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An Air Quality Target for Welsh Ecosystems

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Contributing authors & reviewers The Welsh Government seeks independent and expert advice on the need for a new air quality target (or targets) in Wales to reflect the pressure and impacts of air pollution on biodiversity and ecosystems. Where sufficient need is identified, the Welsh Government seeks recommendations on the form the target(s) should take and how compliance should be assessed. This document discusses the need for a target through considering air pollution impacts on biodiversity and ecosystems and the wider national and international policy context. It reviews potential options for the basis of the target, i.e. what is the most relevant metric. Scenario modelling would be required to determine an appropriate target metric value and achievement date. The discussion was informed by members of a subgroup formed for this purpose, as indicated below.

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Approved by James Skates (Welsh Government)
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Abbreviations Used in this Report

CAAP	Clean Air Advisory Panel
CBD	Convention on Biological Diversity
CLnutN	Critical Loads for Nutrient Nitrogen
DA	Devolved Administration
ICP Vegetation	International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops
NRW	Natural Resources Wales
POD	Phytotoxic Ozone Dose
SAC	Special Area of Conservation
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
UKCEH	UK Centre for Ecology & Hydrology
VOC	Volatile Organic Compound
WG	Welsh Government

Contents

1 EXECUTIVE SUMMARY

Air pollution has impoverished ecosystems in Wales and caused widespread losses of biodiversity. The Welsh Government is assessing the need for a new air quality target (or targets) in relation to ecosystems and biodiversity. A specific target for air quality that can readily be related to effects on ecosystems and biodiversity would help to raise awareness of air pollution impacts. This report briefly reviews air pollution effects on ecosystems and biodiversity, and presents the recommendations of a subgroup of the Clean Air Advisory Panel (CAAP) that was convened in 2022-23 to discuss the issue. The subgroup recommended that a target be set on the basis of a specific single metric, with clearly defined baseline and achievement dates.

Air pollutants damage ecosystems through direct toxic effects, and by causing eutrophication (over-fertilisation) and acidification. Ammonia is a particularly damaging air pollutant, with severe effects on many mosses and lichens, and forms a large part of the total nitrogen load that falls on Welsh ecosystems. Other atmospheric pollutants such as ozone or heavy metals may harm ecosystems and biodiversity, but evidence of damage from these is less strong than is evidence for damage from ammonia. Ammonia also contributes to the formation of particulate pollution, which is damaging to wildlife as well as to human health. Ammonia pollution is influenced strongly by emissions from within Wales.

The subgroup further recommended that the target be based on:

a. Ammonia concentration in air.
b. Exceedance of the 1 µg NH_3 m^{-3} annual mean critical level, which is currently exceeded over around 50% of Wales. This level is set to protect sensitive mosses and lichens, which are a valuable component of biodiversity, and contribute to water regulation, peat formation and other ecosystem functions.
c. The whole extent of Wales, not only on protected sites or mapped habitat areas.

Progress towards the target would need to be assessed primarily using modelled data, which can be provided for the whole area of Wales, and are less influenced by year-to-year variation in meteorology. Calibration of model outputs against ammonia measurements is however important, and the current UK measurement network may not provide sufficient coverage to ensure data accuracy.

The specific target metric recommended by the CAAP subgroup is **the area of Wales where annual mean concentration of ammonia exceeds the 1 µg m^{-3} annual mean critical level.**

A target defined in terms of relative change (for example, a 10% decrease in the area where the critical level is exceeded) would be more robust against changes in the measurement and/or modelling methods than an absolute-change target (for example, 40% of Wales below the critical level).

The target value would need to be set after scenario modelling has been carried out to assess what is realistically achievable.

2 INTRODUCTION

Air pollution has driven a widespread impoverishment of ecosystems and extinction of plant and lichen species across the globe (Bobbink et al., 2010) and in the UK (Henrys et al., 2011; Stevens et al., 2012). Much of the evidence relates to the impact of reactive nitrogen pollution, which is thought to be the third largest human driver of biodiversity loss worldwide, with only land-use change and climate change being more damaging (Sala et al., 2000). Ecosystems and biodiversity in Wales likely suffer from the same undesired effects, which are often gradual, and hard to distinguish from effects of other pressures (Verheyen et al., 2017). A specific target for air quality that can readily be related to effects on ecosystems and biodiversity would help to raise awareness among stakeholders. This document introduces potential metrics that could form the basis for such a target. A sub-group of the Clean Air Advisory Panel has been formed to discuss the issues and recommend a target metric for consideration by ministers.

The Welsh Government (WG) requires its targets to be SMART (specific, measurable, achievable, relevant and time-bound). The specific value and date for achievement would need to be determined after scenario modelling, to ensure that the target has an appropriate level of ambition as well as being achievable, including that any trends over time in the metric(s) selected can be influenced by WG policies.

In this document we firstly describe the impacts of air pollutants on ecosystems and biodiversity. Then we discuss the pollutants themselves – types of pollutant, routes by which ecosystems or organisms are exposed, thresholds for harmful effects, exposure time, spatial distributions, and sources. Next we briefly explore how receptors (the ecosystems or sites that are affected by pollution) might be mapped for the purpose of target-setting. We then summarise the arguments for adopting a target, and lastly make recommendations as to the basis of this target.

Much of the evidence for air pollution impacts on habitats relates to effects on plants (vascular plants and bryophytes) and lichens (e.g. Pescott et al., 2015). Plants and lichens are comparatively easy to study, since they are sedentary, and experimental treatments can readily be applied to plant communities. Air pollution has sometimes been shown to affect animals including birds (Barton et al., 2023) and butterflies (e.g. Wallis de Vries and Van Swaay, 2006), but studies of effects on animals have so far been relatively limited. However, plant and lichen species are fundamental components of ecosystems (Asplund and Wardle, 2017; Stevens et al., 2018), and underpin the biodiversity of other groups (Pescott et al., 2015).

3 EFFECTS OF AIR POLLUTION ON ECOSYSTEMS AND BIODIVERSITY

3.1 Acidification

Research into acid rain in the 1960s and 1970s led to increasing public awareness of the harmful effects of air pollution on ecosystems (Singh and Agrawal, 2008). Acidifying pollutants cause leaching of nutrient base-cations (calcium, magnesium and potassium) and a decline in soil pH. At pH values below 5, toxic cations such as aluminium increasingly enter the dissolved phase in the soil solution. Some plants are adapted to acidic soils, but many species are adversely affected. The same is true of lichens, with some being adapted to growing on leached, base-poor tree bark, but others being lost to acidification. Calcareous ecosystems such as limestone grassland are particularly species-rich, and acidification causes species loss across the range of soil pH. Acidic ecosystems are also damaged by acidification and can recover only very slowly because in these systems there is little replacement of calcium by weathering of soil minerals (Evans et al., 2014). Acidification also affects freshwater systems, causing the loss of fish and invertebrate species (Ormerod and Durance, 2009). The substantial decreases in sulphur (S) emissions achieved since the 1970s have resulted in widespread recovery from acidification (Hughes et al., 2012; Reynolds et al., 2013; Seaton et al., 2023) and show that pollution policy can be highly effective. However, reactive nitrogen (N) is also an acidifying pollutant whether deposited in oxidised form (NO_x) or reduced form (NH_y) (Reuss and Johnson, 1986), and N emissions have not declined to the same extent. Of the total acidity deposition on open semi-natural habitats in Wales in 2018, 65% was NH_y, 19% was NO_x and only 16% was S (data from Rowe et al., 2022).

3.2 Direct toxic effects

Air pollutants such as ozone, ammonia (NH_3) and oxidised nitrogen (NO_x) can cause harm to organisms through direct uptake. Most of the current evidence relates to effects on plants and lichens, but effects on fauna are increasingly being demonstrated (Agathokleous et al., 2020; Nijssen et al., 2017). Ammonia affects many vascular plant species at relatively low concentrations, and the concentration threshold for many bryophyte and lichen species is even lower. Effects of current ambient atmospheric NO_x concentrations on plant species are less clear-cut, and critical levels for NO_x are the subject of a current evidence review by ICP Vegetation.

Ozone in the stratosphere provides important protection from ultraviolet radiation, but tropospheric (ground-level) ozone is considered a pollutant. Ozone is particularly damaging for fast-growing plant species with large rates of stomatal exchange, such as crops and many tree species (Agathokleous et al., 2020). The likely deleterious impacts of ozone on ecosystems and biodiversity in Wales can be summarised as:

(i) decline in forage quality and quantity, and altered forage composition in pasture systems (Hayes et al., 2016);

(ii) declining crop yield due to chronic increasing background ozone levels and occasional, historically more frequent, acute ozone episodes (Mills et al., 2018);

(iii) differential susceptibility of plant species to ozone (Agathokleous et al., 2020), and, for crops, a tendency for modern, high-yielding varieties to be more susceptible. This is due to breeding for rapid growth and therefore open stomata. For species susceptibility in general, legumes are typically more susceptible to ozone damage than non-legumes, and forbs more than grasses (Bergmann et al., 2017; Hewitt et al., 2016) – however, species interactions can lead to complex responses at the community level (Calvete-Sogo et al., 2016).

Together, these findings suggest Welsh agricultural ecosystems are likely more at risk from ground level ozone pollution than are semi-natural ecosystems and biodiversity. At high altitudes, ozone concentrations tend to be elevated even in the absence of anthropogenic air pollution (Chevalier et al., 2007). Decreasing traffic levels or reduced industry may actually lead to increases in ozone pollution in urban areas, through decreased concentrations of NO which would otherwise react with and remove ozone (Sicard et al., 2018). Ozone may also affect other elements of biodiversity in ecosystems, but these effects remain uncertain. Effects on ecosystems of atmospheric heavy metals, particulates, plastics, and other pollutants are still less clear.

3.3 Eutrophication

Pollutants such as reactive N (NH_y and NO_x) act as nutrients, i.e. are eutrophying, and stimulate the growth of plant species. Plants that are adapted to high nutrient availability respond strongly. Typically, these are species which have thin leaves that can compete strongly for light by growing rapidly and tall, such as nettles. Species that are adapted to low nutrient availability are typically slow-growing and small, and are easily outcompeted due to shading by tall plants. The typical maximum height of plants is a good indicator of the degree of threat that they face (Hodgson et al., 2014) (Figure 3.1). Addition of nutrients stimulates the growth of species adapted to high fertility and causes a loss in overall species richness (Hautier et al., 2009; Muehleisen et al., 2022). Pollution by nutrient nitrogen has caused population declines in many UK plant and lichen species (Stevens et al., 2011b). However, as with vascular plants, some species of bryophytes respond positively to N inputs (Stevens et al., 2011b).

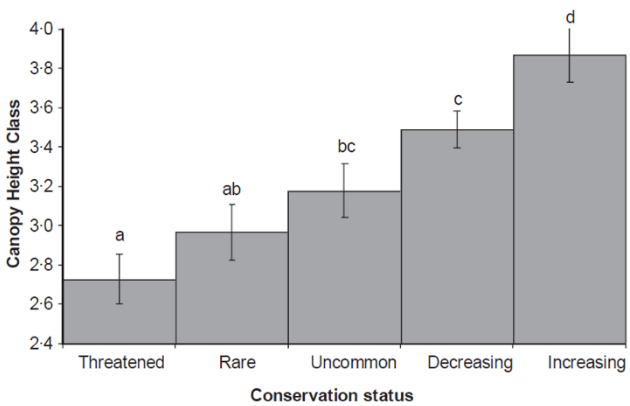

Figure 3.1. Relationship between conservation status of UK plant species and their typical height (Hodgson et al., 2014).

4 AIR POLLUTANTS

4.1 Sources and types of pollutant

Different types of pollutant derive from different sources. Reduced N (NH_y) mainly derives from agricultural ammonia sources, in particular emissions from livestock wastes. In contrast, oxidised N (NO_x), S and to some extent heavy metals are mainly emitted as by-products from burning fossil fuel or during industrial processing. Ozone is formed through atmospheric processes involving NO_x, volatile organic compounds, and sunlight.

Sulphur and reactive nitrogen (N) are acidifying pollutants. Although ammonia gas forms an alkaline solution in water, chemical transformations in the soil mean that reduced nitrogen (NH_y, i.e. ammonia or ammonium) has an acidifying effect. The acidification potential of S, NH_y and NO_x is the same for the same number of equivalents of charge. For example, 1 mole of SO_4^{2-} (2 equivalents of charge) has the same acidifying effect as 2 moles of NO_3^-. Reductions in S emissions, largely due to the installation of scrubbers in power station chimneys, are one of the great successes of environmental policy. Sulphur deposition onto open habitats in the UK declined from 19.8 Geq in 1996 to 4.5 Geq in 2018 (Rowe et al., 2021). However, total N deposition onto these areas only declined from 37.2 Geq to 31.6 Geq over the same period. According to the latest data, N made up around 90 % of acidifying deposition onto the UK in 2019 (Rowe et al., 2022).

As noted above, N is also a eutrophying pollutant. Although some studies have found distinct effects of NH_y and NO_x deposition on ecosystems, the oxidation status of N changes readily in soil and the total input of atmospheric N is generally a sufficient indicator of eutrophication potential (Stevens et al., 2011a).

Ammonia and NO_x concentrations in air have a strong influence on N deposition, and these gases also have direct toxic effects. Ammonia is particularly damaging, and UK-scale reporting focuses on exceedance of ammonia critical levels (Rowe et al., 2021).

Ozone in the stratosphere is of critical importance for protecting the planet from radiation, but tropospheric or ground-level ozone is considered a harmful pollutant. Ozone pollution is of particular concern for croplands and improved grassland, where productivity and yields are decreased. Effects of ozone on semi-natural ecosystems are less clear, although this is partly because field-relevant experimental exposure is difficult. Lack of response may also relate to species change having already occurred due to dynamics engendered by other pollutants e.g. N (Hayes et al., 2019). Although there is a tendency for ozone to increase with elevation, gradients in ozone concentration are less steep and less consistent than gradients in N pollution, which has also limited the evidence base for ozone effects on biodiversity. However, evidence is emerging of effects of ozone on plant growth and flowering within semi-natural ecosystems in Wales (Hayes, 2022).

Atmospheric deposition of heavy metals has been considerably reduced by declines in heavy industry, bans on lead additives to fuel and restrictions on the use of mercury. Toxic metal deposition is not now a major concern in Wales. However, air pollution remains a factor when considering human and ecosystem exposure to heavy metals, because acidification increases the solubility of several important toxic metals. This exposure route, i.e. solubilising toxic metals, may be addressed by measures that reduce acidifying pollutants.

4.2 Exposure route and damage thresholds

Pollutant concentration in air, measured for example in µg m^{-3}, and pollutant deposition rate, measured for example in kg ha^{-1} yr^{-1}, are useful indicators of the amount of pressure on organisms. Atmospheric concentration and deposition rate are simple concepts that do not require explanation of the concept of a threshold for harm. However, ecosystems do have a certain amount of resilience, and this may need to be taken into account when setting an air quality target. For instance, considering deposition alone, without a threshold, would ignore the fact that nitrogen and sulphur are nutrient elements, essential for growth. Individual plant species are adapted to a certain level of ozone exposure, particularly in mountain environments.

Ecosystems can withstand low concentrations of pollutant without harm, but direct toxic effects increase with concentration. The concentration above which organisms come to harm is known as the **critical level**. The critical level for an ecosystem may be set according to whether very sensitive organisms, such as many bryophytes and lichens, are an important component.

Similarly, ecosystems can withstand a certain rate of pollutant deposition. This leads to the concept of a **critical load**, i.e. the deposition rate of pollutant that will not cause harm to the ecosystem, even in the long term. The critical load may depend on the particular type of habitat, and may be modified by environmental conditions such as soil pH or annual precipitation. Differences in the rates of internal processes also contribute to these changes in critical loads between habitats. For example, acidifying pollutants may be neutralised by a flux of base cations from soil weathering and other sources. Nutrient-nitrogen fluxes may be mitigated by fluxes out of the system such as leaching or denitrification (although these nitrogen loss routes can cause harm elsewhere). Considering the flows into and out of the ecosystem on an area basis allows a budget to be calculated. Another consideration is that the deposition rate is strongly affected by the height and surface roughness of vegetation – for example, woodland receives nearly twice as much N deposition as open vegetation, on average.

In fact, pollutants cause harm when organisms take them up, which is always a deposition process. Recognition of this has led to the development of metrics based on uptake rate, for example per cm^2 of leaf. This **flux-based** approach has been particularly useful when considering ozone pollution, which causes more harm when plants have their stomata open e.g. under conditions of high soil moisture. Indeed, plants can be surrounded by high concentrations of ozone but such concentrations have a limited impact if stomata are closed, e.g. due to drought. In contrast, low atmospheric concentrations, which may be expected to be ‘safe’, can have deleterious, chronic impacts if stomata are consistently open. Models can be used to predict ozone flux per area of leaf, from air concentration, water availability and other factors. The critical ozone flux into the leaf, above which the plant is likely to be damaged, is known as the phytotoxic ozone dose (POD). A similar flux-based approach may also be relevant for NO_x, but empirical evidence is lacking.

Damage thresholds as represented by critical levels, critical loads and POD are all defined on the basis of current evidence from experiments and surveys. Exceedance of critical load, critical level or POD is a more accurate indicator of the pressure on the ecosystem and its associated biodiversity than is the total load, concentration, or leaf flux.

4.3 Exposure timescale

Air pollution is variable in time. Emissions may be highly seasonal, for example those resulting from slurry spreading, and atmospheric dispersal is strongly affected by weather conditions and by interactions with other pollutants. Organisms are likely to be affected strongly by episodes of high concentration, even if these are short-lived. The time-period over which concentration is measured is thus an important consideration. Critical levels have mainly been set on the basis of the annual mean concentration, but can also be defined as the maximum allowable concentration in any month, day, or even shorter time periods. However, the evidence base for short-term critical levels is sparse, since frequent measurements of concentrations and of ecosystem responses are required to establish a suitable value.

There is a statistical relationship between annual mean concentration and maximum concentration within a shorter time-period (e.g. Figure 4.1). This means that, where the data exist to establish this relationship for a particular pollutant, an annual mean critical level can be set such that it is likely that shorter-term critical levels will not be exceeded. However, critical levels are actually set on the basis of biodiversity responses related to the timescale in question, e.g. monthly critical levels are set using monthly (or more frequent) data on exposure and responses.

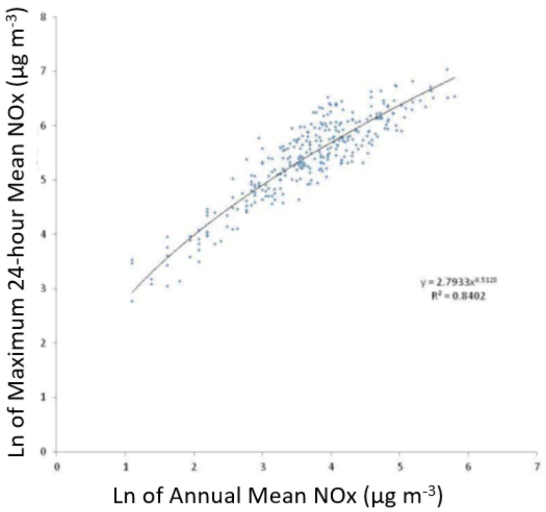

Figure 4.1. Natural logarithms of annual mean NO_x vs maximum 24-hour mean NO_x at all suitable Automatic Urban and Rural Network (AURN) sites over 3 years, excluding industrial sites (AQC, 2018).

Another aspect of exposure timescale is the persistence of the pollutant within the ecosystem. Responses to an increase or decrease in pollutant load may be slowed by chemical delays (buffering of change by soil pools of organic matter, base cations etc.) or by biological delays (slow responses of organisms to the changing environment). Pollutants such as acidity or nutrient-nitrogen may have long-lasting effects. For this reason, some ecosystem impacts are best explained by the cumulative load over years or decades, rather than by the current concentration or load. Rowe et al. (2017) proposed assessing nitrogen impacts on the basis of the total load over the previous 30 years, for soil-based ecosystems that can accumulate substantial amounts of organic nitrogen; or over the previous 3 years, for epiphytic or epilithic ecosystems with little buffering capacity. A study by Payne et al. (2019) showed that a 30-year timeframe is appropriate for soil-based ecosystems.

4.4 Spatial distributions

Air pollutants vary greatly in the typical distance over which they are dispersed before having an impact. This is primarily due to different reactivities with other compounds in the atmosphere, including water and acidic gases. Interactions may lead to the formation of other pollutants, notably ozone and particulates. Meteorology, for example the prevailing wind direction, also greatly affects plume dispersal and dilution. Calm periods of weather will increase the accumulation of pollutants near to sources.

Ozone is formed via reactions among N oxides and volatile organic compounds (VOCs) in the presence of ultraviolet light. However, reactions with nitric oxide (NO) remove ozone from air. The spatial distribution of ozone is therefore complex, with comparatively low levels in urban areas that have high levels of NO. Since VOCs are highly persistent in the atmosphere, they disperse to rural and mountainous areas, and ozone formation can be higher in these areas.

The different forms of reactive N in the air disperse to different distances (Figure 4.2). Ammonia gas dissolves readily in water, including wet surfaces, so much ammonia is deposited within a short distance of emissions sources. Ammonia also dissolves into cloud droplets and is therefore often deposited in areas of high rainfall, for example in mountains that are downwind of areas of intensive agriculture. Another factor is that ammonia reacts with acidic compounds in the air such as NO_x and SO_x. The salts thus formed tend to deposit rapidly and relatively close to sources. With the decrease in SO_x and NO_x pollution in recent years, this removal by acidic compounds has decreased, and ammonia is dispersing higher in the atmosphere and to larger distances. Nitrogen oxides vary in their solubility, and typical dispersal distances vary.

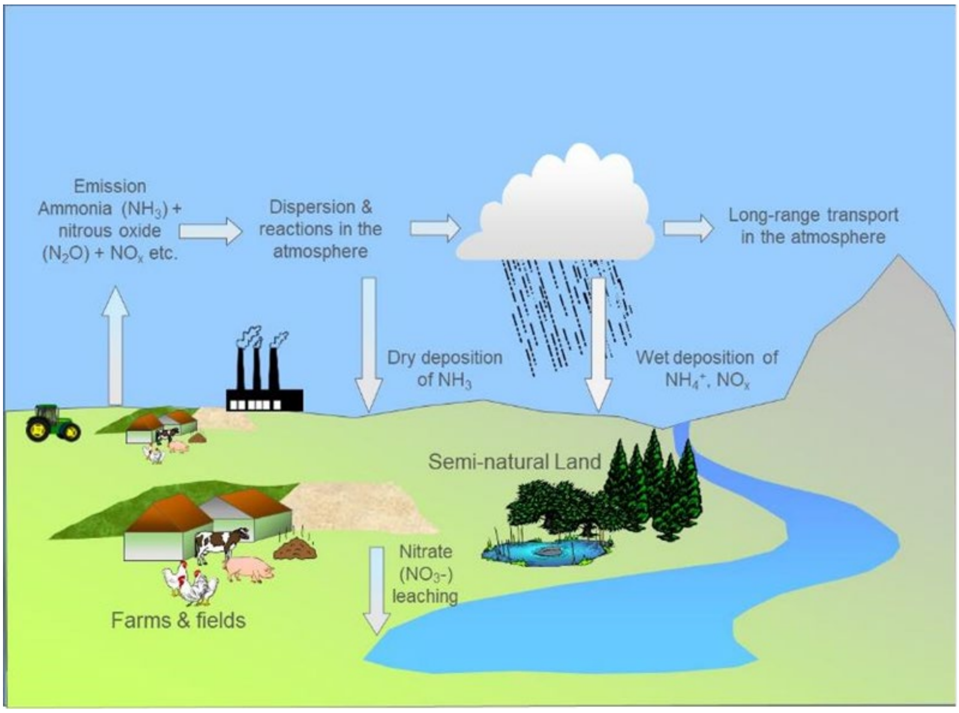

Figure 4.2. Nitrogen pollution: emissions, reactions and transport. Figure: Ulli Dragosits, UKCEH.

4.5 Where does air pollution originate?

Welsh policies and measures will have most influence on pollutants that originate in Wales. The different air pollutants that affect Welsh ecosystems have different proportions coming from sources in Wales, depending on emissions, and on how far they are typically transported. A source apportionment study shows these proportions for different forms of deposited N (Table 4.1). Reduced N, and dry N deposition, are more likely to be of local origin than oxidised N and wet-deposited N. Although source attribution has not been done for gaseous ammonia, ammonia in the air in most of Wales is very likely to come mostly from Welsh emission sources. Air flows across the border with England represent the greatest import and export fluxes. As explained above, ammonia is highly reactive in air and so disperses for comparatively short distances before it is either deposited or undergoes chemical reactions to form more long-lived particles. Wet-deposited N, by contrast, has often travelled over long distances, and includes transboundary input from continental Europe and beyond, from Ireland, and from international shipping.

Table 4.1. Deposition of different forms of pollutant nitrogen onto Wales in 2018, and percentage of this deposition that originates from Wales. Analysis using the FRAME model by Ed Carnell (UKCEH).

	Dry NH_y	Wet NH_y	Dry NO_x	Wet NO_x	Total NH_y	Total NO_x	Total N
Total deposition onto Wales in 2018 (kt N y^{-1})	10.7	7.2	3.1	7.4	17.9	10.5	28.4
Percentage derived from sources in Wales	75	24	26	4	55	10	38

Historically, atmospheric pollution by toxic metals resulted from smelting and other industrial processes, and from the addition of lead to fuel, with most deposition resulting from local sources. With the decline in heavy industry in Wales, and measures to restrict emissions such as the ban on lead-based fuel additives, atmospheric metal pollution is not now a major concern in Wales.

The formation of ozone is a relatively complex process, involving VOCs, and in which oxides of N can act as both a catalyst for ozone formation and a sink for ozone removal (see previous section). This makes it difficult to assess the sources of tropospheric ozone in Wales, or for a particular location. Ozone has a short lifetime in air with a high concentration of nitric oxide, NO, but can disperse for long distances in relatively unpolluted air (Akimoto, 2003). Local and short-term increases in ozone concentration are likely to be related to local emissions of NOx and VOCs. A steady increase in background ozone levels is attributed to dispersal within the northern hemisphere as a whole, resulting from increases in VOC emissions (Monks et al., 2015).

5 Spatial extent – where are the sensitive ecosystems?

The area over which a target is set is an important consideration. Ecosystems vary in their importance for conservation, their sensitivity to pollutants, and their importance for people. Around the globe, remote and mountainous regions are associated with more pristine ecosystems, but ecosystems close to urban centres may be used and appreciated by more people. In Wales, particularly important sites for conservation have been given protection as Sites of Special Scientific Interest (SSSIs), Special Areas of Conservation (SACs) or Special Protection Areas (SPAs). However, large areas of pollution-sensitive habitats occur outside protected sites.

Pollution metrics and targets have been defined on the basis of several different spatial concepts and conservation designations. The annual Trends Report (e.g. Rowe et al., 2022) reports exceedances of critical loads for nutrient-N or for acidity, for the entire area of sensitive habitat in the UK, and in each of the UK countries. Sensitive habitats are those that have been shown to be affected by air pollution such as bogs, heaths and semi-natural grasslands. The Trends Report also reports exceedances for protected sites that have nutrient-N-sensitive or acid-sensitive features, separately for SSSIs, SACs and SPAs. The UK Clean Air Strategy (Defra, 2019) includes a target for England to reduce “total deposition of reactive N onto nutrient-N sensitive, protected, priority habitat”, which has been interpreted as meaning the entire extent of sensitive priority habitats, not only areas within protected sites. The Defra 25 Year Environment Plan also includes a target for England, “restoring 75% of our one million hectares of terrestrial and freshwater protected sites to favourable condition”. It is not yet clear whether habitat areas must not exceed critical load(s) and critical level(s) to be considered in favourable condition. The method for measuring protected-site area exceeding critical loads or levels has not been defined fully, since reporting of site condition in England is changing in 2023 from whole-site assessment to assessments of units within sites.

As noted above, ground level ozone pollution is a particular concern for productive agricultural systems. It might be appropriate to assess ozone exposure within the areas of improved grassland and arable, rather than across Wales as a whole.

In general, it is important to consider what spatial extent and/or conservation designations any air quality target would apply to for Welsh ecosystems, and whether different targets should be adopted for urban areas, areas where intensive agricultural use predominates, and areas with more semi-natural ecosystems. A target value might be difficult to achieve in more polluted areas, and may be unnecessary where sensitive species have already been lost and are unlikely to recover. Conversely, the target value might be insufficiently protective of more sensitive ecosystems. However, a single target value would be relatively simple to communicate, and decreasing pollution across the whole of Wales would also lead to decreasing pressure on sensitive sites.

6 Uncertainties

In determining the need for a target, the WG needs to be mindful of uncertainties associated with the science, and with the scope of the target. These uncertainties include:

6.1 Whether a target for one pollutant will address air quality issues more generally.

Some air pollutants interact. In some cases this means that addressing one pollutant reduces other types of pollutant. Ammonia contributes to the formation of $PM_{2.5}$, so reducing ammonia emissions tends to decrease particulate pollution. Similarly, ground-level ozone is formed in reactions involving NO_x, so decreasing NO_x can be expected to decrease ozone pollution. However, this simple expectation can be confounded by atmospheric chemistry reactions, as witnessed by increasing ozone levels with reduced NO levels in urban areas during COVID lockdowns (Sicard et al., 2020). In some cases, the interaction has adverse effects – for example, decreasing levels of NO_x and SO_x pollution mean that NH_y now persists longer in air before being deposited or chemically transformed. In other cases there is no direct interaction, and there may be a risk that focusing on one pollutant means that attention is not paid to another pollutant. For example, focusing on NH_y pollution will have little effect on pollution by NO_x, ozone or heavy metals.

6.2 Changing understanding of ecosystem sensitivity

Critical loads and critical levels have been set on the basis of current evidence. As new evidence emerges, critical values may be changed. For example, the recent review of empirical critical loads for nutrient nitrogen (CLnutN) led to changes in the recommended ranges for around half of all habitats, and nearly all of these recommendations were that the critical load be decreased (Bobbink et al., 2022). Although there is unlikely to be another review of CLnutN in the near future, critical loads and critical levels are subject to change in the light of new evidence, and must therefore be considered uncertain.

6.3 Emerging air pollutants

WG may need to revise air quality target(s) in the light of new evidence around novel pollutant impacts on ecosystems and biodiversity. Pollutants in this category could include microplastics, persistent organic pollutants (including from pesticides/herbicides), or methane, which as well as being a greenhouse gas contributes to increased ozone formation. A horizon-scanning exercise would be useful in this context. Ecological evidence regarding novel pollutants is generally too scarce and uncertain to inform target-setting.

6.4 Effects on other elements of biodiversity

Our report concentrates on pollution impacts on vascular plants, mosses and lichens. This can be justified given the importance of these organisms for ecosystem function, but the impacts of air pollution on other taxa may also need consideration. The sensitivity of some organisms vital to ecosystem functioning, such as soil microorganisms, is largely unknown. Animals are also likely to be affected by air pollution, such as butterflies and other pollinators, birds, reptiles and fish. The strongest evidence for effects on animals relates to the impacts of acidification of freshwaters on fish and invertebrates. Since animals are mobile and more difficult to observe than plants and lichens, it is general more difficult to assess pollution impacts on them, and research evidence for N pollution impacts on animals has only been emerging recently. Linking air pollution effects to animal species might increase public awareness of the issues, since animals are generally considered to be more charismatic and interesting to the public than are plants and lichens.

6.5 Changing environmental conditions and pollutant interactions

The toxicity of pollutants can depend on environmental conditions. For example, the effects of ozone on plants can worsen when soil conditions are moist, as stomata are more likely to be open Thus, changing environments might change what is the most appropriate target metric and/or the target value. Taking this into account for future projections would require an understanding of interactions among pollutants and other environmental conditions, and reasonably accurate projections of environmental change. Air pollution also interacts with secondary stress factors such as drought, pests and disease.

6.6 Ecosystem dynamism

Setting air quality targets against effects on particular habitats / ecosystems / species implies that the there is an ideal, static state of the ecosystem. In reality, these systems are dynamic and would change even without air pollution. Targets may need to consider the extent of change that is ‘natural’ and/or can be accepted (including through other influences e.g. climate change) *vs* what is unwanted and attributable to air pollution.

6.7 Ecosystem / habitat / species choice

The choice of what ecosystem state, habitat or species to address with an air quality target is a subjective judgement. Choices can be justified by considering wider effects (e.g. on ecosystem function) and/or could be decided upon by consultation. Wider consultation might change the choice of habitats, species or locations to focus on, and thus the recommended metric.

7 NEED FOR A TARGET

7.1 Air pollutant effects on ecosystems and biodiversity in Wales

Air pollution is causing harm to ecosystems and biodiversity in Wales. There has been a considerable decline in sulphur pollution since the 1980s, but ongoing nitrogen pollution means that acid-sensitive ecosystems across most of Wales are receiving acidity in excess of the critical load, above which harmful effects are likely (Figure 7.1a). Nitrogen deposition also has a eutrophying effect, and very few areas of sensitive habitat in Wales receive less nutrient-nitrogen pollution than the critical load (Figure 7.1b).

Ammonia pollution makes up most of the total nitrogen flux, but gaseous ammonia also has distinct effects. Sensitive flowering plants are likely to be harmed by annual mean concentrations over 3 µg NH_3 m^{-3}, which is the case only in some areas of Carmarthenshire and near the border with England (Figure 7.2a). However, the annual mean critical level for sensitive bryophytes and lichens (1 µg NH_3 m^{-3}) is exceeded over most of Wales, and the area exceeded has been increasing in recent years (Figure 7.2b). Bryophytes (mosses and liverworts) and lichens are important components of biodiversity in their own right, and contribute to the visual quality of areas where they are still abundant. Epiphytic bryophytes are an important element of Atlantic oakwoods, contributing to the distinctive appearance of these iconic ecosystems. Bryophytes and lichens on trees and rocks allow winter hibernation by many invertebrates, and by acting as sponges they contribute to flood attenuation. *Sphagnum* moss species are important for peat formation and carbon storage. Bryophytes and lichens may also reflect the responses of other aspects of biodiversity for which sensitivity to ammonia pollution is currently unknown (e.g. invertebrates).

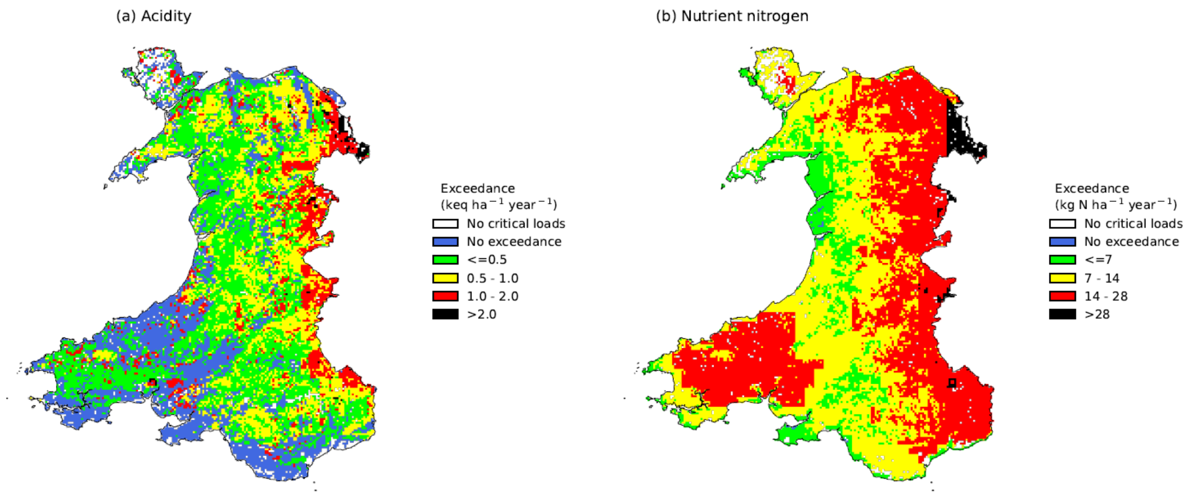

Figure 7.1. a) Excess Acidity and b) Excess Nitrogen in Wales, annual mean for 2018-2020. Areas where the Critical Load is not exceeded are shown in blue. Data from Rowe et al. 2023).

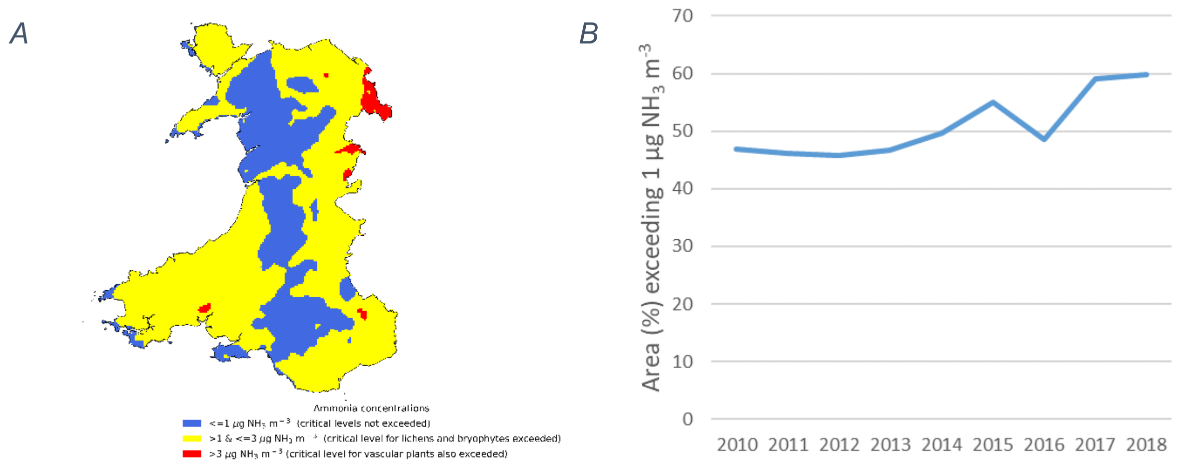

Figure 7.2. a) areas of Wales in 2018 with exceedance of the Critical Levels of ammonia set to protect sensitive vascular plants (in red) and set to protect sensitive bryophytes and lichens (in yellow). b) changes in the percentage of land area in Wales where the Critical Level of ammonia set to protect sensitive bryophytes and lichens was exceeded, 2010 - 2018. Data from Rowe et al. (2022).

7.2 International commitments

We are grateful to Adam Cole King, Lead Specialist Advisor on Biodiversity Policy at NRW, for assistance with writing this section.

The Welsh Government has commitments under national legislation, and international treaties. Wales is subject to the UK Habitats Regulations, rather than to the EU Habitats Directive. However, a number of statutory obligations under the Habitats Regulations that apply in Wales (and the rest of the UK), are still defined by reference to provisions in the Habitats Directive, and also the EU Birds Directive. An example is the duty under Regulation 9 for competent authorities to have regard to the requirements of the Habitats and Birds Directives in the exercise of their functions. The continuing effect of this obligation was recently upheld in a High Court judgment[1] against the Environment Agency in England. Currently, EU case law on interpretation of Directives where the rulings were issued before Brexit still applies to UK courts hearing cases concerning retained EU laws.

Wales is not itself a signatory to international conventions such as the UN Convention on Biological Diversity (CBD), the Ramsar wetlands convention, and the Bern Convention on conservation of European wildlife. However the UK is a signatory to these international agreements, and therefore any obligations the UK has under them apply equally in Wales. None of these three conventions are transposed into legislation in the UK, so neither the UK nor Welsh governments have any statutory obligations under them. However, they impose 'softer' obligations on the UK and there is an expectation that the devolved administrations (DAs) will contribute to fulfilling them. For example, all three include explicit

[1] Harris & Anor v Environment Agency [2022] EWHC 2264 (Admin) (06 September 2022). https://www.bailii.org/ew/cases/EWHC/Admin/2022/2264.html

commitments to provide national reports, and WG has an obligation to contribute to UK-scale reporting.

Another important international policy initiative is the “30 by 30” target to designate 30% of the Earth’s land and ocean as protected areas or other effective area-based conservation measures, which the Welsh Government committed to in 2021. Air quality is not directly related to this target, since although the areas need to be under effective management, at present protected areas are not required to be in favourable condition to be included in the 30%. In any case, it is not yet clear whether sites have to not be in exceedance of critical loads and critical levels to be considered in favourable condition. In the most recent data (for 2019) the nutrient-N critical load was exceeded for 96% of Welsh Sites of Special Scientific Interest (Rowe et al., 2022).

The UK remains committed to a target to reduce ammonia emissions by 16% between 2015 and 2030, originally set under the EU National Emission Ceilings Directive and continuing under the UK National Emission Ceilings Regulations. The Clean Air Strategy 2019 indicates that DAs have an obligation to achieve the same proportional reduction in ammonia emissions.

7.3 Recommendation on the need for a target

We recommend that one or more SMART targets are developed in relation to the effects of air pollution on biodiversity and ecosystems. Air pollution is thought to be the third largest cause of biodiversity loss worldwide, after land use change and climate change (Sala et al., 2000). These effects are not widely appreciated, perhaps because they are insidious. It is difficult to notice when species become less common over decades and then disappear, leading to an “extinction of experience” (Miller, 2005). Few studies have addressed biodiversity impacts of air pollution specifically for Wales, but an NRW study of the macrolichen *Alectoria nigricans* concluded that nitrogen pollution has been a key reason for the loss of this species from all but one of the sites where it formerly occurred (Turner, 2021).

Welsh ecosystems have undoubtedly been impoverished by air pollution. A target would be useful for raising awareness of these issues. A well-constructed target would also guide the policies and measures that need to be introduced to reduce ecosystem impacts of air pollution.

8 SUMMARY OF POTENTIAL METRICS

Targets are most useful when set in relation to a quantifiable metric. Considerations of threshold, timescale and spatial extent are summarised in Table 8.1 for different types of metric. These questions are relevant to most types of pollutant. The metrics most relevant to air pollution impacts on biodiversity and ecosystems are listed in Table 8.2, which focuses on the type of pollutant and the exposure route.

The spatial extent over which the target is to be achieved is a key consideration, since it will emphasise a) habitat recovery in more polluted areas, b) protecting the broad extent of sensitive habitats, or c) protecting the best-quality examples of habitats. Whatever decision is made, it will be important to define precisely the basis for mapping the target area, e.g. which protected sites, which habitats, and how maps will be updated.

Table 8.1. Metrics: considerations of threshold, timescale and spatial extent.

Metric	**Advantages**
Threshold	
Exceedance of critical level or critical load, e.g. Excess Nitrogen	- Takes into account ecosystem resilience (which varies depending on the habitat or species)
Absolute measurements of concentration or flux	- Easier to explain than exceedance
Timescale	
Annual mean	- Requires less frequent measurement than short-term metrics, and modelled data are more certain. - Most evidence for impacts on biodiversity and ecosystems is in relation to annual mean.
Maximum concentration during a shorter period, e.g. monthly.	- May better reflect the acute effects of short-term peaks
Spatial extent	
All Wales	- Takes into account urban areas and areas of degraded habitat
Sensitive habitats	- Focuses on areas known to be sensitive to air pollution
Restoration areas	- Includes areas targeted for restoration of habitats and improving habitat connectivity
Protected sites (e.g. SSSIs)	- Focuses on better quality examples of habitats and/or particularly vulnerable species

Table 8.2. Metrics: considerations of type of pollutant.

Metric	Advantages	Disadvantages
NH_3 emissions	- Possible to influence by WG policy and legislation - Estimated annually as part of the UK's National Atmospheric Emission Inventory (modelling approach)	- Not directly linked to ecosystem pressure or impacts
NO_x emissions	- Possible to influence by WG policy and legislation - Estimated annually as part of the UK's National Atmospheric Emission Inventory (modelling approach)	- Not directly linked to ecosystem pressure or impacts - Already being reduced e.g. under Net Zero initiatives
Total N deposition	- Reflects the atmospheric pollution pressure on ecosystems for which there is strongest evidence	- Measurement requires intensive monitoring including meteorology - Some aspects of N deposition cannot currently be measured routinely - Around 62 % of N deposition in Wales originates from elsewhere so cannot be directly influenced by WG policies
Total acidity deposition	- Reflects an important mechanism by which ecosystems lose species and functionality	- Measurement requires intensive monitoring including meteorology - Now largely composed of N deposition, because S pollution has declined - A large proportion of acidity deposition in Wales originates from elsewhere so cannot be directly influenced by WG policies
Ammonia concentration	- Reflects toxic effects of NH_3 - NH_3 concentration is an important influence on total N flux - A large proportion of ammonia in the air in Wales derives from Welsh sources - Can be measured using relatively low-cost passive samplers, which allows a relatively dense monitoring network	- Not as directly related to eutrophication pressure as is total N deposition
NO_x concentration	- Reflects toxic effects of NO_2 and other oxidised gaseous forms of N - Can be measured using passive samplers	- Less evidence for direct toxic effects of NO_x than for NH_3 - Current UK NOx monitoring is mostly focused on human health aspects, and samplers have been located accordingly.
Ozone concentration	- Reflects damage to crops and trees - Can be measured using relatively cheap passive samplers	- Ozone effects on semi-natural habitats are not well-established
Metals deposition	- Reflects pressure from toxic metals such as lead and mercury	- Atmospheric pollution by metals is not thought to be a major pressure on ecosystems and biodiversity
Microplastics deposition	- Reflects pressure from ecosystem contamination by small plastic particles	- The effects of microplastics on ecosystems remain unclear

9 DISCUSSION

A draft of this document was circulated in August 2022 to the CAAP subgroup members. An online meeting was held on 20th September 2022 with representatives from WG, JNCC, NRW and UKCEH (see subgroup members above). Key points made in the discussion were:

- Habitats sensitive to air pollution are widely dispersed in Wales. Large areas of habitat sensitive to nutrient-N and/or acidity pollution exist in upland Wales, but areas and fragments exist throughout Wales.
- It is important to protect habitats throughout Wales.
- There may be a need for short-, medium- and long-term targets.
- Ammonia emission sources have strong local effects on nearby sensitive habitats and designated sites.
- Measures that improve air quality locally are likely to also reduce long-range dispersal.
- Exceedance of the critical level for ammonia is a better indicator of harm than simply the concentration of ammonia.
- A target in relation to protected sites might be appropriate, but assessment of which SSSIs are particularly sensitive to ammonia is not yet complete for Wales.
- A target in relation to the area of sensitive habitats would be more appropriate than a target for all Wales. Habitat sensitivities to nitrogen deposition and to acidity deposition have been mapped, but habitat sensitivity to gaseous ammonia has not been mapped.
- Well under 50% of Wales is now suitable for sensitive bryophytes and lichens, due to ammonia pollution.
- National-scale atmospheric models do not represent concentration and deposition patterns around small sources particularly well, but are useful for assessing larger-scale patterns and for assessing the wider sources of pollution at a particular location.
- A target for particulates ($PM_{2.5}$) in relation to human health is being developed in a separate CAAP subgroup. This target is likely to be based directly on measurements.
- The failure of sites to achieve Favourable Conservation Status is commonly because of exceedance of air and water pollution thresholds, so a focus on reducing air pollution impacts is essential to meet the “30 x 30” target (30% of Earth’s land and sea to be conserved by 2030) under the UN Post-2020 Global Biodiversity Framework.
- A potential basis for the target could be that no protected sites are compromised by ammonia pollution, i.e. do not exceed the critical level.
- Ideally, a target will be set such that progress towards meeting it can be achieved by measures taken within Wales.
- It is important to establish relationships between potential targets. For example, decreases in gaseous ammonia are likely to decrease total N deposition, although the latter is also affected by other factors.
- A target could be set with multiple aspects, e.g. to decrease both absolute ammonia concentration and exceedance of critical levels. However, multifaceted targets can be complex, and achievement is harder to assess.
- If air quality target(s) are achieved, lags in ecological systems will still mean there is a delay in response and return of a system to favourable condition. Active restoration/conservation measures may be needed to ensure the protection of biodiversity and ecosystems.

A second meeting of the subgroup was held on 15th December 2022, in which the following additional points were made:

- Bryophytes and lichens are important components of ecosystems, contributing to flood regulation (by intercepting rainfall) and peat formation, and providing refugia for invertebrates. This argues for the importance of the 1 µg m^{-3} annual mean critical level for these groups. Currently around half of Wales (see Figure 7.2) is unsuitable for sensitive bryophytes and lichens due to ammonia concentrations above 1 µg m^{-3}, and so the functioning of ecosystems is impaired across much of Wales.

- The target could be based on **measured or modelled data**. The following points argue for basing the target on monitoring data:
  a) Monitoring data provide a clear indication of air quality, which can be considered objective if monitoring locations are carefully considered and unbiased.
  b) Air quality targets for public health are based solely on monitoring data.
  c) Modelled data are subject to change, due to changes to the modelling method, or a change of model.

- The following points argue for basing the target on modelled data:
  a) Particulate pollution (the main cause of human health impacts) is generally localised, and monitoring can be focused on known locations. By contrast, the impacts of ammonia pollution (a key pressure on ecosystems) are widespread.
  b) Modelled data are more robust against outlying measurements.
  c) Monitoring data are also subject to change, e.g. due to a change in method or a reconfiguration of the network
  d) Basing a target on monitoring data could lead to spot-implementation of measures around monitoring points rather than addressing wider issues.
  e) Model outputs can be generated for all of Wales, and so take into account areas where there are gaps in the monitoring network.

- Both measured and modelled data are potentially subject to error and bias. Improved measurements of atmospheric pollution, e.g. through a more extensive ammonia monitoring network, will be essential regardless of whether the target is based on modelled data or direct measurements. The accuracy of modelled data can be greatly improved by calibration to measurements, and this approach is used to generate the data used in the UK Trends Report (Rowe et al., 2022).

- The Sustainable Farms Scheme is likely to be implemented in 2025. Ideally, baseline monitoring would be set up in 2024, so that the effects of the scheme on air quality can be assessed.

- The target could be based on **national or localised** data. Arguments were made against national-scale targets:
  a) A national target could be met by reducing pollution pressure in the areas most affected currently, but without reducing pollution in areas that are currently relatively unaffected.
  b) A national target might encourage disproportionate actions such as reducing pollution in areas where it is currently high, when it might be more efficient to target measures on areas where extant ecosystems and biodiversity are likely more sensitive to pollutant pressures e.g. more remote and/or protected sites.

- Arguments for a target in relation to the whole area of Wales were also presented:
  a) Ecosystem functioning is being affected across a large area of Wales (see note above on the importance of bryophytes).
  b) Such a target would not be subject to change due to changes in habitat mapping methods, protected site boundaries and designations, etc.

c) Such a target would be clear and easy to communicate.
d) It is important to preserve biodiversity close to centres of population as well as in relatively remote areas.
e) Ammonia is dispersed widely, so measures to reduce emissions in relatively polluted areas will also reduce ammonia exposure in relatively pristine areas, as well as total N deposition.
f) A broad target for Wales would be easier to justify and communicate than targets which could be perceived to focus on particular sectors or locations e.g. individual farms close to protected areas.

- A relative-change target (for example, an x % decrease in the area where critical load is exceeded) would be more robust against changes in the measurement and/or modelling method than an absolute-change target (for example, x % of Wales below critical load), provided the same method is used for the baseline and target years.
- However, a relative-change target would still be somewhat affected by a change of model.
- It may be possible to develop an assessment approach which is a hybrid approach of monitoring and modelling, e.g. by calibrating model outputs to measurements.
- Any target set for air quality with respect to biodiversity and ecosystems must not be confused with targets for habitat condition.

- The meeting agreed to recommend that the Wales target for air quality with respect to ecosystems and biodiversity be based on:
  a) Ammonia (NH_3) concentration.
  b) Area where the 1 µg NH_3 m^{-3} annual mean critical level, set to protect sensitive bryophytes and lichens, is exceeded (see Figure 7.2).
  c) Data for all of Wales, rather than for protected sites, sensitive habitats, or other localised areas.
  d) Modelled data calibrated to measurements.
  e) Relative change from baseline values.

10 RECOMMENDATIONS

10.1 Overall recommendations

If a target in relation to air pollution effects on ecosystems and biodiversity is to be adopted by the Welsh Government, it is recommended that:

a) The target is set on the basis of a specific, clearly defined, single metric.

b) The achievement date and target value for the metric are decided after scenario modelling.

c) If a metric based on relative change over time is used, it is clear which is the baseline year.

d) If a metric based on percentage change is used, it is clear what the percentage is of, for example percentage of land area (absolute change), or percentage of the baseline value (relative change).

e) The metric is based on ammonia concentration in air, since ammonia concentration: has direct effects on species and ecosystems; is directly related to total N and total acidity deposition, which are major causes of biodiversity loss in Wales; is influenced strongly by emissions from within Wales; is currently not decreasing, in contrast to NOx emissions which are linked to fossil fuel use; and is relatively easy to monitor.

f) The metric is not based on NO_x, heavy metals, ozone or an emerging pollutant such as microplastics. The importance of NO_x and heavy metal pollution is declining across Wales; impacts of ozone on semi-natural communities are unclear, and evidence for impacts of emerging pollutants is limited.

g) Specifically, the metric is based on exceedance of the 1 µg m^{-3} annual mean critical level for ammonia, set to protect sensitive bryophytes and lichens (see Figure 7.2).

h) Progress towards the target is primarily assessed using modelled data, calibrated against measurements from the ammonia monitoring network. Modelled data can provide a comprehensive assessment for the whole of Wales, or of specific areas. Although measurements provide more empirical evidence, they are influenced by year-to-year variation in meteorology, and will be affected by any future changes to the measurement network. The current Welsh ammonia monitoring network provides limited evidence, particularly for rural and upland areas, and efforts must continue to improve the measurement network and ensure that modelled data provide an accurate representation of reality.

i) The metric is based on the whole extent of Wales, not only on protected sites or mapped habitat areas, because it is important to protect sensitive species and habitats throughout Wales.

j) The choice of target and metric should be kept under review in case of emerging pollutants and/or new evidence around air pollutant impacts on ecosystems and biodiversity

10.2 Specific recommendation

The metric recommended by the CAAP subgroup is:

The area of Wales where annual mean concentration of ammonia exceeds the 1 µg m^{-3} critical level.

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