Air pollution and biodiversity: a review

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Executive Summary
The following review assesses the impact of air pollution on biodiversity. Rather than looking at the issue on a habitat by habitat basis, or by examining effects on successive groups of plants and animals, it draws some general ecological conclusions regarding the impact of air pollution on biodiversity. The following main conclusions are drawn:

- Lower life forms are usually more affected by air pollution than higher life forms;
- In general, plants are more affected than animals on land, but not in freshwater;
- Most affected species decline due to pollution, but a minority increase.

Impacts on wild plants and animals

- Air pollution has played a key role in changing the distribution of many plant species, and the ecology of susceptible plant communities in polluted areas;
- Impacts on invertebrates appear to be wide-ranging, but few general assessments have been attempted;
- Impacts on higher animals are most commonly linked with food loss and reproductive effects, rather than to direct toxic effects on adults;
- Indeed, many animals have proved to be reasonably adaptable to air pollution;
- Responses to air pollution also differ markedly *within* many animal groups.

Complexities of air pollution

- Different air pollutants have a range of effects on a single species;
- Some pollutants can appear to be initially beneficial to a particular species, but later become harmful, or are harmful to the ecosystem as a whole;
- Air pollution does not constitute a single problem, but presents an array of threats and opportunities to plants and animals;
- Tropospheric air pollution interacts with other pollution effects, including ozone depletion and climate change;
- Air pollutants also interact with other natural and anthropogenic factors, such as climate, land management etc.

Ecosystem responses

- Some environments are particularly susceptible to air pollution damage, including: environments with a low buffering capacity; environments open to regular or occasional episodes of intense pollution; and environments containing particularly sensitive keystone species;

- Air pollution tends to reduce biodiversity, but not necessarily biomass or primary productivity;

- Air pollution does not respect the boundaries of nature reserves and conservation areas;

- Ecosystem management cannot offset all the ecological problems caused by air pollution, and can sometimes cause further disruption to natural systems;

- Air pollution is therefore a significant, contributory factor in the decline of global biodiversity.

The only effective response to air pollution problems is to reduce pollution at source, through: a reduction in energy demand; energy conservation methods; fuel-switching; and technical pollution controls.

1.Introduction

Concerns about the environmental effects of air pollution stretch back for hundreds of years. In 1661, the English pamphleteer John Evelyn wrote Fumifugium - or the smoake of London dissipated Evelyn 1661, sic) about air pollution in the capital, and the term "acid rain" was first used in the mid 19th century in the north of England (Smith, 1872). Maps of sulphur dioxide levels drawn using the decline of lichens as the system of measurement were available prior to the First World War. Ecological effects can be measured back for hundreds of years.

More recent interest in the long-range effects of air pollution date from the 1960s. Attempts to control local air pollution problems, mainly by dispersal via high chimneys, resulted in the incorporation of sulphur and nitrogen dioxides into the atmosphere and the creation of sulphuric and nitric acids in the air. These fall to earth, sometimes hundreds of miles from their source, in the form of rain, mists and snow. A growing understanding about the ecological implications of so-called "acid rain" helped focus attention onto the issue of air pollution, and several other problems or potential problems were identified.

The pollutants

Acid rain is a general and simplified term used to describe a range of pollution effects. Several air pollutants can cause acidification of the environment. These include sulphur and nitrogen oxides (SO_2 and NO_X), which are given off when fossil fuels are burnt in power stations, industrial boilers and motor vehicles, and when plant material such as wood is burnt. Acidification occurs in two ways:

- either the gases convert chemically in the atmosphere, turning into acids and falling as rain, mists or snow;
- or they fall to earth as dry gases and are converted to acids through the action of rainwater.

These pollutants can also cause ecological damage in their gaseous form. Other important gaseous air pollutants occur, including hydrocarbons, which are pollutants themselves and can also react with nitrogen oxides in the presence of sunlight to form photochemical ozone (O_3), itself an important pollutant in the troposphere. To a lesser extent, ammonia (NH_4) from livestock slurry, and trace metals from industrial processes, also have important effects on the environment.

Critical loads

Some measure of the importance of these effects, from an ecological perspective, can be gained from the use of the critical load concept.

A critical load is the *quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on sensitive elements of the environment do not occur according to present knowledge*[1], ie a measure of the damage threshold for pollutants. Critical loads can be set for a range of different habitats and species. Scientists acting under the auspices of the United Nations Economic Commission for Europe (UNECE) have collated critical load data for sulphur and acidity levels throughout Europe, and have produced maps showing where the tolerance of soils and waters is already exceeded, or is likely to be exceeded in the future[2]. A recent research project for WWF pinpoints important European nature conservation areas that are likely to be at high risk from air pollution. Under controls proposed by the 1985 sulphur protocol, some 71 per cent of the protected areas studied are in areas suffering excess acid pollution. Even if countries were to adopt far more radical environmental scenarios, between 20-25 per cent of Europe's protected areas would remain at risk from acidification. High risk countries include Austria, Belgium, Denmark, Germany, Ireland, the Netherlands, Norway, Sweden, Switzerland and the UK[3].

Air pollution and biodiversity

Several attempts have been made to analyze the impacts of air pollution on wildlife[456]. More recently, research for WWF has assessed the impacts on wildlife through a literature survey which identified effects on 1,300 species, including 11 mammals, 29 birds, 10 amphibians, 398 higher plants, 305 fungi, 238 lichens and 65 invertebrates, providing the most detailed survey to date[7]. In general, the studies have concentrated on either specific ecosystems, or individual groups of plants and animals.

Whilst these investigations have all been useful in helping to identify the existence and scale of the problem relating to biodiversity and air pollution, they have not, on the whole, attempted to look at general trends. Drawing on the overviews referred to above, and on other published papers, the current paper proposes some general ecological considerations regarding the issue, and backs these with relevant data and examples.

2.General considerations

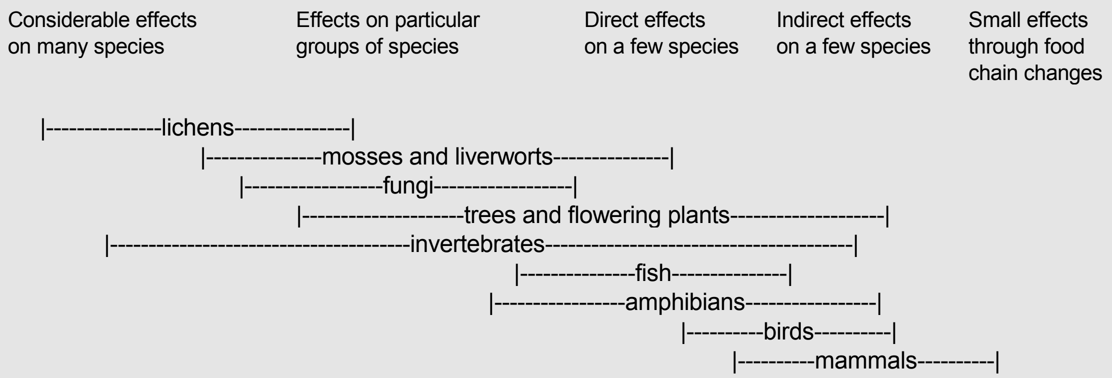
■Lower life forms are usually more affected by air pollution than higher life-forms.

Early attempts to look at the link between air pollution and wildlife focused mainly on the so-called "charismatic megafauna", ie on large and "colourful" species of animals. In fact, the most widely affected species - in terms of both number of species suffering damage from air pollution and also sensitivity of individual species to pollution - are amongst the lower life forms. In particular, lichens, bryophytes, fungi, and soft-bodied aquatic invertebrates are likely to be at risk.

Impacts of pollution in these *high risk* groups are likely to be general across many species, and directly related to the toxic effects of pollution itself. On the other hand, impacts on higher plants and, particularly, on higher animals are likely to be limited to sensitive species, and to act on the whole through secondary affects, such as changes to food supply, or inter-specific competition.

Some relationships are illustrated in general form in Figure 1 below.

Figure 1: Likely Impacts of Atmospheric Pollution on Plant and Animal Groups



Notes: The diagram represents *qualitative* relationships rather than *quantifiable* data.

Groups are ranked with respect to their *main responses* to air pollution; in most groups there will be many species largely unaffected by ambient air pollution.

Source: EQU!L!BR!UM, 1995

For example, both gaseous sulphur dioxide pollution[8910] and acid deposition[111213] are known to damage literally hundreds of lichen species in the UK. Air pollution has caused the extirpation of many species from industrial areas and the decline of others, even in remote parts of western Britain[14]. On the other hand, years of research have to date only found two birds whose range has been affected; the house martin (*Delichon urbica*) by sulphur dioxide[15] and the dipper (*Cinclus cinclus*) by the impacts of freshwater acidification on its food species[16] (although there may also have been some impacts on fish feeding birds). Neither of these species appears at risk of serious decline, and the former has now recolonised some areas due to a decline in SO_2 levels[17].

■In general, plants are more affected by air pollution than animals on land, but not in freshwater.

Although precise comparative studies have not been carried out, there seem to be greater losses amongst terrestrial plant communities than amongst land animals under conditions of high air pollution. By their nature, plants are less able to adapt to sudden changes in pollution levels and climatology than animals, which often have the option of moving or changing food source. For example, in the literature survey referred to above[18], evidence was found for pollution effects on over three times as many terrestrial plants as animals. Whilst some of these differences may indicate a bias towards certain groups amongst researchers, it accords well with other findings referred to above.

This situation apparently changes in freshwater ecosystems, where decline due to increasing acidity is greater among animals than plants. Studies of benthic fauna in Sweden found that diversity amongst animal species declined by 40 per cent for a pH reduction of 1 unit, while plant species declined by only 25 per cent under the same conditions[19].

■Most affected species decline due to pollution, but a minority increase.

Studies suggest that if a species is affected by air pollution at all, it is likely to decline. However, a minority of species thrive under polluted conditions. There are two reasons for this:

- ■ some species appear to be stimulated by pollutants. For example, many aphids grow faster in conditions of high sulphur dioxide and nitrogen oxides[20];

- ■ some species are resistant to pollution and expand to fill the spaces left by the disappearance of more sensitive species.

These issues will be returned to in Section 5.

3.Impacts on wild plants and animals

Most studies of wildlife effects have concentrated on individual species or particular groups. In the following section, an attempt is made to synthesise this information into a more general analysis of impacts.

■Air pollution has played a key role in changing the distribution of plant species and the ecology of susceptible plant communities in polluted regions

Air pollution affects plants in many ways which have implications for overall biodiversity and ecology. Effects have been studied in detail for lichens[21,22,23,24,25] and trees[26,27,28,29,30,31,32,33,34,35,36], and also researched for bryophytes[37,38,39,40,41,42], fungi[43,44,45] and herbaceous flowering plants[46,47,48]. It is clear that susceptible individuals in all these groups can be affected by pollution, although debate remains in some cases about both the severity and the threshold of effects. Impacts occur as a result of various factors, including:

- **Direct toxic effects on adult plants from either gaseous pollutants or acid deposition**: these effects have been studied in particular detail for some crop species[49,50,51], but results remain relevant for many wild species as well. Interaction between gaseous and wet acid deposition also sometimes changes the nature of the response[52].

- **Toxic effects on plants' reproductive capacity**: there is evidence that air pollution can reduce some plants' ability to reproduce, thus causing long-term changes to population ecology[53].

- **Changes in soil fertility due to pollutant deposition, particularly of nitrogen compounds**: increased deposition of nitrogen can sometimes have a fertilizing effect on plants, particularly in ecosystems where nitrogen levels are the factor controlling growth rate of plants. In other cases, an excess of nitrogen can, conversely, reduce growth[54].

- **Changes in soil acidification**: airborne acid pollution has been linked to accelerated acidification of soil in base-poor environments[55], and to a consequent decline in calcicole (calcium-loving) plants, potential aluminium toxicity, leaching of nutrients and base cations, effects on mycorrhizae etc.

- **Increased or decreased competition from other plants**: in polluted ecosystems, a small number of resistant plant species can dominate plant communities. For example, green algae such as *Pleurococcus vulgaris* can replace epiphytic lichens on trees[56,57], while *Spahgnum* species regularly replace other macrophytes in acidified waters[58,59].

- **Increased predation through impacts of air pollutants on plant pests such as aphids**: growth in many aphid species is increased by exposure to atmospheric sulphur dioxide and nitrogen oxides, and also in some cases to mixtures of pollutants. There is now strong evidence that aphid predators will not be able to keep up with this population increase and that the health of feed plants will suffer in consequence[60].

The end results include changes in the structure of plant communities. After initial research that concentrated mainly on commercially-valuable trees, crop plants and lichens, evidence has now also accumulated on effects on other wild plants. Some examples are given in Table 1 below.

Table 1: Examples of damage to wild plants by atmospheric pollutants

Name	Scientific names	Notes and sources
blue green algae	*Nostoc*, *Scytonema* etc	Endangered all over Europe due to air pollution[61].
lichens	Many foliar species, eg *Usnea*, *Ramalina*.	Declined due to SO_2 pollution.
lichens	*Lobaria pulmonaria*, *Leptogium burgessii* etc	Declined due to wet acid deposition.
mosses and liverworts	*Hypnum cupressiforme*, *Grimmia pulvinata*, *Bryum*, *Orthotrichium* and others.	Susceptible to damage by SO_2[62].
bog mosses	*Sphagnum* spp.	Research in the English Pennines suggests that many *Sphagnum* species are damaged by SO_2, and perhaps also by NO_X[63] and nitrogen deposition; however, *Sphagnum* increases in acidified waters[64].
woolly fringe moss	*Racomitrium lanuginosum*	Nitrogen deposition is thought to be at least partly responsible for decline of this moss over most of southern Scotland[65].
mosses	*Antitrichia curtipendula*, *Neckera*, *Orthotrichium*, and *Rhytidiadelphus*	Decline in Oxford and Berkshire in the UK due to soil acidification[66].
fungi	Many mycorrhizal fungi including *Cantharellus cinabrius*, *Russula* spp, *Lactarius* spp, *Hygrphorus* spp and *Hygrocybe* spp	Mycorrhizal fungi are badly affected by nitrogen deposition in acidified forests[67][68]
fungi	many species, including *Lactarius mairei* and *Sarcodon imbricatus*	Fungi can also be damaged by soil acidification[69].
aquatic flowering plants	*Lobelia dortmanna*, *Littorella uniflora*, *Isoetes echinospora*,	Declined due to acidification in freshwaters[70].
herbaceous flowering plants	Many species, including *Primula veris*, *Vicia sepium*, *Trifolium medium*, *Melica nutans*, *Hepatica nutans*, etc	Declined due to soil acidification[71][72].
broadleaved trees	*Quercus robur*, *Quercus alba*, *Acer saccarina*, *Populus tremulens* and others	Sensitive to acute damage by ozone and other air pollutants[73][74], also to indirect effects of soil acidification and to increased nitrogen deposition.
coniferous trees	*Larix europeaus*, *Picea abies*, and others	Sensitive to acute damage by ozone and other air pollutants[75].

■Impacts on invertebrates appear to be wide-ranging, but few general assessments have been attempted.

Most evidence linking groups or species of invertebrates with population changes due to air pollution is statistical, ie few studies have been carried out into the mechanisms by which pollution is affecting invertebrate life cycles. Tables 2 summarises some key results for freshwater invertebrates.

Table 2: Freshwater invertebrates affected by acid deposition

Name	Scientific name	Notes
Animals that decrease		
Zooplankton		The range of species is reduced in acidified waters sometimes by over 50%[76][77][78][79].
Sponges	*Porifera*	Disappear in acid waters[80].
Flatworms	*Platyhelminthes*	Disappear in acid waters[81].
Worms	*Annelida*	Disappear in acid waters[82].
Leeches	*Annelida: Hirudinae*	Disappear in acid waters[83].
Snails and bivalve shells	*Mollusca*	*Sphaerium*, *Pisidium*, and other molluscs in Norway decline in acid lakes[84][85]. The river limpet, *Ancylus lacustris* disappears from acid waters in the English Lake District[86].
Small crustaceans	*Crustracea: Cladocera*	Small crustaceans, like *Daphnia*, usually disappear in water below *pH* 5.5[87][88].
Freshwater shrimps etc	*Crustacea*	*Gammarus* has virtually disappeared when pH of water drops to 6[89]. The water slater *Asellus aquaticus* also disappears[90].
Freshwater crayfish	*Crustacea: Astacus astacus* and *Pacifastacus leniusculus*	Decline due to acidification has been studied in Sweden[91].
Mayfly and stonefly larvae	*Insecta: Ephemeroptera* and *Plecoptera*	Most mayfly species decline or disappear in acid waters [92][93] although some, such as *Siphlonuris lacustris* appear more tolerant[94]. Susceptible stonefly larvae include *Isoperla grammatica* and *Leuctra inermis*[95].
Animals that increase		
Phantom midge	*Crustacea: Chaoborus* spp.	Replaces *Gammarus* and *Asellus* in acid waters[96].
Water boatmen	*Insecta: Hemiptera: Corixidae* and *Gyrinidae*	Thrive in acid waters, often reaching high numbers in the absence of fish predation[97].

Alder fly and caddis fly larvae	*Insecta: Sialis* spp. and *Trichoptera*	Thrive in acid waters[98].
Some stonefly larvae	*Insecta: Plecoptera*	In acidified Welsh streams, most species disappear, but *Amphinemura sulcicollis* and *Chloroperla tormentium* are ubiquitous[99].
Dragonfly and damselfly larvae	*Insecta: Odonata*	Thrive in acid waters, sometimes replacing fish as the top predators[100].

Data for land invertebrates tends to be more patchy, and based largely on statistical or circumstantial evidence. Whilst there is an increasing acceptance among scientists that some invertebrate species are damaged by air pollution, no large scale or general studies have been attempted, except on a limited scale for land molluscs. Some impacts, or possible impacts, are outlined in Table 3 below.

Table 3: Examples of land invertebrates damaged by air pollution

Name of group and/or species	**Scientific name**	**Notes**
Worms	***Annelida**: Lumbricidae*	Only three species of earthworms can survive below pH4 in Scandinavia[101].
Slugs and snails	***Mollusca***	
two-lipped door snail	*Balea perversa*	Significant decline in acidic areas of the UK, where they are confined to trees with more basic bark[102].
various land snails	*Cepea nemoralis*, *Helix aspersa*, etc	Show an apparent decline in areas suffering high levels of air pollution[103].
various land snails	*Carychium tridentatum, Cochlicopa lubricella, Vertigo pusilla, Macrogastra plicatus, Vitrina pellucida, Trichia hispida, Helicigona lapicida*, etc	Research in Sweden suggests a link between decline of land molluscs and acidification[104], including some which decline with a fall in soil pH and others, such as *Ena obscura*. and the slug *Limax marginatus*, which are tree climbers and decline even in calcium-rich habitats, perhaps due to loss of food[105].
Arthropods: Spiders	***Arachnida***	
various small species		Research in Denmark has linked decline in some spider species with high levels of SO_2[106][107].
various larger species		Research in Sweden found that density of raptoral spiders over 2.5mm was lower in spruce forests undergoing heavy needle loss than in healthy spruce forests[108][109][110].
Arthropods: Insects	***Insecta***	
butterflies and moths	*Lepidoptera*	Several studies show a decline in polluted atmosphere[111].
Apollo butterfly	*Parnassius apollo*	It is suggested that decline in polluted areas is due in part to caterpillars ingesting manganese where the host plant is growing on acidified soil[112].

ringlet butterfly	*Aphantopus hyperantus*	Decline is greatest in areas of high SO_2 levels[113].
beetles	*Carabus* spp	Decline in acid soils in Sweden[114].
wasps		Particularly sensitive to SO_2 pollution[115].
springtails	*Collembola*	Decrease in both number and variety in forests experiencing air pollution[116].

In addition, some species apparently benefit from air pollution, as discussed below.

■Impacts on higher animals are most commonly linked with food loss and reproductive effects, rather than to direct toxic effects on adults.

Relatively few examples are known of higher animals suffering direct toxic effects from either acidity or gaseous air pollution. A number of mammals are known to build up high levels of heavy metals and other pollutants in contaminated environments. For example, cadmium levels in the internal organs of game animals in Sweden have prompted authorities to recommend that the kidneys of older elk are not eaten and that liver from game is not eaten more than once or twice a month[117]. Deterioration in the antlers of roe deer (*Capreolus capreolus*) in Poland has been linked to sulphur and heavy metal pollution[118][119]. Research in former Czechoslovakia found high sulphur levels in hares (*Lepus capensis*) living in polluted areas[120]. Wild mink (*Mustela vision*) and Canadian otter (*Lutra canadensis*) have both been found to have high mercury levels near industrial sites[121]. However, the long term ecological effects of these contamination levels remain unknown.

Measurable effects on wild animals, when they do occur, are generally due to either loss of food or loss of ability to reproduce. For example, studies on mammals and birds have found the strongest links between declines and loss of food species, often through freshwater acidification. Some examples are given in Table 4 below.

Table 4: Mammals and birds affected by loss of food organisms due to air pollution effects

Common name	**Scientific name**	**Notes**
Otter	*Lutra lutra*	Decline in otter populations due to loss of fish in acidified regions has been suggested for Galloway, Scotland[122], and other parts of the UK[123].
Caribou		Impacts on caribou lichen (*Cladina stellaris*) could have a serious impact on caribou populations[124].
Small rodents		Research in the USA suggests that in heavily polluted areas, reduction in insect populations could affect small birds and mammals such as mice[125].
American Black Duck	*Anas rubripes*	Experiments suggest increased duckling mortality in acid waters, probably due to a decrease in total food supply[126].
Dipper	*Cinclus cinclus*	Studies in mid Wales have linked decline in the dipper to food loss in acidified streams[127].
Osprey	*Pandion halietus*	Research in Scandinavia has linked decline in breeding success to loss of fish from acidified lakes[128][129].

Amongst the animals of slightly lower orders, including particularly amphibians[130] and fish, impacts are more commonly related to loss of reproductive capacity. In most cases, acidity itself does not appear to be the problem, but rather the impact that acidification has of releasing metals such as aluminium into the water[131].

There has, in addition, long been a debate about the role that acidification and aluminium could play in eggshell thinning in certain bird species. Some examples of impacts on reproductive success are given in Table 5 below.

Table 5: Decline in animals due to reproductive failure as a result of air pollution

Common name	Scientific name	Notes
Atlantic salmon and brown trout	*Salmo salar* and *S. trutta*	Declined due to reproductive failure in acidified waters in many areas, including for example the Tovdal River[132] and other areas of Norway[133], upland lochs in Galloway, Scotland[134], the English Lake District[135] and mid Wales[136].
Brook trout	*Salvelinus fontinalis*	Declined in areas of North America where acidification has changed water chemistry. Brook trout have usually disappeared by the time pH drops to 5.5[137].
Spotted salamander	*Ambystoma maculatum*	Undergone declines in New York state due to acidification of breeding pools[138][139][140].
American toad and American tree frog	*Bufo americanus* and *Rana sylvatica*	Reduced breeding demonstrated in acidic conditions[141][142].
Common frog	*Rana temporaria*	Decline of the common frog has been studied in acidified lakes in Sweden, where in one case extirpation took place in six years between the first sighting of dead spawn and the disappearance of the common frog[143][144]. Similar effects have since been found elsewhere[145].
Natterjack toad	*Bufo calamita*	Decline of relic populations in England linked to increased acidification of breeding pools[146][147][148].
Great tit (also blue tit, nuthatch and great spotted woodpecker)	*Parus major*	A decline in calcium levels in acidified forest soils, leading to decreased calcium in tree leaves, and hence in the prey species of passerine birds such as caterpillars, has been linked to eggshell thinning in the Netherlands[149].
Great tit, pied flycatcher, collared flycatcher	*Parus major*, *Ficedula hypoleuca* and *F albicollis*	Breeding success in Poland has been depressed, possibly as a result of elevated levels of lead and cadmium as a result of pollution[150].
Pied flycatcher, bluethroat, reed bunting and willow warbler	*Ficedula hypoleuca*, *Luscinia syccica*, *Emberiza schoeniclus* and *Phylloscopus trochilus*	A link has been proposed between aluminium released during freshwater acidification and impaired breeding in passerine birds, by eggshell thinning, impact on clutch size and hatching and the health of breeding birds[151][152].

■**In contrast, many higher animals have proved to be reasonably adaptable to air pollution.**
Apart from a few specialised feeders referred to above, most animals at or near the top of the food chain have proved adaptable to changing conditions created by atmospheric pollution. For example, unlike the dipper, the grey wagtail (*Motacilla cinera*) proved able to survive in acidified streams in Wales[153] and Sweden[154], probably by changing its feeding from freshwater to bankside invertebrates. Pelagic pursuit feeding water birds such as divers (*Gavia* spp.) and the goosander (*Mergus serrator*) can compensate for reduced fish density in partly acidified lakes through better hunting success because of increased water transparency, due to disappearance of many algae. In a survey of 45 oligotrophic lakes in Sweden, goosanders and black throated divers (*Gavia arctica*) were found to favour partly acidified lakes. Adult divers appear capable of switching food for young from small fish to aquatic invertebrates, and in Sweden higher production of young occurred on acidified lakes, perhaps partly because of reduced predation from pike (*Esox lucius*)[155156157].

These adaptations have their limits, and evidence from the USA suggests that if most or all the fish disappear from acidified lakes, divers (known as loons in North America) will decline[158]. However, the fact that high or top predators can often adapt quite effectively to changing conditions means that their status under acidified or polluted conditions remains complex.

■**Responses to air pollution also differ markedly *within* many animal groups.**
These sometimes divide clearly between different subgroups, in other cases susceptibility or resistance to air pollution appears to be more individual. Some examples are given below:

- **Terrestrial insects**: distinct types of response to SO_2 pollution have been identified which distinguish some groups of land-living insect, for example:

    - Very susceptible: eg many butterflies and moths;
    - Moderately susceptible, eg the beetle *Ips dentatus* and the flatbug *Aradus cinnamoneus*;
    - Very tolerant and sometimes benefitted by SO_2 pollution: aphids[159].

- **Stonefly larvae: *Plectoptera***: most species decline rapidly in acidified waters but a few, such as *Amphinemura sulcicollis* and *Chloroperla tormentium* can withstand high levels of acidity and in consequence will dominate acidified streams[160].

- **Fish**: variations in susceptibility to acidification occur both within and between species. Some survival thresholds for some common species are given below:

Table 6: Progression of fish deaths in acidified European freshwaters[161]

Fish species	Scientific names	pH where decline starts	pH where death starts
salmon, trout, roach	*Salmo sala*, *Salmo trutta*, *Rutilus rutilus*	6.8	6.0
grayling	*Thymallus thymallus*	6.5	5.5
perch, pike	*Perca fluviatilis*, *Esox lucius*	6.0	5.0
eel	*Anguilla anguilla*	5.5	4.5

4. Complexities of air pollution

The previous section has given some indications of the scale and breadth of impacts on individual species. However, air pollution is far from a single or simple phenomenon. In the following section, some of the *interactions* between different pollutants, and between pollutants and other factors, are briefly examined.

■Different pollutants have a range of impacts on a single species.

Wild plants and animals do not face a single problem, or a simple range of pollution effects. The cocktail of atmospheric pollutants facing species in many parts of the world varies enormously, and each combination has a slightly different effect. Combinations can sometimes produce a joint effect greater than the sum of individual effects (synergism) and on other occasions effectively cancel each other out. Identifying a response, or a suspected response, to a mixture of pollutants is often easier than identifying the particular role that individual pollutants play in any observed responses, or discovering how the pollutant acts to cause changes. Our knowledge of pollutant interactions remains limited, but some information on varying responses has been built up over the last few years. For example:

- Some lichens are more sensitive to gaseous sulphur dioxide than to wet acid deposition, while in other species the reverse is true[162].

- Several *Sphagnum* moss species decline under conditions of high sulphur dioxide pollution[163] and a few are also susceptible to nitrogen oxides. However, many of the same species *increase* in acidified waters, where wet acid deposition has reduced pH levels and eliminated other macrophyte plants[164].

- Fumigation experiments with crop plants have found a wide range of responses according to whether the plant is exposed to sulphur dioxide, nitrogen oxides, ozone or varying combinations and mixes of these and other pollutants[165].

■**Some pollutants can appear to be initially beneficial to particular species but later become harmful, or are harmful to the ecosystem as a whole.**

Air pollution can benefit certain species at the expense of others, either because they are particularly resistant, or because the surrounding habitat changes in a way that benefits them over other species. For example:

- **Flowering plants**: Whilst soil acidification often leads to an overall loss in flowering plant variety, some species will expand as a result of increased nitrogen availability, lack of competition etc. Studies in Sweden found, for example, that dogs mercury (*Mercuralis perennis*), woodruff (*Galium odoratum*) and wood sorrel (*Oxalis acetosella*) all increased under conditions of acidification[166].

- **Insects**: At least twenty species of aphids show increased mean rate of growth under conditions of high levels of SO_2, NO_X or mixtures of the two[167]. Experiments suggest that changes are mediated via the food plant in response to pollutant-induced changes in the plant[168]. Increased growth rate is usually accompanied by increased reproduction. Whilst this boosts populations of aphids it also, in consequence, increases pressure on host plants and disrupts ecosystem stability.

- **Amphibians**: Research on the impacts of acidification on the survival of common frogs (*Rana temporaria*) suggests that early mortality of a proportion of eggs can actually increase the number surviving to adulthood in some cases, because of reduced competition and increased availability of food. However, this early mortality also reduces the options facing the population, and is likely to lead to a decline in the long term, as observed elsewhere[169].

- **Birds**: Studies in Germany suggest that tree decline can result in a temporary increase in some endangered bird species, including the three-toed woodpecker (*Picoides tridactylus*), citril finch (*Serinus citrinella*), crossbill (*Loxia curvirostrata*), rock bunting (*Emberiza cia*), black grouse (*Lyrurus tetrix*) and nightjar (*Anthus campestris*), by increasing the number of dead trees and the herb and shrub layer in managed forests[170]. However, the research also suggests that a greater number of species suffer through forest decline (and in any case the problems of the species listed above were originally caused by forest management that eliminated several important stages in the forest succession).

■**Air pollution does not constitute a single problem, but presents an array of threats and opportunities to plants and animals.**

There is no single "air pollution problem". A wide array of pollutants, acting at different times and in a wide variety of combinations, interact with natural and with other anthropogenic factors to alter ecosystems.

For example, acidification presents freshwater birds with a range of different threats and opportunities; some face immediate problems, some can adapt to a certain level of changes but not to extreme acidification, while a third group may even benefit. Some of the factors affecting water birds are illustrated in Figure 2 below[171].

Figure 2: Factors potentially affecting water birds

Acidifying Effect	Implications
Transparency increases	Greater hunting success
Metal ions increase	Toxic and reproductive effects
Some insect species increase	Increased food
Many invertebrate species decrease	Less food
Fish decrease	Less food, less competition, less nestling predation

Different bird species react in different ways. Some surface feeding ducks tend to increase due to growth in number of insects and decreased competition from fish. Reproductive success can be increased further if pike disappear. Diving ducks such as the goosander can use the greater transparency to increase catch and also sometimes switch food from fish to invertebrates. Plunge feeders, such as terns, already have maximum visibility and cannot use greater transparency to increase their catch.

In forest ecosystems, years of research effort have failed to find a single factor influencing trees, but rather a whole array of different stress factors, which may or may not play an important role in any particular decline. Some stress factors on forest trees are illustrated below in Figure 3.

Figure 3: Combined air pollution impacts on forest trees

Many air pollutants combine to affect trees....

Sulphur oxides Nitrogen oxides Hydrocarbons Heavy metals

Sulphuric acid Nitric acids Ozone

...and act in a variety of ways...

Acid rain, mist and snow ↓

Dry deposition of ozone, sulphur and nitrogen oxides ↓

Increased pest numbers through SO_2 pollution ↓

Nitrogen fertilisation of soil ⇕

Soil acidification, and release of metal ions ↓

Depression of mycorrhizal fungi ↓

...in concert with a range of other factors including climate, pests, diseases, management systems etc.

■Tropospheric air pollution interacts with other pollution effects, including ozone depletion and climate change.

Figure 4: The range of pollution effects

	→	Destruction of stratospheric ozone
	→	Global warming
	→	Long-range air pollution/wet acid deposition
INDUSTRIAL SOCIETY	→	Short-range air pollution/dry deposition
	→	Pollution of water courses
	→	Pollution of soils

Air pollution and acid rain are part of a more general pollution problem, all components of which can cause harmful impacts on the natural world.

The current report concentrates on long and short range tropospheric pollution, the middle two points in Figure 4. Research suggests that other forms of pollution also cause harmful impacts on wildlife, and that sometimes different pollutant types can act together to magnify their net effects. For example:

- Research in the Cascade Mountains of the USA suggests that ozone depletion is resulting in a decline in amphibian populations through its role in increasing egg mortality. Experiments using filtered and unfiltered light on high altitude, shallow water pools found that egg mortality in the Cascade frog (*Rana cascada*) and the western toad (*Bufo borealis*) was 40 per cent, as compared with 10-20 per cent in the control, while egg mortality in the northwestern salamander (*Ambystoma gracile*) reached 90 per cent[172].

- The predicted impact of global warming will be a net loss of biodiversity and ecosystem stability, particularly in some key habitats, such as boreal forests, mangrove ecosystems, cloud forests and some wetland and peatland habitats[173]. Some of these factors may interact with acid deposition. For example, research in the Netherlands suggests that the predicted increase in prolonged droughts may cause additional damage to moorland pools because of atmospherically-derived sulphur compounds. Drying out in fens can cause fish deaths through acid surges, and invasions of plants such as the filamentous algae *Tribonema minus* and the rush *Juncus bulbosus*[174].

■**Pollutants also interact with other natural and anthropogenic factors**

Pollution impacts are further complicated by the fact that in most situations pollutants are acting in the presence of other factors which themselves have an impact on ecosystems. Separating out the key, or most important, factors is often difficult. Contributory factors fall into three main types:

- anthropogenic factors: such as forest management systems
- natural factors: such as landform and soil type
- factors which appear to be natural but have been influenced to some extent by human activities: such as climate changes induced by global warming, and introduced plant diseases.

Separating out the second two factors is now virtually impossible in many cases. For example, in Figure 3, a variety of pollution impacts on trees were illustrated. However, these impacts also act in the presence of a range of other factors, some of which are illustrated in Table 7 below. Deciding which of these factors plays a dominant role, a key role or even a contributory role is frequently an extremely time-consuming process, and one in which the scientific debate can often be coloured by political considerations. The overlap between natural and anthropogenic factors becomes particularly complex when factors such as climate, incidence of fire and pest and disease attack are considered.

Table 7: Some additional factors which may contribute to forest decline[175176]

Factor	Anthropogenic	Natural	Combination
Drought		•	•
Floods		•	•
Frost		•	•
Fire	•	•	•
Underlying rock		•	
Soil condition	•	•	•
Landform		•	
Altitude		•	
Nutrient deficiency	•	•	•
Poor planting	•		
Management methods	•		
Narrow genetic base	•	•	•
Natural pests and diseases		•	•
Introduced pests and diseases	•		
Human damage	•		

Air pollution effects are thus both more complex and more wide-ranging than simply assessment of the damage to a few individual species might suggest. Some species gain in a polluted environment, at the expense of what is usually a larger majority that decline. In the following section, some ecosystem responses to these changes are briefly outlined.

5.Ecosystem responses

Responses to air pollution are not spread evenly throughout the world. The response depends in part on the nature, concentration and timing of air pollution, but also on the existing status and nature of a particular habitat. In the following section, some general points are made about susceptibility to air pollution, along with a brief overview of some environments that have proved to be particularly at risk.

■**Some environments are particularly susceptible to air pollution damage.**
Ecosystems are likely to be most at risk if they:

- are already on substrates with a low buffering capacity, ie a low ability to neutralise acids
- receive occasional, heavy doses of pollution
- contain key species that are vulnerable

These relationships are illustrated in Figure 5 below.

Figure 5: Environments particularly susceptible to air pollution

Three broad categories of environment or micro-environment are particularly susceptible to air pollution from the perspective of ecology and biodiversity; these are listed below along with relevant examples:

- **Environments with a low buffering capacity**
  - plant communities on base-poor rock
  - communities on base-poor or previously acidic soils
  - many communities on thin soils
  - soft water aquatic communities
  - epiphyte plants and climbing animals on trees with acidic bark
- **Environments open to regular or occasional episodes of intense pollution**
  - areas near sources of intense pollution
  - ecosystems liable to experience occasional high levels of pollution, such as those caused by acid flushes from snowmelt or heavy rainfall after drought
  - ecosystems liable to experience regular pollution from long-range sources, due to particular prevailing weather patterns
- **Environments containing particularly sensitive keystone species**
  - bark-living communities dependent on foliar lichens and epiphyte mosses

:

In the following section, some of the key pollution-susceptible environments are identified and discussed.

- **Freshwater ecosystems in base-poor areas**: The water in base-poor lakes and pools receiving a heavy load of acidifying pollutants tends to become more acid, with a range of environmental effects. Analysis of the composition of populations of diatom algae found in lake sediments has allowed researchers to trace the course of acidification[177178179180]. Typically, acid deposition is neutralised by basic materials in the water until these are used up, then acidity rises sharply; the so-called "titration effect"[181182]. In a few cases, acidification effects can occur episodically in relatively neutral or basic water, due to a sudden and temporary flush of acid. This can be caused by snow-melt in the spring, or by heavy rains following drought, which wash accumulated pollutants from trees and vegetation into water courses. These acid flushes can sometimes result in large fish kills[183184].

  Acidification has been identified from many areas of Europe, including southern Norway[185], Sweden[186], Finland[187], Denmark[188], Belgium[189], mid-Wales[190191], Scotland[192] It has also affected large areas of North America, including parts of Canada[193194] such as Nova Scotia[195], Ontario[196] and Quebec[197] and some of the eastern USA[198]. Impacts on freshwater life increase with the level of acidity. Some species and groups disappear quickly with the onset of acidification, while others remain resistant to damage and may increase in the absence of competition.

- **Forest ecosystems in polluted environments**: Forests are affected by air pollution, although issues of cause and effect remain contentious. A decline in tree health due to air pollution was recognised at least a hundred years ago, and in the 1930s conifer plantations were abandoned in parts of northern England because high SO_2 levels inhibited growth[199]. In the 1970s, a new form of tree decline was seen in the Black Forest in Germany, and similar changes have been found in much of Europe, including wide areas of Scandinavia[200201]. Monitoring suggests that about 25 per cent of European trees show serious signs of ill-health, and that the situation has grown worse in the last 20 years. Current surveys cover 34 European countries. In 1993[202], 22.6 per cent of the total sample suffered defoliation greater than 25 per cent, thus being classified as damaged. This included 20.4 per cent of all broadleaved trees and 23.9 per cent of conifers. Countries suffering particularly severe damage included the Czech Republic (53.0 per cent of trees suffering moderate to severe damage); and Poland (50.0 per cent). For 11 out of 12 common species, the proportion of damaged trees has increased significantly since surveys began in 1988. Amongst the worst affected of the common European trees were oak (*Quercus*), pine (*Pinus*) and spruce (*Abies*). In some cases, this has also led to the death of many trees in particular forests. Similar declines have been observed in parts including North America[203], Asia and the Pacific[204].

  Decline symptoms include chlorosis (or yellowing) in leaves and needles; premature needle loss or leaf fall; deformation in leaf shape and size; changes in the tree canopy including thinning and development of "storks' nest" shapes in conifers; abnormal branching patterns, including downward tilting of secondary conifer branches, known as the "tinsel effect"; deformation in roots; disruption of natural regeneration; bark necrosis; and increased susceptibility to disease and pest attack. Most researchers now agree that air pollution plays an important role in this decline, along with a mixture of other factors including climate changes, management and pest and disease attack - the **multiple stress hypothesis**. Some of these factors are inter-related; for example in some cases air pollution can increase the chances of pest attack, or weaken trees so that they are more susceptible to disease. Air pollution may also be contributing to observed changes in climate.

- **Mountain environments**: Several research projects suggest that high altitude or montane environments will be amongst the first to show effects of acidification. Harsh climatic conditions limit plant growth, so that plants are unable to absorb additional atmospheric nitrogen, which then leaks into watercourses[205]. Wind regimes tend to transport pollutants from surrounding areas up into mountains[206]. Although pollution often decreases with altitude, pollution deposition can remain high because of greater precipitation levels. Research in Norway suggests that washout rates for pollutants such as magnesium, calcium and sulphates was 5-15 times higher in mountains than in urban environments[207]. Ozone levels also increase with altitude according to measurements taken in the Bavarian Alps[208] A series of measurements in North America[209] and Europe[210] suggest that tree growth rates have increased due at least in part to deposited pollutants.

  Despite clear evidence for the fragility of upland ecosystems, these have received far less attention than either forests or freshwaters, probably due to the lack of strong commercial or sports interests in many mountain areas.

Whilst these two ecosystems have been the most carefully studied, evidence for important impacts also occur elsewhere, for example:

- **Peat ecosystems**: Most peat bogs and mires are already acid or neutral, and an additional acid load can cause serious changes to the ecosystem.

- **Heathlands**: Acidic or base-poor heathlands can undergo major changes as a result of air pollution. For example, excess nitrogen inputs to unmanaged heathland in the Netherlands has resulted in nitrophilous grass species replacing slower growing heath species[211].

- **Microhabitats on acid tree bark**: Lichens are likely to decline more rapidly on acid rather than alkali tree bark[212].

- **Plankton communities in the ocean**: Research suggests that increased nutrient loading, and eutrophication, is having an important impact on plankton in some areas. Part of this nutrient loading is thought to come from atmospheric pollution[213].

■**Air pollution tends to reduce *biodiversity*, but not necessarily *biomass* or primary productivity.** Studies have shown that biodiversity tends to decrease under conditions of acidification and heavy dry deposition of air pollutants. This tendency extends across all groups of plants and animals studied in sufficient detail to draw meaningful conclusions. Some examples are given in Table 8 below.

Table 8: Biodiversity loss due to air pollution

Habitat/Group/Species	Scientific name	Details and sources
Freshwater ecosystems		Estimates indicate that at least 20% of plant and animal species have died out in the 15,000-25,000 European lakes where pH has fallen by over 0.5 units as a result of anthropogenic acid deposition[214215].
Phytoplankton		In many acidified Swedish lakes, numbers of species of phytoplankton have fallen by over 50%[216].
Mussels and bivalve snails	*Mollusca*	Have disappeared almost completely from most of the 3,000-5,000 lakes in Sweden where the pH has fallen below 5[217].
Leeches	*Annelida: Hirudinae*	Have disappeared from most of the acidified lakes below pH 5 in Sweden[218].
Freshwater shrimps etc	*Crustacea*	Acidification reduces biodiversity[219].
Freshwater fish including perch, northern pike, roach, brown trout, salmon	*Perca fluviatilis*, *Esox lucius*, *Rutilus rutilus*, *Salmo trutta*	Fish decline as a result of acidification. Research in Sweden has found the percentage of lakes where fish disappear as perch (8%), northern pike (9%), brown trout (18%) and roach (18-20%)[220].
Lichens, mosses and flowering plants		Over a hundred species have been extirpated, sometimes from quite large areas, due to air pollution in Britain[221].
Lichens		Diversity declines dramatically due to SO_2 and wet acid deposition. In Epping Forest, near London, diversity declined from around

		150 species to 36. *Cladonia stellaris* has been extirpated in the UK in part because of air pollution[222].
Lichens		In Finland, out of 12 indicator lichens, only 4 are found in central Helsinki[223]. *Usnea longissima* has apparently been extirpated in Finland mainly due to pollution[224].

These losses usually represent a decline in rarer, more sensitive species. Their places are, on the whole, taken over by commoner and more robust species. In the case of plants, this can include many successful alien or weed species that are adapted to a wide range of soil and climate conditions, and which can evolve fast enough to offset the problems presented by pollution. Air pollution thus presents an *additional* factor contributing to the overall global decline in plant and animal biodiversity.The Swedish Environmental Protection Agency states that:

> Acidification of both terrestrial and aquatic ecosystems almost always results in a decline in biodiversity[225].

■Air pollution does not respect the boundaries of nature reserves and conservation areas.
Over the past few decades, habitat loss has been the greatest single threat to biodiversity and ecosystem stability in most parts of the world. As a result, conservation effort has been directed towards reduction of these threats through establishment of reserves and protected areas and also, more recently, through changes in management. However, establishment of conservation areas offer little protection against change from air pollution, and research has now shown that many "protected areas" are, in fact, being reduced in value through the impacts of air pollution[226].

Indeed, protected areas may be particularly at risk. Recent analysis within Europe has suggested that conservation areas will suffer a disproportionately greater risk of pollution damage, as measured by critical loads, than the environment as a whole[227]. National parks and other conservation areas have tended to be established on land that is less suitable for agriculture or other commercial uses[228], and thus often on acidic or base-poor soils, where effects of acidification are generally more acute.

■Ecosystem manipulation cannot offset all the ecological problems caused by air pollution, and can sometimes cause further disruption.
Ecosystem managers are left with few options for addressing problems from air pollution. Pollution control is a matter for governments and industry, and frequently for international diplomacy. Those charged with management of individual sites, or even with a single country's forests or freshwaters, have attempted to take steps to reduce the problem at the site of damage.

Options remains fairly limited. Some foresters have attempted to plant more pollution-resistant trees, but success has been limited and this approach offers few advantages to other wildlife species. The other main option, and the one implemented most widely in Europe, is to attempt to artificially reverse acidification by the addition of basic materials to an ecosystem, usually in the form of solid lime.

Liming of freshwaters has now been practised in parts of Scandinavia for well over a decade, and more recently liming of forest soils has also been attempted. The ecological impacts of lake liming has been studied in a series of research projects in Scandinavia and in the UK[229230]. It has been shown that many species recolonise following treatment[231232].

Fish species also often recover, and a study of 112 limed lakes in Sweden found that fish populations increased from an average of 3.2 species per lake before liming, to 4.0 after 2-4 years and 4.1 after 5-9 years[233]. Other studies found little evidence of increased diversity, but the return of sensitive species such as salmon and trout[234]. Post-liming growth increases have been measured particularly for perch, char and pike. Several invertebrate species and groups also return, including mayfly species[235]. On the other hand, groups that increased under conditions of acidification, including *Sphagnum* and the goldeneye (*Bucephala clangula*) and mallard (*Anas platyrhynhcos*)[236], have decreased.

However, there are also a number of potential or actual problems with liming, in terms of ecosystem disruption, long term changes in water chemistry and the risk of causing further damage by the shock of a sudden change in pH. Table 9 below outlines some advantages and disadvantages of liming in freshwater.

Table 9: Advantages and disadvantages of liming aquatic systems[237]

Advantages	Disadvantages
Recolonisation of species generally takes place.	Vegetation of limed wetlands is often considerably changed/damaged.
Species numbers and diversity increase in most cases.	Species new to the water may appear and occasionally influence natural food webs.
Normalisation of decomposition processes is likely to occur in most cases.	Precipitation of metals may sometimes exert a temporary stress to species.
Re-establishment of natural food webs seem generally to occur.	Algal blooms and mass development of plants may occasionally occur.
Enhanced fish production occurs in most cases.	Disturbance of bird breeding occur on a few occasions.
Re-establishment of functional groups such as shredders is common.	
Elimination of threatened species can often be prevented.	
Decrease or elimination of species favoured by acidification is usual.	

A similar mixture of benefits and problems occur in the case of liming forest soils.

The fundamental problem of liming, and of all other attempts to treat the site of pollution damage rather than the source of pollution, is that any gains are both partial and temporary, as long as pollution continues. Costs are borne by the receiver, rather than the emitter, of the pollution. Changes in financial circumstances, and in political will, can change the response.

There are already reportedly signs that the Swedish government, for example, is considering the reduction of its liming programme for economic reasons[238].

■**Air pollution is a significant, contributory factor in the global decline in biodiversity.**
To date, research suggests that air pollution has been involved in decline and extirpation of species, rather than in their extinction. This situation is likely to change in the future, for the following reasons:

- particularly susceptible groups in temperate regions will continue to decline until they become extinct, and for example this remains a real possibility for some lichens;

- pollution effects are already starting to be seen on a broader scale in some areas of the tropics, where both biodiversity and ecosystem fragility are greater.

This report began with a qualitative diagram of likely wildlife effects from the various air pollutants commonly found today. Below, in Table 10, a summary is given of the wildlife effects outlined above.

Table 10: Summary of biodiversity impacts from air pollution

Group	**Summary of effects**
Algae	Blue-green algae are particularly susceptible to a range of air pollutants, and some species are at risk in polluted areas.
Lichens	Probably the single group showing the strongest responses to pollution, both from dry deposited sulphur dioxide and from wet acid deposition. Many local and some national extirpations.
Bryophytes	Similarly highly sensitive to many air pollutants, particularly in the case of tree-living or bog mosses.
Fungi	Many mycorrhizal fungi decline in acidified environments.
Pteriodyophytes	Evidence for decline in some fern and many club moss species in polluted air.
Herbaceous flowering plants	Increasing body of evidence for decline, both through SO_2 pollution and on acidified soils.
Broadleaved trees	Many trees decline in polluted environments, due to the impacts of both air pollution and other stress factors: the *multiple stress* problem.
Conifer trees	As above.
Micro-organisms	Zooplankton decline in diversity in acidified waters, and soil micro-organisms decline in acid soils.
Soft-bodied invertebrates	Almost all lower invertebrates decline in acid waters. A decline in many species, such as earthworms, is also known in acid soils. Increasing evidence exists that molluscs and other species are directly or indirectly affected by air pollution on land.
Arthropods	Many crustaceans and insects decline in acid waters, although a minority of insect species thrive in the absence of competition. Fragmentary information suggests that many species are likely to decline on land due to air pollution

	although some, particularly aphids, thrive and increase in environments with a high SO_2 level.
Fish	Species show a range of responses to acidification, with some disappearing in slightly acid waters and others able to withstand even fairly severe acidification. Decline has occurred widely in Europe and North America.
Amphibians	Many species decline in acidified waters, primarily due to reproductive failure. A few resistant species thrive in the absence of competition.
Reptiles	No information has been found on reactions of reptiles to acidification or air pollution.
Birds	A minority of species decline due to food chain effects from losses, particularly in acidified waters, while other species have proved adaptable enough to cope with any changes. Others are apparently directly affected by SO_2.
Mammals	Despite much evidence for build-up of heavy metals and sulphur in mammals in polluted environments, the main effects noted for mammals come from food chain effects in species such as the otter and elk.

References for the various statements are given throughout the text.

6.Conclusions

■The only effective policy response to air pollution problems is to reduce pollution at source, through a cutback in demand, energy conservation measures, fuel-switching and technical pollution controls.

The biological impacts of pollution outlined above constitute a serious problem for biodiversity in many industrialised parts of the world. They are another, compelling, reason for reducing pollution at source. This needs to be achieved through an array of different strategies, including:

- reducing demand through energy conservation and social adaptations
- fuel-switching away from the most polluting sources
- technical pollution controls

At the moment, there are a number of worrying signs that governments are slipping in their commitments to previous agreements regarding pollution reduction, and are throwing up fresh obstacles in the way of further controls. Yet repeated public opinion polls show that people support pollution control. Firm guidance from existing internationall initiatives, including the Convention on Biological Diversity, could help focus governments' attention on addressing these issues at source.

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