Nitrogen

Perspective

Selecting Biomonitors of Atmospheric Nitrogen Deposition: Guidelines for Practitioners and Decision Makers

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Abstract: Environmental pollution is a major threat to public health and is the cause of important economic losses worldwide. Atmospheric nitrogen deposition is one of the most significant components of environmental pollution, which, in addition to being a health risk, is one of the leading drivers of global biodiversity loss. However, monitoring pollution is not possible in many regions of the world because the instrumentation, deployment, operation, and maintenance of automated systems is onerous. An affordable alternative is the use of biomonitors, naturally occurring or transplanted organisms that respond to environmental pollution with a consistent and measurable ecophysiological response. This policy brief advocates for the use of biomonitors of atmospheric nitrogen deposition. Descriptions of the biological and monitoring particularities of commonly utilized biomonitor lichens, bryophytes, vascular epiphytes, herbs, and woody plants, are followed by a discussion of the principal ecophysiological parameters that have been shown to respond to the different nitrogen emissions and their rate of deposition.

Keywords: atmospheric pollution; environmental management; planetary boundaries; public policy; public health

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1. Introduction

The purpose of this policy brief is to recommend the use of biomonitors of atmospheric nitrogen deposition. In particular, we focus on lichens and plants, the most common organisms utilized for quantifying deposition. Their importance, the opportunities for use, and the main characteristics of each type of organism are reviewed. A description is also included for the principal analytical techniques utilized for measuring the biomonitor responses to nitrogen deposition.

Biomonitoring of atmospheric deposition is becoming an increasingly accepted practice, although it is still most common in temperate regions of the Northern Hemisphere (Figure 1). While an effort has been made to reduce the utilization of jargon for clarity, the work is based on a systematic review of the academic literature and the authors' experience on biomonitoring. Practitioners looking to implement biomonitoring efforts and readers interested in the biogeochemical, ecophysiological, and analytical aspects of biomonitoring will find the underlying references in the Supplementary Material.

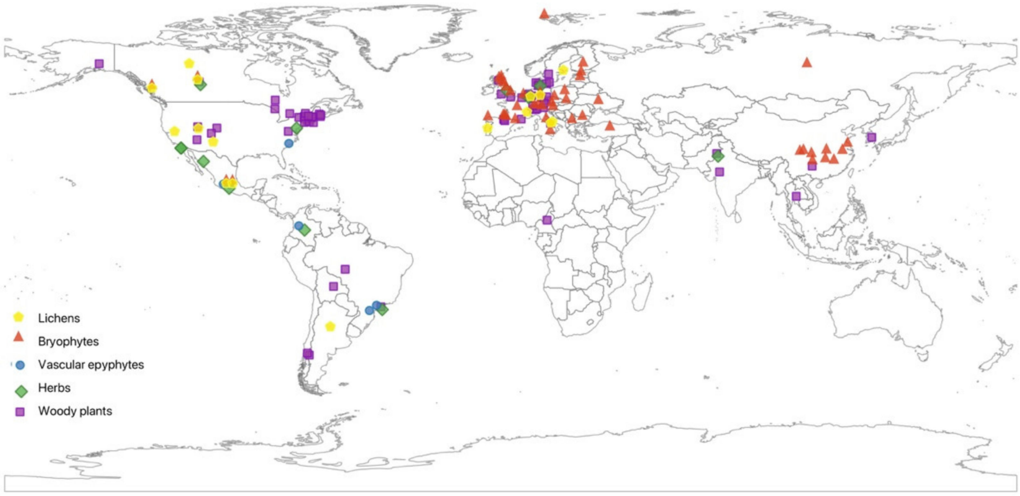

Figure 1. Biomonitoring experiences with lichens, bryophytes, vascular epiphytes, herbs, and woody plants. See underlying studies in the Supplementary Material.

2. Why Should Pollution Be Monitored?

Environmental pollution is a severe threat to public health. In addition to causing significant economic losses due to associated illness and missed days of work, which globally amounted to USD 21 billion in 2015, for example, pollution is responsible for one out of five premature deaths; this is more than the combined mortality of war and other forms of violence, plus that from pandemics such as AIDS, tuberculosis, and malaria [1,2]. Atmospheric pollution is of special concern, as it originates from economic activities such as transportation, industries, and agriculture, which are usually conducted in sites where people are concentrated. A common denominator for these polluting activities is their reliance on fossil fuels, whose combustion releases carbon dioxide and other greenhouse gases that, in addition to their better-known effect of causing climate change [3], have been associated with respiratory disease, stroke, and the accumulation of heavy metals in the internal organs of city dwellers [2,4].

The burden that pollution exerts on public health and general wellbeing is such that access to a clean environment has been elevated to the status of a basic human right [5]. In order to determine whether the public is exposed to safe levels (or not) of various noxious environmental pollutants, governments have issued standards of exposure to substances that comprise atmospheric pollution. Specifically, at least six atmospheric pollutants are usually monitored in cities, namely ozone (O_3) at the ground level, carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen dioxide (NO_2), lead (Pb), and particulate matter, especially suspended particles in the air with diameters below 10 μm (PM_{10}) and below 2.5 μm ($PM_{2.5}$) [6–8].

3. Why Is There a Special Concern about Nitrogen Deposition?

Nitrogen is arguably the most important component of environmental pollution. This may seem counterintuitive considering that nitrogen is an essential element for life and that it is the most abundant gas in the atmosphere, where its molecular form (N_2) is essentially inert. However, ca. 124 Tg of the reactive species of nitrogen, such as NO_x (i.e., NO and NO_2) and NH_x (NH_3, NH_4^+), are released annually into the environment as a result of human activities, mostly from the use of synthetic fertilizers required for food production and as by-products of internal combustion engines; in contrast, the natural nitrogen fixation by lightning and soil microorganisms does not even reach 30% of such an amount [9]. Although reactive nitrogen compounds can be directly taken up by crops and plants in general, substantial amounts can linger in the environment, with noxious effects on human (and animal) physiology, in addition to being precursors for other forms of pollution, including particulate matter and ozone at the ground level [10,11].

Different maladies have been associated with specific forms of anthropogenic reactive nitrogen. For instance, nitrites (NO_2^-) in the water compete with oxygen in hemoglobin in young children leading to blue-baby syndrome [12]. In addition, direct exposure to gaseous nitrogen oxides has been associated with an increased incidence of respiratory illness in cities [13]. In turn, exposure to NH_3 and NH_4^+ has also been linked with respiratory illness and to various insulin and neurological disorders [14,15]. Nitrogen pollution can also favor the proliferation of vectors and disease agents of mosquito-borne diseases, as well as cholera outbreaks and toxic algal blooms [13].

In addition to the public health and economic consequences of nitrogen pollution, the anthropogenic alteration of the nitrogen biogeochemical cycle is one of the most important causes of biodiversity loss [16–18]. For instance, the deposition of reactive atmospheric nitrogen on the ground leads to soil acidification, which in turn releases ions of aluminum and manganese that are toxic at high concentrations, and to the eutrophication of water bodies that reduces available oxygen for aquatic organisms and can promote the proliferation of noxious organisms [19,20]. Plant herbivory is also stimulated by increased nitrogen deposition, leading, in some cases, to the explosive proliferation of agricultural pests, even in natural environments [21].

Given its biogeochemical importance, monitoring nitrogenous pollution can provide information on the rate and type of reactive nitrogen emissions, as well as on overall ecosystem integrity and air quality.

4. When Is Biomonitoring of Atmospheric Pollution Recommended?

The use of automated or manual stations that utilize electro-physical sensors and chemical analyses is the gold standard for measuring atmospheric concentrations of various compounds of interest. However, the deployment, operation, and maintenance of such systems are onerous and can be out of financial reach in some locations. For example, despite the fact that environmental regulations mandate that atmospheric pollution be monitored in Mexican cities with populations above 500,000, numerous municipalities lack monitoring networks or have stations that are non-operational due to a lack of personnel and other budgetary reasons [22,23].

Biological monitoring of atmospheric pollution has become an increasingly accepted practice for characterizing environmental pollution, including in situations where monitoring stations are lacking [24–26]. Biomonitors are naturally occurring or transplanted organisms that respond in a quantitative manner to the prevalent levels of environmental pollutants [25,27]. Depending on their responses, they can be classified as accumulation or impact/effect biomonitors [28]. The former can accumulate pollutants of interest in their tissues with a magnitude that is proportional to the ambient magnitude. In turn impact or effect biomonitors are able to display specific ecophysiological responses that are also proportional to the prevailing environmental concentrations of the pollutant of interest. Lichens and plants have proved particularly useful for biomonitoring nitrogen deposition, and atmospheric pollution in general, owing to some of their biological characteristics. First, because they are sessile, i.e., they are attached to a substrate in a given site for the duration of their life, which allows them to integrate the environmental conditions over prolonged time periods and they are easily collected, especially when they are abundant in a region of interest [29]. Second, at least part of their nutrient acquisition is conducted directly from the surrounding atmosphere, either by gas exchange or by foliar (or thallus, in the case of lichens) absorption. Third, some of the chemical forms of nitrogen that are deposited as part of atmospheric pollution can actually be assimilated directly by the biomonitor, so that the measurement of ecophysiological processes can help characterize the extent of the surrounding pollution.

5. Guidelines for Biomonitoring Nitrogen Deposition: What, Who, and How

5.1. What: Pathways of Nitrogen Deposition

Anthropogenic reactive nitrogen emissions reach the ground via two pathways of deposition, dry and wet. Depending on the amount of annual rainfall in the region of interest, one or the other can be the most prevalent.

- **Dry deposition** is the process by which atmospheric pollutants, either gases or suspended particles, "fall" on different surfaces at the ground level by the direct action of gravity [30]. Additionally, gaseous compounds can be taken up directly by the vegetation through their leaf stomata [31]. Compounds such as ammonia (NH_3), nitric acid (HNO_3), and nitrogen dioxide (NO_2) make up part of the dry deposition;
- **Wet deposition** occurs when the reactive forms of nitrogen are "washed" from the atmosphere by water. Thus, they are deposited by being dissolved in the rain, fog, snow, or aerosols such as mist spray. It is mainly composed of ammonium (NH_4^+) and nitrate (NO_3^-) ions, but other chemical forms can also be deposited with water, including nitric acid, one of the components of acid rain [31];
- Finally, the sum of all of the nitrogen pollutants that are deposited through the dry and the wet pathways constitutes the **bulk deposition** [32,33].

5.2. Who: Suitable Organisms for Biomonitoring Nitrogen Deposition

Biomonitors have been utilized in various parts of the world to characterize nitrogen deposition, gaining special favor in the Northern Hemisphere (Figure 1; see particular studies in the Supplementary Material). Different species of lichens, bryophytes, and vascular plants, which take up reactive forms of nitrogen, either by their aerial organs or by their root systems, have been utilized to this end (Figure 2). Bryophytic biomonitors are the most frequently utilized in temperate regions, while successful biomonitoring has been conducted with epiphytes in the humid tropics, grasses in drylands, and woody plants in urban areas.

5.2.1. Lichens

Lichens are a symbiotic association between fungus and green algae or cyanobacteria. These organisms grow on rocks, trees, and other surfaces, where they take up nutrients directly from atmospheric deposition because they lack a cuticle [34,35]. Such a direct uptake can result in a deterioration of cell membrane integrity for sensitive species, which in turn leads to the disappearance of some species that have been documented in urban and other polluted areas [36–38].

For tolerant species, the direct uptake and assimilation of nitrogen deposition allow for accurate characterization of the prevalent pollution levels. However, the lack of a cuticle can also permit leaching of the accumulated nitrogen and other nutrients, the proportion depending on the intensity and frequency of precipitation events and the exposure of the lichen [39]. Because this may lead to seasonal fluctuations in the responses to nitrogen deposition, lichen biomonitors are best suited for characterizing dry deposition [25,40].

5.2.2. Bryophytes

Bryophytes, i.e., mosses, liverworts, and hornworts, are the most frequently utilized organisms for biomonitoring atmospheric pollution. Because they also lack a cuticle, they can readily take up and assimilate the prevailing nitrogen pollution, either by direct gas diffusion or when dissolved in water [41]. Similar to the case of lichens, because their tolerance to nitrogen deposition is species-dependent, the presence or absence of certain species can indicate the status of atmospheric pollution in a qualitative manner. Alternatively, the ecophysiological responses of tolerant species can help characterize the sources of reactive nitrogen emissions, the rates of deposition, and the spatial distribution of atmospheric pollution in large areas [42]. In fact, equations have been developed to estimate rates of nitrogen deposition based on the tissue nitrogen content for these plants [43–45]. A weakness of bryophytic biomonitors is that they can become physiologically inactive during prolonged periods of low environmental humidity, such as the dry season in regions with distinct rainy and dry seasons. As a result, these biomonitors cannot absorb nor record any pollution during such periods of physiological inactivity.

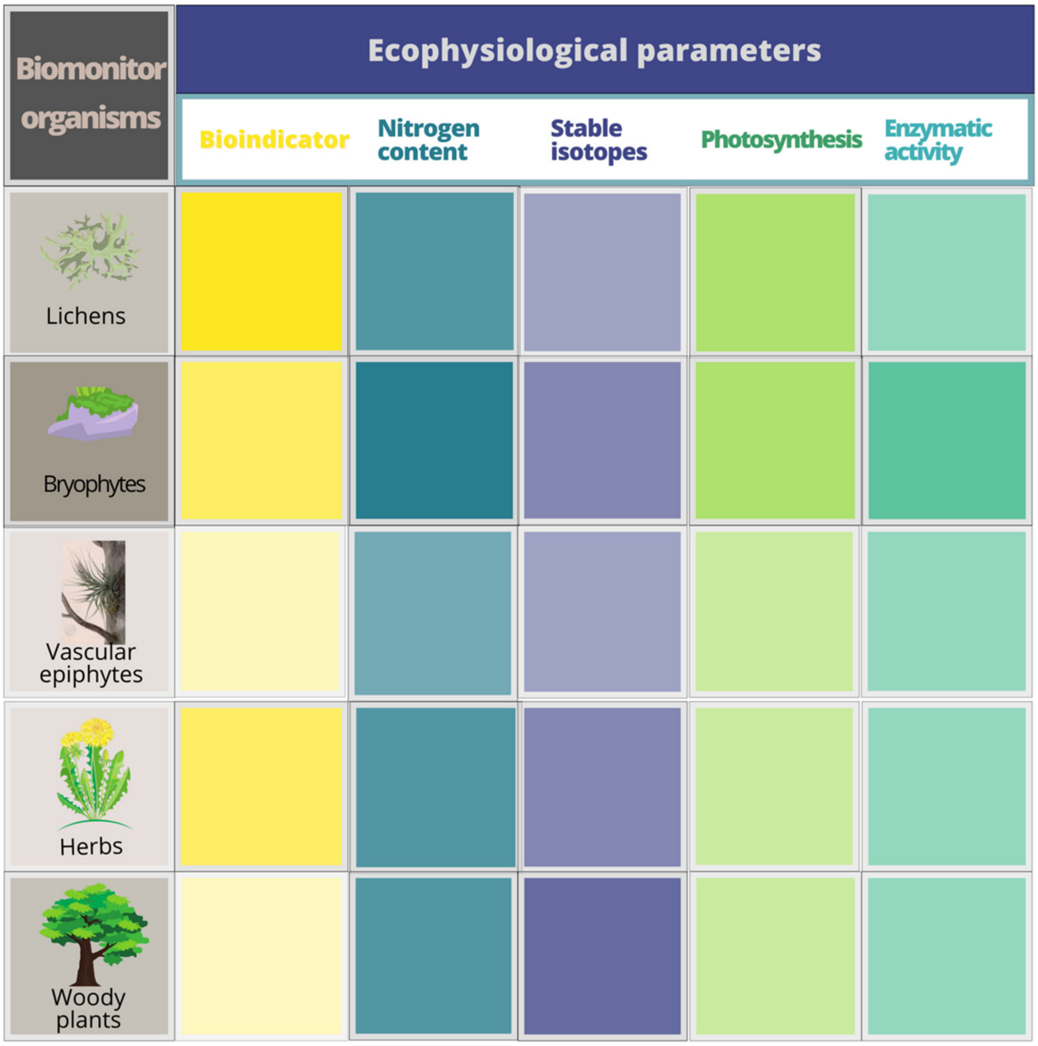

Figure 2. Commonly utilized biomonitoring organisms and ecophysiological parameters that are responsive to the rate and type of atmospheric nitrogen deposition. The intensity of the cell color for biomonitor and parameter intersections is indicative of its relative frequency based on a review of the academic literature. See underlying studies in the Supplementary Material.

5.2.3. Vascular Epiphytes

Both lichens and bryophytes, which often grow on inert substrates, such as rocks, tree trunks, or built structures, have great biomonitoring potential because their mineral nutrition can be predominantly obtained from atmospheric deposition. However, their lack of a cuticle can seasonally limit their utilization and dampen the pollution signal during the rainy season. This limitation has been overcome by the use of epiphytic vascular plants, which also have predominant (and sometimes exclusive) atmospheric nutrition, but their adaptation to the extremely variable hydric environment of the epiphytic habit, allows them to be physiologically active throughout the year [25,46]. Indeed, the use of atmospheric bromeliads is amply documented in the American continent, especially plants of the genus *Tillandsia*, which occur from the southern United States to Argentina [47]. Two species, *Tillandsia recurvata* (the common name is ball moss) and *T. usneoides* (Spanish moss), are recognized as exceptional biomonitors of dry deposition, as they allow tracking the source and concentration of gaseous nitrogen pollutants throughout the year. In contrast, their responses to wet deposition are weak, precisely as a consequence of their water-conservation and low-nutrient adaptations [25,48].

For parts of the world where tillandsias are not native, vascular plants with similar characteristics can be considered for biomonitoring, including, for example, epiphytic species in the Polypodiaceae (ferns) or Araceae (aurum family) families, which are cosmopolitan [49]. Epiphytic orchids can also be considered for biomonitoring both dry and wet nitrogen deposition [40–52]. In addition to having ecophysiological characteristics similar to those of the tillandsias, some orchids produce pseudobulbs, which are nutrient and water reserve organs that develop every growing season, and are able to record and compartmentalize the prevailing nitrogen deposition over multiple years [52].

5.2.4. Herbs

Grasses and forbs obtain their nitrogen, and nutrients in general, primarily through their roots, which have access to both naturally fixed nitrogen and to nitrogen that reached the soil via wet deposition; in addition, these plants are able to take up gaseous and dry deposited nitrogen through their leaf stomata [53]. As a consequence of their ability to utilize nitrogen from various sources, identifying the effect of a particular signal on these rooted plants can be difficult. However, measurements of the tissue nitrogen concentration and isotopic composition for these plants have been shown to integrate different soil processes in response to increased nitrogen availability and still be able to detect vehicular emissions [54–56]. Herbs can thus make adequate urban biomonitors of nitrogen deposition because they occur spontaneously in disturbed environments and, in some cases, they are actually favored by the increased nitrogen availability that results from pollution [57,58]. Given their tolerance to environmental stress, even in arid regions, herbs have been successfully utilized to biomonitor nitrogen deposition, for instance, to contrast years and identify trends in the emission of N pollutants and urbanization intensity [49,55,56,59,60].

5.2.5. Woody Plants

Shrubs and trees also take up nitrogen from different sources, including from dry and wet deposition. Contrasting with herbs, many of which are ephemeral, the longevity of woody plants allows their utilization to biomonitor nitrogen deposition over many years. Indeed, the study of the nitrogen content and isotopic signals of their growth rings allows for the compilation of time series to determine trends in pollutant emissions [61,62]. Additionally, because these plants are common elements of cities, either because they were "tolerated" in the process of urbanization, because they were deliberately planted as ornamentals, or because their proliferation is favored by the urban environment, trees can provide a somewhat standardized means for biomonitoring nitrogen deposition across different cities [26,59,63,64].

Woody plants can thus be useful biomonitors of dry nitrogen deposition. For example, it has been estimated that these plants are able to assimilate up to 60% of the nitric acid intercepted by their canopies [65], whose source can be tracked by means of isotopic analysis of plant foliar tissues [49,66]. This is particularly important for semiarid regions where the dry deposition represents the largest portion of atmospheric pollution [26,64,67]. The nitrogen content of woody plants also responded to the rate of dry deposition. In particular, their nitrogen content increases with the proximity to highways or industries [59,66,68,69].

Woody plants are also useful biomonitors of wet deposition, with their root uptake of nitrogen from the soil solution. The most straightforward responses are their nitrogen content, which has been found to increase with the rate of atmospheric deposition, and their isotopic status, which can reflect the source of pollution [63]. In addition, the nitrogen isotopic status of trees and shrubs can be utilized for determining nitrogen saturation in different ecosystems [70], the process by which chronic nitrogen deposition alters different ecosystem processes [71,72].

5.3. How: Ecophysiological Parameters That Respond to Nitrogen Deposition

Various ecophysiological parameters can be measured to determine the response of biomonitor species to atmospheric nitrogen deposition (Figure 2). The most adequate suite of techniques to be utilized should be chosen in consideration of the lifeform of the biomonitor, the environmental conditions of the region of interest, and the laboratory and material resources available.

5.3.1. Responses of Bioindicator Species

The most straightforward use of biological organisms for characterizing environmental pollution is based on the presence (or disappearance) of certain species in a region of interest [28]. Lichens have been widely utilized as qualitative bioindicators for identifying the increasing effects of environmental pollution, including those from nitrogen deposition [27,34]. Considering that multiple factors can lead to the local disappearance of species, care should be taken when interpreting the results of bioindicator surveys, as factors such as climate, city greenery maintenance protocols, and the presence of pollution emission sources, need to be considered. For such reasons, it is recommended that bioindicator surveys be conducted periodically, each year, for example, in order to identify changes in the species distribution and abundance as they respond to pollution.

5.3.2. Nitrogen Concentration

Because nitrogen is an essential nutrient and its baseline "natural" availability is rather low, plants readily take up available nitrogen and incorporate it into their tissues. For this reason, when nitrogen deposition increases, so does the total concentration of this element in the tissues of biomonitors. Total nitrogen concentration in plant tissues (measured as the percent of dry weight) can be as low as 0.5%, but it has been measured to be twice as high for plants growing where nitrogen deposition is substantial [44,50,73]. In addition to its ecophysiological usefulness for biomonitoring, measurements of tissue nitrogen concentration are rather inexpensive and are performed by many analytical environmental laboratories internationally.

5.3.3. $\delta^{15}N$

The proportion of ^{15}N present in biomonitor tissues can reflect the predominant form of pollution in a determined area and the nitrogen saturation status in an ecosystem [25,26,70].

The different sources of nitrogenous compounds have specific $\delta^{15}N$ values, which are traceable in the vegetation from different environments. In general terms, oxidized nitrogen compounds from emissions in urban environments tend to be positive. For example, NO_x and NO_3^- can reach $\delta^{15}N$ values of 26‰ and 15‰, respectively [74,75]. These values contrast with those of the natural environments that tend to be negative, but close to zero [76]. In turn, reduced nitrogen compounds, from both urban and rural environments, have very negative values, reaching −56‰ for NH_3 and −15‰ for NH_4^+ [77,78].

With respect to the saturation state of the ecosystems, the $\delta^{15}N$ values for plants of natural environments are close to zero. However, as the rate of bulk nitrogen deposition increases, the natural nitrogen reactions of soil are subjected to profound alterations, on one hand, owing to a loss of soil microorganisms associated with the nitrogen biogeochemical cycle, and on other hand, because the nitrogen losses increase. As a consequence, the $\delta^{15}N$ values of terrestrial plants become positive, a value that is a conspicuous indicator of nitrogen saturation [25,70].

5.3.4. Photosynthesis Related Parameters

Pigments are essential components of several steps and processes of photosynthesis and plant metabolism. An effect of increased nitrogen availability is an increased pigment concentration, especially chlorophyll [79]. Measuring chlorophyll content by colorimetry in the laboratory is quite straightforward and various portable optical instruments, which are rather inexpensive, are available for non-destructive measurements of chlorophyll content in the field [80,81]. Additionally, changes in the chlorophyll *a/b* ratio have been shown to fluctuate in response to increasing nitrogen deposition, and the concentrations of accessory pigments, particularly those from the xanthophyll cycle, can indicate the plant sensitivity to different pollutants [50,79,82]. The development of portable instruments that measure chlorophyll fluorescence, has enabled field measurements of plant photosynthetic activity, which has proven to be most sensitive to nitrogen deposition [50,79,83].

5.3.5. Enzymatic Activity

Measurements of activity for enzymes related to nitrogen metabolism have been useful in quantitative and semiquantitative biomonitoring of atmospheric deposition [48,79]. Nitrate reductase, for instance, is the first enzyme involved in nitrogen assimilation, as it reduces the nitrates taken up from the soil solution into nitrites [84]. For this enzyme, an increase of available nitrogen, such as that resulting from atmospheric deposition, increases its activity [48,85,86]. However, after a certain nitrogen concentration, this enzyme becomes saturated, so a decrease in its activity has been observed in highly polluted sites [85,87].

Phosphomonoesterase is another important enzyme whose activity increases in response to nitrogen deposition, being able to tolerate higher levels of pollution than nitrate reductase [48,79,88]. The activity for this enzyme increases with atmospheric deposition as a plant response to a phosphorus limitation that results from the excess nitrogen in the soil [89]. Enzymatic activity for these enzymes can be measured colorimetrically in the laboratory for fresh plant tissue samples.

6. Policy Perspectives

- Implementation of biomonitoring in localities where automatic stations are not available can help local governments assess whether the human right to a clean environment is being fulfilled.
- The distribution and abundance of conspicuous bioindicator species, especially those with ample geographic distributions, lend themselves to recruit citizen scientist volunteers, who can help create participatory maps of environmental quality in regions of interest.
- Suitable biomonitoring species of different lifeforms can be identified in regions of interest that are relatively abundant and tolerant to the prevailing levels of pollution. The specific parameters to be measured are dependent on the available resources.
- Caution needs to be exercised when selecting biomonitors. Increased rates of nitrogen deposition seem to favor, in some cases, the proliferation of potentially invasive species. While species such as buffelgrass [60] and the castor bean [59] can be excellent biomonitors, they are quite noxious invasive species, so their introduction to new sites is never recommended.
- Because biomonitors can take up various chemical compounds that comprise atmospheric pollution, in addition to those from nitrogen deposition, their adoption can help in an integrated characterization of environmental quality, including responses to various criteria pollutants and other contaminants of concern in each region of interest.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/nitrogen2030021/s1, Figure S1: PRISMA flow diagram for the systematic literature review conducted for biomonitors of nitrogen deposition, Figure S2: Number of studies identified in the literature review that utilized different biomonitor lifeforms (a) and total number of species per lifeform reported in the literature (b), Table S1: Biomonitors of nitrogen deposition identified in the systematic literature review, which includes references [90–124].

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References

1. OECD. *The Economic Consequences of Outdoor Air Pollution*; OECD Publishing: Paris, France, 2016; pp. 13–30. [CrossRef]
2. Landrigan, P.J.; Fuller, R.; Acosta, N.J.R.; Adeyi, O.; Arnold, R.; Basu, N.; Baldé, A.B.; Bertollini, R.; Bose-O'Reilly, S.; Boufford, J.I.; et al. The Lancet Commission on Pollution and Health. *Lancet* **2017**, *391*, 1–51. [CrossRef]
3. IPCC Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/ (accessed on 27 May 2021).
4. Stevens, G.; Dias, R.H.; Thomas, K.J.A.; Rivera, J.A.; Carvalho, N.; Barquera, S.; Hill, K.; Ezzati, M. Characterizing the epidemiological transition in Mexico: National and subnational burden of diseases, injuries, and risk factors. *PLoS Med.* **2008**, *5*, e125. [CrossRef]
5. United Nations. *Right to a Healthy Environment: Good Practices*; United Nations: New York, NY, USA, 2019; pp. 1–27.
6. SEMARNAT Diario Oficial de La Federación. NORMA Oficial Mexicana NOM-172-SEMARNAT-2019, Lineamientos Para La Obtención y Comunicación Del Índice de Calidad Del Aire y Riesgos a La Salud. Available online: https://www.dof.gob.mx/nota_detalle.php?codigo=5579387&fecha=20/11/2019 (accessed on 26 May 2021).
7. Criteria Air Pollutants | US EPA. Available online: https://www.epa.gov/criteria-air-pollutants (accessed on 26 May 2021).
8. Standards—Air Quality—Environment—European Commission. Available online: https://ec.europa.eu/environment/air/quality/standards.htm (accessed on 26 May 2021).
9. Fowler, D.; Muller, J.B.A.; Sheppard, L.J. The GaNE Programme in a Global Perspective. *Water Air Soil Pollut. Focus* **2004**, *4*, 3–8. [CrossRef]
10. 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]
11. Feng, Z.; De Marco, A.; Anav, A.; Gualtieri, M.; Sicard, P.; Tian, H.; Fornasier, F.; Tao, F.; Guo, A.; Paoletti, E. Economic Losses Due to Ozone Impacts on Human Health, Forest Productivity and Crop Yield across China. *Environ. Int.* **2019**, *131*, 104966. [CrossRef] [PubMed]
12. WHO. *Nitrate and Nitrite in Drinking-Water*; World Health Organization: Geneva, Switzerland, 2011; pp. 1–23.
13. Townsend, A.R.; Howarth, R.W.; Bazzaz, F.A.; Booth, M.S.; Cleveland, C.C.; Collinge, S.K.; Dobson, A.P.; Epstein, P.R.; Holland, E.A.; Keeney, D.R.; et al. Human Health Effects of a Changing Global Nitrogen Cycle. *Front. Ecol. Environ.* **2003**, *1*, 240. [CrossRef]
14. Britto, D.T.; Kronzucker, H.J. NH4+ Toxicity in Higher Plants: A Critical Review. *J. Plant Physiol.* **2002**, *159*, 567–584. [CrossRef]
15. Adlimoghaddam, A.; Sabbir, M.G.; Albensi, B.C. Ammonia as a Potential Neurotoxic Factor in Alzheimer's Disease. *Front. Mol. Neurosci.* **2016**, *9*, 57. [CrossRef] [PubMed]
16. Sala, O.E.; Chapin, F.S., III; Armesto, J.J.; Berlow, E.; Dirzo, R.; Huber-sanwald, E.; Huenneke, L.F.; Robert, B.; Kinzig, A.; Leemans, R.; et al. Global Biodiversity Scenarios for the Year 2100. *Science* **2000**, *287*, 1770–1774. [CrossRef]
17. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855. [CrossRef]
18. Phoenix, G.K.; Hicks, W.K.; Cinderby, S.; Kuylenstierna, J.C.I.; Stock, W.D.; Dentener, F.J.; Giller, K.E.; Austin, A.T.; Lefroy, R.D.B.; Gimeno, B.S.; et al. Atmospheric Nitrogen Deposition in World Biodiversity Hotspots: The Need for a Greater Global Perspective in Assessing N Deposition Impacts. *Glob. Chang. Biol.* **2006**, *12*, 470–476. [CrossRef]
19. Horswill, P.; O'Sullivan, O.; Phoenix, G.K.; Lee, J.A.; Leake, J.R. Base Cation Depletion, Eutrophication and Acidification of Species-Rich Grasslands in Response to Long-Term Simulated Nitrogen Deposition. *Environ. Pollut.* **2008**, *155*, 336–349. [CrossRef] [PubMed]
20. Tian, D.S.; Niu, S.L. A Global Analysis of Soil Acidification Caused by Nitrogen Addition. *Environ. Res. Lett.* **2015**, *10*, 024019. [CrossRef]

21. Throop, H.L. Nitrogen Deposition and Herbivory Affect Biomass Production and Allocation in an Annual Plant. *Oikos* **2005**, *111*, 91–100. [CrossRef]
22. SEMARNAT Diario Oficial de La Federación. NORMA Oficial Mexicana NOM-156-SEMARNAT-2012, Establecimiento y Operación de Sistemas de Monitoreo de La Calidad Del Aire. Available online: http://www.dof.gob.mx/nota_detalle.php?codigo=5259464&fecha=16%2F07%2F2012 (accessed on 27 May 2021).
23. SINAICA Instituto Nacional de Ecología y Cambio Climático. Available online: https://sinaica.inecc.gob.mx/ (accessed on 21 May 2021).
24. ICP Vegetation. Available online: https://icpvegetation.ceh.ac.uk/ (accessed on 27 May 2021).
25. Díaz-Álvarez, E.A.; Lindig-Cisneros, R.; de la Barrera, E. Biomonitors of Atmospheric Nitrogen Deposition: Potential Uses and Limitations. *Conserv. Physiol.* **2018**, *6*, 1093–1110. [CrossRef]
26. 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 (δ^{13}C, δ^{15}N) Profiles as Reliable Urban Pollution Biomonitoring Tools. *Urban For. Urban Green.* **2021**, *57*, 126918. [CrossRef]
27. Conti, M.E.; Cecchetti, G. Biological Monitoring: Lichens as Bioindicators of Air Pollution Assessment—A Review. *Environ. Pollut.* **2001**, *114*, 471–492. [CrossRef]
28. Markert, B.A.; Breure, A.M.; Zechmeister, H.G. *Bioindicators & Biomonitors, Principles, Concepts and Applications*; Elsevier Science Ltd.: Kidlington, Oxford, UK, 2003; p. 967.
29. Dokulil, M.T. Algae as ecological bio-indicators. In *Bioindicators and Biomonitors, Principles, Concepts and Applications*; Markert, B.A., Breure, A.M., Zechmeister, H.G., Eds.; Elsevier Science Ltd.: Kidlington, Oxford, UK, 2003; pp. 238–285.
30. Beckett, K.P.; Freer-Smith, P.H.; Taylor, G. Urban Woodlands: Their Role in Reducing the Effects of Particulate Pollution. *Environ. Pollut.* **1998**, *99*, 347–360. [CrossRef]
31. Cieslik, S.; Tuovinen, J.P.; Baumgarten, M.; Matyssek, R.; Brito, P.; Wieser, G. *Gaseous Exchange between Forests and the Atmosphere*, 1st ed.; Elsevier Ltd.: Amsterdam, The Netherlands, 2013; Volume 13, ISBN 978-0-08-098349-3.
32. Eugster, W.; Haeni, M. Nutrients or pollutants? Nitrogen deposition to European forests. In *Climate Change, Air Pollution and Global Challenges*; Karnosky, D.F., Percy, K.E., Chappelka, A.H., Simpson, C., Pikkarainen, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2013; pp. 37–56. ISBN 978-0-08-098349-3.
33. Staelens, J.; De Schrijver, A.; Van Avermaet, P.; Genouw, G.; Verhoest, N. A Comparison of Bulk and Wet-Only Deposition at Two Adjacent Sites in Melle (Belgium). *Atmos. Environ.* **2005**, *39*, 7–15. [CrossRef]
34. Hawksworth, D.L.; Iturriaga, T.; Crespo, A. Lichens as Rapid Bioindicators of Pollution and Habit Disturbance in the Tropics. *Rev. Iberoam. Micol.* **2005**, *22*, 71–82. [CrossRef]
35. Grimm, M.; Grube, M.; Schiefelbein, U.; Zühlke, D.; Bernhardt, J.; Riedel, K. *The Lichens' Microbiota, Still a Mystery?* Frontiers Media S.A.: Lausanne, Switzerland, 2021; Volume 12.
36. Ruisi, S.; Zucconi, L.; Fornasier, F.; Paoli, L.; Frati, L.; Loppi, S. Israel Journal of Plant Sciences Mapping Environmental Effects of Agriculture with Epiphytic Lichens. *Isr. J. Plant Sci.* **2005**, *53*, 115–124. [CrossRef]
37. De Bruyn, U.; Linders, H.W.; Mohr, K. Epiphytische Flechten Im Wandel von Immissionen Und Klima Ergebnisse Einer Vergleichskartierung 1989/2007 in Nordwestdeutschland. *Umweltwiss. Schadst. Forsch.* **2009**, *21*, 63–75. [CrossRef]
38. Rangel-Osornio, V.; Fernández-Salegui, A.B.; Gómez-Reyes, V.M.; Cuevas-Villanueva, R.A.; Lopez-Toledo, L. Effects of Air Pollution on Chlorophyll Content and Morphology of Lichens Transplanted around a Paper Industry (Morelia, Mexico). *Bryologist* **2021**, *124*, 52–67. [CrossRef]
39. Branquinho, C.; Gaio-Oliveira, G.; Augusto, S.; Pinho, P.; Máguas, C.; Correia, O. Biomonitoring Spatial and Temporal Impact of Atmospheric Dust from a Cement Industry. *Environ. Pollut.* **2008**, *151*, 292–299. [CrossRef] [PubMed]
40. 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]
41. Liu, X.Y.; Koba, K.; Liu, C.Q.; Li, X.D.; Yoh, M. Pitfalls and New Mechanisms in Moss Isotope Biomonitoring of Atmospheric Nitrogen Deposition. *Environ. Sci. Technol.* **2012**, *46*, 12557–12566. [CrossRef]
42. Xiao, H.Y.; Xie, Z.Y.; Tang, C.G.; Wang, Y.L.; Liu, C.Q. Epilithic Moss as a Bio-Monitor of Atmospheric N Deposition in South China. *J. Geophys. Res. Atmos.* **2011**, *116*, D24301. [CrossRef]
43. Zechmeister, H.G.; Richter, A.; Smidt, S.; Hohenwallner, D.; Roder, I.; Maringer, S.; Wanek, W. Total Nitrogen Content and δ^{15}N Signatures in Moss Tissue: Indicative Value for Nitrogen Deposition Patterns and Source Allocation on a Nationwide Scale. *Environ. Sci. Technol.* **2008**, *42*, 8661–8667. [CrossRef]
44. 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]
45. Harmens, H.; Norris, D.; Cooper, D.; Hall, J. *Spatial Trends in Nitrogen Concentrations in Mosses across Europe in 2005/2006. Report on Nitrogen in European Mosses*; NERC/Centre for Ecology & Hydrology: Wallingford, UK, 2008.
46. De La Barrera, E.; Andrade, J.L. Challenges to Plant Megadiversity: How Environmental Physiology Can Help. *New Phytol.* **2005**, *167*, 5–8. [CrossRef]
47. Benzing, D.H. *The Biology of Bromeliads*; Mad River Press: Eureka, CA, USA, 1980.

48. Díaz-Álvarez, E.A.; De La Barrera, E.; Barrios-Hernández, E.Y.; Arróniz-crespo, M.; de la Barrera, E.; Barrios-hernández, E.Y.; Arróniz-crespo, M. Morphophysiological Screening of Potential Organisms for Biomonitoring Nitrogen Deposition. *Ecol. Indic.* **2020**, *108*, 105729. [CrossRef]
49. Stewart, G.R.; Aidar, M.P.M.M.; Joly, C.A.; Schmidt, S. Impact of Point Source Pollution on Nitrogen Isotope Signatures (δ^{15}N) of Vegetation in SE Brazil. *Oecologia* **2002**, *131*, 468–472. [CrossRef]
50. Díaz-Álvarez, E.A.; Lindig-Cisneros, R.; De La Barrera, E. Responses to Simulated Nitrogen Deposition by the Neotropical Epiphytic Orchid Laelia Speciosa. *PeerJ* **2015**, *3*, e1021. [CrossRef] [PubMed]
51. Díaz-Álvarez, E.A.; Felix, J.D.; de la Barrera, E. Elemental and Isotopic Assessment for Colombian Orchids from a Montane Cloud Forest: A Baseline for Global Environmental Change. *Acta Physiol. Plant.* **2019**, *41*, 99. [CrossRef]
52. Díaz-Álvarez, E.A.; Reyes-García, C.; de la Barrera, E. A δ^{15}N Assessment of Nitrogen Deposition for the Endangered Epiphytic Orchid Laelia Speciosa from a City and an Oak Forest in Mexico. *J. Plant Res.* **2016**, *129*, 863–872. [CrossRef] [PubMed]
53. Tegeder, M.; Masclaux-Daubresse, C. Source and Sink Mechanisms of Nitrogen Transport and Use. *New Phytol.* **2018**, *217*, 35–53. [CrossRef]
54. Gebauer, G.; Dietrich, P. Nitrogen Isotope Ratios in Different Compartments of a Mixed Stand of Spruce, Larch and Beech Trees and of Understorey Vegetation Including Fungi. *Isot. Environ. Health Stud.* **1993**, *29*, 35–44. [CrossRef]
55. Wang, W.; Pataki, D.E. Spatial Patterns of Plant Isotope Tracers in the Los Angeles Urban Region. *Landsc. Ecol.* **2009**, *25*, 35–52. [CrossRef]
56. Redling, K.; Elliott, E.; Bain, D.; Sherwell, J. Highway Contributions to Reactive Nitrogen Deposition: Tracing the Fate of Vehicular NOx Using Stable Isotopes and Plant Biomonitors. *Biogeochemistry* **2013**, *116*, 261–274. [CrossRef]
57. Power, S.A.; Collins, C.M. Use of *Calluna vulgaris* to Detect Signals of Nitrogen Deposition across an Urban-Rural Gradient. *Atmos. Environ.* **2010**, *44*, 1772–1780. [CrossRef]
58. Martínez, D.N.; De la Barrera, E. Physiological Screening of Ruderal Weed Biomonitors of Atmospheric Nitrogen Deposition. *Bot. Sci.* **2021**, *1*, 573–587. [CrossRef]
59. Khalid, N.; Noman, A.; Masood, A.; Tufail, A.; Hadayat, N.; Alnusairi, G.S.H.; Alamri, S.; Hashem, M.; Aqeel, M. Air Pollution on Highways and Motorways Perturbs Carbon and Nitrogen Levels in Roadside Ecosystems. *Chem. Ecol.* **2020**, *36*, 868–880. [CrossRef]
60. Díaz-Álvarez, E.A.; de la Barrera, E. Influence of Land Use on the C and N Status of a C_4 Invasive Grass in a Semi-Arid Region: Implications for Biomonitoring. *Plants* **2021**, *10*, 942. [CrossRef] [PubMed]
61. Saurer, M.; Cherubini, P.; Ammann, M.; De Cinti, B.; Siegwolf, R. First Detection of Nitrogen from NO_x in Tree Rings: A ^{15}N/^{14}N Study near a Motorway. *Atmos. Environ.* **2004**, *38*, 2779–2787. [CrossRef]
62. Van Der Sleen, P.; Vlam, M.; Groenendijk, P.; Anten, N.P.R.; Bongers, F.; Bunyavejchewin, S.; Hietz, P.; Pons, T.L.; Zuidema, P.A. ^{15}N 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]
63. Boltersdorf, S.H.; Pesch, R.; Werner, W. Comparative Use of Lichens, Mosses and Tree Bark to Evaluate Nitrogen Deposition in Germany. *Environ. Pollut.* **2014**, *189*, 43–53. [CrossRef] [PubMed]
64. Cobley, L.A.E.; Pataki, D.E. Vehicle Emissions and Fertilizer Impact the Leaf Chemistry of Urban Trees in Salt Lake Valley, UT. *Environ. Pollut.* **2019**, *254*, 112984. [CrossRef] [PubMed]
65. Padgett, P.E.; Cook, H.; Bytnerowicz, A.; Heath, R.L. Foliar Loading and Metabolic Assimilation of Dry Deposited Nitric Acid Air Pollutants by Trees. *J. Environ. Monit.* **2009**, *11*, 75–84. [CrossRef] [PubMed]
66. Ammann, M.; Siegwolf, R.; Pichlmayer, F.; Suter, M.; Saurer, M.; Brunold, C. Estimating the Uptake of Traffic-Derived NO_2 from ^{15}N Abundance in Norway Spruce Needles. *Oecologia* **1999**, *118*, 124–131. [CrossRef]
67. Kenkel, J.A.; Sisk, T.D.; Hultine, K.R.; Sesnie, S.E.; Bowker, M.A.; Johnson, N.C. Indicators of Vehicular Emission Inputs into Semi-Arid Roadside Ecosystems. *J. Arid Environ.* **2016**, *134*, 150–159. [CrossRef]
68. Xu, Y.; Xiao, H.; Guan, H.; Long, C. Monitoring Atmospheric Nitrogen Pollution in Guiyang (SW China) by Contrasting Use of *Cinnamomum Camphora* Leaves, Branch Bark and Bark as Biomonitors. *Environ. Pollut.* **2018**, *233*, 1037–1048. [CrossRef]
69. Wieder, R.K.; Vile, M.A.; Scott, K.D.; Albright, C.M.; Quinn, J.C.; Vitt, D.H. Bog Plant/Lichen Tissue Nitrogen and Sulfur Concentrations as Indicators of Emissions from Oil Sands Development in Alberta, Canada. *Environ. Monit. Assess.* **2021**, *193*, 1–18. [CrossRef]
70. Pardo, L.H.; Templer, P.H.; Goodale, C.L.; Duke, S.; Groffman, P.M.; Adams, M.B.; Boeckx, P.; Boggs, J.; Campbell, J.; Colman, B.; et al. Regional Assessment of N Saturation Using Foliar and Root Δ15N. *Biogeochemistry* **2006**, *80*, 143–171. [CrossRef]
71. Aber, J.D.; Nadelhoffer, K.J.; Steudler, P.; Melillo, J.M. Nitrogen Saturation in Northern Forest Ecosystems. *BioScience* **1989**, *39*, 378–386. [CrossRef]
72. Aber, J.; McDowell, W.; Nadelhoffer, K.; Magill, A.; Berntson, G.; Kamakea, M.; McNulty, S.; Currie, W.; Rustad, L.; Fernandez, I. Nitrogen Saturation in Temperate Forest Ecosystems. *BioScience* **1998**, *48*, 921–934. [CrossRef]
73. Sommer, S.G. A Simple Biomonitor for Measuring Ammonia Deposition in Rural Areas. *Biol. Fertil. Soils* **1988**, *6*, 61–64. [CrossRef]
74. Hoering, T. The Isotopic Composition of the Ammonia and the Nitrate Ion in Rain. *Geochim. Cosmochim. Acta* **1957**, *12*, 97–102. [CrossRef]
75. Heaton, T.H.E. 15N/14N Ratios of NO_x from Vehicle Engines and Coal-fired Power Stations. *Tellus* **1990**, *42B*, 304–307. [CrossRef]

76. Wania, R.; Hietz, P.; Wanek, W. Natural ^{15}N Abundance of Epiphytes Depends on the Position within the Forest Canopy: Source Signals and Isotope Fractionation. *Plant Cell Environ.* **2002**, *25*, 581–589. [CrossRef]
77. Moore, H. The Isotopic Composition of Ammonia, Nitrogen Dioxide and Nitrate in the Atmosphere. *Atmospheric Environ.* **1977**, *11*, 1239–1243. [CrossRef]
78. Felix, J.D.; Avery, G.B.; Mead, R.N.; Kieber, R.J.; Willey, J.D. Nitrogen Content and Isotopic Composition of Spanish Moss (*Tillandsia Usneoides* L.): Reactive Nitrogen Variations and Source Implications Across an Urban Coastal Air Shed. *Environ. Process.* **2016**, *3*, 711–722. [CrossRef]
79. 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]
80. Lichtenthaler, H.K.; Buschmann, C. Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Curr. Protoc. Food Anal. Chem.* **2001**, *8*, F4.3.1–F4.3.8. [CrossRef]
81. Zhang, Y.; He, N.; Zhang, G.; Huang, J.; Han, X. Nitrogen Deposition and Leymus Chinensis Leaf Chlorophyll Content in Inner Mongolian Grassland. *Shengtai Xuebao Acta Ecol. Sin.* **2013**, *33*, 6786–6794. [CrossRef]
82. Ashraf, M.; Harris, P.J.C. Photosynthesis under Stressful Environments: An Overview. *Photosynthetica* **2013**, *51*, 163–190. [CrossRef]
83. Maxwell, K.; Johnson, G.N. Chlorophyll Fluorescence—A Practical Guide. *J. Exp. Bot.* **2000**, *51*, 659–668. [CrossRef]
84. Lambers, H.; Chapin III, F.S.; Pons, T.L. *Plant Physiological Ecology*, 2nd ed.; Springer: New Jersey, NJ, USA, 2008; ISBN 978-0-387-78340-6.
85. Woodin, S.J.; Lee, J.A. The Effects of Nitrate, Ammonium and Temperature on Nitrate Reductase Activity in Sphagnum Species. *New Phytol.* **1987**, *105*, 103–115. [CrossRef] [PubMed]
86. Pearce, I.S.K.; Woodin, S.J.; Van Der Wal, R. Physiological and Growth Responses of the Montane Bryophyte Racomitrium Lanuginosum to Atmospheric Nitrogen Deposition. *New Phytol.* **2003**, *160*, 145–155. [CrossRef] [PubMed]
87. Díaz-Álvarez, E.A.; De la Barrera, E.; Arciga-Pedraza, A.; Arróniz-Crespo, M.; de la Barrera, E.; Arciga-Pedraza, A.; Arróniz-Crespo, M.; De la Barrera, E.; Arciga-Pedraza, A.; Arróniz-Crespo, M.; et al. Bryophyte Enzymatic Responses to Atmospheric Nitrogen Deposition: A Field Validation for Potential Biomonitors. *Bryologist* **2019**, *122*, 396–403. [CrossRef]
88. Phoenix, G.K.; Booth, R.E.; Leake, J.R.; Read, D.J.; Grime, J.P.; Lee, J.A. Effects of Enhanced Nitrogen Deposition and Phosphorus Limitation on Nitrogen Budgets of Semi-Natural Grasslands. *Glob. Chang. Biol.* **2003**, *9*, 1309–1321. [CrossRef]
89. Johnson, D.; Leake, J.R.; Lee, J.A. The Effects of Quantity and Duration of Simulated Pollutant Nitrogen Deposition on Root-Surface Phosphatase Activities in Calcareous and Acid Grasslands: A Bioassay Approach. *New Phytol.* **1999**, *141*, 433–442. [CrossRef]
90. PRISMA. Available online: http://www.prisma-statement.org/ (accessed on 27 May 2021).
91. 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]
92. Díaz-Alvarez, E.; de la Barrera, E. Mapping Pollution in a Megalopolis: The Case for Atmospheric Biomonitors of Nitrogen Deposition. *Sci. Rep.* **2017**, *11*, 11–14. [CrossRef]
93. Paoli, L.; Munzi, S.; Guttová, A.; Senko, D.; Sardella, G.; Loppi, S. Lichens as Suitable Indicators of the Biological Effects of Atmospheric Pollutants around a Municipal Solid Waste Incinerator (S Italy). *Ecol. Indic.* **2015**, *52*, 362–370. [CrossRef]
94. 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]
95. 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]
96. Pinho, P.; Martins-Loução, M.-A.; Máguas, C.; Branquinho, C. Calibrating Total Nitrogen Concentration in Lichens with Emissions of Reduced Nitrogen at the Regional Scale. In *Nitrogen Deposition, Critical Loads and Biodiversity*; Sutton, M.A., Mason, K.E., Sverdrup, L.J.S.H., Haeuber, R., Hicks, W.K., Eds.; Springer: New York, NY, USA, 2014; pp. 217–227. ISBN 978-1-62623-977-7.
97. Gombert, S.; Asta, J.; Seaward, M.R.D. Lichens and Tobacco Plants as Complementary Biomonitors of Air Pollution in the Grenoble Area (Isère, Southeast France). *Ecol. Indic.* **2006**, *6*, 429–443. [CrossRef]
98. González, C.M.; Orellana, L.C.; Casanovas, S.S.; Pignata, M.L. Environmental Conditions and Chemical Response of a Transplanted Lichen to an Urban Area. *J. Environ. Manag.* **1998**, *53*, 73–81. [CrossRef]
99. Boltersdorf, S.H.; Werner, W. Lichens as a Useful Mapping Tool? An Approach to Assess Atmospheric N Loads in Germany by Total N Content and Stable Isotope Signature. *Environ. Monit. Assess.* **2014**, *186*, 4767–4778. [CrossRef]
100. Meyer, M.; Schröder, W.; Nickel, S.; Leblond, S.; Lindroos, A.-J.; Mohr, K.; Poikolainen, J.; Santamaria, J.M.; Skudnik, M.; Thöni, L.; et al. Relevance of Canopy Drip for the Accumulation of Nitrogen in Moss Used as Biomonitors for Atmospheric Nitrogen Deposition in Europe. *Sci. Total Environ.* **2015**, *538*, 600–610. [CrossRef] [PubMed]
101. Schröder, W.; Holy, M.; Pesch, R.; Harmens, H.; Fagerli, H.; Alber, R.; Coşkun, M.; De Temmerman, L.; Frolova, M.; González-Miqueo, L.; et al. First Europe-Wide Correlation Analysis Identifying Factors Best Explaining the Total Nitrogen Concentration in Mosses. *Atmos. Environ.* **2010**, *44*, 3485–3491. [CrossRef]
102. Bonanno, G. Nitrogen Multitemporal Monitoring through Mosses in Urban Areas Affected by Mud Volcanoes around Mt. Etna, Italy. *Environ. Monit. Assess.* **2013**, *185*, 8115–8123. [CrossRef] [PubMed]

103. Pearson, J.; Wells, D.M.; Seller, K.J.; Bennett, A.; Soares, A.; Woodall, J.; Ingrouille, M.J. Traffic Exposure Increases Natural 15N and Heavy Metal Concentrations in Mosses. *New Phytol.* **2000**, *147*, 317–326. [CrossRef]
104. Gordon, C.; Wynn, J.M.; Woodin, S.J. Impacts of Increased Nitrogen Supply on High Arctic Heath: The Importance of Bryophytes and Phosphorus Availability. *New Phytol.* **2001**, *149*, 461–471. [CrossRef] [PubMed]
105. Delgado, V.; Ederra, A.; Santamaría, J.M. Nitrogen and Carbon Contents and Δ15N and Δ13C Signatures in Six Bryophyte Species: Assessment of Long-Term Deposition Changes (1980–2010) in Spanish Beech Forests. *Glob. Chang. Biol.* **2013**, *19*, 2221–2228. [CrossRef] [PubMed]
106. Harmens, H.; Norris, D.A.; Sharps, K.; Mills, G.; Alber, R.; Aleksiayenak, Y.; Blum, O.; Cucu-Man, S.M.; Dam, M.; De Temmerman, L.; et al. Heavy Metal and Nitrogen Concentrations in Mosses Are Declining across Europe Whilst Some "Hotspots" Remain in 2010. *Environ. Pollut.* **2015**, *200*, 93–104. [CrossRef]
107. Hicks, W.K.; Leith, I.D.; Woodin, S.J.; Fowler, D. Can the Foliar Nitrogen Concentration of Upland Vegetation Be Used for Predicting Atmospheric Nitrogen Deposition? Evidence from Field Surveys. *Environ. Pollut.* **2000**, *107*, 367–376. [CrossRef]
108. González-Miqueo, L.; Elustondo, D.; Lasheras, E.; Bermejo, R.; Santamaría, J.M. Spatial Trends in Heavy Metals and Nitrogen Deposition in Navarra (Northern Spain) Based on Moss Analysis. *J. Atmospheric Chem.* **2009**, *62*, 59–72. [CrossRef]
109. González-Miqueo, L.; Elustondo, D.; Lasheras, E.; Santamaría, J. Use of Native Mosses as Biomonitors of Heavy Metals and Nitrogen Deposition in the Surroundings of Two Steel Works. *Chemosphere* **2010**, *78*, 965–971. [CrossRef]
110. Izquieta-Rojano, S.; Elustondo, D.; Ederra, A.; Lasheras, E.; Santamaría, C.; Santamaría, J.M. Pleurochaete Squarrosa (Brid.) Lindb. as an Alternative Moss Species for Biomonitoring Surveys of Heavy Metal, Nitrogen Deposition and Δ15N Signatures in a Mediterranean Area. *Ecol. Indic.* **2016**, *60*, 1221–1228. [CrossRef]
111. Izquieta-Rojano, S.; López-Aizpún, M.; Irigoyen, J.J.; Santamaría, J.M.; Santamaría, C.; Lasheras, E.; Ochoa-Hueso, R.; Elustondo, D. Eco-Physiological Response of Hypnum Cupressiforme Hedw. to Increased Atmospheric Ammonia Concentrations in a Forest Agrosystem. *Sci. Total Environ.* **2018**, *619–620*, 883–895. [CrossRef] [PubMed]
112. Kosonen, Z.; Thimonier, A.; Schnyder, E.; Thöni, L. Nitrogen Concentration in Moss Compared with N Load in Precipitation and with Total N Deposition in Switzerland. *Environ. Pollut.* **2018**, *239*, 169–178. [CrossRef]
113. 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]
114. Gerdol, R.; Marchesini, R.; Iacumin, P.; Brancaleoni, L. Monitoring Temporal Trends of Air Pollution in an Urban Area Using Mosses and Lichens as Biomonitors. *Chemosphere* **2014**, *108*, 388–395. [CrossRef] [PubMed]
115. Piazzetta, K.D.; Ramsdorf, W.A.; Maranho, L.T. Use of Airplant Tillandsia Recurvata L., Bromeliaceae, as Biomonitor of Urban Air Pollution. *Aerobiologia* **2019**, *35*, 125–137. [CrossRef]
116. Cardoso-Gustavson, P.; Fernandes, F.F.; Alves, E.S.; Victorio, M.P.; Moura, B.B.; Domingos, M.; Rodrigues, C.A.; Ribeiro, A.P.; Nievola, C.C.; Figueiredo, A.M.G. Tillandsia Usneoides: A Successful Alternative for Biomonitoring Changes in Air Quality Due to a New Highway in São Paulo, Brazil. *Environ. Sci. Pollut. Res.* **2016**, *23*, 1779–1788. [CrossRef]
117. Sommer, S.G.; Østerg\aard, H.S.; Løfstrøm, P.; Andersen, H.V.; Jensen, L.S. Validation of Model Calculation of Ammonia Deposition in the Neighbourhood of a Poultry Farm Using Measured NH3 Concentrations and N Deposition. *Atmos. Environ.* **2009**, *43*, 915–920. [CrossRef]
118. Kapoor, C.S.; Bamniya, B.R.; Kapoor, K. Efficient Control of Air Pollution through Plants, a Cost-Effective Alternative: Studies on Dalbergia Sissoo Roxb. *Environ. Monit. Assess.* **2013**, *185*, 7565–7580. [CrossRef]
119. Gebauer, G.; Schulze, E.-D. Oecologia of a Healthy and a Declining Picea Abies Forest in the Fichtelgebirge. *Oecologia* **1991**, *87*, 198–207. [CrossRef]
120. Gebauer, G.; Giesemann, A.; Schulze, E.D.; Jäger, H.J. Isotope Ratios and Concentrations of Sulfur and Nitrogen in Needles and Soils of Picea Abies Stands as Influenced by Atmospheric Deposition of Sulfur and Nitrogen Compounds. *Plant Soil* **1994**, *164*, 267–281. [CrossRef]
121. Thoene, B.; Schröder, P.; Papen, H.; Egger, A.; Rennenberg, H. Absorption of Atmospheric NO_2 by Spruce (Picea Abies L. Karst.) Trees: I. NO_2 Influx and Its Correlation with Nitrate Reduction. *New Phytol.* **1991**, *117*, 575–585. [CrossRef]
122. Yang, H.I.; Park, H.J.; Lee, K.S.; Lim, S.S.; Kwak, J.H.; Lee, S.I.S.M.S.I.; Chang, S.X.; Lee, S.I.S.M.S.I.; Choi, W.J. Δ13C, Δ15N, N Concentration, C/N, and Ca/Al of Pinus Densiflora Foliage in Korean Cities of Different Precipitation PH and Atmospheric NO_2 and SO_2 Levels. *Ecol. Indic.* **2018**, *88*, 27–36. [CrossRef]
123. Jung, K.; Gebauer, G.; Gehre, M.; Hofmann, D.; Weißflog, L.; Schüürmann, G. Anthropogenic Impacts on Natural Nitrogen Isotope Variations in Pinus Sylvestris Stands in an Industrially Polluted Area. *Environ. Pollut.* **1997**, *97*, 175–181. [CrossRef]
124. Hietz, P.; Dünisch, O.; Wanek, W. Long-Term Trends in Nitrogen Isotope Composition and Nitrogen Concentration in Brazilian Rainforest Trees Suggest Changes in Nitrogen Cycle. *Environ. Sci. Technol.* **2010**, *44*, 1191–1196. [CrossRef] [PubMed]