premature deaths annually; synergy under mitigation scenarios	Strong-primary modelling and health impact studies globally	NH ₃ contributes ~30% of global PM _{2.5} ; 1.88 million combined premature deaths annually from Nr-associated PM _{2.5} and ozone exposure; 1.88 million premature deaths from Nr-associated PM _{2.5} annually; high-ambition Nr mitigation could prevent up to 20 million premature deaths by 2050	[8,30,32]
SDG 6	Clean Water and Sanitation	Nitrate leaching from fertilised croplands to groundwater and surface waters; atmospheric Nr deposition to freshwater bodies	Trade-off-persistent nitrate contamination and eutrophication	Strong-primary field and modelling studies across major river basins	Global cropland nitrate leaching = 12.9–15.4 Tg N yr ^{−1} ; groundwater legacy N time lags = 9–35+ years depending on basin; agriculture contributes 70–80% of total nitrate leaching globally	[2,11,16,29]
SDG 7	Affordable and Clean Energy	Haber–Bosch N fixation consuming 1–2% of global energy supply and generating ~300 million tonnes of CO ₂ annually	Trade-off under fossil-fuel-based ammonia production; potential synergy under green ammonia transition	Moderate-primary modelling studies on energy–food–climate nexus	Haber–Bosch process accounts for 1–2% of global energy consumption and ~300 Mt CO ₂ yr ^{−1} ; transition to green hydrogen-based ammonia could simultaneously reduce Nr GHG emissions and energy sector carbon burden	[7,10]
SDG 13	Climate Action	N ₂ O from nitrification and denitrification in fertilised agricultural soils; indirect N ₂ O from Nr cascade to aquatic systems	Trade-off under current N management; synergy with strong mitigation potential	Very strong-global budget, primary field and modelling studies	Agricultural N ₂ O emissions = 3.9 Tg N yr ^{−1} in 2020; cropland N ₂ O quadrupled 1961–2020 to 1.2 Tg N ₂ O-N yr ^{−1} ; mitigation potential = 0.7 Tg N ₂ O-N yr ^{−1} without compromising food production; N ₂ O contributes 6.4% of total enhanced radiative forcing since 1750	[14,15,18,30]

Table 2. *Cont.*

SDG	SDG Title	Primary Nr Pathway from AFOLU	Interaction Direction	Evidence Strength	Key Quantitative Indicator	Primary Research Sources
SDG 15	Life on Land	Atmospheric Nr deposition from NH ₃ volatilisation and NO _x emissions; land-use change amplifying soil Nr losses and removing canopy buffering capacity	Trade-off-Nr deposition drives terrestrial biodiversity loss through eutrophication and acidification	Strong—primary meta-analyses and modelling studies	In 2015 nearly 300 Mha of terrestrial ecosystems in East Asia and 120 Mha in South Asia exceeded N critical loads; high-ambition Nr policy could reduce exceedance areas by 420 Mha by 2050 (69% reduction); forest conversion increases net nitrification by 150% amplifying localised Nr deposition hotspots	[2,17,31,32]
SDG 17	Partnerships for the Goals	Fragmented governance of the full Nr cascade across UNECE, CBD, and NDC frameworks with no integrated global nitrogen agreement	Trade-off-policy fragmentation means Nr mitigation targeting one pathway generates trade-offs elsewhere; synergy under integrated governance	Moderate—primary structured reviews and cross-SDG quantification studies	Nr use enables 76 of 169 SDG targets while potentially hindering 36; N management across 11 of 17 SDGs affects outcomes in China	[7,9,33]

Abbreviations: AFOLU, agriculture, forestry, and other land use; CBD, Convention on Biological Diversity; Mha, million hectares; NDC, nationally determined contribution; Nr, reactive nitrogen; NUE, nitrogen use efficiency; PM_{2.5}, fine particulate matter with aerodynamic diameter below 2.5 micrometres; SDG, Sustainable Development Goal; UNECE, United Nations Economic Commission for Europe. **Note on evidence strength categories:** Very strong indicates multiple independent primary experimental and modelling studies with globally consistent findings. Strong indicates several primary studies across different regions with broadly consistent direction of effect. Moderate indicates primary modelling or synthetic studies where field-level validation remains incomplete or context-specific. All interactions marked as trade-offs may become synergies under improved Nr management, consistent with the analytical framework of this review.

5. Mitigation Strategies: Reducing Nitrogen Losses Across the Afolu System

5.1. Precision Nitrogen Management and 4R Nutrient Stewardship

The 4R Nutrient Stewardship framework, comprising right source, right rate, right time, and right place, provides an operationally tractable structure for reducing Nr losses from fertilised croplands while maintaining or improving yield [27]. Field-scale implementation of 4R principles reduces the temporal and spatial mismatch between nitrogen application and crop nitrogen demand, which is the primary driver of excess nitrate accumulation in soils that subsequently undergoes nitrification and denitrification to produce N₂O [12]. A synthesis of 1521 global field observations identified 11 key measures spanning rate, source, timing, and placement optimisation that together could reduce nitrogen losses to air and water by 30 to 70% and increase NUE by 10 to 80%, while simultaneously increasing crop yield by 10 to 30% relative to conventional management [27]. These figures demonstrate that the trade-off between nitrogen reduction and food production is largely an artefact of poor management rather than a physical constraint on food production.

Precision agriculture tools substantially amplify the effectiveness of 4R principles. Remote sensing-based variable-rate nitrogen application, leaf colour charts for in-season nitrogen status assessment, and sensor-based soil nitrate monitoring allow farmers to match nitrogen inputs to spatially variable crop demand within individual fields, reducing over-application in high-productivity zones without sacrificing yield in nutrient-limited patches [28]. In South Asian rice systems, analysis of over 31,000 farmer fields demonstrated that 55% of surveyed farmers overuse nitrogen fertiliser and could reduce application by 18 kg of nitrogen per hectare without compromising yield, with the primary improvement

pathway being earlier transplanting and improved water management rather than simply cutting fertiliser rates [28]. This finding illustrates that NUE improvement under precision management requires systemic crop management adjustments rather than fertiliser rate reduction alone, and that the IPCC 2022 mitigation report may have underestimated this yield-gain pathway as a co-benefit of NUE improvement [28]. Adoption of precision nitrogen management in smallholder systems remains constrained by the cost of sensing equipment, limited access to agronomic advisory services, and land tenure insecurity that reduces farmer incentives to invest in soil-improving practices [24]. These barriers are particularly acute in sub-Saharan Africa and South Asia where the nitrogen deficit is greatest, creating a governance challenge that cannot be resolved through technology alone and requires complementary policy and financing instruments addressed in Section 6.

5.2. Nitrification Inhibitors and Controlled-Release Fertilisers

Nitrification inhibitors (NIs) reduce N_2O emissions by suppressing the activity of AOB through inhibition of ammonia monooxygenase, encoded by the *amoA* gene, which catalyses the rate-limiting conversion of NH_4^+ to NO_2^- [12]. The two most widely investigated synthetic NIs are dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP). A three-decade global meta-analysis of 146 peer-reviewed studies found that DCD reduced N_2O emissions by an average of 47% and DMPP by 39% across diverse soil and cropping systems, with efficacy strongly modulated by soil pH, temperature, and water-filled pore space [34]. DCD demonstrated higher relative efficacy in acidic chemically fertilised soils, whereas DMPP showed greater suitability for alkaline soils and maize-based systems [34]. Context-specificity remains a fundamental limitation, as NI performance varies substantially across soil texture, organic carbon content, and climatic zone, meaning that no single product or application rate can be universally recommended without site-level characterisation. This context dependence has direct implications for how NI efficacy should be reported and interpreted. The 39 to 47% reduction figures represent averages across diverse conditions rather than reliable point estimates for any individual soil or farming system, and site-specific trials remain necessary before recommending a given NI product at scale [34]. Adoption in smallholder systems is further constrained by cost, with NI-treated fertilisers typically commanding a price premium over conventional urea, requiring targeted subsidy mechanisms to achieve widespread uptake at the scale necessary to contribute meaningfully to SDG 13 targets [14]. Controlled-release fertilisers (CRFs) represent a complementary approach that physically slows nitrogen release through polymer coatings, reducing the peak NH_4^+ concentrations in soil that drive both nitrification-derived N_2O and NH_3 volatilisation [12]. A two-year field experiment with one-time double-layer placement of controlled-release urea in wheat production demonstrated simultaneous improvements in yield, NUE, and N_2O emission reductions relative to conventional urea application, suggesting that optimised CRF placement strategies can address both agronomic and climate objectives within a single management intervention [35].

5.3. Biochar Soil Amendment

Biochar reduces N_2O emissions through three primary mechanisms. Its alkaline pH buffers soil acidity and reduces nitrification-derived N_2O production. Its porous structure improves soil aeration and shifts denitrification end-products toward inert N_2 by upregulating the *nosZ* gene. Its aromatic carbon adsorbs NH_4^+ and NO_3^- , reducing substrate availability for N_2O -producing microbial pathways [12]. A meta-analysis of 78 primary studies demonstrated that biochar amendment significantly increased soil porosity, total carbon, and soil organic carbon while reducing N_2O and CH_4 emissions, with higher application rates generating greater mitigation efficacy [36]. The functional diversity of

nitrogen-cycling genes, particularly the ratio of N₂O-producing genes to N₂O-reducing genes such as *nosZ*, proved to be a more reliable predictor of N₂O emissions under biochar amendment than the diversity of fungal or bacterial taxa overall, demonstrating the importance of mechanistic monitoring in biochar deployment programmes [36]. As with nitrification inhibitors, biochar efficacy is not uniform across soils and management systems. Mitigation outcomes depend strongly on feedstock type, pyrolysis temperature, application rate, and the baseline soil properties into which biochar is incorporated, meaning that reported emission reductions from any single study should not be assumed to generalise across soil types without local validation [36]. Biochar co-benefits for soil carbon sequestration and water retention generate simultaneous synergies with SDG 2 through improved crop productivity and soil health. Scalability limitations persist, however, as production cost, feedstock availability, and transport requirements currently restrict biochar deployment primarily to high-value horticultural systems and regions with abundant agricultural residues [27].

5.4. Agroforestry and Biological Nitrogen Fixation

Agroforestry systems integrate nitrogen-fixing trees and shrubs with crops and livestock, providing a structural alternative to synthetic nitrogen fertiliser that can simultaneously improve soil nitrogen stocks, reduce Nr losses, and sequester carbon [37]. The global average annual N₂ fixation by leguminous trees in agroforestry systems is approximately 240 kg N ha⁻¹ yr⁻¹, with improved fallow systems achieving fixation rates of 300 to 650 kg N ha⁻¹ yr⁻¹, demonstrating substantial capacity to substitute synthetic nitrogen inputs in nitrogen-deficient farming systems [37]. This biological nitrogen input reduces overall Nr loading only when it displaces synthetic nitrogen fertiliser that would otherwise have been applied. Where biological nitrogen fixation is introduced additively alongside unchanged synthetic fertiliser rates, it increases rather than reduces the total nitrogen loading of the system. The net Nr benefit therefore depends entirely on the extent to which farmers substitute rather than supplement existing nitrogen inputs [37]. Where substitution does occur, this biological nitrogen input directly reduces the Nr loading that drives both N₂O emissions and nitrate leaching, generating co-benefits simultaneously for SDG 13 and SDG 6. Agroforestry systems consistently show reductions in nitrogen losses through erosion, runoff, and leaching relative to adjacent monocropped fields, and nitrogen sequestration rates in agroforestry soil pools of 98 to 154 kg N ha⁻¹ yr⁻¹ are approximately three times higher than in above-ground biomass pools [37]. These nitrogen retention co-benefits directly advance SDG 6 targets on water quality by reducing the nitrate loads that reach freshwater systems from agricultural landscapes. Evidence on N₂O emissions from agroforestry systems remains mixed, with some systems showing increases relative to monocropping depending on tree species, soil moisture regime, and management intensity, and most available field data originate from tropical systems, leaving temperate agroforestry N₂O dynamics poorly characterised [37]. This evidence gap is identified as a priority for future research in Section 7 and requires targeted field-scale studies before agroforestry can be reliably quantified in national N₂O inventories or credited within carbon market frameworks.

5.5. Livestock Manure Management and Circular Nitrogen Use

Livestock manure is a major source of both N₂O and NH₃ from AFOLU systems, generating Nr losses across the full chain of storage, composting, and field application [15]. Anaerobic digestion (AD) of manure interrupts open-air NH₃ volatilisation and denitrification-driven N₂O production by converting manure organic nitrogen into more stable ammonium in digestate, simultaneously generating biogas that displaces fossil

fuel energy and thus contributes co-benefits for SDG 7 [38]. This benefit is conditional rather than automatic. Digestate produced by anaerobic digestion has a higher concentration of readily available ammonium than raw manure, and if digestate storage and field application are not managed to minimise volatilisation, for example through covered storage and rapid soil incorporation, the NH_3 losses that AD prevents at the storage stage can reappear, or even increase, at the digestate storage and application stage [38]. AD should therefore be understood as relocating rather than eliminating NH_3 loss risk unless paired with best practice digestate handling. Closed-loop nutrient systems that recover and apply digestate as a substitute for synthetic fertiliser reduce total Nr inputs to the food system, compounding emission reductions across the full reactive nitrogen cascade. Despite this multi-pathway mitigation potential, adoption barriers in smallholder and pastoral systems remain substantial, as AD requires upfront capital investment, reliable feedstock supply, and technical capacity for operation and maintenance that are frequently absent in low-income agricultural contexts [38]. These equity dimensions mean that manure management mitigation benefits are currently concentrated in large-scale industrial livestock operations in high-income countries, while the majority of global manure-related Nr losses occur in smallholder mixed crop-livestock systems where intervention pathways remain underdeveloped.

Alternate wetting and drying (AWD) in paddy rice fields provides a complementary water and nitrogen management strategy with significant GHG co-benefits. A meta-analysis of 47 field studies found that AWD reduced CH_4 emissions by 51.6% compared to continuous flooding while maintaining rice yield, though partial offsets from increased N_2O emissions under aerobic soil conditions mean that net global warming potential reduction requires careful site-specific assessment [39]. AWD simultaneously reduces irrigation water use by 20 to 50%, generating direct co-benefits for SDG 6 in water-scarce rice-producing regions of South and Southeast Asia [39]. Figure 2 synthesises the nitrogen loss pathways from AFOLU systems and the intervention points for each of the five mitigation strategies described in this section, with arrows indicating the primary SDG co-benefits generated at each node.

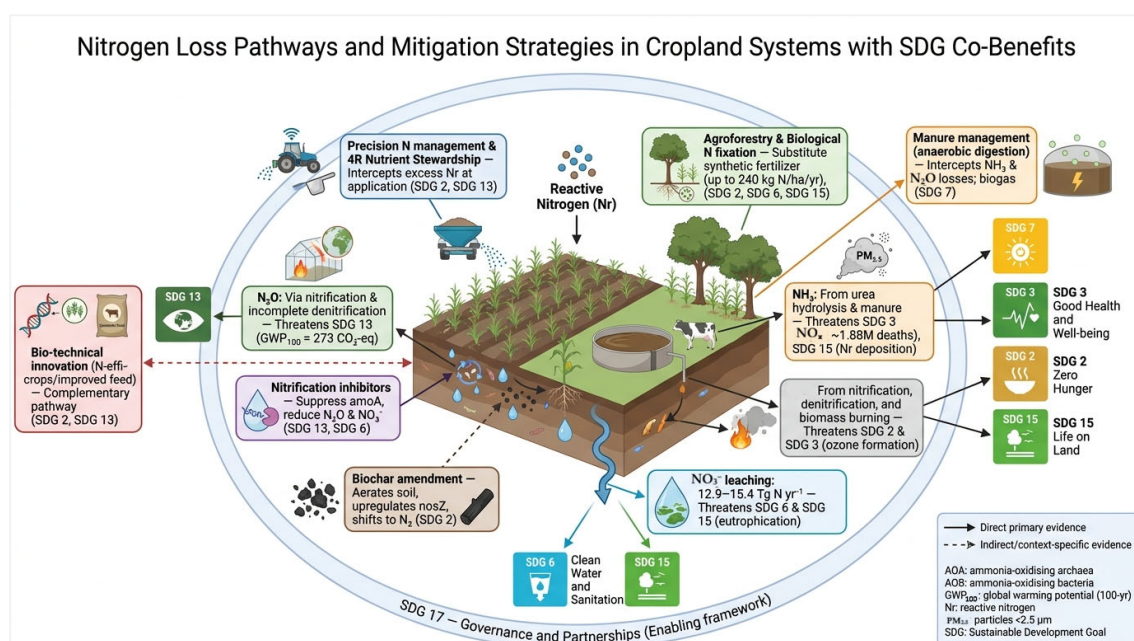


Figure 2. Nitrogen loss pathways and mitigation strategies in cropland systems, with Sustainable Development Goal co-benefits. Reactive nitrogen (Nr) released from cropland systems flows through

four principal loss pathways. N_2O is produced via nitrification and incomplete denitrification, threatening SDG 13 through a global warming potential of 273 CO_2 -equivalents over 100 years [12]. NH_3 , volatilised from urea hydrolysis and manure, forms secondary $\text{PM}_{2.5}$ aerosols that threaten SDG 3 through an estimated 1.88 million premature deaths annually and drives Nr deposition threatening SDG 15 [8]. NO_x , emitted from nitrification, denitrification, and biomass burning, contributes to tropospheric ozone formation that threatens SDG 2 and SDG 3 [8]. NO_3^- leaching, estimated at 12.9 to 15.4 Tg N yr^{-1} , threatens SDG 6 and SDG 15 through eutrophication [11]. Six mitigation strategies intercept these pathways. Precision nitrogen management and 4R Nutrient Stewardship intercept excess Nr at the point of fertiliser application, advancing SDG 2 and SDG 13 [27]. Nitrification inhibitors suppress *amoA*-mediated ammonium oxidation, reducing N_2O and NO_3^- generation and advancing SDG 13 and SDG 6 [34]. Biochar amendment aerates soil and upregulates the *nosZ* gene, shifting denitrification toward inert N_2 and advancing SDG 2 [36]. Agroforestry and biological nitrogen fixation substitute up to 240 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ of synthetic fertiliser, advancing SDG 2, SDG 6, and SDG 15 [37]. Manure management through anaerobic digestion intercepts NH_3 and N_2O losses from storage and generates biogas, advancing SDG 7 [38]. Bio-technical innovation, including nitrogen-efficient crop cultivars and improved livestock feed, offers a complementary pathway advancing SDG 2 and SDG 13 [24,38]. Solid arrows indicate direct primary evidence. Dashed arrows indicate indirect or context-specific evidence, including the bio-technical innovation pathway, which remains at an earlier stage of field validation than the other five strategies [25]. The outer ring denotes SDG 17 as the enabling governance framework coordinating action across all pathways [33]. **Abbreviations:** AOA, ammonia-oxidising archaea; AOB, ammonia-oxidising bacteria; GWP_{100} , global warming potential over a 100-year horizon; Nr, reactive nitrogen; $\text{PM}_{2.5}$, fine particulate matter with aerodynamic diameter below 2.5 micrometres; SDG, Sustainable Development Goal.

5.6. Pollution Swapping Among N_2O , NH_3 , NO_3^- , and CH_4

A recurring theme across the mitigation strategies described above is that interventions targeting one Nr pathway can inadvertently increase losses through another, a phenomenon known as pollution swapping. Nitrification inhibitors and biochar amendment both reduce N_2O by shifting nitrogen transformation pathways, but their effects on NH_3 volatilisation and NO_3^- leaching are less consistently characterised and can vary in direction depending on soil conditions [12,36]. Anaerobic digestion of manure reduces N_2O and stabilises nitrogen as ammonium, but this same ammonium enrichment increases the NH_3 volatilisation risk of the resulting digestate unless storage and application are carefully managed, as described in Section 5.5 [38]. Alternate wetting and drying reduces CH_4 emissions substantially in paddy rice but partially offsets this benefit through increased N_2O emissions under the intermittently aerobic soil conditions it creates, meaning that its net climate benefit depends on the relative global warming potential of CH_4 avoided against N_2O generated [39]. These interactions mean that single-pathway mitigation reporting, for example an N_2O reduction percentage reported in isolation, can overstate the net environmental benefit of an intervention if compensating increases in other Nr species are not simultaneously measured and reported. A pollution-swapping-aware approach to mitigation evaluation, in which candidate interventions are assessed against the full suite of N_2O , NH_3 , NO_3^- , and CH_4 outcomes rather than a single target pollutant, would strengthen the evidence base underlying AFOLU nitrogen policy and is identified as a priority alongside the other evidence gaps discussed in Section 7.

5.7. Bio-Technical Innovations and Agro-Husbandry Approaches

Beyond the soil- and manure-management strategies described above, bio-technical innovation in crop breeding offers a complementary mitigation pathway. The development of nitrogen-efficient crop cultivars, including varieties selected or engineered for improved root nitrogen uptake capacity and reduced reliance on high fertiliser inputs, represents an emerging area of crop science with the potential to lower the nitrogen input

required to sustain current yields, though most such cultivars remain at earlier stages of field validation relative to the agronomic management strategies discussed above and require further multi-environment testing before broad recommendation [24]. Advances in agro-husbandry, including improved livestock feed formulation designed to reduce nitrogen excretion and integrated crop-livestock management systems that better match feed nitrogen content to animal requirements, offer a further avenue for reducing Nr losses at the livestock production stage, complementing the manure management strategies described in Section 5.5 [38]. These bio-technical and agro-husbandry approaches remain less mature than the field-tested strategies described in Section 5.1 through Section 5.5 and are presented here as an emerging complement to, rather than a substitute for, established nitrogen management practice.

6. Policy Frameworks, Financing Gaps, and Governance

6.1. Nitrogen in NDCs and Agricultural Policies

Despite agriculture contributing approximately 81% of global anthropogenic N₂O emissions, most nationally determined contributions treat nitrogen management as a secondary or implicit component of broader agricultural GHG commitments rather than as an explicit mitigation target [4]. Specific N₂O reduction targets tied to fertiliser efficiency thresholds or NUE benchmarks are rare across the NDC landscape, creating a monitoring and accountability gap that limits both ambition and verifiable progress [30]. The importance of policy-driven nitrogen management at national scale is illustrated by China, where fertiliser reduction mandates contributed to a 16% reduction in NH₃ and a 30% reduction in N₂O agricultural emissions between 2015 and 2022, with policy synergies between NH₃ and N₂O co-control accounting for approximately 90% of abatements in the post-2015 period [7]. These reductions demonstrate that coordinated policy targeting multiple Nr species simultaneously generates greater co-benefits than single-pollutant approaches, a principle with direct relevance for NDC design globally. Coherent alignment between agricultural subsidy reform and nitrogen reduction objectives is essential. Where fertiliser subsidies maintain artificially low input costs, they actively counteract the market signals that would otherwise incentivise NUE improvement, creating a structural barrier to SDG-compatible nitrogen governance that requires fiscal reform rather than purely technical intervention. The European Union's Farm to Fork Strategy and LULUCF Regulation represent the most comprehensive regional integration of nitrogen reduction targets into agricultural climate policy, though evidence on their effectiveness in achieving verifiable N₂O emission reductions at field scale remains nascent [4].

6.2. The Climate Finance Gap for AFOLU Nitrogen Mitigation

AFOLU received less than 4% of the USD 1.3 trillion in climate finance mobilised in 2021 and 2022, despite the sector harbouring the largest near-term GHG mitigation potential of any economic sector [40]. The annual investment needed to align agrifood systems with a 1.5 degrees Celsius pathway is estimated at USD 1.1 trillion, against an actual flow of USD 7 billion directed specifically toward AFOLU mitigation in 2021 and 2022 [40]. Nitrogen-specific mitigation technologies including NIs, CRFs, precision sensing equipment, and biochar production infrastructure are systematically excluded from existing carbon market methodologies, meaning that the GHG abatement value generated by improved nitrogen management is rarely monetised through carbon credits in ways that would incentivise adoption [30]. Blended finance mechanisms that combine public concessional capital with private investment, payments for ecosystem services linked to verified Nr reduction, and green ammonia transition funding represent the most tractable near-term pathways

for closing the finance gap. SDG 17 provides the enabling governance mandate for the cross-institutional partnerships required to mobilise these mechanisms at scale [33].

6.3. Toward Integrated Global Nitrogen Governance

No binding international nitrogen agreement equivalent to the Paris Agreement for carbon currently exists. Nitrogen governance remains fragmented across the UNECE Geneva Convention on Long-range Transboundary Air Pollution, the Convention on Biological Diversity, and individual NDC frameworks, none of which provides the integrated cross-sectoral mandate that the scale of the nitrogen challenge requires [33]. The Colombo Declaration on Sustainable Nitrogen Management called for halving nitrogen waste by 2030 but lacks the enforcement mechanisms or financing commitments necessary to drive systemic change at the pace required to restore the biogeochemical flow planetary boundary [1]. The International Nitrogen Management System, hosted by UNEP, is working toward an International Nitrogen Assessment that could provide the scientific foundation for a more binding governance instrument, but its outputs currently remain advisory in nature [30]. The equity dimension of any future nitrogen governance framework is non-negotiable. A global nitrogen agreement that mandates uniform reductions without differentiating between nitrogen-surplus and nitrogen-deficit regions risks penalising food-insecure nations in sub-Saharan Africa and parts of South Asia that urgently need increased nitrogen access to close yield gaps and advance SDG 2 [22]. The novel analytical framework advanced by this review positions spatially explicit NUE improvement and nitrogen redistribution as the core design principle that can reconcile global boundary recovery with regional food security equity, providing a scientific foundation for governance frameworks that are simultaneously ambitious and just. Mitigation measures targeting one specific Nr pathway often generate trade-offs elsewhere, emphasising that integrated Nr management across sectors and regions is the only path to synergistic SDG progress rather than isolated gains [33].

7. Knowledge Gaps and Future Research Priorities

Several critical evidence gaps constrain the integration of nitrogen management into coherent cross-SDG policy. National and subnational N₂O emission inventories carry estimated uncertainties of 30 to 60%, substantially larger than uncertainties in energy sector GHG estimates, limiting the reliability of NDC monitoring and progress tracking for agricultural N₂O targets [4]. Development of spatially explicit, crop-specific N₂O emission factors calibrated to regional soil and climate conditions is a priority identified by both Cui et al. [14] and Tian et al. [15] but remains far from implementation in most non-Annex I countries. Field-scale evidence on long-term NUE improvement and N₂O mitigation under realistic smallholder conditions is sparse, particularly for agroforestry systems in temperate regions and for integrated NI combined with precision management approaches under variable climate conditions [37]. The efficacy of nitrification inhibitors also requires investigation under sustained multi-year application, as community shifts in ammonia-oxidising microorganisms may progressively reduce inhibitor effectiveness over time, a dynamic that has not yet been adequately characterised across the diverse agroclimatic zones where NIs are most needed [34].

The equity and gender dimensions of nitrogen mitigation strategies are almost entirely absent from the primary literature. Women farmers in sub-Saharan Africa face a 21% gender gap in fertiliser access relative to male farmers, yet gender-disaggregated analyses of how Nr mitigation policies affect women's agricultural productivity and income are rarely conducted [23]. Dietary transition pathways as leverage points for reducing total food system Nr demand remain understudied in the SDG context, particularly their interaction

with food security objectives in nitrogen-deficit regions where protein access is already inadequate. The cascading feedback between nitrogen boundary transgression and other planetary boundaries, while conceptually established by Richardson et al. [1], lacks quantitative primary field evidence at the level required for Earth system model parameterisation. Closing these gaps requires coordinated investment in long-term nitrogen monitoring networks, participatory action research with smallholder farmers, and interdisciplinary synthesis bridging biogeochemical modelling, food systems science, and equity research. Figure 3 maps the critical evidence gaps identified above against the AFOLU nitrogen–SDG interaction domains, providing a visual research priority framework to guide future investigation and complement the analytical framework advanced throughout this review.

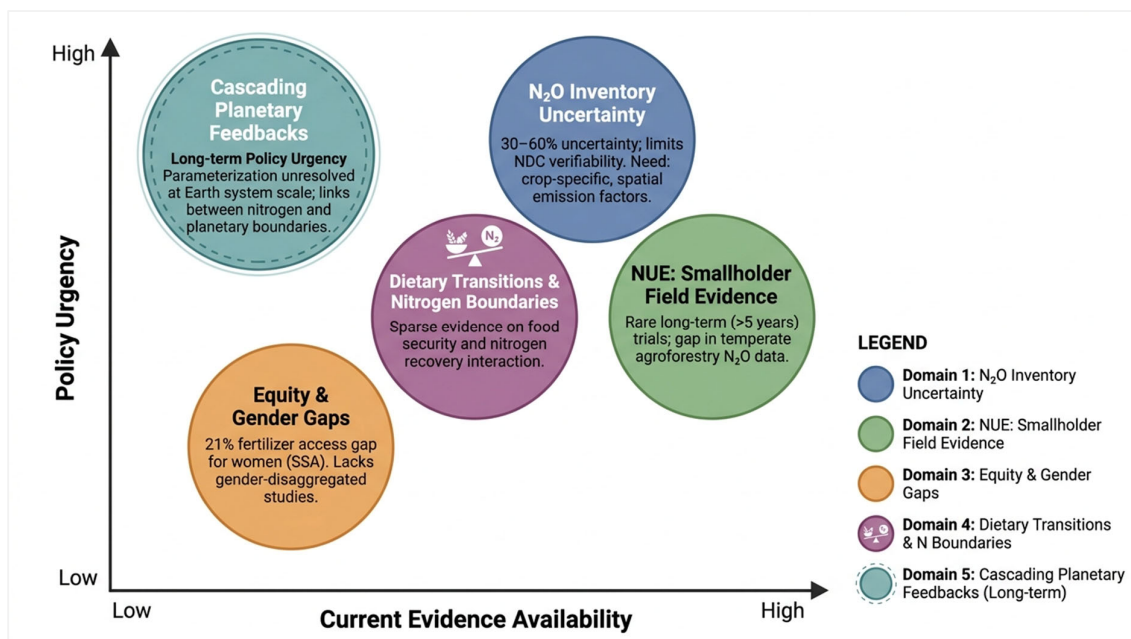


Figure 3. Research priority map identifying critical evidence gaps across five AFOLU nitrogen–SDG interaction domains, positioned by policy urgency and current evidence availability. Cascading planetary feedback represents the domain of highest long-term policy urgency and lowest current evidence, since the parameterisation of nitrogen boundary transgression cascading into other planetary boundaries remains conceptually established but quantitatively unresolved at Earth system model scale [1]. N₂O inventory uncertainty combines high policy urgency with a moderate degree of existing evidence, reflecting that national inventories are relatively widespread but carry 30 to 60% uncertainty, substantially limiting their usefulness for verifying nationally determined contribution progress and motivating the development of crop-specific, spatially explicit emission factors [4,14]. Dietary transitions and nitrogen boundaries occupy an intermediate position on both axes, reflecting sparse but emerging evidence on how dietary shifts interact with food security outcomes in nitrogen-deficit regions [22]. Nitrogen use efficiency evidence for smallholder systems sits at a comparatively high level of current evidence availability alongside moderate policy urgency, since some field studies exist but long-term trials exceeding five years remain rare, particularly for temperate agroforestry N₂O dynamics [23,34,37]. Equity and gender gaps in nitrogen mitigation policy represent the domain of lowest current evidence and lowest policy urgency recognition to date, despite a documented 21% fertiliser access gap for women farmers in sub-Saharan Africa and a near-total absence of gender-disaggregated studies [23]. Read together, the five domains illustrate that policy urgency and evidence scarcity do not always align. Some gaps, such as N₂O inventory uncertainty, involve evidence that exists but is imprecise, while others, such as equity and gender dimensions, involve evidence that is largely absent rather than merely uncertain.

8. Conclusions

This review has argued that reactive nitrogen management in fertilised cropland systems is not a single-sector emissions problem. It is a cross-cutting sustainability variable whose mismanagement simultaneously threatens food security, water quality, climate stability, biodiversity, and human health. The novel analytical framework advanced here demonstrates that these impacts are not parallel or independent phenomena. They are sequential consequences of a single cascade that begins when nitrogen is applied beyond crop demand or lost from agricultural soils through poorly managed pathways. This framing carries direct policy implications. Investments in nitrogen use efficiency, spatial nitrogen redistribution, and circular nitrogen management do not trade off against food security or economic development goals. Under spatially explicit governance, they generate co-benefits across food security, clean water, climate action, life on land, and partnership goals simultaneously. The evidence reviewed here confirms that the technical mitigation potential for cropland nitrogen is substantial. Global cropland nitrogen use efficiency can be improved by roughly thirty percent through currently available management practices without compromising crop yield. Nitrification inhibitors reduce soil nitrous oxide emissions by around forty percent under appropriate soil conditions, although this benefit depends strongly on soil type and management context. Alternate wetting and drying in paddy rice reduces methane emissions by more than half while maintaining yield. Spatial redistribution of current global nitrogen inputs, without any net increase, could substantially raise food production in the most food-insecure nations while reducing the concentration of nitrogen surplus in already saturated regions. What separates this potential from realisation is governance rather than technology. The absence of a binding international nitrogen agreement, the severe underinvestment of agriculture and land use systems in global climate finance, and the exclusion of nitrogen specific metrics from most nationally determined contributions together prevent the integration that the nitrogen challenge demands. Addressing this gap requires that nitrogen be elevated from a sectoral agronomy concern to a global sustainability governance priority. It should be treated with the same institutional seriousness as carbon dioxide and biodiversity and financed at a scale that matches its reach across food systems, water systems, and the climate.

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