environments

MDPI

Article

Fitness for Purpose of Reactive Nitrogen Monitoring Methods in Ecosystems: A Multi-Faceted Comparative Assessment

Ibán González-Fuente [1] and Arturo H. Ariño [2,3,*]

[1] Escuela Internacional de Doctorado, National Distance Education University (U.N.E.D.), Bravo Murillo 38 3º, 28015 Madrid, Spain; igonzalez320@alumno.uned.es
[2] Associate Center, National Distance Education University (U.N.E.D.), 31006 Pamplona, Spain
[3] Biodiversity and Environment Institute BIOMA, University of Navarra, 31080 Pamplona, Spain
* Correspondence: artarip@unav.es

Abstract

Anthropogenic reactive nitrogen (Nr) production now greatly exceeds natural creation, generating cascading environmental impacts on the environment and human health. Effective monitoring of Nr in ecosystems is essential for early warning and policy response, yet the landscape of available monitoring methods is wide and heterogeneous, varying substantially in accuracy, purpose, cost, and ecological scope. This study evaluates nineteen Nr-monitoring methods, grouped into chemistry-based (CM), biodiversity-based (BM), and transplant-based (TM) methods, against 36 fitness-for-purpose (FFP) indicator facets. Facets are organized into intrinsic (direct measurement of nitrogen cycle components), projected (ecological effects the method can indicate), and extrinsic (metaproperties such as cost or precision) types. Scores are derived from 89 core papers, ranked using evidence-normalized weighted-sums (WS) and non-metric multidimensional scaling (NMDS) approaches. CMs generally outperform BMs and TMs, with critical loads, total tissue nitrogen, and nitrogen isotopes leading overall. Lichen diversity, ectomycorrhizal fungi, and Ellenberg's N lead among BMs, particularly for projected facets. The NMDS reveals a structural divide and monitoring complementarity between CMs and BMs, with CMs serving as early warning indicators, whereas BMs integrate cumulative, persistent ecosystem impacts. While no single method seems adequate for comprehensive monitoring, the FFP matrix facilitates selecting optimal monitoring combinations.

Keywords: reactive nitrogen; monitoring; biomonitoring; methodologies; fitness-for-purpose

Check for updates

Academic Editor: Gabriel Gascó Guerrero

Received: 11 June 2026
Revised: 29 July 2026
Accepted: 3 August 2026
Published: 14 August 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Human activity has fundamentally altered the environment, transitioning the planet into a new geological epoch often referred to as the Anthropocene [1]. In particular, the global nitrogen cycle has been heavily impacted. Global production of reactive nitrogen has risen to approximately 203 Tg N per year, a value that vastly exceeds natural baselines [2]. This surge is largely attributed to two distinct anthropogenic drivers: the Haber–Bosch process, which converts inert atmospheric nitrogen (N_2) into ammonia (NH_3) for agricultural fertilizer, and high-temperature combustion processes in transport and industry that oxidize atmospheric nitrogen into nitrogen oxides (NO_x) [3]. While this anthropogenic intervention has supported population growth through intensified agriculture—sustaining many more people than natural nitrogen availability would likely sustain, estimated at nearly 3.87 billion people ([4])—it has generated environmental challenges that threaten ecosystem stability on a planetary scale.

Climate change is expected to exacerbate these processes further. For example, ammonia (NH_3) emissions, typically associated with agricultural manure and fertilizer application, are highly temperature-dependent [5]; volatilization rates increase exponentially with ambient heat. Consequently, global NH_3 emissions are projected to rise significantly from 65 Tg N yr^{-1} in 2008 to 93 Tg N yr^{-1} by 2100 due solely to projected temperature increases of 5 °C [6]. When combined with the increased livestock demand anticipated for a growing global population, these emissions have been projected to reach 135 Tg N yr^{-1} [6].

The environmental consequences of this excess nitrogen are severe and multifaceted, often described as the "nitrogen cascade" [7]. This concept implies that a single atom of reactive nitrogen can cycle through the environment, causing sequential effects from driving ozone formation in the troposphere to depositing into soil, interfering with biological nitrification processes in the soil, and finally leaching into waterways to drive eutrophication. Ammonium's toxicity may displace sensitive lichens and mosses, while on the other hand, excess nitrogen may also affect biodiversity by competitively promoting nitrophilous plants growth and area expansion, encroaching other plants. A 2011 study by Ariño et al. showed that, in Spain, the ratio of nitrophilous plant occurrence records has steadily increased over the 20th century, more than doubling their presence in herbaria [8].

In terms of public health, exposure to nitrogen compounds is linked to chronic respiratory diseases, including asthma and premature mortality driven by certain types of fine particulate matter ($PM_{2.5}$) formed from atmospheric ammonia and NO_x [9]. Furthermore, water (and especially groundwater) contamination leads to specific acute conditions like methemoglobinemia ("blue baby syndrome"), where nitrate ingestion interferes with the oxygen-carrying capacity of hemoglobin in infants, posing a fatal risk in agricultural regions [10–12]. Keeping NO_2 under the World Health Organization (WHO) air quality guideline levels would prevent over two thousand new cases of pediatric asthma in Western Europe [13]. In the EU, an increase of 10 $\mu g \cdot m^3$ in air would result in a 5.5% increase in mortality rate, and over fifty thousand premature deaths could be attributed to exposure to NO_2 in Europe [14].

The increase in deposited reactive nitrogen has therefore become an important challenge both in environmental and human health terms, either directly or indirectly through interplay with climate change. The consensus in a recent multi-agency guidance report resulting from an extensive consultation to practitioners highlights the complexity of the nitrogen impacts on human health, the environment, and structures due to the variety of N cycle governing factors, reactions, and exposures [15].

To mitigate these risks, effective monitoring [16] is essential: using consistent and accepted methods to produce high-quality data in a cost-effective manner. Physical sensors can measure air concentrations and soil deposition, but the ecological impact must be assessed from a variety of additional parameters (often biological) that respond to the upset of the cycle. On the other hand, bioindicators offer a practical, biologically relevant tool to assess nitrogen loads, atmospheric concentrations, and valid biological effects as they integrate the effect of the nitrogen loads in the ecosystem's components. Monitoring reactive nitrogen may offer a way to assess, and might eventually help correct, these loads before irreversible damage occurs.

However, there are several monitoring methods, varying wildly in terms of accuracy, purpose, practicality, costs, and other characteristics. When used in environmental studies, ascertaining these characteristics helps defining their fitness for purpose (FFP): whether a reactive nitrogen assessment method can potentially achieve the goal sought, including producing the information relevant to the study and the context to interpret it [17]. These methods can therefore be roughly divided into two camps: methods that seek to observe or quantify the presence of the reactive nitrogen species in the environment, which can

be largely reliant on chemical analyses, physical sensing, or biochemical evaluations, and methods targeting the effects on ecosystems of such species, that usually work at the population or community level and may include biological experimentation.

A comprehensive literature review successfully evaluated the biomonitoring of atmospheric deposition based on five types of organisms (lichens, bryophytes, vascular epiphytes, herbs, and woody plants) across five methods or parameters (bioindicator value, nitrogen content, stable isotopes, photosynthesis, and enzymatic activity), and advocated for the use of biomonitors as an affordable alternative when other systems or methods might not be adequate or cost-effective [18]; these methods have often been used to assess both the nitrogen cycle alterations and their effect on ecosystems [15,19–24]. More recently, a very comprehensive global assessment of N impacts on humans and the environment, largely based on critical loads, provided critical guidance for the development of monitoring programs and strategies at local and global scales [15]. We followed a comparable approach but for the wider spectrum of monitoring methods, cases, and aspects and with a different, formally defined scoring system, not restricted to organisms, that also considers existing methods not covered in previous reviews.

Our aim is to provide further context to inform about the fitness for purpose of Nr assessment methods for environmental monitoring, by pitching them to a variety of characteristics, aspects, features, or parameters (hereinafter "facets") that could become relevant in their selection, based on a critical review and meta-analysis of a representative sample of published research.

2. Materials and Methods

In 2023, we conducted structured searches in Web of Science (WoS) and Google Scholar (GS) for highly cited references dealing with methods to assess and monitor reactive nitrogen in ecosystems over the previous two decades (e.g., [6,25,26]). Separate searches were conducted in abstracts in WoS for the search terms *nitrogen* + *deposition* + *indicator*, *nitrogen* + *bioindicat*[*or* | *ion*], *environment* + *nitrogen* + *monitoring*, and *reactive* + *nitrogen* + *deposition*. After duplicate removal across searches, 11,268 records remained. These were sorted by citations. The topmost papers were manually examined in sequence, one by one, and snowballed via additional searches for specific methods and use cases as they were discovered in the examined texts. Snowballing proceeded both in WoS and GS without time restrictions and continued until over 400 distinct references were assembled. All references were then filtered manually by deeper examination. References that (i) did not provide adequate methodology descriptors; (ii) did not report clearly measurable effects; or (iii) reported second-hand data already reported in another paper were discarded. A sample of 89 core references positively reporting at least one method in an unambiguous context of reactive nitrogen monitoring remained for full analysis (see Supplementary Material File S1). For each selected paper, data was collected on which method(s) were used, what was being measured, what the purpose was, and in what context. The methods were pooled, and each one was then evaluated for three types of facets:

- Intrinsic facets (IF) targeting the actual aspects of the N cycle that the method is designed to measure, assessing specific stocks, flows, or concentrations of various Nr forms (e.g., deposition, fixation, cycling, atmospheric concentration);
- Projected facets (PF) informing the biological efficacy and environmental effects of Nr, for example the method's sensitivity to detect subtle changes in species composition and its ability to statistically correlate deposition rates with declines in species richness; and

- Extrinsic facets (EF) focusing on the methods' usability, availability, or popularity (e.g., cost of implementation, availability of historical data baselines, or frequency of updates)—i.e., transversal concepts that can be applicable to any methodology being analyzed.

While intrinsic and projected facets are more directly related to FFP, indicating their suitability for the intended task, extrinsic facets were also taken into account, following Hamilton et al. (2022) criterion of taking into account practicality in addition to accuracy or reliability, as an indirect measure of their fitness through their actual usage scope [17].

All data were combined in a 3-tuple dataset with each record including a unique combination of one facet in one method in one reference.

For each facet, a three-level score (low-, medium-, high-) was established based on the literature review to assess each method's suitability to determine that specific facet (Table 1). Levels were established either by analyzing whether and how the methods would cope with, or be able to, assess a facet in detail, often quantitatively, or have actually been used to assess a facet (frequency of use in the literature, with thresholds established according to either octaves, with upper level set at twice the lower level, or majority, with a 50% threshold for the upper level and 10% cutoff for the lower level; see Table 1 for specific cutoffs).

Table 1. Facets used to evaluate each method across the literature corpus and threshold levels or inclusion criteria for each level. Red: intrinsic (IF); blue: projected (PF); gray: extrinsic (EF). See Supplementary File S2 for further details.

		Suitability Level		
Facet	**Assessment Criterion**	**Low**	**Medium**	**High**
atmosphere	Ability to assess reactive nitrogen presence in the atmosphere	generic detection	qualitative identification	quantitative
deposition	Ability to assess the direct transfer of Nr from the atmosphere to the biosphere, soil, and waters	n/a	indirect or ordinal	quantitative
fixation	Ability to assess nitrogen fixation to mobilizable stocks	n/a	either fluxes or stocks measured	fluxes and stocks measured
health	Ability to assess how well the method measures Nr concentrations whose pathological effects have been established	indirect relation with morbidity	qualitative relation with morbidity	correlation with morbidity
limit	Ability to measure exceedance of critical loads	n/a	binary	quantitative
lifetime	Ability to calculate half-lives of nitrogen compounds emitted to the atmosphere	n/a	half-lives ordered	half-lives quantified
reaction	Ability to assess short-lived Nr (NO, NO_2, NO_3^-)	generic detection	qualitative identification	quantitative
recovery	Ability to assess ecosystem recovery after nitrogen deposition decline	n/a	indirect or ordinal	quantitative
reservoir	Ability to assess mobilizable and immobilizable Nr stocks	n/a	quantitative (immobilized) or qualitative	quantitative (mobilizable)
soil	Ability to assess Nr presence in soil	generic detection	qualitative identification	quantitative
source	Ability to measure the inflow of Nr entering the ecosystem	source(s) identified	single source quantified	multiple sources quantified

Table 1. *Cont.*

		Suitability Level		
Facet	**Assessment Criterion**	**Low**	**Medium**	**High**
acidity	References reporting the method as a diagnostic tool to assess ecosystem acidification	<10%	10–50%	>50%
aqu	References using the method as an indicator of air quality reduction	<10%	10–50%	>50%
biomass	References reporting the method for biomass change assessments	<10%	10–50%	>50%
capture	References reporting the method in CO_2 capture assessments	<10%	10–50%	>50%
cycle	References reporting the method in quantified N cycle assessments	<10%	10–50%	>50%
eutrophy	References reporting the method in eutrophication risk assessments	<10%	10–50%	>50%
fire	References using the method as an ecological indicator of wildfire risk	<10%	10–50%	>50%
ghg	Method's relationship with assessment of greenhouse gasses (GHG) changes (other than N_2O)	n/a	indirect	direct
nitrous	References using the method to report atmospheric N_2O (as a GHG)	<10%	10–50%	>50%
ozone	References reporting the method as a factor in tropospheric or stratospheric O_3 assessments	<10%	10–50%	>50%
pests	References reporting the method in pathogen and pest proliferation	<10%	10–50%	>50%
richness	Method's relationship with species richness changes in communities	potential	qualitative	quantitative or ordinal
sequester	References reporting the method in carbon sequestration estimates	<10%	10–50%	>50%
shift	Method's relationship with species composition shifts in communities	potential	qualitative	quantitative or ordinal
toxicity	References reporting the method as a factor in Al, Mn leaching assessments	<10%	10–50%	>50%
data	Instances of use of a method to diagnose nitrogen effects at the ecosystem level *	<50	50–100	>100
update	References using the method within the last 5 years of the sample	<5%	5–10%	>10%
relevant	References citing the method	<5%	5–10%	>10%
cost	Relative resource requirements (field equipment, expertise, laboratory analyses)	heavy	medium	low
precision	Range of possible values a method can express when measuring effects	binary	<30	>30
scale	Type of measurement scale the method can provide	nominal	ordinal	quantitative
climate	Number of the 11 Köppen climate types the method has been used in	<3	3–5	>5
time	How long the method requires to produce reliable, high-precision results	>1 yr	1 mo–1 yr	<1 mo
location	Breadth of places (from sites to biomes) the method can be applied to	narrow	medium	wide
kingdom	Biological kingdoms where biomonitoring has been identified	1	2–3	≥4

(*) Uses of the method over a time series were not considered separate instances.

For each facet, we proposed specific conditions for a method to be included in each level based on the literature analysis, frequency of use, or type of evidence, for applicable facets. A high suitability means that the method is adequate to evaluate that facet, while a low suitability indicates that the method is generally inadequate to provide a correct evaluation. A medium suitability still enables the method to assess the facet although in a limited way. All suitability scores were agreed upon by both authors.

Comparable, additional, or more recent cases supporting the suitability were navigated by using Consensus AI for Research (consensus.app, Pro version, April 2026) [27], by issuing the generic prompt "*Find recent references supporting or discussing the use of [method] to measure | assess [intrinsic facet | projected facet] in the context of reactive nitrogen in ecosystems*". Supplementary Material File S2 systematically describes specific details leading to the selection of each facet and provides literature evidence.

The resulting matrix of method-facet scores was seriated [28] both for rows and columns in Excel by calculating evidence-normalized weighted sums [29], with nonevidence penalty as

$$WS_i = \frac{(L_i + 2M_i + 3H_i)(E - N_i)}{3E^2}$$

where for each i method (or facet) out of E, the number of high (H), medium (M), low (L), and no evidence (N) facets (or methods) was computed, both overall (WS) and within method and facet groups (WS_f).

Relative differences between methods based on the facet scores were found by nonmetric multidimensional scaling (NMDS) [30], and significance between groups of methods by analysis of similarity (ANOSIM) [31] based on the Gower distance index [32] using PAST v.4 [33].

3. Results

3.1. Identified Methods

We identified nineteen methods directly relevant to reactive nitrogen monitoring in ecosystems in the literature sample (Table 2). These could be categorized into three distinct functional groups, each offering a different "lens" through which to assess reactive nitrogen in the context of environmental studies:

1. Chemistry-based methods (CM), involving either a direct measurement of nitrogen or nitrogen forms contents in the environment, or analyzing specific physiological responses within organisms to gauge nitrogen stress such as, e.g., critical loads, tissue nitrogen, enzymatic activity, isotopic analysis (nine methods);
2. Biodiversity-based methods (BM), where shifts in the community structure, species composition, or ecological factors attributable to nitrogen loads are observed over time, such as Ellenberg indicator values or diversity surveys (nine methods); and
3. Transplant-based methods (TM), an experimental approach involving moving native or standardized organisms (often sensitive lichens like *Usnea* or mosses like *Sphagnum*) from clean "background" environments to polluted sites and measuring stress indicators (e.g., membrane integrity) over a defined exposure period (two methods).

The prevalence in the analyzed literature ranged from 1% (one reference using the Zarzicky ecological indicator values) to 36% for the critical loads (CRL) method. The chemistry-based methods were used almost twice as often (85%) as the biodiversity-based methods (45%), while six transplant experiments were identified (7%).

N availability was the focus in 60% of papers, while 47% dealt with N deposition. Other targets identified were assimilation (22%), N cycle (21%), limitations (18%), exposure (15%), N as nutrient (11%), N status and emissions (8% each), stress or enrichment (7% each), and N mineralization (5%).

Table 2. Methods described in the analyzed core literature sample (n = 89). Pr.: Prevalence (as percent of citing references) of the method in the literature sample. Header colors mark the types of methods in the corresponding plots.

1. Chemistry-based methods (CM)					
Abbr.	**Method**	**Description**	**Target**	**Ref.**	**Pr.**
AAS	Amino acids	Analysis of free amino-acid contents in tissues	N status	[34]	8%
CFL	Chlorophyll fluorescence	Measurement of photosystem II efficiency	N stress	[35]	7%
CRL	Critical loads	Deposition thresholds below which significant harmful effects on sensitive ecosystem elements do not occur	N deposition	[36]	36%
CNR	C:N ratio	Ratio of carbon to nitrogen in soil or organic matter	N availability	[37]	27%
EZA	Enzyme activity	Measurement of key enzymes	N assimilation	[38]	22%
SGF	Gas fluxes	Measurement of N-containing gas emissions (N_2O, NO_x, NH_3) from soil	N emissions	[39]	8%
NIS	Nitrogen isotopes	Use of stable ($^{15}N/^{14}N$) or radioactive isotopes to trace N	N cycle	[40]	20%
NPR	N:P ratio	Foliar or tissue N:P molar ratio	N limitation	[41]	18%
TNT	Total nitrogen in tissues	Measurement of total N concentration in plant or lichen tissue	N availability	[42]	25%
2. Biodiversity-based methods (BM)					
Abbr.	**Method**	**Description**	**Target**	**Ref.**	**Pr.**
ELN	Ellenberg's N	Indicator values for Central European vascular plants on a 9-point N scale	N availability	[43]	25%
EMF	Ectomycorrhizal fungi	Changes in diversity and composition of ectomycorrhizal fungal communities	N deposition	[44]	11%
FNS	Functional Nitrogen Index for Species	An index for forest vascular plants	N mineralization	[45]	5%
INR	Invertebrate response	Use of invertebrate community composition (e.g., soil fauna)	N enrichment	[46]	7%
LAN	Landolt	Ecological indicator values for the Swiss flora	N as nutrient	[47]	8%
LDV	Lichen biodiversity	Use of epiphytic lichen diversity and community composition	N exposure	[48]	10%
TDP	Tsyganov, Didukh & Plyuta	Ecological indicator values for the flora of Russia and Ukraine	N as nutrient	[49,50]	3%
ZAR	Zarzycki	Ecological indicator values for vascular plants of Poland	N availability	[51]	1%
3. Transplant-based methods (TM)					
Abbr.	**Method**	**Description**	**Target**	**Ref.**	**Pr.**
LTR	Lichen transplants	Transplanting lichens from pristine to polluted sites	N exposure	[52]	3%
PTR	Plant transplants	Transplanting either laboratory-standardized or locally collected native material across N gradients	N exposure	[53]	5%

3.2. Classification and Ranking

Figure 1 shows the methods seriated according to their overall fitness as measured by the evidence-normalized weighted sum (WS) of facets' suitability scores, separately for each facet type (intrinsic, projected, extrinsic). Unsurprisingly, most chemistry-based methods (CM) scored higher overall than biodiversity- or transplant-based methods, and the facets most strongly associated with them were extrinsic or intrinsic facets. Projected facets drove a more mixed seriation among method types. Critical loads (CRL) was the CM more consistently ranking high across intrinsic and projected facets, while lichen diversity (LDV) and ectomycorrhizal fungi (EMF) were the fittest biodiversity methods (BM) overall but particularly for projected facets. Ellenberg's N (ELN) was the most extrinsically faceted fit BM. Transplant-based methods (TMs) scored higher for intrinsic facets than for projected or extrinsic facets.

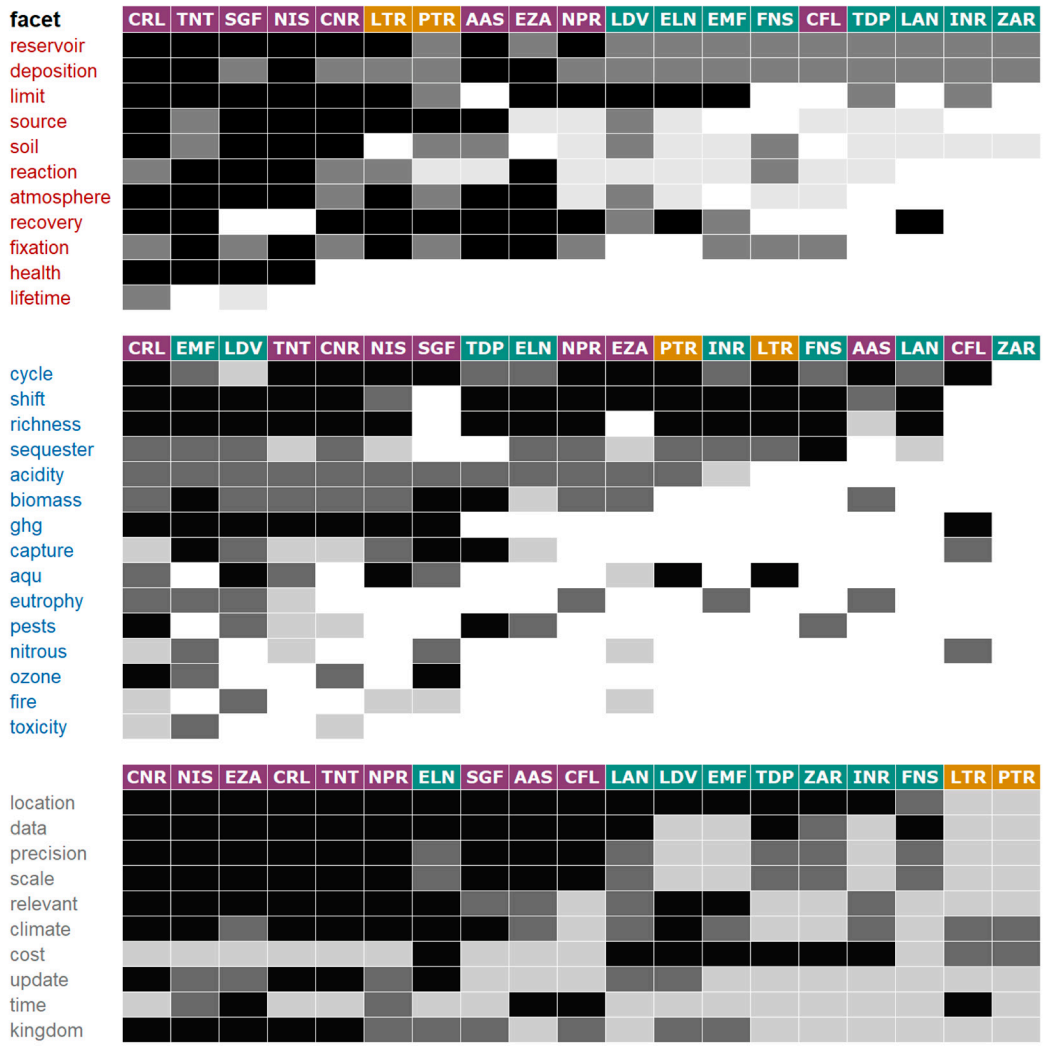


Figure 1. Table of methods (columns) and their facet (rows) scores: high (black), medium (dark gray), low (light gray), seriated by evidence-normalized weighted sums from top to bottom separately by facet type, and left to right within each facet type. Blank cells: no evidence about the facet for the method across the literature sample. Methods: chemistry-based (purple), biodiversity-based (teal), transplant-based (gold). See abbreviations in Table 2. Facets: top (red): intrinsic, middle (blue): projected, bottom (gray): extrinsic.

The intrinsic facets *reservoir* and *deposition* were present in all methods, while all other facets were missing from at least three methods each. Among the projected facets, *cycle* was present in all by one method (ZAR) and *shift* and *richness* in all but three; all other facets were more limited.

Being independent from the methods' designs, all extrinsic facets could be evaluated for all methods but the intrinsic facets *reservoir* and *deposition* were the only ones that all methods could assess to at least some degree. Among the projected facets, only *cycle* was common to all methods but one, and *shift* and *richness* were common to more than 80% of methods. The facets *nitrous*, *fire*, and *toxicity* could only be assessed by one BM each.

The group-specific WS_f of methods apportioned among the three types of facets is shown, ordered, in Figure 2. The apportioning procedure attributes WS separately to each of the three facet types and renormalizes it to the 0–1 interval for the addition of the three, resulting in a slightly different ranking. As compared with the overall seriation, CM scored better than BM or TM. While the top CM trio was identical, critical loads (CRL) scored better than total nitrogen (TNT) or nitrogen isotopes (NIS). Among BM, lichen diversity (LDV) was also best, but ectomycorrhyzal fungi (EMF) and Ellenberg's N (ELN) exchanged positions. The main driver of the change in ranking was the set projected facets, with extrinsic facets having a lesser discriminating role.

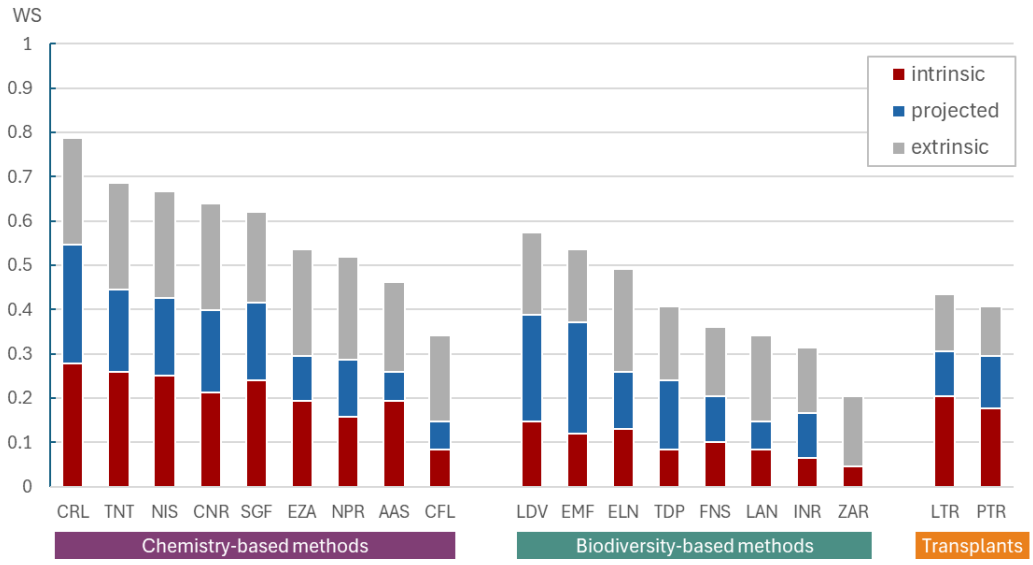


Figure 2. Methods ordered by type and evidence-normalized weighted sum (WS), where WSs have been calculated separately for each group of facets (intrinsic, projected, extrinsic) and apportioned proportionally to the number of facets in each group. ANOSIM's R between groups (Gower) = 0.67, $p < 0.001$.

Relationships between methods are represented in Figure 3 as their coordinates in the first two factors of the NMDS based on Gower distances, accounting for 61.1% of the variance in 2D space. There is a clear divide between CMs and BMs, mostly along the main variation factor (axis I, which largely reproduces the seriation). TMs occupy an intermediate position, with lichen transplant (LTR) lining up with CMs and plant transplant (PTR) with BMs. The second source of variation (axis II) is the main driver that separates three methods from the rest: CLR, LDV, and EMF, with chlorophyl fluorescence (CFL) coming apart at the opposite side. This axis seems more related to the number (as opposed to the value) of the facets that could provide evidence in each method. Ellenberg's N (ELN) is the BM that has the closest relationship with CMs overall.



Figure 3. Non-metric multidimensional scaling (NMDS) of the method-facet matrix showing the Gower distance for methods. See abbreviations in Table 2. Stress = 0.2, R^2 = 0.57. Purple: CM; teal: BM; gold: TM.

4. Discussion

4.1. Facets

When used as monitoring tools, the nineteen methods we identified in the literature sample had varying degrees of relevance and a variety of limitations, arising from their nature or application fields that offered facets amenable to analysis. The formal analysis of these facets is a new, distinctive feature of our review that enables a reproducible framework to evaluate new methods as they come, as well as a tool to re-evaluate existing methods as new evidence are published. While some of these facets arose naturally from the literature review, the final roster was the result of extensive discussions, the examination of the nature of the problem at hand (systematize what the methods were good for), and general considerations about the fitness-for-purpose concept. Some facets were relatively straightforward as FFP components, and for them we proposed relatively simple scores (Table 1), even though for some of these we have defined arbitrary thresholds to attribute "good" or "medium" fitness to a method that, nonetheless, strived to maintain a consistent set of cutoffs across all facets. However, scoring tiers for other facets are less amenable to quantification and their selection rationales are more reliant on direct or indirect evidence found across the literature corpus of the use of the method to assess the facet.

The choice to separate facets into intrinsic, projected and extrinsic may also introduce some bias. While we attributed identical weight to each facet, the groups themselves were uneven. We compensated for this, somewhat, by apportioning equal weights to the groups for the classification of methods by type of method. Other researchers may want to attribute different weights to facets, and that should certainly cause a different seriation [28]. However, we believe that the separation by facet type does offer additional insight. For example, the intrinsic facets dealt mostly with components of Nr and their cycles, while the projected facets focused on the ecosystem effects. It is thus natural to pitch both types of facets and observe which intrinsic components seem most associated with what projected effects on the ecosystem. Tabulating all possible pairs between intrinsic and projected facets across the literature sample, some projected facets were more often associated than not with intrinsic facets: *cycle* co-occurred in 85% of the instances with *deposition*, 82% with *reservoir* and 56% with *soil*, while a shift co-occurred in 67% of instances with *deposition* and 58% with *reservoir* (Figure 4.)

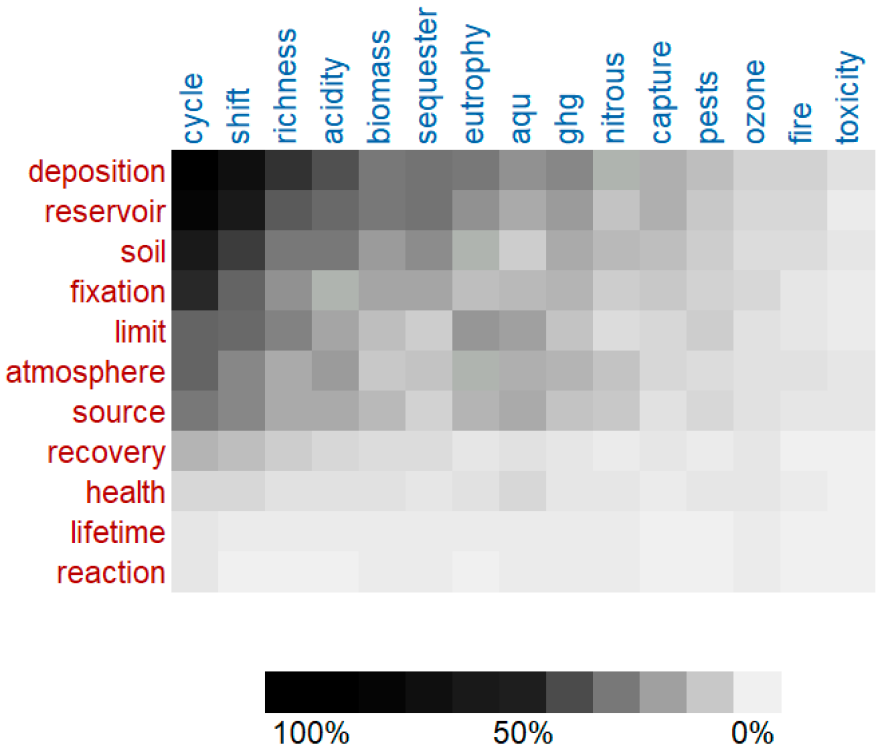


Figure 4. Co-occurrence of projected (columns, blue) and intrinsic (rows, red) facets across the literature sample, as percentage.

The two decades covered by the literature sample also revealed a shifting pattern, reflecting how the priorities for Nr monitoring have changed (Figure 5). The bulk of the literature centered around 2017–2019 analyzed intrinsic facets, whereas the projected facets were spread further over the period, with a higher fraction of papers covering intrinsic facets than projected facets (higher in the plot). Among the projected facets, the shift for the most prevalent facets evolves from older interests (left in the plot) in *eutrophy* and *acidity*, two sharply delimited and often linked ecosystem issues [54–56], to the more generic facets, *cycle* (changes in the nitrogen balance and flow), *shift* (change in the species composition), and *richness* (change in the biodiversity), possibly reflecting a corresponding shift in the research priorities and perceived risks in the scientific community (e.g., [57–59]).

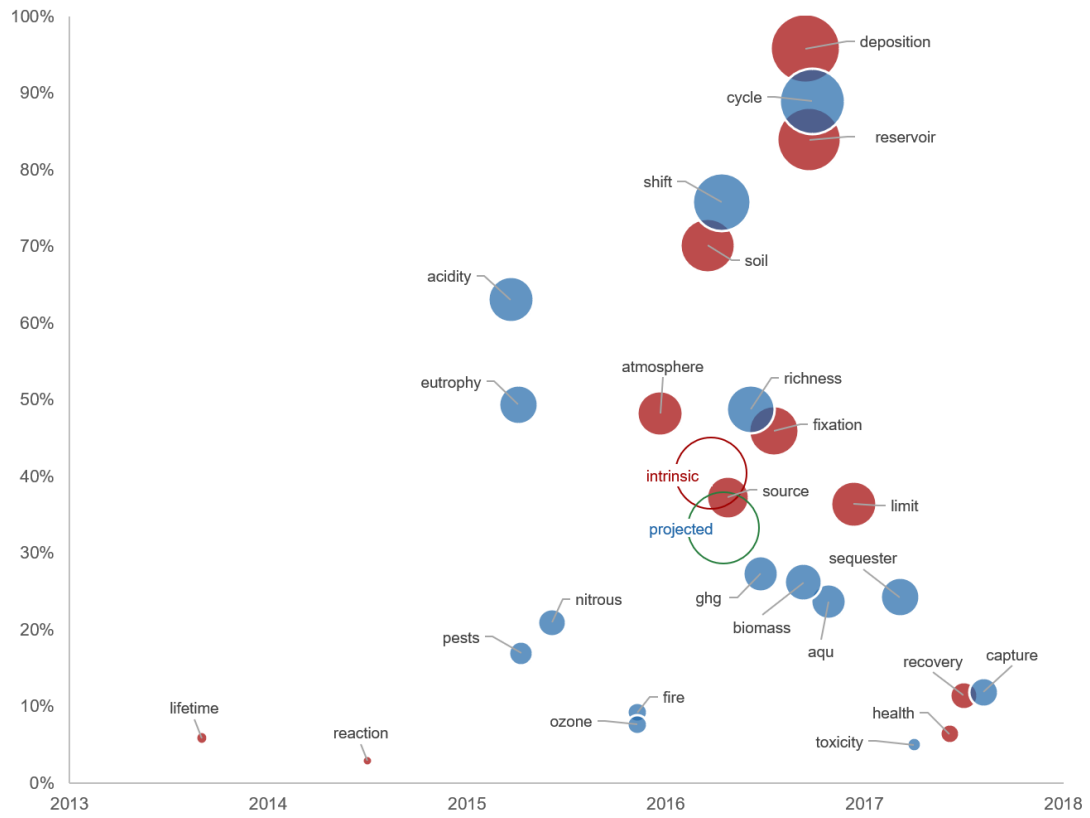


Figure 5. Evolution of facets in the analyzed literature over the two decades 2010–2020. The coordinates of each facet represent the centroid of the publication years of the articles where the facet appeared (horizontal axis, more recent to the right) and the fraction of papers where it appears (vertical axis, more frequent to the top). Symbol areas correspond to the total number of instances. The hollow circles represent the centroids for the ensemble intrinsic (red) and projected (blue) facets.

4.2. FFP

The assessment of stocks, deposition, nitrogen cycle aspects, and changes in the community structure (richness and species composition shifts) are the intrinsic and project facets that most methods seem relatively well-suited to determine. However, these two types of facets are best served by different categories of methods.

CMs perform well for determining the origin of nitrogen, although they vary in their capacity to distinguish specific atmospheric chemical species and therefore their monitoring fitness may be biased. Physical indicators demonstrate that while total tissue nitrogen (TNT) reliably signals general enrichment [60], it responds unevenly to different chemical inputs, often prioritizing nitrate and reduced ammonium in wet precipitation over dry gaseous forms and not distinguishing species [22,60,61]. The cost of reducing nitrate favors assimilation of already-reduced nitrogen (ammonia, organic compounds) by mosses, which may directly alter enzyme activity (EZA) and amino acid (AAS) readings. Conversely, SGF can pinpoint fine parameters like the soil compensation point for gaseous ammonia, though ambient temperature variations can alter readings by an order of magnitude [22,62]. Short-lived reactive radicals (NO_x) are best captured via tissue concentration kinetics in sensitive lichens [63], which show linear uptake curves within weeks.

On the other hand, BMs monitor the effects of Nr in the ecosystem, but this effect may be affected by multiple factors often working in opposite directions, e.g., the time lag of the ecosystem response (the endpoint, as opposed to the chemically characterizable midpoint [64]) and the persistence of the effects. While tissue-based CMs (TNT, AAS, NPR) can show the incorporation and washout of compounds quickly and as they happen,

usually within weeks to months, some effects induce cascades at the community level that only BMs can observe [65]. Ellenberg's N (ELN) and Functional Nitrogen (FNS) look at the plant floristic profiles, and these can be affected by persistent competitive exclusion by nitrophilous species that can last years or decades [66]. Ectomycorrhizal fungal (EMF) sporocarp production can normalize within 5 years; underlying soil mycelial community profiles remain altered for decades [67]. An increased plant vulnerability to herbivorous insects and fungal infections due to a past history of high tissue nitrogen no longer detectable through TNT or AAS could be revealed by invertebrate response (INR) [68]. In that sense, BMs act as accumulators and registers of Nr effects long after the deposition took place and are the best fit to reveal the past history of ecosystem impact.

Several methods can also be used to indirectly monitor other environmental stresses, and their fitness might change by use in combination. For example, tropospheric ozone accelerates leaf aging (a CFL target) [69], which can result in root biomass decline that could be detected through EMF [70]; both methods in combination could be fit as a proxy for ozone impact. Wildfire risk in desertified ecosystems might be predicted through rapid nitrophilous grass growth and subsequent dryout that can be favored by even small CRL exceedances [71–73]. Combining C:N ratio (CNR) and gas fluxes (SGF) may assess denitrification rate, which in turn may help with monitoring N_2O emissions for global warming potential calculations.

While most methods can be considered as universally applicable, some methods' parameters or required datasets are tailored for the region of use—for example, though the Ellenberg method is conceptually unique, its use depends on localized lists of plants. A method well suited for a region may need a specific set of parameters lest it gives the wrong values.

4.3. Limitations

The main strength in this study, but also its main limitation, is the literature selection strategy. Over 11,000 references on reactive nitrogen monitoring in ecosystems can be found in peer-reviewed literature, which cannot possibly be reviewed manually. While an automated keyword analysis is certainly doable and more so with the aid of a modern large-language model (not available at the time we initiated this study), it may offer a partial picture by potentially missing semantics that are crucial here: how to identify and attribute the facets offered by the methods. We observed this prima facie when having to prune the snowball by over 80%, as many papers were not actually establishing the method-purpose facet we were investigating (and that a blind keyword analysis might have taken for good). We therefore decided to do a manual review, which would enable us to capture the actual facets and measurements contained in the corpus. This necessarily entailed sampling the literature to select which references to analyze through the snowball strategy, but this choice also introduces a known bias toward well-established methodologies rooted in the reference seeds we used and for which FFP uncertainty might be low.

In addition, and despite its use in a tightly controlled workflow, the use of a purpose-specific AI for supplementary literature discovery, retrieval, and facet confirmation might have reinforced bias towards established, highly cited methods. The AI-assisted search was seeded from the facets set for the 2000–2020 literature sample, but the timeframe was not forward-restricted and the search branches might be overlooking potentially emerging methods or facets such as environmental DNA metabarcoding, remote sensing, or machine-learning models because they might not be sufficiently cited. It should be noted, though, that these technologies do not yet constitute methods to directly assess Nr, although they could become very useful tools to provide data for BM and CM—for example, helping assess the extent of populations of known, ground-truthed species in ELN or FNS, or ammonia levels in atmospheric layers or pinpointing sources in SGF, or

finding new targets for EZA. Future updates to the FFP matrix, once a substantial mass of cases is built over the next decade, will doubtlessly introduce more facets, as exemplified in the preference shift clearly observed in Figure 5, and newer tools that now may not be methods might soon become so.

Our choice to try a well-known ordination technique, the normalized weighted sums with nonevidence penalty (WS), might be considered too straightforward. While we created simple H, M, and L suitability levels as an ordinal score and tried to be consistent along comparable facets, the thresholds for each level were based on very rough rules (such as the 2:1 ratio) that themselves rely on simple lineal or logarithmic assumptions. Other thresholds, more levels, or nonlinear weighting schemes might likely bring about different ordinations, possibly changing our results. Additionally, in our formula we normalized for amount of evidence with penalization (facets lacking evidence bumped down the method ranking). While this is a well-established method in the decision-making literature, for some facets the boundary between "no evidence" and "low" is blurry—most prominently for binary-type facets such as *limit* or *lifetime* that effectively lack a "low" score.

Finally, the FFP assessment is inherently context-dependent: a method with a low global WS may be the only adequate tool in a specific context. Zarzycki (ZAR), for instance, has the lowest overall WS but provides irreplaceable historical baseline data for Polish and Central European flora. Method rankings should therefore always be interpreted alongside the specific monitoring question rather than applied as absolute quality measures.

4.4. Guidance

Considering the above limitations, we can suggest using the results of our comparative analysis to help the selection of the best fit between methods and purpose in a monitoring endeavor, across four aspects:

(i) The FFP matrix (Figure 1) shows, at a glance, which methods seem a better fit for a particular purpose, be it a component to be measured (intrinsic facet), its effects (projected facet) and the practicalities (extrinsic facets). The selection could start by either deciding what to measure (intrinsic facet, top tier of the table) or what for (projected facet, middle tier), according to the monitoring needs. Methods having a high suitability (black) for most facets of interest should be considered first, and a majority rule could be enacted. The extrinsic facets (bottom tier of the table) could rule out those initially selected methods that could not meet the resources available, scale or scope, precision required, etc. If the selection runs out of high-suitability methods, the practitioner could consider facets with medium or low suitability (grays). However, a necessary facet having a blank cell should discard the method for that purpose.

(ii) In the context of specific types of monitoring, Figure 2 can help zeroing within chemistry- or biodiversity-based methods. Often, the type of monitoring has been already pre-set. For example, citizen-science campaigns, or analyses of nitrophilic plant distribution data, will almost exclusively be reliant on biodiversity-based methods, whereas atmospheric-targeted programs such as those in remote sensing will only concern chemistry-based methods. This figure ranks the methods across the facet types but within each method type. The practitioner may select the type and run from left to right within each block and pick the first method that seems practical for the monitoring program.

(iii) Sometimes a method seems a good choice according to the above protocol, but for practical reasons is not feasible. In this case, perhaps an alternate method could be chosen. This can be helped by Figure 3: methods appearing close together are the most similar according to overall facet suitability, and a reasonable alternate candidate could be examined among the methods closest to the optimal one.

(iv) As methods evolve over time, a selection factor could also be the comparability of monitoring results. Figure 5 helps observe what intrinsic and projected facets are becoming more important, helping guide the choice towards methods strong for those facets enabling a data provision and synergy that can facilitate comparison with other, concurrent monitoring programs, leading to gap filling from which knowledge can be gained.

Finally, examples of use of methods, and a good understanding of the facets, could be quite useful to help handling the above aspects. These details are provided in Supplementary File S2.

5. Conclusions

No single method is adequate for comprehensive nitrogen monitoring. Chemistry-based methods generally outperformed biodiversity- and transplant-based methods across most facets, led by critical loads (CRL), total tissue nitrogen (TNT), and nitrogen isotopes (NIS) (Figure 2). CRL was the only method to provide assessable evidence across all 35 facets. Biodiversity-based methods, particularly lichen diversity (LDV), ectomycorrhizal fungi (EMF) and Ellenberg's N (ELN), provided the strongest signals for long-term community-level change, the facets most directly relevant to biodiversity conservation policy. Transplant-based methods occupy a methodologically intermediate position and shift greatly along facet typologies; lichen transplants (LTR) ranked substantially closer to CM than plant transplants (PTR), likely reflecting their greater response precision.

Effective assessment and, eventually, management of reactive nitrogen pollution requires monitoring systems that can simultaneously provide early physiological alerts, quantify deposition fluxes, and track long-term ecological trajectories. A deliberate combination of complementary methods, selected according to the FFP framework proposed here through the sequential and iterative process described in the Guidance subsection, offers a defensible and policy-relevant approach that can complement existing procedures based on specific methods.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13080452/s1: File S1, Data table and literature corpus list [2,18,20–23,26,67,71,74–153]; File S2, Detailed method-by-method and facet-by-facet description, and discussion with additional references [154–272]; File S3, Excel template with facet-method scoring breakdown and WS calculations.

Author Contributions: Both authors contributed equally to this work. Conceptualization, I.G.-F. and A.H.A.; methodology, A.H.A.; validation, I.G.-F. and A.H.A.; formal analysis, A.H.A.; investigation, I.G.-F.; data curation, I.G.-F. and A.H.A.; writing—original draft preparation, I.G.-F.; writing—review and editing, A.H.A.; visualization, A.H.A.; supervision, A.H.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data files are available in the Supplementary Materials.

Acknowledgments: During the preparation of this manuscript, the authors used the following AI-driven tools: (1) consensus.app for additional reference recovery and citation checks; (2) Claude Sonnet 4.6 to help with the translation, condensation, and restructuring of the original large, Spanish-language research manuscript; (3) Grammarly v 1.2 for spelling and syntax checks. The authors have reviewed and edited the output and take full responsibility for the content of this publication. The authors wish to thank three anonymous reviewers for constructive criticism of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AAS	Amino acids
AI	Artificial Intelligence
ANOSIM	Analysis of similarity
BM	Biodiversity-based method(s)
CFL	Chlorophyll fluorescence
CM	Chemistry-based method(s)
CNR	C:N ratio
CRL	Critical loads
E	Number of evidence
ELN	Ellenberg's N
EMF	Ectomycorrhizal fungi
EZA	Enzyme activity
FFP	Fitness for purpose
FNS	Functional Nitrogen Index for Species
GS	Google Scholar
H	Facet with high suitability
INR	Invertebrate response
L	Facet with low suitability
LAN	Landolt
LDV	Lichen biodiversity
LTR	Lichen transplants
M	Facet with medium suitability
N	Facets with no available evidence | Nitrogen [context-dependent]
NIS	Nitrogen isotopes
NMDS	Non-metric multidimensional scaling
NPR	N:P ratio
Nr	Reactive nitrogen
PTR	Plant transplants
SGF	Gas fluxes
TDP	Tsyganov, Didukh & Plyuta
Tg	Teragram
TM	Transplant-based method(s)
TNT	Total nitrogen in tissues
WoS	Web of Science
WS	Evidence-normalized weighted sum
ZAR	Zarzycki

References

1. Crutzen, P.J. The "Anthropocene". *J. Phys. IV JP* **2002**, *12*, 1–5. [CrossRef]
2. Fowler, D.; Coyle, M.; Skiba, U.; Sutton, M.A.; Cape, J.N.; Reis, S.; Sheppard, L.J.; Jenkins, A.; Grizzetti, B.; Galloway, J.N.; et al. The Global Nitrogen Cycle in the Twentyfirst Century. *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130164. [CrossRef] [PubMed]
3. Vitousek, P.M.; Aber, J.D.; Howarth, R.W.; Likens, G.E.; Matson, P.A.; Schindler, D.W.; Schlesinger, W.H.; Tilman, D.G. Human Alteration of the Global Nitrogen Cycle: Sources and Consequences. *Ecol. Appl.* **1997**, *7*, 737–750. [CrossRef]
4. Ritchie, H. How Many People Does Synthetic Fertilizer Feed? Available online: https://archive.ourworldindata.org/20260518-090244/how-many-people-does-synthetic-fertilizer-feed.html (accessed on 1 March 2026).
5. Pagans, E.; Barrena, R.; Font, X.; Sánchez, A. Ammonia Emissions from the Composting of Different Organic Wastes. Dependency on Process Temperature. *Chemosphere* **2006**, *62*, 1534–1542. [CrossRef]
6. Fowler, D.; Steadman, C.E.; Stevenson, D.; Coyle, M.; Rees, R.M.; Skiba, U.M.; Sutton, M.A.; Cape, J.N.; Dore, A.J.; Vieno, M.; et al. Effects of Global Change during the 21st Century on the Nitrogen Cycle. *Atmos. Chem. Phys.* **2015**, *15*, 13849–13893. [CrossRef]
7. Galloway, J.N.; Aber, J.D.; Erisman, J.W.; Seitzinger, S.P.; Howarth, R.W.; Cowling, E.B.; Cosby, B.J. The Nitrogen Cascade. *Bioscience* **2003**, *53*, 341–356. [CrossRef]

8. Ariño, A.H.; Sánchez Gimeno, B.; Pérez de Zabalza, A.; Ibáñez, R.; Ederra, A.; Santamaría, J.M. Influence of Nitrogen Deposition on Plant Biodiversity at Natura 2000 Sites in Spain. In *Nitrogen Deposition and Natura 2000: Science and Practice in Determining Environmental Impacts*; Hicks, W.K., Whitfield, C.P., Bealey, W.J., Sutton, M.A., Eds.; European Science Foundation: Strasbourg, France, 2011; pp. 140–146.
9. U.S. EPA. Air Pollutant Emissions Trends Data. National Tier 1 CAPS Trends. Available online: https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data (accessed on 1 March 2026).
10. Avery, A.A. Infantile Methemoglobinemia: Reexamining the Role of Drinking Water Nitrates. *Environ. Health Perspect.* **1999**, *107*, 583–586. [CrossRef] [PubMed]
11. Shaban, J.; Al-Najar, H.; Kocadal, K.; Almghari, K.; Saygi, S. The Effect of Nitrate-Contaminated Drinking Water and Vegetables on the Prevalence of Acquired Methemoglobinemia in Beit Lahia City in Palestine. *Water* **2023**, *15*, 1989. [CrossRef]
12. Galaviz-Villa, I.; Landeros-Sánchez, C.; Castañeda-Chávez, M.d.R.; Martínez-Dávila, J.P.; Pérez-Vázquez, A.; Nikolskii-Gavrilov, I.; Lango-Reynoso, F. Agricultural Contamination of Subterranean Water with Nitrates and Nitrites: An Environmental and Public Health Problem. *J. Agric. Sci.* **2010**, *2*, 17–30. [CrossRef]
13. Khreis, H.; Cirach, M.; Mueller, N.; de Hoogh, K.; Hoek, G.; Nieuwenhuijsen, M.J.; Rojas-Rueda, D. Outdoor Air Pollution and the Burden of Childhood Asthma across Europe. *Eur. Respir. J.* **2019**, *54*, 1802194. [CrossRef]
14. EEA. *Air Quality in Europe—2020 Report*; EEA: København K, Denmark, 2020. Available online: https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2020-report (accessed on 1 March 2026).
15. Shibata, H.; Baron, J.S.; Leach, A.; Liptzin, D.; Oita, A.; Weinmann, T.; Adhya, T.; Allen, I.; Alonso, R.; Artioli, Y.; et al. *Guidance Document on Nitrogen Impact Assessment Methods International Nitrogen Management System*; INMS Guidance; Sutton, M.A., Schlegel, M., Baron, J.S., van Grinsven, H.M.J., Eds.; UK Centre for Ecology & Hydrology: Edinburgh, UK, 2025. [CrossRef]
16. Lovett, G.M.; Burns, D.A.; Driscoll, C.T.; Jenkins, J.C.; Mitchell, M.J.; Rustad, L.; Shanley, J.B.; Likens, G.E.; Haeuber, R. Who Needs Environmental Monitoring? *Front. Ecol. Environ.* **2007**, *5*, 253–260. [CrossRef]
17. Hamilton, S.H.; Pollino, C.A.; Stratford, D.S.; Fu, B.; Jakeman, A.J. Fit-for-Purpose Environmental Modeling: Targeting the Intersection of Usability, Reliability and Feasibility. *Environ. Model. Softw.* **2022**, *148*, 105278. [CrossRef]
18. Martínez, D.N.; Díaz-Álvarez, E.A.; de la Barrera, E. Selecting Biomonitors of Atmospheric Nitrogen Deposition: Guidelines for Practitioners and Decision Makers. *Nitrogen* **2021**, *2*, 308–320. [CrossRef]
19. Ellenberg, H.; Düll, R.; Wirth, V.; Werner, W.; Paulißen, D. *Zeigerwerte Von Pflanzen in Mitteleuropa*, 2nd ed.; Verlag Erich Goltze KG: Göttingen, Germany, 1991.
20. Sutton, M.A.; Pitcairn, C.E.R.; Whitfield, C.P. (Eds.) *Bioindicator and Biomonitoring Methods for Assessing the Effects of Atmospheric Nitrogen on Statutory Nature Conservation Sites*; JNCC Report No. 356; JNCC: Peterborough, UK, 2004; ISSN 0963-8091. Available online: https://data.jncc.gov.uk/data/ff165313-018d-46b9-9c4d-3f3dc25d9a27/JNCC-Report-356-FINAL-WEB.pdf (accessed on 1 March 2026).
21. van Dobben, H.F.; de Vries, W. The Contribution of Nitrogen Deposition to the Eutrophication Signal in Understorey Plant Communities of European Forests. *Ecol. Evol.* **2017**, *7*, 214–227. [CrossRef] [PubMed]
22. Díaz-Álvarez, E.A.; Lindig-Cisneros, R.; de la Barrera, E. Biomonitors of Atmospheric Nitrogen Deposition: Potential Uses and Limitations. *Conserv. Physiol.* **2018**, *6*, coy011. [CrossRef] [PubMed]
23. Nayeli Martínez, D.; de la Barrera, E. Physiological Screening of Ruderal Weed Biomonitors of AtmosPheric Nitrogen DePosition. *Bot. Sci.* **2021**, *99*, 573–587. [CrossRef]
24. Tichý, L.; Axmanová, I.; Dengler, J.; Guarino, R.; Jansen, F.; Midolo, G.; Nobis, M.P.; Van Meerbeek, K.; Aćić, S.; Attorre, F.; et al. Ellenberg-Type Indicator Values for European Vascular Plant Species. *J. Veg. Sci.* **2023**, *34*, e13168. [CrossRef]
25. Bobbink, R.; Hicks, K.; Galloway, J.; Spranger, T.; Alkemade, R.; Ashmore, M.; Bustamante, M.; Cinderby, S.; Davidson, E.; Dentener, F.; et al. Global Assessment of Nitrogen Deposition Effects on Terrestrial Plant Diversity: A Synthesis. *Ecol. Appl.* **2010**, *20*, 30–59. [CrossRef] [PubMed]
26. Zhang, Q.; Li, Y.; Wang, M.; Wang, K.; Meng, F.; Liu, L.; Zhao, Y.; Ma, L.; Zhu, Q.; Xu, W.; et al. Atmospheric Nitrogen Deposition: A Review of Quantification Methods and Its Spatial Pattern Derived from the Global Monitoring Networks. *Ecotoxicol. Environ. Saf.* **2021**, *216*, 112180. [CrossRef] [PubMed]
27. Faix, A. Consensus: Using AI to Analyze Scientific Literature. *Libr. Trends* **2025**, *73*, 344–354. [CrossRef]
28. Liiv, I. Review Seriation and Matrix Reordering Methods: An Historical Overview. *Stat. Anal. Data Min.* **2010**, *3*, 70–91. [CrossRef]
29. Hwang, C.-L.; Yoon, K. *Multiple Attribute Decision Making*; Lecture Notes in Economics and Mathematical Systems; Springer: Berlin/Heidelberg, Germany, 1981; Volume 186. [CrossRef]
30. Buja, A.; Swayne, D.F.; Littman, M.L.; Dean, N.; Hofmann, H.; Chen, L. Data Visualization with Multidimensional Scaling. *J. Comput. Graph. Stat.* **2008**, *17*, 444–472. [CrossRef]
31. Somerfield, P.J.; Clarke, K.R.; Gorley, R.N. A Generalised Analysis of Similarities (ANOSIM) Statistic for Designs with Ordered Factors. *Austral Ecol.* **2021**, *46*, 901–910. [CrossRef]
32. Gower, J.C. A General Coefficient of Similarity and Some of Its Properties. *Biometrics* **1971**, *27*, 857. [CrossRef]

33. Hammer, O.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontol. Electron.* **2001**, *4*, 9.
34. Näsholm Ann-Brittedfast, T.; Ericsson, A.; Nordén, L. Accumulation of Amino Acids in Some Boreal Forest Plants in Response to Increased Nitrogen Availability. *New Phytol.* **1994**, *126*, 137–143. [CrossRef]
35. Murchie, E.H.; Lawson, T. Chlorophyll Fluorescence Analysis: A Guide to Good Practice and Understanding Some New Applications. *J. Exp. Bot.* **2013**, *64*, 3983–3998. [CrossRef] [PubMed]
36. Nilsson, J.; Grennfelt, P. *Critical Loads for Sulfur and Nitrogen*; Nordic Council of Ministers: Skokloster, Sweden, 1988.
37. Waksman, S.A.; Tenney, F.G. The Composition of Natural Organic Materials and Their Decomposition in the Soil: I. Methods of Quantitative Analysis of Plant Materials. *Soil Sci.* **1927**, *24*, 275–284. [CrossRef]
38. Beevers, L.; Hageman, R.H. Nitrate Reduction in Higher Plants. *Annu. Rev. Plant Physiol.* **1969**, *20*, 495–522. [CrossRef]
39. Denmead, O.T.; Raupach, M.R. *Methods for Measuring Atmospheric Gas Transport in Agricultural and Forest Systems*; ASA, CSSA, and SSSA: Madison, WI, USA, 1993; pp. 19–43. [CrossRef]
40. Shearer, G.; Kohl, D. N_2-Fixation in Field Settings: Estimations Based on Natural 15N Abundance. *Aust. J. Plant Physiol.* **1986**, *13*, 699–756. [CrossRef]
41. Koerselman, W.; Meuleman, A.F.M. The Vegetation N:P Ratio: A New Tool to Detect the Nature of Nutrient Limitation. *J. Appl. Ecol.* **1996**, *33*, 1441. [CrossRef] [PubMed]
42. Kjeldahl, J. Neue Methode Zur Bestimmung Des Stickstoffs in Organischen Körpern. *Fresenius' Z. Für Anal. Chem.* **1883**, *22*, 366–382. [CrossRef]
43. Ellenberg, H. Zeigerwerte Der Gefässpflanzen Mitteleuropas. *Scr. Geobot.* **1974**, *9*, 1–97.
44. Wallenda, T.; Kottke, I. Nitrogen Deposition and Ectomycorrhizas. *New Phytol.* **1998**, *139*, 169–187. [CrossRef]
45. Diekmann, M.; Falkengren-Grerup, U. A New Species Index for Forest Vascular Plants: Development of Functional Indices Based on Mineralization Rates of Various Forms of Soil Nitrogen. *J. Ecol.* **1998**, *86*, 269–283. [CrossRef]
46. Haddad, N.M.; Haarstad, J.; Tilman, D. The Effects of Long-Term Nitrogen Loading Grassland Insect Communities. *Oecologia* **2000**, *124*, 73–84. [CrossRef] [PubMed]
47. Landlot, E. *Ökologische Zeigerwerte Zur Schweizer Flora*; Veröffentlichungen des Geobotanischen Institutes der ETH: Zürich, Switzerland, 1977.
48. Van Herk, C.M. Mapping of Ammonia Pollution with Epiphytic Lichens in the Netherlands. *Lichenologist* **1999**, *31*, 9–20. [CrossRef]
49. Tsyganov, D.N. *Phytoindication of Ecological Regimes in the Mixed Coniferous-Broad-Leaved Forest Subzone*; Nauka, Ed.; Nauka: Moscow, Russia, 1983.
50. Didukh, Y.P.; Plyuta, P.G. Fitoindikatciia Ekologicheskikh Faktorov. In *The Phytoindication of Ecological Factors*; Naukova Dumka: Kiev, Ukraine, 1994.
51. Zarzycki, K. Ekologiczne Liczby Wskaźnikowe Roślin Naczyniowych Polski. In *Indicator Values of Vascular Plants in Poland*; Instytut Botaniki, Polska Akademia Nauk: Kraków, Poland, 1984.
52. Brodo, I.M. Transplant Experiments with Corticolous Lichens Using a New Technique. *Ecology* **1961**, *42*, 838–841. [CrossRef]
53. Goodman, G.; Roberts, T. Plants and Soils as Indicators of Metals in the Air. *Nature* **1971**, *231*, 287–292. [CrossRef] [PubMed]
54. Gamfeldt, L.; Lefcheck, J.S.; Byrnes, J.E.K.; Cardinale, B.J.; Duffy, J.E.; Griffin, J.N. Marine Biodiversity and Ecosystem Functioning: What's Known and What's Next? *Oikos* **2015**, *124*, 252–265. [CrossRef]
55. Dai, M.; Zhao, Y.; Chai, F.; Chen, M.; Chen, N.; Chen, Y.; Cheng, D.; Gan, J.; Guan, D.; Hong, Y.; et al. Persistent Eutrophication and Hypoxia in the Coastal Ocean. *Camb. Prism. Coast. Futur.* **2023**, *1*, e19. [CrossRef]
56. Hutchins, D.A.; Capone, D.G. The Marine Nitrogen Cycle: New Developments and Global Change. *Nat. Rev. Microbiol.* **2022**, *20*, 401–414. Correction in *Nat. Rev. Microbiol.* **2022**, *20*, 444. https://doi.org/10.1038/s41579-022-00752-7. [CrossRef] [PubMed]
57. Rast, W.; Thornton, J.A. Trends in Eutrophication Research and Control. *Hydrol. Process.* **1996**, *10*, 295–313. [CrossRef]
58. Hillebrand, H.; Blasius, B.; Borer, E.T.; Chase, J.M.; Downing, J.A.; Eriksson, B.K.; Filstrup, C.T.; Harpole, W.S.; Hodapp, D.; Larsen, S.; et al. Biodiversity Change Is Uncoupled from Species Richness Trends: Consequences for Conservation and Monitoring. *J. Appl. Ecol.* **2018**, *55*, 169–184. [CrossRef]
59. Mattoo, R.; Mallikarjuna, S.B.; Hemachar, N. Ecosystem and Climate Change Impacts on the Nitrogen Cycle and Biodiversity. *Nitrogen* **2025**, *6*, 78. [CrossRef]
60. Walker, J.T.; Chen, X.; Wu, Z.; Schwede, D.; Daly, R.; Djurkovic, A.; Oishi, A.C.; Edgerton, E.; Bash, J.; Knoepp, J.; et al. Atmospheric Deposition of Reactive Nitrogen to a Deciduous Forest in the Southern Appalachian Mountains. *Biogeosciences* **2023**, *20*, 971–995. [CrossRef] [PubMed]
61. Dong, Y.P.; Liu, X.Y. Fates of Atmospheric Reactive Nitrogen Emissions from Polluted Regions. *Glob. Change Biol.* **2026**, *32*, e70664. [CrossRef] [PubMed]
62. Delaria, E.R.; Cohen, R.C. Measurements of Atmosphere-Biosphere Exchange of Oxidized Nitrogen and Implications for the Chemistry of Atmospheric NO_x. *Acc. Chem. Res.* **2023**, *56*, 1720–1730. [CrossRef] [PubMed]

63. Niepsch, D.; Clarke, L.J.; Tzoulas, K.; Cavan, G. Distinguishing Atmospheric Nitrogen Compounds (Nitrate and Ammonium) in Lichen Biomonitoring Studies. *Environ. Sci. Process. Impacts* **2021**, *23*, 2021–2036. [CrossRef] [PubMed]
64. De Schryver, A.M.; van Zelm, R.; Huijbregts, M.A.J.; Goedkoop, M. Addressing Land Use and Ecotoxicological Impacts in Life Cycle Assessments of Food Production Technologies. In *Environmental Assessment and Management in the Food Industry*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 177–206. [CrossRef]
65. Liu, J.; Zhu, M.; Shi, X.; Hui, C.; Sun, Y.; Zhang, R.; Jin, D.; Li, Z.; Chen, H.; Zhao, Z. Cascading Impacts of Nitrogen Deposition on Soil Microbiome and Herbivore Communities in Desert Steppes. *Sci. Total Environ.* **2024**, *955*, 176892. [CrossRef] [PubMed]
66. Pitcairn, C.E.R.; Fowler, D.; Leith, I.D.; Sheppard, L.J.; Sutton, M.A.; Kennedy, V.; Okello, E. Bioindicators of Enhanced Nitrogen Deposition. *Environ. Pollut.* **2003**, *126*, 353–361. [CrossRef] [PubMed]
67. Pardo, L.H.; Fenn, M.E.; Goodale, C.L.; Geiser, L.H.; Driscoll, C.T.; Allen, E.B.; Baron, J.S.; Bobbink, R.; Bowman, W.D.; Clark, C.M.; et al. Effects of Nitrogen Deposition and Empirical Nitrogen Critical Loads for Ecoregions of the United States. *Ecol. Appl.* **2011**, *21*, 3049–3082. [CrossRef]
68. Borer, E.T.; Stevens, C.J. Nitrogen Deposition and Climate: An Integrated Synthesis. *Trends Ecol. Evol.* **2022**, *37*, 541–552. [CrossRef] [PubMed]
69. Juráň, S.; Grace, J.; Urban, O. Temporal Changes in Ozone Concentrations and Their Impact on Vegetation. *Atmosphere* **2021**, *12*, 82. [CrossRef]
70. Wu, J.; Hou, X.Z.; Zhu, J.L.; Miao, R.H.; Adomako, M.O. Nitrogen Addition and Drought Impose Divergent Effects on Belowground Bud Banks of Grassland Community: A Meta-Analysis. *Front. Plant Sci.* **2024**, *15*, 1464973. [CrossRef] [PubMed]
71. Ochoa-Hueso, R.; Allen, E.B.; Branquinho, C.; Cruz, C.; Dias, T.; Fenn, M.E.; Manrique, E.; Pérez-Corona, M.E.; Sheppard, L.J.; Stock, W.D. Nitrogen Deposition Effects on Mediterranean-Type Ecosystems: An Ecological Assessment. *Environ. Pollut.* **2011**, *159*, 2265–2279. [CrossRef] [PubMed]
72. Pan, B.; Xia, L.; Lam, S.K.; Wang, E.; Zhang, Y.; Mosier, A.; Chen, D. A Global Synthesis of Soil Denitrification: Driving Factors and Mitigation Strategies. *Agric. Ecosyst. Environ.* **2022**, *2022*, 107850. [CrossRef]
73. Caspi, T.; Hartz, L.A.; Soto Villa, A.E.; Loesberg, J.A.; Robins, C.R.; Meyer, W.M. Impacts of Invasive Annuals on Soil Carbon and Nitrogen Storage in Southern California Depend on the Identity of the Invader. *Ecol. Evol.* **2019**, *9*, 4980–4993. [CrossRef] [PubMed]
74. Arróniz-Crespo, M.; Ochoa-Hueso, R.; Manrique Reol, E. Biomonitorización Del Depósito de Nitrógeno Atmosférico En México: Detección y Prevención de Daños En Ecosistemas Naturales. In *Avances y Perspectivas de la Depositación Ácida en México*; Universidad Autónoma del Carmen: Campeche, Mexico, 2012; pp. 81–98.
75. Baumann, M.; Dittrich, S.; Körner, M.; von Oheimb, G. Temporal Changes in the Ground Vegetation in Spruce Forests in the Erzgebirge (Ore Mountains)—Bryophytes Are Better Indicators of the Impact of Liming and of Sulphur and Nitrogen Deposition than the Herb Layer. *Appl. Veg. Sci.* **2021**, *24*, e12598. [CrossRef]
76. Bobbink, R.; Tomassen, H.; Weijters, M.; van den Berg, L.; Strengbom, J.; Braun, S.; Nordin, A.; Schütz, K.; Hettelingh, J.-P. *Effects and Empirical Critical Loads of Nitrogen for Europe*; Springer: Dordrecht, The Netherlands, 2015. [CrossRef]
77. Branquinho, C.; Pinho, P.; Dias, T.; Cruz, C. Lichen Transplants at Our Service for Atmospheric NH 3 Deposition Assessments. *Bibl. Lichenol. J. Cramer Gebrüder Borntraeger Verlagsbuchhandlung* **2015**, *2010*, 103–112.
78. Carter, T.S.; Clark, C.M.; Fenn, M.E.; Jovan, S.; Perakis, S.S.; Riddell, J.; Schaberg, P.G.; Greaver, T.L.; Hastings, M.G. Mechanisms of Nitrogen Deposition Effects on Temperate Forest Lichens and Trees. *Ecosphere* **2017**, *8*, e01717. [CrossRef] [PubMed]
79. Chalmandrier, L.; Albouy, C.; Pellissier, L. Species Pool Distributions along Functional Trade-Offs Shape Plant Productivity-Diversity Relationships. *Sci. Rep.* **2017**, *7*, 15405. [CrossRef] [PubMed]
80. Clark, C.M.; Simkin, S.M.; Allen, E.B.; Bowman, W.D.; Belnap, J.; Brooks, M.L.; Collins, S.L.; Geiser, L.H.; Gilliam, F.S.; Jovan, S.E.; et al. Potential Vulnerability of 348 Herbaceous Species to Atmospheric Deposition of Nitrogen and Sulfur in the United States. *Nat. Plants* **2019**, *5*, 697–705. [CrossRef] [PubMed]
81. Clark, C.M.; Bell, M.D.; Boyd, J.W.; Compton, J.E.; Davidson, E.A.; Davis, C.; Fenn, M.E.; Geiser, L.; Jones, L.; Blett, T.F. Nitrogen-induced Terrestrial Eutrophication: Cascading Effects and Impacts on Ecosystem Services. *Ecosphere* **2017**, *8*, e01877. [CrossRef] [PubMed]
82. CLO. *Exceedance of Critical Loads for Nitrogen Deposition on Nature, 1995–2016 (Indicator 2045, Version 04, 6 May 2019)*; CLO: The Hague, The Netherlands, 2019.
83. Delon, C.; Galy-Lacaux, C.; Serça, D.; Loubet, B.; Camara, N.; Gardrat, E.; Saneh, I.; Fensholt, R.; Tagesson, T.; Le Dantec, V.; et al. Soil and Vegetation-Atmosphere Exchange of NO, NH_3, and N_2O from Field Measurements in a Semi Arid Grazed Ecosystem in Senegal. *Atmos. Environ.* **2017**, *156*, 36–51. [CrossRef]
84. Díaz-Álvarez, E.A.; de la Barrera, E.; Barrios-Hernández, E.Y.; Arróniz-Crespo, M. Morphophysiological Screening of Potential Organisms for Biomonitoring Nitrogen Deposition. *Ecol. Indic.* **2018**, *2020*, 105729. [CrossRef]
85. Diekmann, M.; Falkengren-Grerup, U. Prediction of Species Response to Atmospheric Nitrogen Deposition by Means of Ecological Measures and Life History Traits. *J. Ecol.* **2002**, *90*, 108–120. [CrossRef]

86. Diekmann, M.; Brunet, J.; Rühling, Å.; Falkengren-Grerup, U. Effects of Nitrogen Deposition: Results of a Temporal-Spatial Analysis of Deciduous Forests in South Sweden. *Plant Biol.* **1999**, *1*, 471–481. [CrossRef]
87. Dirnböck, T.; Pröll, G.; Austnes, K.; Beloica, J.; Beudert, B.; Canullo, R.; De Marco, A.; Fornasier, M.F.; Futter, M.; Goergen, K.; et al. Currently Legislated Decreases in Nitrogen Deposition Will Yield Only Limited Plant Species Recovery in European Forests. *Environ. Res. Lett.* **2018**, *13*, 125010. [CrossRef]
88. Dzwonko, Z.; Loster, S. Testing of Ellenberg and Zarzycki Indicator Values as Predictors of Soil and Light Conditions in Woodlands. *Fragm. Florist. Geobot.* **2000**, *45*, 49–62.
89. Evangelista, A.; Frate, L.; Carranza, M.L.; Attorre, F.; Pelino, G.; Stanisci, A. Changes in Composition, Ecology and Structure of High-Mountain Vegetation: A Re-Visitation Study over 42 Years. *AoB Plants* **2016**, *8*, plw004. [CrossRef] [PubMed]
90. Falkengren-Grerup, U.; Schöttelndreier, M. Vascular Plants as Indicators of Nitrogen Enrichment in Soils. *Plant Ecol.* **2004**, *172*, 51–62. [CrossRef]
91. Fan, J.; Luo, R.; McConkey, B.G.; Ziadi, N. Effects of Nitrogen Deposition and Litter Layer Management on Soil CO_2, N_2O, and CH_4 Emissions in a Subtropical Pine Forestland. *Sci. Rep.* **2020**, *10*, 8959. [CrossRef] [PubMed]
92. Fenn, M.E.; Allen, E.B.; Weiss, S.B.; Jovan, S.; Geiser, L.H.; Tonnesen, G.S.; Johnson, R.F.; Rao, L.E.; Gimeno, B.S.; Yuan, F.; et al. Nitrogen Critical Loads and Management Alternatives for N-Impacted Ecosystems in California. *J. Environ. Manag.* **2010**, *91*, 2404–2423. [CrossRef] [PubMed]
93. Ferretti, M.; Calderisi, M.; Marchetto, A.; Waldner, P.; Thimonier, A.; Jonard, M.; Cools, N.; Rautio, P.; Clarke, N.; Hansen, K.; et al. Variables Related to Nitrogen Deposition Improve Defoliation Models for European Forests. *Ann. For. Sci.* **2015**, *72*, 897–906. [CrossRef]
94. Forsius, M.; Posch, M.; Holmberg, M.; Vuorenmaa, J.; Kleemola, S.; Augustaitis, A.; Beudert, B.; Bochenek, W.; Clarke, N.; de Wit, H.A.; et al. Assessing Critical Load Exceedances and Ecosystem Impacts of Anthropogenic Nitrogen and Sulphur Deposition at Unmanaged Forested Catchments in Europe. *Sci. Total Environ.* **2021**, *753*, 141791. [CrossRef] [PubMed]
95. Fusaro, L.; Palma, A.; Salvatori, E.; Basile, A.; Maresca, V.; Karam, E.A.; Manes, F. Functional Indicators of Response Mechanisms to Nitrogen Deposition, Ozone, and Their Interaction in Two Mediterranean Tree Species. *PLoS ONE* **2017**, *12*, e0185836. [CrossRef] [PubMed]
96. Geiser, L.H.; Nelson, P.R.; Jovan, S.E.; Root, H.T.; Clark, C.M. Assessing Ecological Risks from Atmospheric Deposition of Nitrogen and Sulfur to US Forests Using Epiphytic Macrolichens. *Diversity* **2019**, *11*, 87. [CrossRef] [PubMed]
97. Geiser, L.H.; Root, H.; Smith, R.J.; Jovan, S.E.; St Clair, L.; Dillman, K.L. Lichen-Based Critical Loads for Deposition of Nitrogen and Sulfur in US Forests. *Environ. Pollut.* **2021**, *291*, 118187. [CrossRef] [PubMed]
98. Gilliam, F.S. Responses of Forest Ecosystems to Nitrogen Deposition. *Forests* **2021**, *12*, 1190. [CrossRef]
99. Gilliam, F.S.; Burns, D.A.; Driscoll, C.T.; Frey, S.D.; Lovett, G.M.; Watmough, S.A. Decreased Atmospheric Nitrogen Deposition in Eastern North America: Predicted Responses of Forest Ecosystems. *Environ. Pollut.* **2019**, *244*, 560–574. [CrossRef] [PubMed]
100. Grytnes, J.A.; Kapfer, J.; Jurasinski, G.; Birks, H.J.B.H.; Henriksen, H.; Klanderud, K.; Odland, A.; Ohlson, M.; Wipf, S.; Birks, H.J.B.H. Identifying the Driving Factors behind Observed Elevational Range Shifts on European Mountains. *Glob. Ecol. Biogeogr.* **2014**, *23*, 876–884. [CrossRef]
101. Hoffman, A.S.; Albeke, S.E.; McMurray, J.A.; Evans, R.D.; Williams, D.G. Nitrogen Deposition Sources and Patterns in the Greater Yellowstone Ecosystem Determined from Ion Exchange Resin Collectors, Lichens, and Isotopes. *Sci. Total Environ.* **2019**, *683*, 709–718. [CrossRef] [PubMed]
102. Hogan, E.J.; Minnullina, G.; Sheppard, L.J.; Leith, I.D.; Crittenden, P.D. Response of Phosphomonoesterase Activity in the Lichen *Cladonia portentosa* to Nitrogen and Phosphorus Enrichment in a Field Manipulation Experiment. *New Phytol.* **2010**, *186*, 926–933. [CrossRef] [PubMed]
103. Högberg, P.; Granström, A.; Johansson, T.; Lundmark-Thelin, A.; Näsholm, T. Plant Nitrate Reductase Activity as an Indicator of Availability of Nitrate in Forest Soils. *Can. J. For. Res.* **1986**, *16*, 1165–1169. [CrossRef]
104. Johansson, O.; Nordin, A.; Olofsson, J.; Palmqvist, K. Responses of Epiphytic Lichens to an Experimental Whole-Tree Nitrogen-Deposition Gradient. *New Phytol.* **2010**, *188*, 1075–1084. [CrossRef] [PubMed]
105. Kelleghan, D.B.; Hayes, E.T.; Everard, M.; Keating, P.; Lesniak-Podsiadlo, A.; Curran, T.P. Atmospheric Ammonia and Nitrogen Deposition on Irish Natura 2000 Sites: Implications for Irish Agriculture. *Atmos. Environ.* **2021**, *261*, 118611. [CrossRef]
106. Komarov, A.; Priputina, I.; Shanin, V. Plant Biodiversity and Soil Nitrogen and Carbon Pools Changes as a Result of Nitrogen Deposition at Permanent Pine Plots in Central Russia. In *Geophysical Research Abstracts*; EGU: Vienna, Austria, 2014.
107. Kwon, T.; Shibata, H.; Kepfer-Rojas, S.; Schmidt, I.K.; Larsen, K.S.; Beier, C.; Berg, B.; Verheyen, K.; Lamarque, J.F.; Hagedorn, F.; et al. Effects of Climate and Atmospheric Nitrogen Deposition on Early to Mid-Term Stage Litter Decomposition Across Biomes. *Front. For. Glob. Change* **2021**, *4*, 678480. [CrossRef]
108. Lee, H.M.; Paulot, F.; Henze, D.K.; Travis, K.; Jacob, D.J.; Pardo, L.H.; Schichtel, B.A. Sources of Nitrogen Deposition in Federal Class i Areas in the US. *Atmos. Chem. Phys.* **2016**, *16*, 525–540. [CrossRef]

109. Li, S.; Zhao, Z.; Dong, S.; Shen, H.; Xu, Y.; Xiao, J.; Gao, X.; Wu, S.; Stufkens, P. Synchronous Responses of Plant Functional Traits to Nitrogen Deposition from Dominant Species to Functional Groups and Whole Communities in Alpine Grasslands on the Qinghai-Tibetan Plateau. *Front. Plant Sci.* **2022**, *13*, 827035. [CrossRef] [PubMed]
110. Lilleskov, E.A.; Kuyper, T.W.; Bidartondo, M.I.; Hobbie, E.A. Atmospheric Nitrogen Deposition Impacts on the Structure and Function of Forest Mycorrhizal Communities: A Review. *Environ. Pollut.* **2019**, *246*, 148–162. [CrossRef] [PubMed]
111. Lin, B.L.; Kumon, Y.; Inoue, K.; Tobari, N.; Xue, M.; Tsunemi, K.; Terada, A. Increased Nitrogen Deposition Contributes to Plant Biodiversity Loss in Japan: Insights from Long-Term Historical Monitoring Data. *Environ. Pollut.* **2021**, *290*, 118033. [CrossRef] [PubMed]
112. Lo Cascio, M.; Morillas, L.; Ochoa-Hueso, R.; Delgado-Baquerizo, M.; Munzi, S.; Roales, J.; Spano, D.; Cruz, C.; Gallardo, A.; Manrique, E.; et al. Nitrogen Deposition Effects on Soil Properties, Microbial Abundance, and Litter Decomposition Across Three Shrublands Ecosystems from the Mediterranean Basin. *Front. Environ. Sci.* **2021**, *9*, 709391. [CrossRef]
113. Lu, X.; Vitousek, P.M.; Mao, Q.; Gilliam, F.S.; Luo, Y.; Turner, B.L.; Zhou, G.; Mo, J. Nitrogen Deposition Accelerates Soil Carbon Sequestration in Tropical Forests. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2020790118. [CrossRef] [PubMed]
114. Ochoa-Hueso, R.; Arróniz-Crespo, M.; Bowker, M.A.; Maestre, F.T.; Pérez-Corona, M.E.; Theobald, M.R.; Vivanco, M.G.; Manrique, E. Biogeochemical Indicators of Elevated Nitrogen Deposition in Semiarid Mediterranean Ecosystems. *Environ. Monit. Assess.* **2014**, *186*, 5831–5842. [CrossRef] [PubMed]
115. Ochoa-Hueso, R.; Maestre, F.T.; de Los Ríos, A.; Valea, S.; Theobald, M.R.; Vivanco, M.G.; Manrique, E.; Bowker, M.A. Nitrogen Deposition Alters Nitrogen Cycling and Reduces Soil Carbon Content in Low-Productivity Semiarid Mediterranean Ecosystems. *Environ. Pollut.* **2013**, *179*, 185–193. [CrossRef] [PubMed]
116. Ochoa-Hueso, R.; Munzi, S.; Alonso, R.; Arróniz-Crespo, M.; Avila, A.; Bermejo, V.; Bobbink, R.; Branquinho, C.; Concostrina-Zubiri, L.; Cruz, C.; et al. Ecological Impacts of Atmospheric Pollution and Interactions with Climate Change in Terrestrial Ecosystems of the Mediterranean Basin: Current Research and Future Directions. *Environ. Pollut.* **2017**, *227*, 194–206. [CrossRef] [PubMed]
117. Payne, R.J.; Dise, N.B.; Field, C.D.; Dore, A.J.; Caporn, S.J.M.; Stevens, C.J. Nitrogen Deposition and Plant Biodiversity: Past, Present, and Future. *Front. Ecol. Environ.* **2017**, *15*, 431–436. [CrossRef]
118. Perring, M.P.; Diekmann, M.; Midolo, G.; Schellenberger Costa, D.; Bernhardt-Römermann, M.; Otto, J.C.J.; Gilliam, F.S.; Hedwall, P.O.; Nordin, A.; Dirnböck, T.; et al. Understanding Context Dependency in the Response of Forest Understorey Plant Communities to Nitrogen Deposition. *Environ. Pollut.* **2018**, *242*, 1787–1799. [CrossRef] [PubMed]
119. Peter, V.D.S.; Vlam, M.; Groenendijk, P.; Anten, N.P.R.; Bongers, F.; Bunyavejchewin, S.; Hietz, P.; Pons, T.L.; Zuidema, P.A. 15N in Tree Rings as a Bio-Indicator of Changing Nitrogen Cycling in Tropical Forests: An Evaluation at Three Sites Using Two Sampling Methods. *Front. Plant Sci.* **2015**, *6*, 229. [CrossRef] [PubMed]
120. Pinho, P.; Theobald, M.R.; Dias, T.; Tang, Y.S.; Cruz, C.; Martins-Loução, M.A.; Máguas, C.; Sutton, M.; Branquinho, C. Critical Loads of Nitrogen Deposition and Critical Levels of Atmospheric Ammonia for Semi-Natural Mediterranean Evergreen Woodlands. *Biogeosciences* **2012**, *9*, 1205–1215. [CrossRef]
121. Posch, M.; Sander, R.; Schöpp, W.; Amann, M. *The 2017 Critical Loads Data: Differences to Earlier Estimates and Implications for Current and Future Ecosystems Protections*; IIASA: Laxenburg, Austria, 2018; pp. 1–16.
122. Priputina, I.V.; Zubkova, E.V.; Komarov, A.S. Retrospective Assessment of the Dynamics of Nitrogen Availability in Pine Forests of the Near-Moscow Region Based on the Data of Phytoindication. *Contemp. Probl. Ecol.* **2015**, *8*, 916–924. [CrossRef]
123. Priputina, I.; Zubkova, E.; Shanin, V.; Smirnov, V.; Komarov, A. Evidence of Plant Biodiversity Changes as a Result of Nitrogen Deposition in Permanent Pine Forest Plots in Central Russia. *Ecoscience* **2014**, *21*, 286–300. [CrossRef]
124. Raymond, B.A.; Bassingthwaighte, T.; Shaw, D.P. Measuring Nitrogen and Sulphur Deposition in the Georgia Basin, British Columbia, Using Lichens and Moss. *J. Limnol.* **2010**, *69*, 22–32. [CrossRef]
125. Rihm, B. Critical Loads of Nitrogen and Their Exceedances. *BUWAL Environ. Ser.* **2016**, *275*, 1–74.
126. Root, H.T.; Jovan, S.; Fenn, M.; Amacher, M.; Hall, J.; Shaw, J.D. Lichen Bioindicators of Nitrogen and Sulfur Deposition in Dry Forests of Utah and New Mexico, USA. *Ecol. Indic.* **2021**, *127*, 107727. [CrossRef]
127. Roth, T.; Kohli, L.; Bühler, C.; Rihm, B.; Meuli, R.G.; Meier, R.; Amrhein, V. Species Turnover Reveals Hidden Effects of Decreasing Nitrogen Deposition in Mountain Hay Meadows. *PeerJ* **2019**, *7*, e6347. [CrossRef] [PubMed]
128. Roth, T.; Kohli, L.; Rihm, B.; Meier, R.; Achermann, B. Using change-point models to estimate empirical critical loads for nitrogen in mountain ecosystems. *Environ. Pollut.* **2017**, *220*, 1480–1487. [CrossRef] [PubMed]
129. Roth, M.; Michiels, H.G.; Puhlmann, H.; Sucker, C.; Winter, M.B.; Hauck, M. Responses of Temperate Forests to Nitrogen Deposition: Testing the Explanatory Power of Modeled Deposition Datasets for Vegetation Gradients. *Ecosystems* **2021**, *24*, 1222–1238. [CrossRef]
130. Rowe, E.C.; Jones, L.; Dise, N.B.; Evans, C.D.; Mills, G.; Hall, J.; Stevens, C.J.; Mitchell, R.J.; Field, C.; Caporn, S.J.M.; et al. Metrics for Evaluating the Ecological Benefits of Decreased Nitrogen Deposition. *Biol. Conserv.* **2017**, *212*, 454–463. [CrossRef]

131. Rowe, E.; Hina, N.S.; Carnell, E.; Vieno, M.; Levy, P.; Raine, B.; Sawicka, K.; Tomlinson, S.; Martin-Hernandez, C.; Jones, L. *Trends Report 2022: Trends in Critical Load and Critical Level Exceedances in the UK*; Report to Defra under Contract AQ0849, UKCEH project 07617; Defra: London, UK, 2022; Volume 7617, pp. 1–17.
132. Salehi, M.; Walthert, L.; Zimmermann, S.; Waldner, P.; Schmitt, M.; Schleppi, P.; Liechti, K.; Ahmadi, M.; Zahedi Amiri, G.; Brunner, I.; et al. Leaf Morphological Traits and Leaf Nutrient Concentrations of European Beech Across a Water Availability Gradient in Switzerland. *Front. For. Glob. Change* **2020**, *3*, 19. [CrossRef]
133. Schmitz, A.; Sanders, T.G.M.; Bolte, A.; Bussotti, F.; Dirnböck, T.; Johnson, J.; Peñuelas, J.; Pollastrini, M.; Prescher, A.-K.; Sardans, J.; et al. Responses of Forest Ecosystems in Europe to Decreasing Nitrogen Deposition. *Environ. Pollut.* **2019**, *244*, 980–994. [CrossRef] [PubMed]
134. Schulte-Uebbing, L.F.; Ros, G.H.; de Vries, W. Experimental Evidence Shows Minor Contribution of Nitrogen Deposition to Global Forest Carbon Sequestration. *Glob. Change Biol.* **2022**, *28*, 899–917. [CrossRef] [PubMed]
135. Shen, H.; Dong, S.; Li, S.; Wang, W.; Xiao, J.; Yang, M.; Zhang, J.; Gao, X.; Xu, Y.; Zhi, Y.; et al. Effects of Warming and N Deposition on the Physiological Performances of *Leymus secalinus* in Alpine Meadow of Qinghai-Tibetan Plateau. *Front. Plant Sci.* **2020**, *10*, 1804. [CrossRef] [PubMed]
136. Soba, D.; Gámez, A.L.; Úriz, N.; Ruiz de Larrinaga, L.; Gonzalez-Murua, C.; Becerril, J.M.; Esteban, R.; Serret, D.; Araus, J.L.; Aranjuelo, I. Foliar Heavy Metals and Stable Isotope (Δ13C, Δ15N) Profiles as Reliable Urban Pollution Biomonitoring Tools. *Urban For. Urban Green.* **2021**, *57*, 126918. [CrossRef]
137. Stevens, C.J.; Manning, P.; Van Den Berg, L.J.L.; De Graaf, M.C.C.; Wamelink, G.W.W.; Boxman, A.W.; Bleeker, A.; Vergeer, P.; Arroniz-Crespo, M.; Limpens, J.; et al. Ecosystem Responses to Reduced and Oxidised Nitrogen Inputs in European Terrestrial Habitats. *Environ. Pollut.* **2011**, *159*, 665–676. [CrossRef] [PubMed]
138. Stevens, C.J. How Long Do Ecosystems Take to Recover from Atmospheric Nitrogen Deposition? *Biol. Conserv.* **2016**, *200*, 160–167. [CrossRef]
139. Stevens, C.J.; David, T.I.; Storkey, J. Atmospheric Nitrogen Deposition in Terrestrial Ecosystems: Its Impact on Plant Communities and Consequences across Trophic Levels. *Funct. Ecol.* **2018**, *32*, 1757–1769. [CrossRef]
140. Sutton, M.A.; Van Dijk, N.; Levy, P.E.; Jones, M.R.; Leith, I.D.; Sheppard, L.J.; Leeson, S.; Sim Tang, Y.; Stephens, A.; Braban, C.F.; et al. Alkaline Air: Changing Perspectives on Nitrogen and Air Pollution in an Ammonia-Rich World: Alkaline Air. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2020**, *378*, 20190315. [CrossRef] [PubMed]
141. Suz, L.M.; Bidartondo, M.I.; van der Linde, S.; Kuyper, T.W. Ectomycorrhizas and Tipping Points in Forest Ecosystems. *New Phytol.* **2021**, *231*, 1700–1707. [CrossRef] [PubMed]
142. Thimonier, A.; Graf Pannatier, E.; Schmitt, M.; Waldner, P.; Walthert, L.; Schleppi, P.; Dobbertin, M.; Kräuchi, N. Does Exceeding the Critical Loads for Nitrogen Alter Nitrate Leaching, the Nutrient Status of Trees and Their Crown Condition at Swiss Long-Term Forest Ecosystem Research (LWF) Sites? *Eur. J. For. Res.* **2010**, *129*, 443–461. [CrossRef]
143. Tyler, T.; Herbertsson, L.; Olofsson, J.; Olsson, P.A. Ecological Indicator and Traits Values for Swedish Vascular Plants. *Ecol. Indic.* **2021**, *120*, 106923. [CrossRef]
144. van der Sleen, P.; Zuidema, P.A.; Pons, T.L. Stable Isotopes in Tropical Tree Rings: Theory, Methods and Applications. *Funct. Ecol.* **2017**, *31*, 1674–1689. [CrossRef]
145. Varela, Z.; García-Seoane, R.; Arróniz-Crespo, M.; Carballeira, A.; Fernández, J.A.; Aboal, J.R. Evaluation of the Use of Moss Transplants (*Pseudoscleropodium purum*) for Biomonitoring Different Forms of Air Pollutant Nitrogen Compounds. *Environ. Pollut.* **2016**, *213*, 841–849. [CrossRef] [PubMed]
146. Vesala, R.; Kiheri, H.; Hobbie, E.A.; van Dijk, N.; Dise, N.; Larmola, T. Atmospheric Nitrogen Enrichment Changes Nutrient Stoichiometry and Reduces Fungal N Supply to Peatland Ericoid Mycorrhizal Shrubs. *Sci. Total Environ.* **2021**, *794*, 148737. [CrossRef] [PubMed]
147. Vitousek, P.M.; Menge, D.N.L.; Reed, S.C.; Cleveland, C.C. Biological Nitrogen Fixation: Rates, Patterns and Ecological Controls in Terrestrial Ecosystems. *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130119. [CrossRef] [PubMed]
148. Vourlitis, G.L.; Kirby, K.; Vallejo, I.; Asaeli, J.; Holloway, J.M. Potential Soil Extracellular Enzyme Activity Is Altered by Long-Term Experimental Nitrogen Deposition in Semiarid Shrublands. *Appl. Soil Ecol.* **2020**, *2021*, 103779. [CrossRef]
149. Wright, L.P.; Zhang, L.; Cheng, I.; Aherne, J.; Wentworth, G.R. Impacts and Effects Indicators of Atmospheric Deposition of Major Pollutants to Various Ecosystems-A Review. *Aerosol Air Qual. Res.* **2018**, *18*, 1953–1992. [CrossRef]
150. Xu, R.; Wang, Y.Y.; Wang, Y.Y.; Niu, H.; Liu, Y.; Zhuang, Q. Estimating N 2 O Emissions from Soils under Natural Vegetation in China. *Plant Soil* **2019**, *434*, 271–287. [CrossRef]
151. Zarabska-Bożejewicz, D. The Impact of Nitrogen Pollution in the Agricultural Landscape on Lichens: A Review of Their Responses at the Community, Species, Biont and Physiological Levels. *Agronomy* **2020**, *10*, 1852. [CrossRef]
152. Zhu, J.; Wang, Q.; He, N.; Smith, M.D.; Elser, J.J.; Du, J.; Yuan, G.; Yu, G.; Yu, Q. Imbalanced Atmospheric Nitrogen and Phosphorus Depositions in China: Implications for Nutrient Limitation. *J. Geophys. Res. Biogeosci.* **2016**, *121*, 1605–1616. [CrossRef]

153. Zhu, R.; Xiao, H.-Y.; Zhang, Z.; Lai, Y. Compound-Specific Δ15N Composition of Free Amino Acids in Moss as Indicators of Atmospheric Nitrogen Sources. *Sci. Rep.* **2018**, *8*, 14347. [CrossRef] [PubMed]
154. Zhang, W.; Ni, K.; Long, L.; Ruan, J. Nitrogen Transport and Assimilation in Tea Plant (*Camellia sinensis*): A Review. *Front. Plant Sci.* **2023**, *14*, 249202. [CrossRef] [PubMed]
155. Okumoto, S.; Pilot, G. Amino Acid Export in Plants: A Missing Link in Nitrogen Cycling. *Mol. Plant* **2011**, *4*, 453–463. [CrossRef] [PubMed]
156. Scarpelli, T.R. The Role of Amino Acids in the Nitrogen Cycle of Peatlands. Master's Thesis, Michigan Technological University, Houghton, MI, USA, 2016; Volume 105. Available online: https://digitalcommons.mtu.edu/cgi/viewcontent.cgi?article=1144&context=etdr (accessed on 1 March 2026).
157. Calanni, J.; Berg, E.; Wood, M.; Mangis, D.; Boyce, R.; Weathers, W.; Sievering, H. Atmospheric Nitrogen Deposition at a Conifer Forest: Response of Free Amino Acids in Engelmann Spruce Needles. *Environ. Pollut.* **1999**, *105*, 79–89. [CrossRef]
158. Throop, H.L.; Lerdau, M.T. Effects of Nitrogen Deposition on Insect Herbivory: Implications for Community and Ecosystem Processes. *Ecosystems* **2004**, *7*, 109–133. [CrossRef]
159. Maxwell, K.; Johnson, G.N. Chlorophyll Fluorescence—A Practical Guide. *J. Exp. Bot.* **2000**, *51*, 659–668. [CrossRef]
160. Zhang, R.; Wu, J.; Li, Q.; Hänninen, H.; Peng, C.; Yao, H.; Song, X.; Ying, Y. Nitrogen Deposition Enhances Photosynthesis in Moso Bamboo but Increases Susceptibility to Other Stress Factors. *Front. Plant Sci.* **2017**, *8*, 1975. [CrossRef] [PubMed]
161. Wang, Q.; Jin, Z.-X.; Peng, L.-Q. Effects of Nitrogen Deposition on Leaf Physiological and Ecological Characteristics of *Lindera aggregata* Seedlings. *J. Appl. Ecol.* **2012**, *23*, 2766–2772.
162. Bobbink, R.; Loran, C.; Tomassen, H. Review and Revision of Empirical Critical Loads of Nitrogen for Europe. *Ger. Environ. Agency* **2022**, *358*, 2022. Available online: https://www.umweltbundesamt.de/publikationen/review-revision-of-empirical-critical-loads-of (accessed on 1 March 2026).
163. Makar, P.A.; Cheung, P.; Hogrefe, C.; Akingunola, A.; Alyuz, U.; Bash, J.O.; Bell, M.D.; Bellasio, R.; Bianconi, R.; Butler, T.; et al. Critical Load Exceedances for North America and Europe Using an Ensemble of Models and an Investigation of Causes of Environmental Impact Estimate Variability: An AQMEII4 Study. *Atmos. Chem. Phys.* **2025**, *25*, 3049–3107. [CrossRef] [PubMed]
164. Stevens, C.J.; Dise, N.B.; Mountford, J.O.; Gowing, D.J. Impact of Nitrogen Deposition on the Species Richness of Grasslands. *Science* **2004**, *303*, 1876–1879. [CrossRef] [PubMed]
165. Spranger, T.; Hettelingh, J.-P.P.; Slootweg, J.; Posch, M. Modelling and Mapping Long-Term Risks Due to Reactive Nitrogen Effects: An Overview of LRTAP Convention Activities. *Environ. Pollut.* **2008**, *154*, 482–487. [CrossRef] [PubMed]
166. Vivanco, M.G.; Theobald, M.R.; García-Gómez, H.; Luis Garrido, J.; Prank, M.; Aas, W.; Adani, M.; Alyuz, U.; Andersson, C.; Bellasio, R.; et al. Modeled Deposition of Nitrogen and Sulfur in Europe Estimated by 14 Air Quality Model Systems: Evaluation, Effects of Changes in Emissions and Implications for Habitat Protection. *Atmos. Chem. Phys.* **2018**, *18*, 10199–10218. [CrossRef] [PubMed]
167. Briggs, W.M.; Hanekamp, J.C. Nitrogen Critical Loads: Critical Reflections on Past Experiments, Ecological Endpoints, and Uncertainties. *Dose-Response* **2022**, *20*, 15593258221075513. [CrossRef] [PubMed]
168. Callesen, I.; Raulund-Rasmussen, K.; Westman, C.J.; Tau-Strand, L. Nitrogen Pools and C:N Ratios in Well-Drained Nordic Forest Soils Related to Climate and Soil Texture. *Boreal Environ. Res.* **2007**, *12*, 681–692.
169. Marty, C.; Houle, D.; Gagnon, C.; Courchesne, F. The Relationships of Soil Total Nitrogen Concentrations, Pools and C:N Ratios with Climate, Vegetation Types and Nitrate Deposition in Temperate and Boreal Forests of Eastern Canada. *Catena* **2017**, *152*, 163–172. [CrossRef]
170. DeForest, J.L.; Zak, D.R.; Pregitzer, K.S.; Burton, A.J. Atmospheric Nitrate Deposition and the Microbial Degradation of Cellobiose and Vanillin in a Northern Hardwood Forest. *Soil Biol. Biochem.* **2004**, *36*, 965–971. [CrossRef]
171. Ma, J.; Kang, F.; Cheng, X.; Han, H. Response of Soil Organic Carbon and Nitrogen to Nitrogen Deposition in a *Larix principis-rupprechtii* Plantation. *Sci. Rep.* **2018**, *8*, 8638. [CrossRef] [PubMed]
172. Aguillaume, L. La Deposición de Nitrógeno En Encinares Mediterráneos: Cargas e Indicadores. *Ecosistemas* **2016**, *25*, 110–113. [CrossRef]
173. Li, Z.; Tang, Z.; Song, Z.; Chen, W.; Tian, D.; Tang, S.; Wang, X.; Wang, J.; Liu, W.; Wang, Y.; et al. Variations and Controlling Factors of Soil Denitrification Rate. *Glob. Change Biol.* **2022**, *28*, 2133–2145. [CrossRef] [PubMed]
174. Butterbach-Bahl, K.; Baggs, E.M.; Dannenmann, M.; Kiese, R.; Zechmeister-Boltenstern, S. Nitrous Oxide Emissions from Soils: How Well Do We Understand the Processes and Their Controls? *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130122. [CrossRef] [PubMed]
175. Munzi, S.; Branquinho, C.; Cruz, C.; Máguas, C.; Leith, I.D.; Sheppard, L.J.; Sutton, M.A. Δ 15 N of Lichens Reflects the Isotopic Signature of Ammonia Source. *Sci. Total Environ.* **2019**, *653*, 698–704. [CrossRef] [PubMed]
176. Beyn, F.; Matthias, V.; Aulinger, A.; Dähnke, K. Do N-Isotopes in Atmospheric Nitrate Deposition Reflect Air Pollution Levels? *Atmos. Environ.* **2015**, *107*, 281–288. [CrossRef]

177. Zhao, Z.Y.; Cao, F.; Fan, M.Y.; Zhang, W.Q.; Zhai, X.Y.; Wang, Q.; Zhang, Y.L. Coal and Biomass Burning as Major Emissions of NO_x in Northeast China: Implication from Dual Isotopes Analysis of Fine Nitrate Aerosols. *Atmos. Environ.* **2020**, *242*, 117762. [CrossRef]
178. Sun, Z.; Zong, Z.; Tan, Y.; Tian, C.; Liu, Z.; Zhang, F.; Sun, R.; Chen, Y.; Li, J.; Zhang, G. Characterization of the Nitrogen Stable Isotope Composition (Δ15N) of Ship-Emitted NO_x. *Atmos. Chem. Phys.* **2023**, *23*, 12851–12865. [CrossRef]
179. Amundson, R.; Austin, A.T.; Schuur, E.A.G.; Yoo, K.; Matzek, V.; Kendall, C.; Uebersax, A.; Brenner, D.; Baisden, W.T. Global Patterns of the Isotopic Composition of Soil and Plant Nitrogen. *Glob. Biogeochem. Cycles* **2003**, *17*, 1031. [CrossRef]
180. Craine, J.M.; Elmore, A.J.; Wang, L.; Augusto, L.; Baisden, W.T.; Brookshire, E.N.J.; Cramer, M.D.; Hasselquist, N.J.; Hobbie, E.A.; Kahmen, A.; et al. Convergence of Soil Nitrogen Isotopes across Global Climate Gradients. *Sci. Rep.* **2015**, *5*, srep08280. [CrossRef] [PubMed]
181. Roeling, I.S.; Ozinga, W.A.; van Dijk, J.; Eppinga, M.B.; Wassen, M.J. Plant Species Occurrence Patterns in Eurasian Grasslands Reflect Adaptation to Nutrient Ratios. *Oecologia* **2018**, *186*, 1055–1067. [CrossRef] [PubMed]
182. Güsewell, S. N:P Ratios in Terrestrial Plants: Variation and Functional Significance. *New Phytol.* **2004**, *164*, 243–266. [CrossRef] [PubMed]
183. Pawlikowski, P.; Abramczyk, K.; Szczepaniuk, A.; Kozub, L. Nitrogen: Phosphorus Ratio as the Main Ecological Determinant of the Differences in the Species Composition of Brown-Moss Rich Fens in North-Eastern Poland. *Preslia* **2013**, *85*, 349–367.
184. Zhang, R.; Pan, H.; He, B.; Chen, H.; Zhou, Z. Nitrogen and Phosphorus Stoichiometry of *Schima superba* under Nitrogen Deposition. *Sci. Rep.* **2018**, *8*, 3669. [CrossRef] [PubMed]
185. Mitchell, R.J.; Sutton, M.A.; Truscott, A.M.; Leith, I.D.; Cape, J.N.; Pitcairn, C.E.R.; Van Dijk, N. Growth and Tissue Nitrogen of Epiphytic Atlantic Bryophytes: Effects of Increased and Decreased Atmospheric N Deposition. *Funct. Ecol.* **2004**, *18*, 322–329. [CrossRef]
186. Simmel, J.; Ahrens, M.; Poschlod, P. Ellenberg N Values of Bryophytes in Central Europe*. *J. Veg. Sci.* **2021**, *32*, e12957. [CrossRef]
187. Hill, M.O.; Roy, D.B.; Mountford, J.O.; Bunce, R.G.H. Extending Ellenberg's Indicator Values to a New Area: An Algorithmic Approach. *J. Appl. Ecol.* **2000**, *37*, 3–15. [CrossRef]
188. Pignatti, S.; Bianco, P.; Fanelli, G.; Guarino, R.; Petersen, J.; Tescarollo, P. Reliability and Effectiveness of Ellenberg's Indices in Checking Flora and Vegetation Changes Induced by Climatic Variations. In *"Fingerprints" of Climate Change*; Springer: Boston, MA, USA, 2001; pp. 281–304. [CrossRef]
189. Nordin, A.; Sheppard, L.J.; Strengbom, J.; Bobbink, R.; Gunnarsson, U.; Hicks, W.K.; Sutton, M.A. *New Science on the Effects of Nitrogen Deposition and Concentrations on Natura 2000 Sites (Theme 3): Background Document*; No. Theme 3; COST Office-European Cooperation in Science and Technology: Brussels, Belgium, 2011; pp. 114–198. Available online: https://nora.nerc.ac.uk/id/eprint/16293/ (accessed on 1 March 2026).
190. Smart, S.; Goodwin, A.; Wallace, H.; Jones, M. *MAVIS (Ver 1.03)*; User Manual; NERC Centre for Ecology & Hydrology (CEH): Lancaster, UK, 2016.
191. Gianinazzi, S.; Gollotte, A.; Binet, M.N.; van Tuinen, D.; Redecker, D.; Wipf, D. Agroecology: The Key Role of Arbuscular Mycorrhizas in Ecosystem Services. *Mycorrhiza* **2010**, *20*, 519–530. [CrossRef] [PubMed]
192. Farrer, E.C.; Herman, D.J.; Franzova, E.; Pham, T.; Suding, K.N. Nitrogen Deposition, Plant Carbon Allocation, and Soil Microbes: Changing Interactions Due to Enrichment. *Am. J. Bot.* **2013**, *100*, 1458–1470. [CrossRef] [PubMed]
193. Boxman, A.W.; Blanck, K.; Brandrud, T.E.; Emmett, B.A.; Gundersen, P.; Hogervorst, R.F.; Kjønaas, O.J.; Persson, H.; Timmermann, V. Vegetation and Soil Biota Response to Experimentally-Changed Nitrogen Inputs in Coniferous Forest Ecosystems of the NITREX Project. *For. Ecol. Manag.* **1998**, *101*, 65–79. [CrossRef]
194. Egli, S. Mycorrhizal Mushroom Diversity and Productivity—An Indicator of Forest Health? *Ann. For. Sci.* **2011**, *68*, 81–88. [CrossRef]
195. Treseder, K.K.; Allen, E.B.; Egerton-Warburton, L.M.; Hart, M.M.; Klironomos, J.N.; Maherali, H.; Tedersoo, L. Arbuscular Mycorrhizal Fungi as Mediators of Ecosystem Responses to Nitrogen Deposition: A Trait-Based Predictive Framework. *J. Ecol.* **2018**, *106*, 480–489. [CrossRef]
196. Nessel, M.P.; Konnovitch, T.; Romero, G.Q.; González, A.L. Nitrogen and Phosphorus Enrichment Cause Declines in Invertebrate Populations: A Global Meta-Analysis. *Biol. Rev.* **2021**, *96*, 2617–2637. [CrossRef] [PubMed]
197. Flückiger, W.; Braun, S. Nitrogen and Its Effect on Growth, Nutrient Status and Parasite Attacks in Beech and Norway Spruce. *Water Air Soil Pollut.* **1999**, *116*, 99–110. [CrossRef]
198. Hwang, S.Y.; Liu, C.H.; Shen, T.C. Effects of Plant Nutrient Availability and Host Plant Species on the Performance of Two *Pieris* Butterflies (Lepidoptera: Pieridae). *Biochem. Syst. Ecol.* **2008**, *36*, 505–513. [CrossRef]
199. Diemont, W.H.; Heil, G.W. Some Long-Term Observations on Cyclical and Seral Processes in Dutch Heathlands. *Biol. Conserv.* **1984**, *30*, 283–290. [CrossRef]
200. Griffith, K.A.; Grinath, J.B. Interactive Effects of Precipitation and Nitrogen Enrichment on Multi-Trophic Dynamics in Plant-Arthropod Communities. *PLoS ONE* **2018**, *13*, e0201219. [CrossRef] [PubMed]

201. Jones, M.E.; Fenn, M.E.; Paine, T.D. The Effect of Nitrogen Additions on Bracken Fern and Its Insect Herbivores at Sites with High and Low Atmospheric Pollution. *Arthropod. Plant. Interact.* **2011**, *5*, 163–173. [CrossRef]
202. Landolt, E.; Bäumler, B.; Ehrhardt, A.; Hegg, O.; Klötzli, F.; Lämmler, W.; Nobis, M.; Rudmann-Maurer, K.; Schweingruber, F.H.; Theurillat, J.-P.; et al. *Flora Indicativa: Ökologische Zeigerwerte und Biologische Kennzeichen zur Flora der Schweiz und der Alpen*; Publications of Department of Systematic and Evolutionary Botany: Bern, Switzerland, 2010.
203. Ivanova, N.; Zolotova, E. Landolt Indicator Values in Modern Research: A Review. *Sustainability* **2023**, *15*, 9618. [CrossRef]
204. Kammer, P.M.; Rihm, B.; Schöb, C. Decreasing Nitrogen Deposition Rates: Good News for Oligotrophic Grassland Species? *Basic Appl. Ecol.* **2022**, *63*, 125–138. [CrossRef]
205. Munzi, S.; Pisani, T.; Loppi, S. The Integrity of Lichen Cell Membrane as a Suitable Parameter for Monitoring Biological Effects of Acute Nitrogen Pollution. *Ecotoxicol. Environ. Saf.* **2009**, *72*, 2009–2012. [CrossRef] [PubMed]
206. Stevens, C.J.; Smart, S.M.; Henrys, P.A.; Maskell, L.C.; Crowe, A.; Simkin, J.; Cheffings, C.M.; Whitfield, C.; Gowing, D.J.G.; Rowe, E.C.; et al. Terricolous Lichens as Indicators of Nitrogen Deposition: Evidence from National Records. *Ecol. Indic.* **2012**, *20*, 196–203. [CrossRef]
207. Spier, L.; van Dobben, H.; van Dort, K. Is Bark PH More Important than Tree Species in Determining the Composition of Nitrophytic or Acidophytic Lichen Floras? *Environ. Pollut.* **2010**, *158*, 3607–3611. [CrossRef] [PubMed]
208. Jovan, S.; Riddell, J.; Padgett, P.E.; Nash, T.H. Eutrophic Lichens Respond to Multiple Forms of N: Implications for Critical Levels and Critical Loads Research. *Ecol. Appl.* **2012**, *22*, 1910–1922. [CrossRef] [PubMed]
209. Tilman, D.; May, R.M.; Lehman, C.L.; Nowak, M.A. Habitat Destruction and the Extinction Debt. *Nature* **1994**, *371*, 65–66. [CrossRef]
210. Leith, I.D.; Van Dijk, N.; Pitcairn, C.E.R.; Wolseley, P.A.; Whitfield, C.P.; Sutton, M.A. *Biomonitoring Methods for Assessing the Impacts of Nitrogen Pollution: Refinement and Testing*; JNCC Report No. 386; Joint Nature Conservation Committee (JNCC): Peterborough, UK, 2005; p. 282.
211. Klumpp, A.; Ansel, W.; Klumpp, G.; Belluzzo, N.; Calatayud, V.; Chaplin, N.; Garrec, J.P.; Gutsche, H.J.; Hayes, M.; Hentze, H.W.; et al. EuroBionet: A Pan-European Biomonitoring Network for Urban Air Quality Assessment. *Environ. Sci. Pollut. Res.* **2002**, *9*, 199–203. [CrossRef] [PubMed]
212. Hibbard, D.A. Can Three Native Mojave Desert Perennials Adapt to Increasing Atmospheric Nitrogen Deposition and Annual Grass Invasion in Joshua Tree National Park? Master's Thesis, California State Polytechnic University, Pomona, CA, USA, 2015. Available online: https://scholarwolf.unr.edu/server/api/core/bitstreams/be7c8ed6-ac72-4551-9bfa-0ca03a031ace/content (accessed on 1 March 2026).
213. Pitcairn, C.; Fowler, D.; Leith, I.; Sheppard, L.; Tang, S.; Sutton, M.; Famulari, D. Diagnostic Indicators of Elevated Nitrogen Deposition. *Environ. Pollut.* **2006**, *144*, 941–950. [CrossRef] [PubMed]
214. Harmens, H.; Norris, D.A.; Cooper, D.M.; Mills, G.; Steinnes, E.; Kubin, E.; Thöni, L.; Aboal, J.R.; Alber, R.; Carballeira, A.; et al. Nitrogen Concentrations in Mosses Indicate the Spatial Distribution of Atmospheric Nitrogen Deposition in Europe. *Environ. Pollut.* **2011**, *159*, 2852–2860. [CrossRef] [PubMed]
215. Waldrop, M.P.; Zak, D.R. Response of Oxidative Enzyme Activities to Nitrogen Deposition Affects Soil Concentrations of Dissolved Organic Carbon. *Ecosystems* **2006**, *9*, 921–933. [CrossRef]
216. Arróniz-Crespo, M.; Leake, J.R.; Horton, P.; Phoenix, G.K. Bryophyte Physiological Responses to, and Recovery from, Long-term Nitrogen Deposition and Phosphorus Fertilisation in Acidic Grassland. *New Phytol.* **2008**, *180*, 864–874. [CrossRef] [PubMed]
217. Öckinger, E.; Hammarstedt, O.; Nilsson, S.G.; Smith, H.G. The Relationship between Local Extinctions of Grassland Butterflies and Increased Soil Nitrogen Levels. *Biol. Conserv.* **2006**, *128*, 564–573. [CrossRef]
218. Pöyry, J.; Carvalheiro, L.G.; Heikkinen, R.K.; Kühn, I.; Kuussaari, M.; Schweiger, O.; Valtonen, A.; van Bodegom, P.M.; Franzén, M. The Effects of Soil Eutrophication Propagate to Higher Trophic Levels. *Glob. Ecol. Biogeogr.* **2017**, *26*, 18–30. [CrossRef]
219. Eatough Jones, M.; Paine, T.D.; Fenn, M.E. The Effect of Nitrogen Additions on Oak Foliage and Herbivore Communities at Sites with High and Low Atmospheric Pollution. *Environ. Pollut.* **2008**, *151*, 434–442. [CrossRef] [PubMed]
220. Sparks, J.P. Ecological Ramifications of the Direct Foliar Uptake of Nitrogen. *Oecologia* **2009**, *159*, 1–13. [CrossRef] [PubMed]
221. Limpens, J.; Heijmans, M.M.P.D. Swift Recovery of Sphagnum Nutrient Concentrations after Excess Supply. *Oecologia* **2008**, *157*, 153–161. [CrossRef] [PubMed]
222. van der Linde, S.; Suz, L.M.; Orme, C.D.L.; Cox, F.; Andreae, H.; Asi, E.; Atkinson, B.; Benham, S.; Carroll, C.; Cools, N.; et al. Environment and Host as Large-Scale Controls of Ectomycorrhizal Fungi. *Nature* **2018**, *558*, 243–248. Correction in *Nature* **2018**, *561*, E42. https://doi.org/10.1038/s41586-018-0312-y. [CrossRef] [PubMed]
223. Högberg, P.; Näsholm, T.; Franklin, O.; Högberg, M.N. Tamm Review: On the Nature of the Nitrogen Limitation to Plant Growth in Fennoscandian Boreal Forests. *For. Ecol. Manag.* **2017**, *403*, 161–185. [CrossRef]
224. van Strien, A.J.; Boomsluiter, M.; Noordeloos, M.E.; Verweij, R.J.T.; Kuyper, T.W. Woodland Ectomycorrhizal Fungi Benefit from Large-scale Reduction in Nitrogen Deposition in the Netherlands. *J. Appl. Ecol.* **2018**, *55*, 290–298. [CrossRef]
225. Senwo, Z.N.; Tabatabai, M.A. Amino Acid Composition of Soil Organic Matter. *Biol. Fertil. Soils* **1998**, *26*, 235–242. [CrossRef]

226. Jones, D.L.; Owen, A.G.; Farrar, J.F. Simple Method to Enable the High Resolution Determination of Total Free Amino Acids in Soil Solutions and Soil Extracts. *Soil Biol. Biochem.* **2002**, *34*, 1893–1902. [CrossRef]
227. Bailey, T.; Robinson, N.; Farrell, M.; Macdonald, B.; Weaver, T.; Antille, D.L.; Chin, A.; Brackin, R. Storage of Soil Samples Leads to Over-Representation of the Contribution of Nitrate to Plant-Available Nitrogen. *Soil Res.* **2022**, *60*, 22–32. [CrossRef]
228. Srivastava, H.S. Regulation of Nitrate Reductase Activity in Higher Plants. *Phytochemistry* **1980**, *19*, 725–733. [CrossRef]
229. Pitcairn, C.; Leith, I.; Sheppard, L.; Sutton, M. *Development of a Nitrophobe/Nitrophile Classification for Woodlands, Grasslands and Upland Vegetation in Scotland*; NERC/Centre for Ecology and Hydrology: Edinburgh, UK, 2006. Available online: https://nora.nerc.ac.uk/id/eprint/3379/1/PitcairnSEPARep.pdf (accessed on 1 March 2026).
230. Bermejo-Orduna, R.; McBride, J.R.; Shiraishi, K.; Elustondo, D.; Lasheras, E.; Santamaría, J.M. Biomonitoring of Traffic-Related Nitrogen Pollution Using *Letharia vulpina* (L.) Hue in the Sierra Nevada, California. *Sci. Total Environ.* **2014**, *490*, 205–212. [CrossRef] [PubMed]
231. Giordani, P.; Calatayud, V.; Stofer, S.; Seidling, W.; Granke, O.; Fischer, R. Detecting the Nitrogen Critical Loads on European Forests by Means of Epiphytic Lichens. A Signal-to-Noise Evaluation. *For. Ecol. Manag.* **2014**, *311*, 29–40. [CrossRef]
232. Cape, J.N.N.; van der Eerden, L.J.J.; Sheppard, L.J.J.; Leith, I.D.D.; Sutton, M.A.A. Evidence for Changing the Critical Level for Ammonia. *Environ. Pollut.* **2009**, *157*, 1033–1037. [CrossRef] [PubMed]
233. Jörgensen, K.; Clemmensen, K.E.; Wallander, H.; Lindahl, B.D. Ectomycorrhizal Fungi Are More Sensitive to High Soil Nitrogen Levels in Forests Exposed to Nitrogen Deposition. *New Phytol.* **2024**, *242*, 1725–1738. [CrossRef] [PubMed]
234. Averill, C.; Dietze, M.C.; Bhatnagar, J.M. Continental-scale Nitrogen Pollution Is Shifting Forest Mycorrhizal Associations and Soil Carbon Stocks. *Glob. Change Biol.* **2018**, *24*, 4544–4553. [CrossRef] [PubMed]
235. Bergström, A.; Jansson, M. Atmospheric Nitrogen Deposition Has Caused Nitrogen Enrichment and Eutrophication of Lakes in the Northern Hemisphere. *Glob. Change Biol.* **2006**, *12*, 635–643. [CrossRef]
236. Band, N.; Kadmon, R.; Mandel, M.; DeMalach, N. Assessing the Roles of Nitrogen, Biomass, and Niche Dimensionality as Drivers of Species Loss in Grassland Communities. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2112010119. [CrossRef] [PubMed]
237. Lu, P.; Hao, T.; Li, X.; Wang, H.; Zhai, X.; Tian, Q.; Bai, W.; Stevens, C.; Zhang, W. Ambient Nitrogen Deposition Drives Plant-diversity Decline by Nitrogen Accumulation in a Closed Grassland Ecosystem. *J. Appl. Ecol.* **2021**, *58*, 1888–1898. [CrossRef]
238. Elbert, W.; Weber, B.; Burrows, S.; Steinkamp, J.; Büdel, B.; Andreae, M.O.; Pöschl, U. Contribution of Cryptogamic Covers to the Global Cycles of Carbon and Nitrogen. *Nat. Geosci.* **2012**, *5*, 459–462. [CrossRef]
239. Porada, P.; Weber, B.; Elbert, W.; Pöschl, U.; Kleidon, A. Estimating Global Carbon Uptake by Lichens and Bryophytes with a Process-Based Model. *Biogeosciences* **2013**, *10*, 6989–7033. [CrossRef]
240. Dannenmann, M.; Díaz-Pinés, E.; Kitzler, B.; Karhu, K.; Tejedor, J.; Ambus, P.; Parra, A.; Sánchez-Martin, L.; Resco, V.; Ramírez, D.A.; et al. Postfire Nitrogen Balance of Mediterranean Shrublands: Direct Combustion Losses versus Gaseous and Leaching Losses from the Postfire Soil Mineral Nitrogen Flush. *Glob. Change Biol.* **2018**, *24*, 4505–4520. [CrossRef] [PubMed]
241. Moloney, K.A.; Mudrak, E.L.; Fuentes-Ramirez, A.; Parag, H.; Schat, M.; Holzapfel, C. Increased Fire Risk in Mojave and Sonoran Shrublands Due to Exotic Species and Extreme Rainfall Events. *Ecosphere* **2019**, *10*, e02592. [CrossRef]
242. Moloney, K.A.; Fuentes-Ramirez, A.; Holzapfel, C. Climate Impacts on Fire Risk in Desert Shrublands: A Modeling Study. *Front. Ecol. Evol.* **2021**, *9*, 601877. [CrossRef]
243. Wilder, B.T.; Jarnevich, C.S.; Baldwin, E.; Black, J.S.; Franklin, K.A.; Grissom, P.; Hovanes, K.A.; Olsson, A.; Malusa, J.; Kibria, A.S.M.G.; et al. Grassification and Fast-Evolving Fire Connectivity and Risk in the Sonoran Desert, United States. *Front. Ecol. Evol.* **2021**, *9*, 655561. [CrossRef]
244. Burford, J.R.; Bremner, J.M. Relationships between the Denitrification Capacities of Soils and Total, Water-Soluble and Readily Decomposable Soil Organic Matter. *Soil Biol. Biochem.* **1975**, *7*, 389–394. [CrossRef]
245. Zhang, Y.; Cai, Z.; Zhang, J.; Müller, C. C:N Ratio Is Not a Reliable Predictor of N_2O Production in Acidic Soils after a 30-Day Artificial Manipulation. *Sci. Total Environ.* **2020**, *725*, 138427. [CrossRef] [PubMed]
246. Yao, Z.; Yan, G.; Ma, L.; Wang, Y.; Zhang, H.; Zheng, X.; Wang, R.; Liu, C.; Wang, Y.; Zhu, B.; et al. Soil C/N Ratio Is the Dominant Control of Annual N_2O Fluxes from Organic Soils of Natural and Semi-Natural Ecosystems. *Agric. For. Meteorol.* **2022**, *327*, 109198. [CrossRef]
247. Saifuddin, M.; Bhatnagar, J.M.; Phillips, R.P.; Finzi, A.C. Ectomycorrhizal Fungi Are Associated with Reduced Nitrogen Cycling Rates in Temperate Forest Soils without Corresponding Trends in Bacterial Functional Groups. *Oecologia* **2021**, *196*, 863–875. [CrossRef] [PubMed]
248. Prather, M.J.; Hsu, J. NF_3, the Greenhouse Gas Missing from Kyoto. *Geophys. Res. Lett.* **2008**, *35*, L12810. Correction in *Geophys. Res. Lett.* **2010**, *37*, L11807. https://doi.org/10.1029/2010GL043831. [CrossRef]
249. Liu, Y.; Sheng, J.; Rigby, M.; Ganesan, A.; Kim, J.; Western, L.M.; Mühle, J.; Park, S.; Park, H.; Weiss, R.F.; et al. Increases in Global and East Asian Nitrogen Trifluoride (NF3) Emissions Inferred from Atmospheric Observations. *Environ. Sci. Technol.* **2024**, *58*, 13318–13326. [CrossRef] [PubMed]

250. Jones, M.E.; Eatough, D.J. Air Pollution. In *Insects and Diseases of Mediterranean Forest Systems*; Springer International Publishing: Cham, Switzerland, 2016; pp. 769–799. [CrossRef]
251. Nowroz, F.; Hasanuzzaman, M.; Siddika, A.; Parvin, K.; Caparros, P.G.; Nahar, K.; Prasad, P.V.V.V.V. Elevated Tropospheric Ozone and Crop Production: Potential Negative Effects and Plant Defense Mechanisms. *Front. Plant Sci.* **2023**, *14*, 1244515. [CrossRef] [PubMed]
252. Brunsting, A.A.M.H.; Heil, G.W. The Role of Nutrients in the Interactions Between a Herbivorous Beetle and Some Competing Plant Species in Heathlands. *Oikos* **1985**, *44*, 22–26. [CrossRef]
253. Nordin, A.; Strengbom, J.; Witzell, J.; Näsholm, T.; Ericson, L. Nitrogen Deposition and the Biodiversity of Boreal Forests: Implications for the Nitrogen Critical Load. *Ambio* **2005**, *34*, 20–24. [CrossRef]
254. Strengbom, J.; Nordin, A.; Näsholm, T.; Ericson, L. Parasitic Fungus Mediates Change in Nitrogen-Exposed Boreal Forest Vegetation. *J. Ecol.* **2002**, *90*, 60–67. [CrossRef]
255. Tian, D.; Niu, S. A Global Analysis of Soil Acidification Caused by Nitrogen Addition. *Environ. Res. Lett.* **2015**, *10*, 024019. [CrossRef]
256. Li, S.; Tang, S.; Ju, X.; Zhu, Z.; Zhang, Y.; Chen, H.; Jin, K. Soil Acidification Drives the Negative Effects of Nitrogen Enrichment on Soil Microbial Biomass at the Global Scale. *Plant Soil* **2024**, *503*, 517–528. [CrossRef]
257. Ma, X.; Zhu, B.; Nie, Y.; Liu, Y.; Kuzyakov, Y. Root and Mycorrhizal Strategies for Nutrient Acquisition in Forests under Nitrogen Deposition: A Meta-Analysis. *Soil Biol. Biochem.* **2021**, *163*, 108418. [CrossRef]
258. Persson, H.; Majdi, H. Effects of Acid Deposition on Tree Roots in Swedish Forest Stands. *Water Air Soil Pollut.* **1995**, *85*, 1287–1292. [CrossRef]
259. Bassin, S.; Volk, M.; Fuhrer, J. Species Composition of Subalpine Grassland Is Sensitive to Nitrogen Deposition, but Not to Ozone, After Seven Years of Treatment. *Ecosystems* **2013**, *16*, 1105–1117. [CrossRef]
260. Clark, C.M.; Bai, Y.; Bowman, W.D.; Cowles, J.M.; Fenn, M.E.; Gilliam, F.S.; Phoenix, G.K.; Siddique, I.; Stevens, C.J.; Sverdrup, H.U.; et al. Nitrogen Deposition and Terrestrial Biodiversity. *Encycl. Biodivers. Second. Ed.* **2013**, 519–536. [CrossRef]
261. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. *Science* **2009**, *326*, 123–125. [CrossRef] [PubMed]
262. Roth, M.; Müller-Meißner, A.; Michiels, H.G.; Hauck, M. Vegetation Changes in the Understory of Nitrogen-Sensitive Temperate Forests over the Past 70 Years. *For. Ecol. Manag.* **2021**, *2022*, 503. [CrossRef]
263. Streiner, D.L.; Norman, G.R.; Cairney, J. *Health Measurement Scales*; Oxford University Press: Oxford, UK, 2014. [CrossRef]
264. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*; Routledge: New York, NY, USA, 2013. [CrossRef]
265. Norton, S.B.; Rodier, D.J.; van der Schalie, W.H.; Wood, W.P.; Slimak, M.W.; Gentile, J.H. A Framework for Ecological Risk Assessment at the EPA. *Environ. Toxicol. Chem.* **1992**, *11*, 1663–1672. [CrossRef]
266. Sokal, R.R.; Rohlf, F.J. *Biometry: The Principles and Practice of Statistics in Biological Research*, 4th ed.; W.H. Freeman & Co.: New York, NY, USA, 2012.
267. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated World Map of the Köppen-Geiger Climate Classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
268. Saros, J.E.; Clow, D.W.; Blett, T.; Wolfe, A.P. Critical Nitrogen Deposition Loads in High-Elevation Lakes of the Western US Inferred from Paleolimnological Records. *Water. Air. Soil Pollut.* **2011**, *216*, 193–202. [CrossRef]
269. Vogels, J.J.; Verberk, W.C.E.P.; Kuper, J.T.; Weijters, M.J.; Verbaarschot, E.; Lamers, L.P.M.; Siepel, H. Nitrogen Deposition and Heathland Management Cause Multi-element Stoichiometric Mismatches, Reducing Insect Fitness. *Funct. Ecol.* **2024**, *38*, 2537–2552. [CrossRef]
270. González, A.L.; Merder, J.; Andraczek, K.; Brose, U.; Filipiak, M.; Harpole, W.S.; Hillebrand, H.; Jackson, M.C.; Jochum, M.; Leroux, S.J.; et al. Nitrogen Deposition Reveals Global Patterns in Plant and Animal Stoichiometry. *Nat. Commun.* **2025**, *16*, 10977. [CrossRef] [PubMed]
271. Anderson, C.; Cabana, G. Does Δ15N in River Food Webs Reflect the Intensity and Origin of N Loads from the Watershed? *Sci. Total Environ.* **2006**, *367*, 968–978. [CrossRef] [PubMed]
272. de Vries, W.; Schulte-Uebbing, L.; Kros, H.; Voogd, J.C.; Louwagie, G. Spatially Explicit Boundaries for Agricultural Nitrogen Inputs in the European Union to Meet Air and Water Quality Targets. *Sci. Total Environ.* **2021**, *786*, 147283. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.