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Rethinking Nitrogen N_2 Production and Its Measurement: The Missing Link in Climate Science

Gihan S. Soliman*

The Permaculture Association Britain, United Kingdom

***Corresponding Author:**
Gihan S. Soliman, The Permaculture Association Britain, United Kingdom.

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Abstract

Nitrogen gas (N_2) is the dominant component of Earth's atmosphere and the planet's primary combustion buffer, yet it remains almost entirely absent from climate and nitrogen-emission science. Current monitoring frameworks quantify only reactive nitrogen gases (N_2O, NO_x, NH_3), while the largest and most benign nitrogen flux—microbial production of N_2—is effectively invisible to natural-abundance isotope methods. This omission creates a category error: reactive nitrogen emissions are misinterpreted as total nitrogen loss, obscuring the stabilising return of inert N_2 to the atmosphere.

At the same time, human activity has created a one-way nitrogen pump. The Haber–Bosch process extracts vast quantities of atmospheric N_2 each year, while soil degradation, wastewater diversion, and disrupted waste-to-soil pathways impair the microbial processes that historically returned nitrogen to the atmosphere. The result is a directional nitrogen cycle in which N_2 extraction outpaces N_2 return, with consequences for air pollution, nitrogen saturation, and the long-term stability of the atmosphere itself.

Because N_2 is the planet's primary fire suppressant, even small shifts in the N_2:O_2 ratio have implications for ignition thresholds and wildfire behaviour. Yet these atmospheric consequences remain unexamined because N_2 fluxes are unmeasured. This paper argues that N_2 production is the missing link in climate science and that the failure to measure it distorts emission inventories, ecosystem assessments, and Earth-system models.

To address this blind spot, I propose a four-pillar nitrogen accounting framework that distinguishes between reactive nitrogen emissions, inert nitrogen return, anthropogenic N_2 extraction, and ecosystem nitrogen storage. Recognising N_2 as a climate-stabilising gas reframes nitrogen management as a component of planetary safety and reveals the need for a fundamental mindset shift: not all nitrogen emissions are harmful, and not all nitrogen inputs are pollution. Restoring N_2 to climate science is essential for understanding the true state of the nitrogen cycle and for safeguarding the atmospheric conditions that make Earth habitable.

Introduction

Nitrogen gas (N_2) is the quiet stabiliser of Earth's atmosphere. Making up 78% of the air, it acts as the planet's primary combustion buffer, diluting oxygen to a level that sustains aerobic life while preventing the biosphere from burning uncontrollably (Seinfeld & Pandis, 2016) [1]. This N_2–O_2 ratio is not incidental; it reflects a finely tuned equilibrium maintained by microbial denitrification, atmospheric chemistry, and long-term biogeochemical cycling [2,3]. Without this vast reservoir of inert nitrogen, Earth's atmosphere would be chemically unstable, ecologically volatile, and far more prone to extreme fire behaviour [4].

Yet despite its central role, N_2 is almost entirely absent from climate and nitrogen-emission science. Over the past century, human activity has profoundly reshaped the nitrogen cycle by extracting enormous quantities of atmospheric N_2 through the Haber–Bosch process [5,6]. Each year, hundreds of millions of tonnes of inert N_2 are converted into reactive nitrogen fertilisers that sustain a rapidly expanding global population [6]. Much of this nitrogen becomes locked into agricultural crops, livestock biomass, human bodies, and long-lived organic materials.

At the same time, the natural recycling pathway that once returned nitrogen to the atmosphere—microbial denitrification in soils—has been disrupted. Modern sanitation systems divert human and animal waste into waterways rather than soils, breaking the ecological loop that historically converted reactive nitrogen back into inert N_2 (Jenkins, 2015; Schlesinger & Bernhardt, 2020) [7,8]. As a result, the global nitrogen cycle has become directional: we extract N_2 from the atmosphere far faster than we return it (Davidson & Kanter, 2014) [3,9].

This imbalance has cascading consequences. Excess reactive nitrogen drives air pollution, eutrophication, soil acidification, and greenhouse gas emissions such as N_2O (IPCC, 2021) [10-12]. Meanwhile, even subtle shifts in atmospheric N_2 raise questions about long-term atmospheric composition and fire dynamics, since N_2 is the primary agent that suppresses combustion [4]. A change in the N_2:O_2 ratio, even marginal, could lower ignition thresholds, intensify wildfire behaviour, and destabilise fire-prone ecosystems (Keeley & Syphard, 2016) [13].

But the most critical issue is not only the imbalance itself — it is our inability to measure it with the tools used in routine monitoring. Current nitrogen-emission systems quantify only reactive nitrogen gases (NO_x, N_2O, NH_3), while the dominant and benign nitrogen flux — N_2 — is almost never measured. This does not mean that N_2 cannot be measured; rather, it cannot be detected using natural-abundance isotope methods employed in air-quality and emission monitoring. Soil-derived N_2 is isotopically indistinguishable from atmospheric N_2 at natural abundance, so specialised techniques are required. As Groffman et al. (2006) and Spott & Stange (2007) explicitly state: "Natural-abundance methods cannot resolve N_2 fluxes; ^{15}N enrichment is required." The papers cited here are representative examples of the specialised, labour-intensive, and expensive methods needed to measure N_2; they do not constitute an exhaustive list [15,16]. Because routine monitoring cannot detect N_2, reactive nitrogen losses are systematically misinterpreted as "total nitrogen emissions," creating a fundamental category error: the failure to distinguish between harmful nitrogen pollution and harmless nitrogen return to the atmosphere (Davidson & Kanter, 2014) [3,9].

This distinction is essential: N_2 is measurable in research settings, but invisible to the monitoring systems used to build national inventories, air-quality assessments, and climate-fire models.

This paper argues that N_2 production is the missing link in climate science. Even experts can overlook ecological context. During a discussion about desert truffles — locally known as "the daughters of thunder" for their appearance after storms — I encountered the assumption that all nitrogen inputs are harmful. Yet in arid ecosystems, lightning-derived nitrate is not pollution but a rare nutrient pulse [17-19].

This moment revealed a deeper issue in nitrogen science: the tendency to generalise from nitrogen-saturated systems to nitrogen-limited ones, and to treat all nitrogen as equivalent [10,11].

Without accurate measurement of N_2 fluxes, we cannot assess the true state of the nitrogen cycle, diagnose the imbalance created by Haber–Bosch extraction, or understand the ecological and atmospheric consequences — from pollution to wildfire risk. A new framework is urgently needed, one that recognises N_2 as a critical stabilising force and corrects the flawed logic embedded in current nitrogen-emission monitoring (Davidson & Kanter, 2014) [3,9].

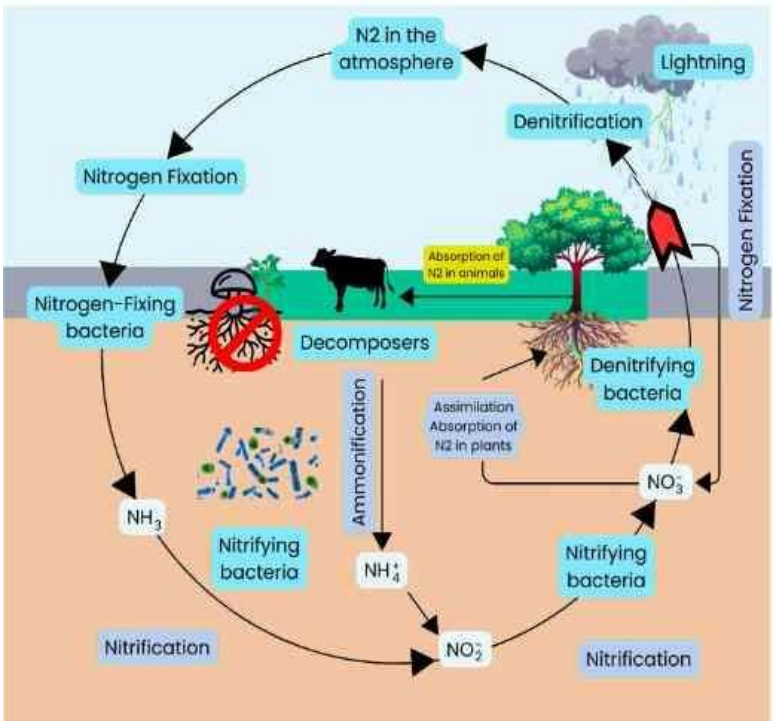

Figure 1: The Conventional Nitrogen Cycle Diagram and Its Two Major Blind Spots

The simplified nitrogen- cycle diagram used in textbooks and policy documents (Schlesinger & Bernhardt, 2020) omits both the dominant N_2 return flux and fungal initiation of denitrification [3,5,8,10]. The red indicates missing data and their significance.

To understand why this blind spot persists, and why nitrogen inputs are so often misinterpreted, we must begin by distinguishing the two fundamentally different forms of nitrogen that underpin the entire cycle: reactive nitrogen and inert atmospheric N_2.

This paper uses N_2 to refer to molecular nitrogen returned to the atmosphere, N to express elemental nitrogen in budgets and stocks, Nr for reactive nitrogen species, and "nitrogen flux" to describe microbial transformations such as nitrification, denitrification, and fertilisation. N_2 production refers specifically to the microbial recycling of nitrogen back into the atmosphere.

Reactive vs. Inert Nitrogen

The Chemical and Ecological Roles of Nitrogen Forms

Nitrogen exists in the environment in two fundamentally different forms: reactive nitrogen (Nr) and inert nitrogen (N_2). This distinction is central to understanding the nitrogen cycle, yet it is routinely blurred in monitoring frameworks and emission inventories [3,5].

Reactive nitrogen encompasses compounds such as nitrate (NO_3^-), nitrite (NO_2^-), ammonia (NH_3), ammonium (NH_4^+), nitrogen oxides (NO_x), and nitrous oxide (N_2O). These molecules are chemically active, biologically available, and capable of driving eutrophication, soil acidification, ozone formation, and greenhouse forcing (IPCC, 2021) [10-12]. They are potent agents of ecological change.

In contrast, molecular nitrogen (N_2) is chemically inert on biological timescales. It constitutes 78% of Earth's atmosphere and acts as a combustion buffer, diluting oxygen to a concentration that supports aerobic life without enabling runaway fire behaviour (Seinfeld & Pandis, 2016) [1,4]. N_2 is the endpoint of denitrification — the microbial process that returns reactive nitrogen to the atmosphere in its harmless form (Schlesinger & Bernhardt, 2020) [2,8]. It is the nitrogen cycle's stabilising force.

Why the Distinction Matters

Reactive nitrogen is ecologically potent; inert nitrogen is ecologically stabilising. Yet monitoring systems routinely treat all nitrogen gases as if they were equivalent. This conflation obscures the fact that N_2 is harmless and climate-neutral, whereas N_2O and NO_x are harmful (IPCC, 2021) [11,12]. The nitrogen cycle depends on the balance between these two categories (Davidson & Kanter, 2014) [3,9].

Beyond its chemical inertness, N_2 plays a critical atmospheric role: it suppresses combustion. By diluting oxygen, absorbing heat, and slowing radical chain reactions, N_2 maintains Earth's fire-resistant atmospheric composition (Keeley & Syphard, 2016) [4,13]. As global temperatures rise and ignition thresholds fall, this buffering function becomes increasingly essential. Any long-term shift in the N_2:O_2 ratio therefore has direct implications for wildfire behaviour and climate stability [4].

This distinction between reactive and inert nitrogen is not merely conceptual — it determines what our instruments can see. Because current monitoring tools detect only reactive nitrogen species, the stabilising N_2 flux remains effectively invisible, setting the stage for the measurement problem explored in the next section.

The Measurement Problem

Technical Limitations of Current Methods

Most nitrogen-emission monitoring relies on gas analysers (infrared, chemiluminescence), natural-abundance isotope tracing, and chamber-based flux measurements. These tools detect reactive nitrogen gases — N_2O, NO_x, NH_3 — with high sensitivity [14]. But they cannot detect N_2 produced by soils. Atmospheric N_2 is overwhelmingly abundant, soil-derived N_2 is isotopically indistinguishable from atmospheric N_2, and natural-abundance ^{15}N signals are far too weak to resolve [15,16].

To measure N_2 directly, researchers must use ^{15}N enrichment, membrane inlet mass spectrometry (MIMS), isotope-pairing techniques, or acetylene inhibition assays — all of which have methodological limitations and can distort the N_2:N_2O ratio (Spott & Stange, 2007) [15,16]. These approaches are labour-intensive, expensive, and unsuitable for routine monitoring [14]. As a result, the dominant nitrogen flux remains invisible.

Measuring N_2 Emission: What's the Big Deal?

A central consequence of the N_2 measurement gap is that we do not actually know what denitrifying microbes produce in real ecosystems. Denitrification is often presented as a neat, linear pathway ending in N_2, but this is an idealised abstraction. In natural soils, denitrifiers generate a mixture of nitrogenous gases — including NO, NO_2, N_2O, hydroxylamine, and transient atomic nitrogen — depending on micro-oxygen gradients, carbon availability, pH,

metal cofactors, and enzyme completeness. Because only N_2O is routinely measured, and N_2 is invisible without ^{15}N enrichment, the field systematically overestimates harmful emissions and underestimates benign ones.

In reality, many soils may produce substantial quantities of **inert N_2**, or large pulses of **short-lived NO**, or dynamic mixtures of intermediates that never appear in chamber studies. Without direct N_2 measurement, we cannot determine whether denitrifiers are primarily generating climate-neutral N_2, reactive NO_x, or a shifting blend of gases shaped by soil microstructure and microbial diversity.

This uncertainty has profound implications: current emission inventories are built on partial data, and microbial communities may be mischaracterised as pollution sources when they are, in fact, performing essential atmospheric maintenance.

The result is a harmful conceptual distortion. By measuring only N_2O, monitoring frameworks inadvertently frame **denitrification** — the very process that returns nitrogen safely to the atmosphere — as a threat. This perspective leads to management strategies that suppress fungi and bacteria, degrade soil structure, and increase N_2O leakage by disabling the final enzymatic step to N_2. The true problem is not denitrification; **the problem is synthesising reactive nitrogen in industrial quantities and dumping it into soils faster than ecosystems can safely process it.**

When N_2 production is unmeasured, the nitrogen cycle appears more harmful than it is, and the microbial partners that maintain atmospheric stability are wrongly vilified instead of valued.

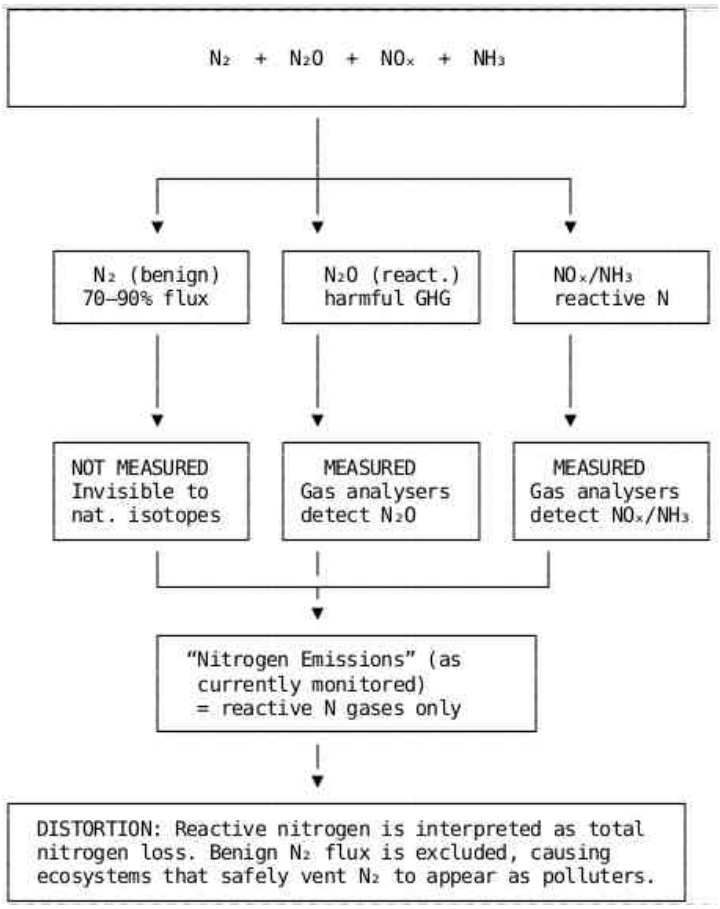

Figure 2: How Reactive-Nitrogen-Only Measurements Distort Interpretations of Total Nitrogen Flux

Consequences of N_2 Invisibility

Because N_2 is unmeasured:

- the dominant nitrogen flux is missing from emission inventories,
- reactive nitrogen appears to dominate gaseous losses,
- ecosystems that efficiently produce N_2 appear to be polluters,
- incomplete denitrification is overestimated,
- complete denitrification is underestimated,
- and the nitrogen cycle appears more harmful than it is.

These distortions are well-documented consequences of relying on N_2O-only measurements (Davidson & Kanter, 2014) [9,14]. This invisibility sets the stage for the logical flaw explored in Section 4: monitoring systems mistake reactive nitrogen for total nitrogen emissions [3].

Link to Anthropogenic Imbalance
The inability to measure N_2 also obscures the consequences of human-driven nitrogen extraction. Through the Haber–Bosch process, vast quantities of atmospheric N_2 are converted into reactive nitrogen each year [5,6]. Without accurate N_2 measurements, it is impossible to determine:

- how much reactive nitrogen is being safely returned to the atmosphere,
- how much is accumulating in soils, waters, and biomass,
- and whether the global N_2:N_2O balance is shifting (Davidson & Kanter, 2014) [9].

This measurement gap prevents assessment of the true magnitude of the nitrogen imbalance created by agriculture, population growth, and disrupted waste-recycling systems (Schlesinger & Bernhardt, 2020) [8]. Because N_2 is invisible to standard monitoring methods, current emission frameworks exclude the very gas that stabilises Earth's combustion environment [4]. Misinterpreting nitrogen fluxes risks obscuring atmospheric changes that could influence fire regimes in a warming climate.

Why Atmospheric N_2 Trends Cannot Be Detected
Although atmospheric N_2 constitutes 78% of the atmosphere, modern monitoring systems are not designed to detect changes in its abundance. Global atmospheric networks measure CO_2, CH_4, N_2O, and the O_2/N_2 ratio — but the latter is used solely to infer oxygen decline, not nitrogen drift (Seinfeld & Pandis, 2016) [1]. Any change in atmospheric N_2 is therefore treated as analytical noise rather than a meaningful signal.

Human activity removes vast quantities of N_2 from the atmosphere each year through the Haber–Bosch process, biomass accumulation, and disrupted waste-to-soil recycling [5,6]. At the same time, reactive nitrogen emissions (N_2O, NO_x, NH_3) continue to rise (IPCC, 2021) [12]. Yet the return of nitrogen to the atmosphere as N_2 — the dominant and benign flux — is almost never measured because soil-derived N_2 is isotopically indistinguishable from atmospheric N_2 at natural abundance (Spott & Stange, 2007) [15,16].

To quantify N_2 production, researchers must artificially enrich soils with ^{15}N-labelled substrates and detect ^{15}N–^{15}N or ^{14}N–^{15}N gas using mass spectrometry — methods that are labour-intensive, expensive, and unsuitable for large-scale monitoring [14]. Consequently, national inventories measure only reactive nitrogen gases, leaving the stabilising N_2 flux unquantified (Davidson & Kanter, 2014) [9].

The absence of detected change in atmospheric N_2 is therefore not evidence of stability — it is evidence of a measurement gap.

This measurement gap does not remain a technical inconvenience; it becomes a structural error in nitrogen accounting. By treating the invisible N_2 flux as nonexistent, monitoring frameworks assume that the nitrogen gases they can detect represent the total nitrogen leaving ecosystems — a logical flaw explored in the next section.

The Logical Flaw in Current Monitoring

Overview

Nitrogen-emission monitoring frameworks rest on a critical but rarely examined assumption: that the nitrogen gases we can readily measure represent the total nitrogen leaving ecosystems. In practice, these systems quantify only reactive nitrogen species — primarily N_2O, NO, NO_2, and NH_3 — because these compounds are detectable with standard gas analysers and natural-abundance isotope methods [14,15]. The dominant gaseous nitrogen flux, molecular nitrogen (N_2), remains almost entirely unmeasured. Without artificial ^{15}N enrichment, soil-derived N_2 is isotopically indistinguishable from atmospheric N_2 (Spott & Stange, 2007) [16].

This selective visibility creates a category error at the heart of nitrogen-emission science. Reactive nitrogen is treated as if it were equivalent to total nitrogen loss, even though N_2 typically constitutes the majority of gaseous nitrogen flux and is ecologically benign (; Davidson & Kanter, 2014) [3,9]. As a result, ecosystems that efficiently convert reactive nitrogen back into inert N_2 may appear, in monitoring data, to be significant "polluters," while systems that leak reactive nitrogen are disproportionately represented in emission inventories [14].

The consequences extend beyond academic interpretation. Policies, models, and mitigation strategies built on reactive-nitrogen-only data risk misdiagnosing ecosystem function, misallocating resources, and misunderstanding the true drivers of nitrogen imbalance [5,11]. To illustrate how this conceptual flaw manifests in published research, the following subsection examines representative studies in which nitrogen emissions are interpreted through a distorted lens — highlighting how methodological limitations can lead to misleading conclusions about microbial processes, plant–soil interactions, and ecosystem nitrogen cycling.

European Wildfires: A Case Study in Climate Misinterpretation
European wildfire regimes over the past decade reveal why temperature-centred climate framing cannot capture the full complexity of fire behaviour. Extreme events in Mediterranean and western Europe arise from compound climatic and ecological conditions: concurrent heatwaves, prolonged drought, high fuel loads, and synoptic fire-weather patterns that

align wind, humidity, and atmospheric instability [20,21]. While warming increases the frequency of fire-weather days, attribution studies typically focus on thermal and hydrological drivers alone, overlooking the atmospheric composition that governs ignition thresholds and combustion dynamics (Keeley & Syphard, 2016) [4,13].

This combustion-buffer function is almost entirely absent from European wildfire assessments. Current monitoring frameworks quantify reactive nitrogen gases (NO_x, N_2O, NH_3) but do not measure N_2 production, leaving the stabilising atmospheric nitrogen flux unaccounted for [14,15]. As a result, wildfire risk is interpreted through a narrow lens that sees only heat and drought, not the full atmospheric system.

At the same time, rising reactive nitrogen emissions and aerosol loads across Europe influence boundary-layer chemistry, fuel desiccation, and radiative balance — all factors known to intensify fire weather (IPCC, 2021) [12]. Temperature sets the stage, but nitrogen cycling determines how flammable that stage becomes. Without integrating N_2 production, atmospheric composition, and anthropogenic nitrogen imbalance into climate-fire models, European wildfire risk will continue to be misdiagnosed as a purely thermal phenomenon.

This case study reinforces the central argument of Section 4: **measurement blind spots create conceptual blind spots.** When N_2 is unmeasured, the combustion environment is mischaracterised, and the role of nitrogen in shaping fire regimes remains invisible — even in regions where wildfire behaviour is rapidly changing.

Case Study: Distorted Interpretations of Nitrogen Emissions in the Literature

Overview

A recurring issue in nitrogen-emission research is the tendency to measure only reactive nitrogen gases (primarily N_2O) and interpret these measurements as representing total nitrogen emissions. This practice systematically excludes N_2, the dominant and benign end-product of denitrification, because it is invisible to natural-abundance isotope methods (Spott & Stange, 2007) [15,16]. As a result, studies often draw conclusions about "nitrogen pollution" from experimental systems that cannot detect the main nitrogen flux [14].

Fungal Inoculation in Sterilised Soils: A Misleading Experimental System

A representative example is the study by Role of Fungi in N_2O Emissions from Nitrogen-Fertilized Lawn Soil [23]. The authors inoculated fungi into sterilised or partially sterilised soils and measured N_2O emissions following nitrogen fertilisation. They concluded that fungal activity increases nitrogen emissions.

However, this conclusion rests on several methodological limitations well-documented in the denitrification literature:

- Sterilisation disrupts the natural microbial network, particularly the final enzymatic step of denitrification ($N_2O \rightarrow N_2$) [15].
- Fungi introduced into sterilised soil rapidly form associations with recolonising bacteria, creating unnatural microbial consortia [24].
- The disrupted system is biased toward incomplete denitrification, artificially inflating N_2O production [14].
- N_2 was not measured, because the system lacked ^{15}N enrichment and therefore could not detect the benign nitrogen flux (Spott & Stange, 2007) [16].

This design ensures that any nitrogen transformation is more likely to appear as N_2O — not because fungi inherently increase pollution, but because the experimental system disables the pathway to N_2. It is a clear example of how reactive nitrogen is mistaken for total nitrogen loss when N_2 is unmeasured.

The "Reduced Plant Uptake → Reduced Emissions" Fallacy

Some studies, including, argue that fungi reduce plant nitrogen uptake and therefore reduce nitrogen emissions [23]. This reasoning is ecologically incomplete.

Reduced plant uptake typically results in:

- more nitrate remaining in soil,
- which increases substrate availability for denitrification,
- which may increase N_2 production (benign),
- or N_2O production (harmful), depending on microbial completeness (Davidson & Kanter, 2014; Firestone & Davidson, 1989) [9,25].

Without measuring N_2, it is impossible to determine whether fungi:

- enhance complete denitrification (more N_2, less N_2O), or
- promote incomplete denitrification (more N_2O).

Thus, the conclusion that "reduced plant uptake reduces emissions" is based on a single-gas measurement and a plant-centric interpretation of a multi-pathway microbial process [14].

Broader Pattern Across the Literature

This distortion is not limited to a single study. Many fungal and microbial nitrogen studies share the same characteristics:

- Measurement restricted to N_2O, rarely N_2 [15].
- Simplified microcosms, often sterilised or artificially inoculated [24].
- Interpretation of N_2O as "nitrogen emissions" [14].
- Generalisation from laboratory artefacts to natural ecosystems [25].

Examples include:

- studies claiming fungi are major contributors to N_2O emissions in agricultural soils,
- experiments using pure fungal cultures without bacterial partners,
- microcosm studies that disrupt the $N_2O \rightarrow N_2$ step,
- papers interpreting increased N_2O as increased "nitrogen pollution" without measuring N_2.

Across these examples, the same blind spot appears: N_2 is unmeasured, and therefore the nitrogen cycle is misrepresented.

Synthesis

These case studies demonstrate that nitrogen-emission research often measures only reactive nitrogen gases while ignoring N_2, the dominant and benign nitrogen flux. Experimental designs using sterilised soils or simplified microbial communities distort the N_2:N_2O ratio, leading to systematic overestimation of nitrogen pollution and misinterpretation of fungal or microbial roles in soil nitrogen cycling [14,15]. These distortions reinforce the central argument of this paper: without quantifying N_2, nitrogen-emission monitoring cannot distinguish between harmful reactive nitrogen loss and harmless atmospheric nitrogen return.

These measurement distortions do not merely affect experimental interpretation; they conceal the largest nitrogen flux of all — the anthropogenic extraction of atmospheric N_2. To understand the scale of this hidden drain, we must examine how human systems convert inert nitrogen into reactive forms far faster than ecosystems can return it.

The Anthropogenic Imbalance: A One-Way Extraction of Atmospheric N_2

The Haber–Bosch Process as a Planetary Pump

The industrial fixation of nitrogen through the Haber–Bosch process represents one of the most consequential biochemical interventions in Earth's history. By converting atmospheric N_2 into reactive nitrogen (Nr) at industrial scales, humanity has effectively created a one-way pump that transfers nitrogen from the atmospheric reservoir into the biosphere.

Each year, Haber–Bosch produces more reactive nitrogen than all natural terrestrial nitrogen-fixing organisms combined. This influx of Nr fuels global food production — supporting approximately 50% of the global population — while the remaining 50% is sustained by biological nitrogen fixation and lightning. Much of this reactive nitrogen becomes locked into crops, livestock, human biomass, soils, and long-lived organic materials, creating a **nitrogen lock-in** that slows its return to the atmosphere.

When combined with nitrogen lock-in, reactive nitrogen pollution, heating gases, and disrupted waste-to-soil pathways, the total anthropogenic diversion of nitrogen is ~25 times larger than Haber–Bosch alone. The result is a directional shift in the nitrogen cycle: atmospheric $N_2 \rightarrow$ reactive nitrogen $\rightarrow$ biomass, soils, waters, and waste streams.

- Haber–Bosch fixes ~200 Mt N/year into reactive forms.
- Denitrification returns far less N_2.
- This creates a directional nitrogen leak.
- Long-term atmospheric composition implications.

The Broken Return Pathway

Under natural conditions, reactive nitrogen is eventually returned to the atmosphere as N_2 through microbial denitrification. This process historically balanced nitrogen fixation, maintaining a stable atmospheric N_2 reservoir.

Modern human systems disrupt this return pathway in several ways:

- Soil degradation reduces denitrifying capacity.
- Wastewater systems divert nitrogen away from soils and into aquatic systems.
- Urbanisation interrupts the recycling of human and livestock waste back to land.
- Agricultural intensification accelerates Nr accumulation faster than ecosystems can process it.
- Reactive nitrogen pollution (NO_x, NH_3, N_2O) leaks into air and water before it can be denitrified.

The consequence is a global imbalance: **we extract N_2 from the atmosphere far faster than we return it.** This is not a closed loop — it is a **leaky, one-directional system.**

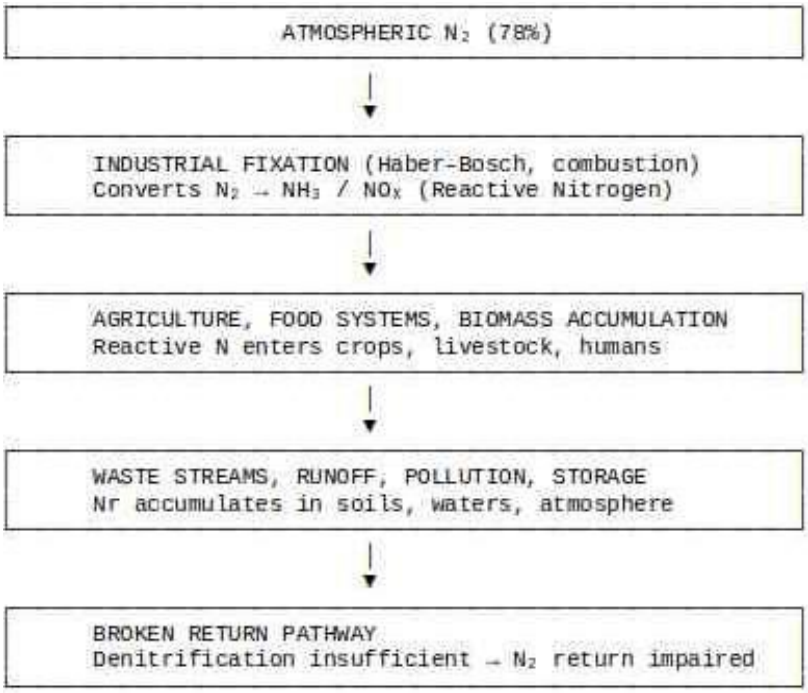

Figure 3: The One Way Extraction of Atmospheric Nitrogin: Human Systems Extract N_2 from the Atmosphere and Convert it into Reactive Nitrogen Faster than Ecosystems Can Return it, Creating a One-Way Imbalance

Biomass Accumulation and the Human Nitrogen Reservoir
A significant portion of reactive nitrogen is now stored in:
- crops
- livestock
- forests
- human bodies
- long-lived organic materials

This represents a **new planetary nitrogen reservoir** that did not exist before industrialisation. Unlike atmospheric N_2, this nitrogen is:
- biologically active
- mobile
- chemically reactive
- prone to leakage
- slow to return to the atmosphere

Humanity has effectively **relocated nitrogen** from the sky into living and semi-living systems.

The Atmospheric Consequence: A Slow Drift in Composition
If the extraction of N_2 continues to outpace its return, the atmospheric N_2 reservoir may undergo a **slow but directional shift**. Even small changes in atmospheric composition can have outsized effects on:
- **combustion thresholds**
- **wildfire behaviour**
- **oxygen availability**
- **climate-fire feedback loops**

As established in Section 7, N_2 is not merely inert — it is the **primary atmospheric fire suppressant**. A long-term reduction in atmospheric N_2 would therefore weaken the planet's natural fire-resistance.

Even if atmospheric N_2 drift is extremely small, fire regimes respond to atmospheric composition rather than any single constituent; tiny shifts in inert-gas buffering, greenhouse gases, or ozone can influence ignition thresholds. This is not an immediate crisis, but it is a long-term systemic risk that current monitoring frameworks are not designed to detect.

Why This Matters for Emission Accounting
The anthropogenic nitrogen imbalance reveals a profound flaw in current monitoring:
- We track **reactive nitrogen pollution**,
- but we do not track **atmospheric N_2 depletion**,
- nor do we track **the failure of ecosystems to return N_2**. This means that nitrogen accounting systems:

- measure the wrong gases,
- miss the dominant flux,
- and overlook the atmospheric stabiliser most relevant to climate and fire regimes.

This accounting failure does not remain confined to inventories and emission reports; it shapes our understanding of ecosystem behaviour itself. Once the atmospheric return pathway is broken, reactive nitrogen accumulates, microbial networks destabilise, and the ecological consequences become visible across soils, waters, and vegetation — the focus of the next section.

Ecological Consequences of the Anthropogenic Nitrogen Imbalance

Accumulation of Reactive Nitrogen in Soils and Waters

The one-way extraction of atmospheric N_2 (Section 5) leads to a persistent accumulation of reactive nitrogen (Nr) across terrestrial and aquatic ecosystems. Because the return pathway to N_2 is impaired, Nr builds up in forms that are chemically active, biologically available, mobile across landscapes, and prone to leakage into air and water [10,11].

This accumulation drives a suite of ecological disruptions:

- soil acidification and reduced microbial diversity (Schlesinger & Bernhardt, 2020) [8,11].
- eutrophication of freshwater and coastal systems [10].
- loss of biodiversity in nitrogen-sensitive habitats [11].
- shifts in plant communities toward fast-growing, nitrogen-responsive species [10].
- increased N_2O emissions, especially in disturbed soils These impacts are not isolated symptoms; they reflect a systemic imbalance in nitrogen flow [14].

Disruption of Microbial Nitrogen Pathways

Microbial communities regulate the transformation of nitrogen between its reactive and inert forms. Nr accumulation alters these pathways in predictable ways:

- denitrifiers become overwhelmed, leading to incomplete denitrification [15].
- N_2O-producing pathways dominate over N_2-producing pathways [14].
- fungal–bacterial interactions shift (Schimel & Schaeffer, 2012) [24].
- soil oxygen gradients change, altering nitrification and denitrification dynamics (Firestone & Davidson, 1989) [25].

The result is a microbial system that leaks reactive nitrogen rather than completing the cycle back to inert N_2.

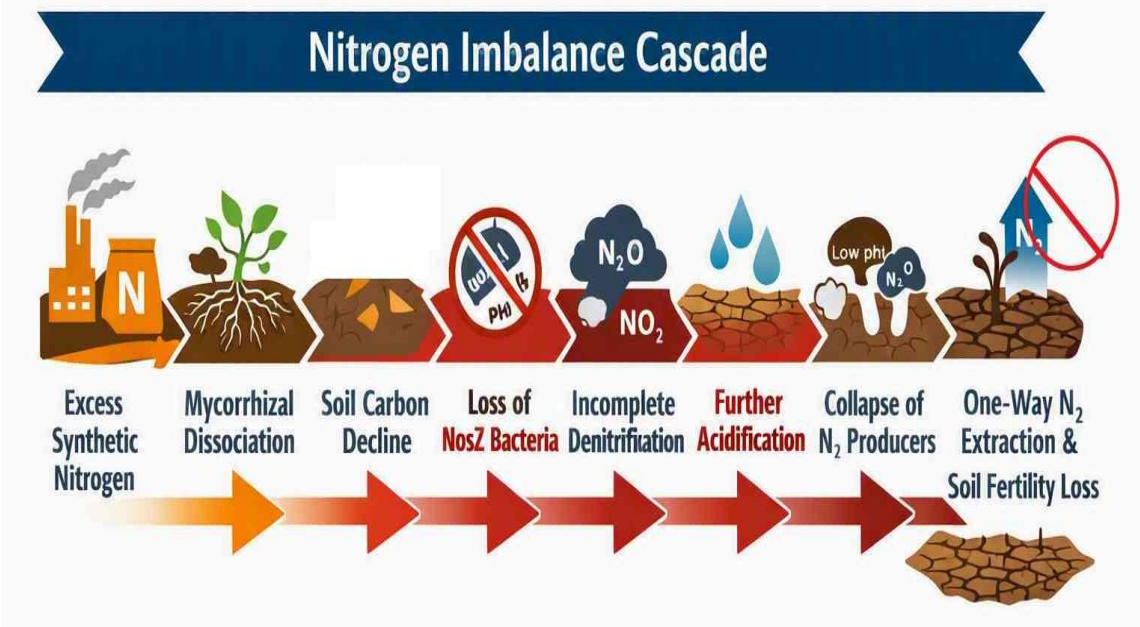

Figure 4: Ecological Cascade of Soil Nitrification

The result is a microbial system that leaks reactive nitrogen rather than completing the cycle back to inert N_2. The ecological cascade can be summarised as follows: Excess synthetic nitrogen → mycorrhizal dissociation (Treseder, K.K. (2004) → soil-carbon decline → soil acidification → loss of NosZ bacteria → incomplete denitrification → further acidification → collapse of fungal and bacterial N_2-producing partners → one-way atmospheric N_2 extraction and loss of soil fertility [26].

Loss of Ecosystem Nitrogen Retention Capacity

Healthy ecosystems retain nitrogen through plant uptake, microbial immobilisation, organic matter formation, and soil

aggregation (Schlesinger & Bernhardt, 2020) [8]. Chronic Nr loading erodes this retention capacity:

- soils become saturated
- organic matter decomposes more rapidly
- vegetation shifts toward shallow-rooted species
- microbial immobilisation declines [10].

This creates a positive feedback loop:
More Nr → lower retention → more leakage → more Nr[11].
The imbalance becomes self-reinforcing.

Increased Leakage of Reactive Nitrogen to the Atmosphere
As retention capacity declines, ecosystems increasingly leak reactive nitrogen gases:

- N_2O (IPCC, 2021) [12].
- NO_x (Seinfeld & Pandis, 2016) [1].
- NH_3 (Sutton et al., 2011) [11].

Because monitoring systems measure only these reactive gases, ecosystems with impaired N_2 return appear to be "high emitters," even when the underlying cause is the failure of the N_2 pathway [14]. The stabilising flux remains invisible, and the harmful flux appears exaggerated.

Underestimation of Soil Dynamics and the Fungal–Bacterial Denitrification Partnership
Current nitrogen frameworks overlook the ecological complexity of soil systems, particularly the cooperative interactions between fungi and N_2-producing denitrifying bacteria. This omission has significant consequences for climate modelling, soil management, and fire-regime prediction.

Healthy soils contain fungal–bacterial consortia that jointly drive complete denitrification. Fungi create carbon-rich, micro-oxic, structured soil aggregates through hyphal growth, respiration, and organic exudation (Schimel & Schaeffer, 2012; Firestone & Davidson, 1989) [24,25]. These micro-habitats provide the exact conditions required by NosZ-bearing bacteria, which perform the final step of denitrification by reducing N_2O to inert N_2 [14,15].

Fungi typically carry out the early steps of denitrification ($NO_2^- \rightarrow NO \rightarrow N_2O$), while bacteria complete the pathway ($N_2O \rightarrow N_2$), forming a functional division of labour (Schlesinger & Bernhardt, 2020) [8].

When this partnership is intact, soils exhibit:

- high N_2 production
- low N_2O leakage
- reduced oxygen penetration
- higher ignition thresholds
- greater fire resistance
- long-term nitrogen balance

However, current agricultural and environmental practices — excess reactive nitrogen inputs, soil disturbance, fungicides, drought, and carbon depletion — disrupt fungal networks and suppress NosZ-bearing bacterial communities (Schimel & Schaeffer, 2012) [14,24]. The result is a collapse of complete denitrification, leading to:

- accumulation of reactive nitrogen [10,11].
- elevated N_2O emissions (IPCC, 2021) [12].
- deeper oxygen penetration into soils (Firestone & Davidson, 1989) [25].
- lower ignition temperatures (Keeley & Syphard, 2016) [4,13].
- increased wildfire susceptibility
- destabilised nitrogen cycling (Schlesinger & Bernhardt, 2020) [8].

Figure 5: The overlooked partnership between fungi and bacteria in complete denitrification in healthy soils. Fungal networks create carbon- rich, micro- oxic soil aggregates through hyphal growth, respiration, and organic exudation, generating the physical and chemical conditions required for denitrification. Within these micro- habitats, NosZ- bearing bacteria perform the final enzymatic step of the pathway ($N_2O \rightarrow N_2$), returning nitrogen safely to the atmosphere as inert N_2 — the planet's primary combustion buffer. Together, fungi and NosZ bacteria form a functional division of labour: fungi generate the habitat and early intermediates ($NO_2^- \rightarrow NO \rightarrow N_2O$), while bacteria complete the pathway to N_2

By underestimating soil dynamics and ignoring the fungal–bacterial partnership, current nitrogen frameworks inadvertently disable the natural pathway that returns nitrogen safely to the atmosphere as N_2 — the very flux that stabilises Earth's combustion environment [3,4].

The Overlooked Partnership: Fungal Conservation and NosZ-Bearing Bacteria

Healthy soils depend on a cooperative microbial partnership that is almost entirely absent from nitrogen science: the association between fungal networks and NosZ-bearing denitrifying bacteria. This consortium jointly drives *complete* denitrification, returning reactive nitrogen to the atmosphere as inert N_2 — the planet's primary combustion buffer.

Fungi contribute:

- Carbon-rich exudates that fuel denitrification
- Hyphal networks that build structured soil aggregates
- Micro-oxic zones created by fungal respiration
- Early denitrification steps ($NO_2^- \rightarrow NO \rightarrow N_2O$)

NosZ bacteria contribute:

- The final enzymatic step ($N_2O \rightarrow N_2$)
- High-affinity N_2O reduction in micro-oxic niches
- Stabilisation of nitrogen cycling through inert N_2 production

Together, they form a division of labour:

- Fungi create the habitat and intermediates
- Bacteria complete the pathway to N_2

Why this matters

Disruption of fungal networks — through excess reactive nitrogen, soil disturbance, fungicides, drought, or carbon depletion — suppresses NosZ activity and collapses complete denitrification. The result is:

- increased N_2O leakage
- deeper oxygen penetration
- lower ignition thresholds
- destabilised nitrogen cycling
- heightened wildfire susceptibility

Conserving fungal networks and supporting NosZ-bearing bacteria is therefore a climate-stabilising strategy, restoring the natural pathway that returns nitrogen safely to the atmosphere and maintains Earth's fire-resistant atmospheric composition.

Altered Fire Regimes Through Changes in Vegetation and Atmospheric Composition

Nitrogen imbalance influences fire regimes through two coupled pathways: vegetation structure and atmospheric composition. Current frameworks emphasise the first and overlook the second, creating a distorted understanding of why fires ignite and spread so readily under modern conditions.

Vegetation Effects

Excess reactive nitrogen promotes:

- rapid biomass accumulation
- dense, nitrogen-rich vegetation
- increased fuel loads
- shifts toward fire-prone species

These changes increase ignition probability and fire intensity. This pathway is well-recognised — but it is only half the story.

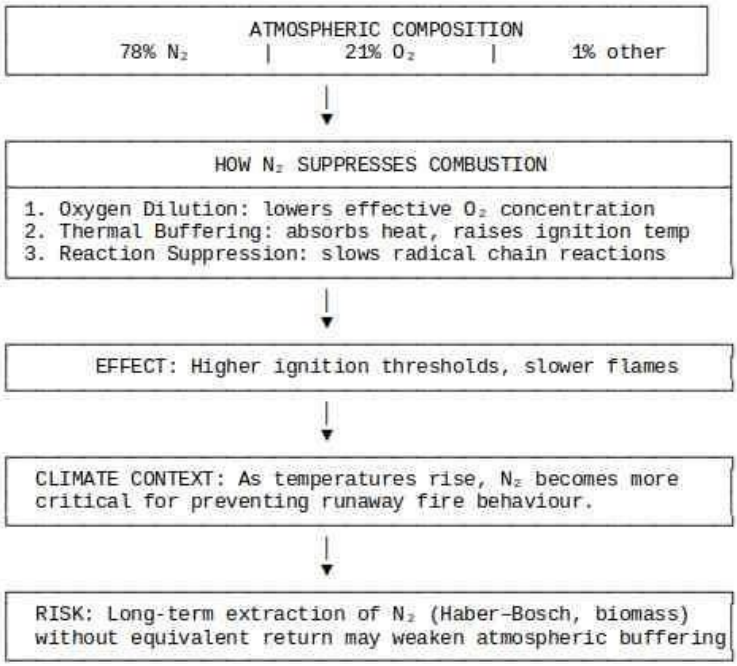

Figure 6: N_2 is the Primary Atmospheric Fire Suppressant. Its Dilution, Thermal, and Kinetic Effects Maintain Earth's Fire-Resistant Climate.

Atmospheric and Soil-Oxygen Effects
The second pathway is rarely acknowledged: the collapse of denitrification reduces N_2 production, altering oxygen availability at the forest floor.

Denitrification is not the enemy — it is a natural fire-buffering process. Complete denitrification produces inert N_2, which rises through soil pores and displaces oxygen. Even small reductions in O_2 concentration:
- raise ignition thresholds
- suppress smouldering
- slow flame spread
- stabilise live vegetation

When denitrification is disrupted by excessive nitrogen inputs, soil compaction, microbial loss, or drought:
- N_2 production drops
- oxygen penetrates deeper into soils
- boundary-layer O_2 increases
- ignition temperatures fall
- fires become self-sustaining at surprisingly low ambient temperatures (e.g., ~40°C)

This explains the paradox: wildfires erupting under temperatures far below the auto-ignition point of live vegetation. The issue is not heat — it is oxygen enrichment caused by nitrogen-cycle imbalance.

The Dilemma
By demonising denitrification while maintaining high nitrogen inputs, we mistake the friend for the enemy. Denitrification is the process that returns nitrogen safely to the atmosphere and maintains the inert-gas buffer that suppresses wildfire behaviour. Suppressing it — without reducing industrial nitrogen inputs — removes a natural fire-protection mechanism and accelerates the shift toward more volatile fire regimes.

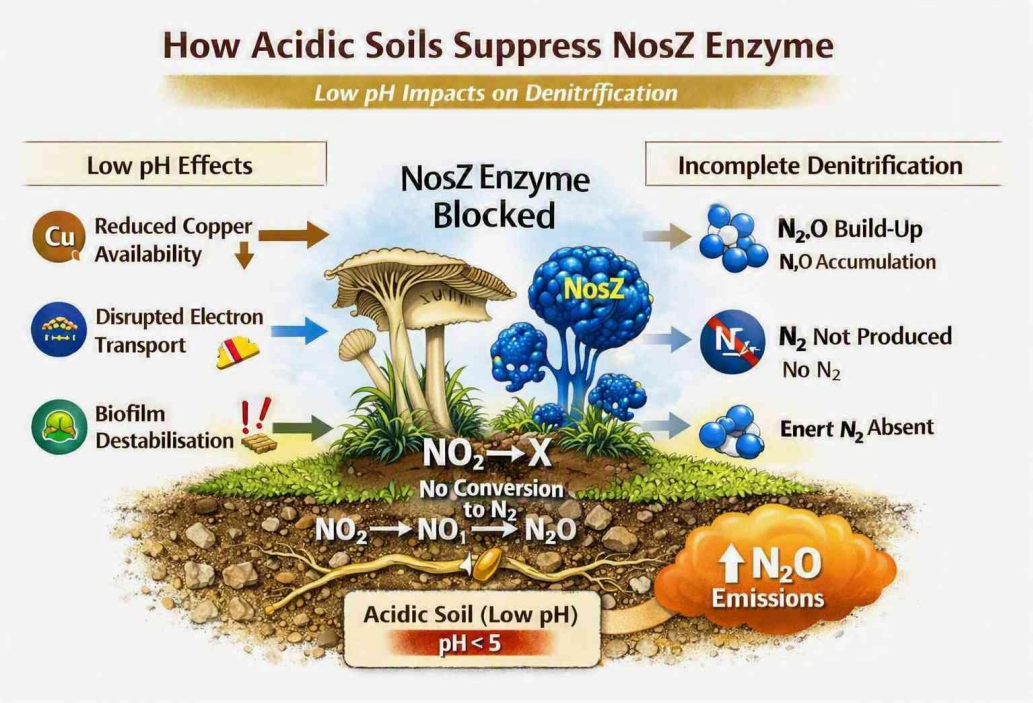

Figure 7: The impact of Soil Acidification on Nitrogen Cycles

Long-Term Risks to Climate Stability
The ecological consequences of nitrogen imbalance accumulate over decades. If the current trajectory continues:
- reactive nitrogen will continue to accumulate in soils and waters
- denitrification will remain incomplete
- N_2 return will remain suppressed
- atmospheric buffering capacity may weaken
- fire regimes may intensify
- climate-fire feedback loops may strengthen

These risks are not speculative; they are the logical outcome of a nitrogen cycle operating under one-way extraction and impaired return.

These long-term risks converge most visibly in Earth's fire systems, where nitrogen imbalance alters both the fuel landscape and the atmospheric conditions that govern combustion. This dual influence makes wildfire behaviour one of the clearest indicators of a nitrogen cycle operating under one-way extraction and impaired N_2 return.

Fire Regimes and Atmospheric N_2 as a Combustion Buffer

Nitrogen imbalance influences fire regimes through both vegetation pathways and atmospheric pathways, creating a dual-mechanism amplification of wildfire risk.

Atmospheric N_2 suppresses combustion by diluting O_2, absorbing heat, and slowing radical chain reactions (Seinfeld & Pandis, 2016) [1]. A reduced atmospheric N_2 fraction increases the effective availability of oxygen, lowering ignition thresholds and increasing flame intensity [4]. At the same time, reactive nitrogen accelerates biomass production, generating more fuel for wildfires [10,11].

The combined effect is:

- higher ignition probability
- faster fire spread
- more intense burns
- stronger climate–fire feedback loops

Monitoring blind spots hide this risk because current systems track reactive nitrogen emissions but not atmospheric N_2 depletion or impaired N_2 return (Davidson & Kanter, 2014) [3,9].

As a result, the nitrogen–fire connection remains largely invisible in policy and emission-accounting frameworks.

Section 7 is intentionally concise: it distils the atmospheric mechanism into a clear, high-impact argument that sets the stage for the accounting framework that follows.

A. Anthropogenic Nitrogen Extraction & Diversion Budget (Tg N/year)

Atmospheric nitrogen pool

- Atmospheric $N_2 \approx 3.9 \times 10^9$ Tg N

Anthropogenic extraction pathways

- **Haber–Bosch industrial fixation:** ~200 Tg N/yr
- **Biological nitrogen fixation for food (feeding the other 50% of humanity):** ~110 Tg N/yr
- **Lightning fixation:** ~5 Tg N/yr
- **Human waste diversion (away from soils):** ~20 Tg N/yr
- **Long-lived nitrogen reservoirs** (biomass, plastics, sediments, landfills, textiles): ~150 Tg N/yr

Total anthropogenic extraction + diversion ≈ 485 Tg N/yr (≈ 2.4 × Haber–Bosch alone)

Atmospheric fraction removed

$4853.9 \times 109 \approx 1.24 \times 10 - 4\%$-per year

Over 1000 years

≈0.124%

Anthropogenic Nitrogen Lock (Storage)

Human biomass

- ~8.2 billion people × 65 kg × 2.5% N ≈ 13 Tg N stored

Livestock biomass (cattle dominant)

- ~1.5 billion cattle × 400 kg × 2.5% N ≈ 15 Tg N stored

Crop nitrogen diverted from soil

- Global crop N harvest: 120–150 Tg N/yr
- ≈100 Tg N/yr diverted away from N_2-producing pathways

Combined nitrogen lock ≈ 13 + 15 + 100 = **128 Tg N** (≈ 256 Tg N_2 equivalent)

Together, these processes create a **persistent nitrogen lock**: nitrogen is extracted from atmospheric N_2, converted into reactive forms, and then trapped in pathways that do not reliably return it to the atmosphere. When all extraction and diversion pathways are combined, total anthropogenic nitrogen diversion exceeds **~485 Tg N per year**, more than **twice** the Haber–Bosch flux.

When nitrogen lock-in, reactive nitrogen pollution, heating gases, and disrupted waste-to-soil recycling are considered together, the **cumulative anthropogenic diversion of nitrogen is approximately 25 times larger than Haber–Bosch alone**. Although this remains too small to measurably change atmospheric N_2 in the short term, it highlights a critical point: **extraction must be evaluated alongside the unmeasured N_2 return flux** to understand long-term nitrogen-cycle balance and atmospheric stability.

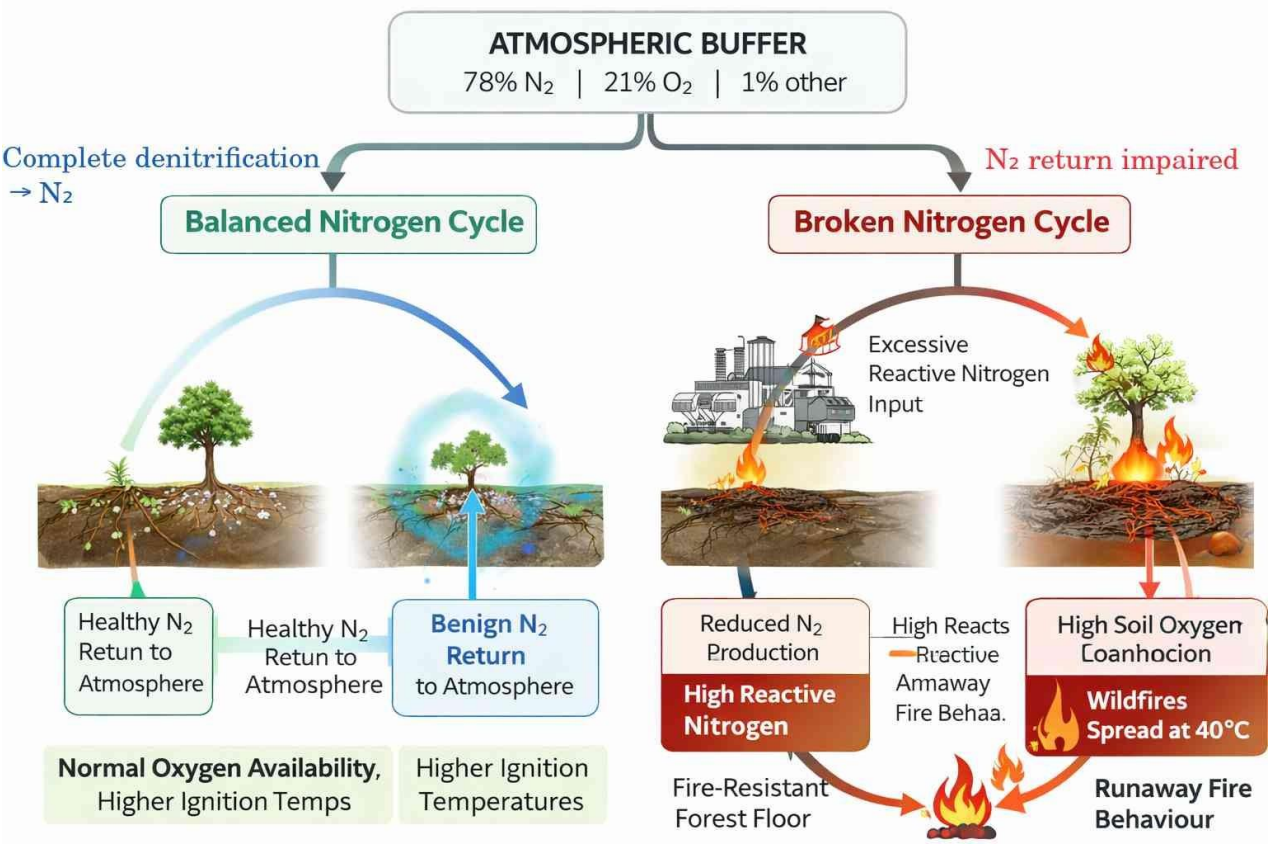

Figure 8: Balanced and Broken Nitrogen Cycles and Their Consequences for Atmospheric Combustion Safety

Broken Anthropogenic Nitrogen Route (Current System)

A directional pathway: nitrogen is extracted from the atmosphere and never fully returned.

- Urbanisation breaks the waste-to-soil loop.
- Crops are short-cycle, but their nitrogen rarely returns to soil for complete denitrification.
- Biomass locking traps nitrogen in humans, livestock, sediments, plastics, wastewater, and eutrophic systems.
- Water-based sanitation diverts human waste into waterways → nitrogen enters rivers, coasts, and sediments → no N_2 return.
- Pollution of waters and atmosphere (NO_x, NH_3, N_2O) reflects incomplete microbial processing.
- Soil degradation (loss of carbon, aggregates, fungi, and NosZ bacteria) breaks the $N_2O \rightarrow N_2$ step.
- Overconsumption, food waste, and obesity increase nitrogen extraction → larger biomass lock → more reactive nitrogen leakage.

Figure 9: Misdiagnosing the Nitrogen Cycle: Faulty Measurement → Bad Diagnosis → Wrong Solutions

This caricature illustrates the misidentification of the nitrogen-cycle problem. The bin-collection truck represents soil denitrification processes that handle nitrogen after fixation — the natural route returning N_2 to the atmosphere (Minter, 2026) [27]. The overflowing waste symbolizes reactive nitrogen emissions (NO_x), often regarded as harmful without considering that these gases are part of the system's attempt to restore balance by removing excess nitrogen. The two women and the man represent societal and scientific misdiagnosis: blaming the truck (denitrification) or proposing larger bins (increasing nitrogen input) instead of addressing the root cause — the excessive reactive nitrogen entering the system. Banning the truck halts nitrogen removal altogether, while buying bigger bins amplifies input without repair. The scene captures how faulty measurement leads to bad diagnosis and wrong solutions, reinforcing the need to distinguish between nitrogen's benign return and its reactive overflow.

Healthy Planetary Nitrogen Cycle (Restored System)
A circular pathway: nitrogen returns to the atmosphere as inert N_2.

- **Complete denitrification** Fungal initiation + bacterial NosZ completion → N_2O → N_2. Requires carbon-rich soils, aggregates, moisture gradients, and intact microbial networks.
- **N_2 measurement and monitoring** Tracking inert nitrogen return rather than only reactive nitrogen emissions.
- **Fungal conservation** Protecting fungi that create denitrification niches and carbon micro-habitats.
- **Human + livestock waste recycling** Returning treated waste to soils → restoring the N_2-producing step → closing the anthropogenic loop.
- **Reduction of consumption, food waste, and obesity** Less nitrogen extraction for food production → smaller biomass lock → lower reactive nitrogen leakage.
- **Reduced artificial fixation** Lower Haber–Bosch output and reduced combustion fixation → less directional drain on atmospheric N_2.
- **Restabilising mycorrhizal populations in acidified, over-fertilised soils** Soil acidification is often attributed solely to microbial oxidation of ammonium, but this explanation omits a critical ecological mechanism. Excess synthetic nitrogen disrupts plant–mycorrhizal signalling, causing fungi to dissociate from roots and enter sporulation (van der Heijden and M.G.A., 2015), particularly below pH ~5. This collapse sharply reduces soil carbon inputs, destabilises aggregates, and lowers buffering capacity [28,29]. As pH declines, NosZ-carrying bacteria lose function, impairing the N_2-producing step of denitrification and reinforcing the acidification loop. In many degraded soils, chemical amendments alone cannot restore pH stability; re-establishing mycorrhizal symbiosis is required to rebuild carbon, recover buffering capacity, and enable complete denitrification.

Outcome: a restored nitrogen cycle in which extraction ≈ return, reactive nitrogen is minimised, and atmospheric N_2 remains stable — preserving Earth's fire-safe oxygen balance.

Earth relies on two oxygen-dilution mechanisms: inert N_2 buffering and temporary NO_x formation. Only the N_2 pathway is safe for humans. NO_x can suppress auto-combustion, but at the cost of ozone depletion and climate warming. A stable, fire-safe atmosphere therefore requires restored N_2 return, not reliance on reactive nitrogen

Toward a Complete Nitrogen Accounting Framework

Why a New Framework Is Needed

Current nitrogen-emission systems quantify only reactive nitrogen gases such as N_2O, NO_x, and NH_3, ignoring the dominant and benign flux of N_2 [14,15]. This omission creates a structural bias: ecosystems that efficiently return nitrogen to the atmosphere as N_2 appear to be "emitters," while systems that leak reactive nitrogen are over-represented in inventories [3].

A complete accounting system must therefore distinguish between:

- reactive nitrogen pollution
- inert nitrogen return
- anthropogenic extraction of atmospheric N_2
- ecosystem nitrogen storage
- Without these distinctions, nitrogen budgets remain conceptually misleading [5,11].

Pillar 1 — Reactive Nitrogen Emissions (Nr)

Reactive nitrogen emissions include N_2O, NO_x, and NH_3 — compounds that drive eutrophication, ozone formation, particulate pollution, and greenhouse forcing (IPCC, 2021) [10,12]. These emissions must be tracked, but they cannot be used as proxies for total nitrogen loss.

Key insight: Reactive nitrogen emissions represent leakage, not the full nitrogen cycle.

Pillar 2 — Inert Nitrogen Return (N_2)

Complete denitrification returns nitrogen to the atmosphere as inert N_2 — the endpoint of the nitrogen cycle and the planet's primary atmospheric stabiliser (Schlesinger & Bernhardt, 2020) [2,8]. Yet N_2 is almost never measured because it is isotopically indistinguishable from atmospheric N_2 without enrichment (Spott & Stange, 2007) [16].

Key insight: N_2 return is protective, not polluting — but current systems cannot see it.

Pillar 3 — Anthropogenic Extraction of Atmospheric N_2

The Haber–Bosch process fixes more nitrogen each year than all natural terrestrial nitrogen fixation combined [5,6]. This extraction removes N_2 from the atmosphere and injects it into biological and chemical pathways that do not reliably return it.

Key insight: Humanity has created a one-way nitrogen pump.

Pillar 4 — Ecosystem Nitrogen Storage

Large quantities of reactive nitrogen now accumulate in:

- crops
- livestock
- forests
- human bodies
- long-lived organic materials and sediments

These reservoirs are biologically active, mobile, and prone to leakage [10,11].

Key insight: Ecosystem and anthropogenic nitrogen storage is not neutral. It represents nitrogen already removed from the atmospheric N_2 reservoir and placed into long-lived pools that do not readily return it. Even without further extraction, humanity holds a substantial quantity of nitrogen that used to be atmospheric N_2.

This underscores the need to manage existing nitrogen stocks carefully and strengthen the ecological processes that safely recycle nitrogen.

Integrating the Four Pillars

A complete nitrogen accounting framework must integrate all four pillars:

- **Nr emissions** — harmful reactive nitrogen leakage
- **N_2 return** — the protective microbial flux that stabilises the atmosphere
- **N_2 extraction** — anthropogenic removal of atmospheric nitrogen
- **Ecosystem + anthropogenic storage** — nitrogen held in biomass, sediments, plastics, and diverted waste streams

Together, Pillars 3 and 4 reveal a critical but overlooked reality: humanity has already removed vast quantities of nitrogen from the atmosphere and placed them into long-lived reservoirs that do not return N_2. This is not a hypothetical future imbalance — it is a present skew in atmospheric composition created simply by sustaining a large global population and modern waste-management systems.

Recognising this existing atmospheric deficit does not imply reducing human numbers; rather, it highlights the need to tread carefully with the nitrogen we already hold and to restore the microbial pathways that return reactive nitrogen to inert N_2.

This four-pillar framework aligns nitrogen science with Earth-system stability rather than narrow pollution metrics (; Davidson & Kanter, 2014) [3,9]. It restores the missing stabilising flux, corrects the category error embedded in current monitoring, and provides a foundation for climate-relevant nitrogen policy.

Reframing Nitrogen in the Earth System

This paper has argued that nitrogen must be understood not only as a nutrient or pollutant, but as a planetary stabiliser. The prevailing focus on reactive nitrogen has obscured the central role of inert N_2 in maintaining atmospheric composition, suppressing combustion, and regulating long-term climate stability (Seinfeld & Pandis, 2016) [1,4]. By measuring only reactive nitrogen gases, current monitoring frameworks misinterpret ecosystem function, underestimate the protective return of N_2, and overlook the atmospheric consequences of anthropogenic nitrogen extraction (Davidson & Kanter, 2014) [3,9].

Together, the four pillars restore the nitrogen cycle's full structure, revealing nitrogen not merely as a pollutant to be controlled but as a planetary stabiliser whose inert return flux must be central to climate and fire-regime science.

The Need for a Complete Nitrogen Accounting Framework

A central conclusion of this work is that nitrogen accounting must distinguish between reactive nitrogen emissions, inert nitrogen return, anthropogenic extraction, and long-lived nitrogen storage. Without this distinction, nitrogen budgets remain incomplete and conceptually misleading [5,11]. The four-pillar framework proposed in Section 8 provides a foundation for a more accurate and ecologically meaningful approach to nitrogen monitoring.

Implications for Climate, Fire Regimes, and Atmospheric Stability

The nitrogen imbalance is not only an ecological issue; it is an atmospheric one. As shown in Section 7, N_2 is the primary atmospheric fire suppressant, and its long-term depletion — even at small rates — could influence ignition thresholds and fire behaviour in a warming world (Seinfeld & Pandis, 2016) [1,4]. The failure to measure N_2 therefore represents a blind spot with implications for:

- climate–fire feedback loops
- atmospheric buffering capacity
- long-term combustion stability
- resilience of fire-prone ecosystems

Recognising N_2 as a climate-stabilising gas reframes nitrogen management as a component of planetary safety.

Research Priorities for the Coming Decades

To address the gaps identified in this paper, future research should prioritise:

- quantifying N_2 production using improved isotopic and mass-spectrometric methods (Spott & Stange, 2007) [15,16].
- mapping global denitrification capacity across soils, wetlands, and aquatic [2].
- tracking anthropogenic N_2 extraction through agriculture, biomass, and human population growth [5].
- integrating N_2 into climate and fire-regime models [4].
- developing monitoring systems that distinguish between reactive nitrogen loss and inert nitrogen return [3].
- restoring soil-to-atmosphere N_2 pathways through ecological and agricultural interventions (Schlesinger & Bernhardt, 2020) [8].

These priorities align nitrogen science with Earth-system stability rather than narrow pollution metrics.

Toward a Planetary Nitrogen Ethic

A central conclusion of this work is that the nitrogen cycle cannot be understood — or repaired — through a mindset that treats all nitrogen emissions as harmful. This framing collapses the distinction between reactive nitrogen pollution and inert nitrogen return, leading to management strategies that suppress the very organisms responsible for stabilising the nitrogen cycle [14].

A striking example appears directly in the scientific literature. The article Managing denitrification to reduce nitrous oxide emissions and nitrate leaching (DOI: 10.1016/j.cosust.2020.08.006) implicitly treats denitrification itself as a harmful process, even though complete denitrification produces inert N_2 — the atmospheric stabiliser whose absence drives the imbalance described in this paper.

By misclassifying denitrification as "pollution," current frameworks undervalue:

- fungi that mobilise carbon and create denitrification niches
- bacteria that complete the $N_2O \rightarrow N_2$ step
- soil aggregates that maintain redox gradients
- plant–microbe symbioses that regulate nitrogen flow

This mindset does not merely distort interpretation; it creates ecological harm. It encourages practices that:

- reduce soil organic matter
- fragment microbial networks
- impair complete denitrification
- increase N_2O leakage
- accelerate nitrogen imbalance

A planetary nitrogen ethic must therefore recognise that **not all emissions are equal**. Reactive nitrogen emissions are harmful; inert nitrogen return is protective. Policies that fail to distinguish between these pathways risk amplifying the very problems they aim to solve.

Restoring the Nitrogen Cycle Through Regenerative and Circular Practices

Because complete denitrification depends on complex, carbon-rich, microbially active soils, restoring the nitrogen cycle requires restoring the ecosystems that complete it. Regenerative and circular practices — including organic matter restoration, microbial-friendly soil management, and the recycling of animal and human waste back to land — rebuild the conditions under which fungi and bacteria can safely return nitrogen to the atmosphere as N_2 (Schlesinger & Bernhardt, 2020) [8].

These practices strengthen:

- soil structure and aggregation
- microbial diversity and symbiosis
- carbon availability for denitrifiers
- moisture retention and redox gradients
- the N_2-producing step of denitrification

By closing the loop between nitrogen extraction and nitrogen return, regenerative systems help re-establish the balance between reactive nitrogen creation and inert nitrogen recovery. This is the foundation of a sustainable nitrogen future.

The Need for Complex, Multi-Variable Soil Experiments

A final implication of this work concerns the experimental mindset that dominates nitrogen research. Much of the literature relies on simplified microcosms, sterilised soils, isolated cultures, or single-variable manipulations — designs that are analytically convenient but ecologically misleading (Schimel & Schaeffer, 2012) [24].

Illustrates how simplified microcosms generate misleading conclusions [30]. By sterilising soils, removing bacterial partners, and measuring only N_2O, the experiment eliminates the ecological conditions under which complete denitrification occurs. The result is an artefact: fungi appear to be major N_2O emitters not because they inherently leak reactive nitrogen, but because the N_2-producing step requires intact, multi-species consortia that the experimental design removes. This pattern is widespread in nitrogen research and underscores the need for complex, multi-variable soil experiments capable of capturing the full denitrification pathway.

Why Acidic Soils Suppress NosZ

NosZ, the enzyme that converts N_2O to N_2, is strongly inhibited in acidic soils. This is because NosZ is a **copper-dependent metalloenzyme**, and low 14 ptpH interferes with both:

- copper bioavailability (Cu becomes less soluble and less accessible to microbes), and
- copper insertion into the NosZ active site, which is essential for catalytic function.

Acidic conditions also disrupt electron transport chains, destabilise denitrifying biofilms, and shift microbial communities toward organisms lacking the $N_2O \rightarrow N_2$ step. As a result, **low-pH soils favour incomplete denitrification**, causing N_2O to accumulate even when fungi and bacteria are present.

In short: acidic soils do not make microbes "produce more N_2O" — they disable the enzyme required to finish the job.

When experiments remove ecological complexity, they remove the very conditions that determine whether nitrogen is returned to the atmosphere as protective N_2 or leaked as harmful N_2O. This reductionist approach leads to three systemic errors:

- mischaracterising microbial behaviour by observing organisms outside their ecological networks
- overestimating N_2O production because the N_2-producing step requires intact, multi-species communities [14].
- underestimating the stabilising role of fungi and bacteria in restoring atmospheric balance
- To understand nitrogen cycling under real conditions, future research must embrace complex-soil experimentation, including:
- intact soil cores

- multi-species microbial consortia
- variable carbon inputs
- realistic moisture and oxygen gradients
- plant–soil–microbe systems
- long-term, dynamic measurements of N_2 and N_2O

These approaches reflect the true complexity of soil ecosystems and allow us to observe the nitrogen cycle as it actually operates — not as it appears in simplified laboratory artefacts.

Changing the Mindset — The "Daughter of Thunder" Story

A few years ago, during a mycological gathering, I spoke with a prominent Glomerales specialist about my research on desert truffles. I mentioned that in many arid regions these truffles are traditionally known as "the daughters of thunder." She was intrigued by the name and asked whether I knew its origin.

I explained that desert truffles reliably appear after early-spring thunderstorms, and that lightning produces reactive nitrogen delivered to the soil in rainwater — a rare nutrient pulse in nitrogen-limited desert ecosystems [17,18]. She dismissed the idea: "Excessive nitrogen is known to cause fungal dissociation."
Excessive nitrogen — in desert sand?!

That moment revealed a deeper issue: a mindset problem. Even experts often treat all nitrogen inputs as harmful, overlooking ecological context and the crucial distinction between:

- reactive nitrogen pollution
- benign — and sometimes critically needed — nitrogen replenishment

This mindset mirrors the broader issue diagnosed in this paper: the narrowing of expertise in ways that obscure the cross-disciplinary complexity of natural cycles. It is the same mindset embedded in titles such as Managing denitrification to reduce nitrous oxide emissions…, where denitrification is framed as inherently harmful simply because N_2 — its protective end-product — is invisible to standard measurement.

A more ecological outlook recognises that:

- Denitrification is not pollution — it is planetary maintenance.
- Fungi and bacteria are climate stabilisers, not emitters, when their full networks remain intact.
- The nitrogen cycle cannot be understood through reductionism; the N_2-producing step is an emergent property of multi-species, multi-variable systems.

The "daughter of thunder" story is therefore more than a cultural curiosity. It is a reminder that context matters, that ecosystems differ, and that nitrogen is not inherently harmful. In deserts, a thunderstorm is not a pollutant — it is a gift.

Recognising this distinction is essential for moving beyond the mindset that has long constrained nitrogen science.

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