PLANT–INSECT INTERACTIONS AND POLLUTION

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Summary

The majority of known insect species are herbivorous, therefore factors that disturb plant physiology have effects on insect fauna relying on plants. A substantial amount of literature indicates that insect herbivore abundance often increases when the host plant is subjected to some abiotic stress. Insect outbreaks have been observed in the surroundings of polluted industrial areas and along highways. Species feeding plant phloem or species that mine or bore in living plant tissues have been more successful on pollutant-exposed plants than chewing insect herbivores. Phloem-feeding aphids are good indicators of pollutant stress on many plant species. Sulfur dioxide (SO_2), oxides of nitrogen, fluorides, or mixtures of pollutants have often promoted aphid performance. SO_2 exposures have shown that response curve of aphids is bell-shaped, with a peak at an air concentration of 100 nL L^{-1} On the other hand, observations of aphid performance on ozone (O_3)-exposed plants have given very confusing results. Depending on the duration and concentration of O_3 exposure or the age of the exposed plants, aphid growth on the same plants can be decreased or increased compared with control plants grown in O_3-free air. Increasing carbon dioxide (CO_2) levels in the atmosphere increase the carbon–nitrogen ratio in plants, and this has resulted in reduced growth of the larvae

of chewing insects despite the fact that the consumption of nitrogen-defiant plant foliage and subsequent plant injury is increased. The effects of CO_2 on aphids and their natural enemies are still poorly known.

1. Introduction

Insects are the most diverse group of organisms to maintain biodiversity on earth. There are 900 000 currently known insect species, forming about 80% of the world's species. Furthermore, different estimates suggest that there are from 2 million to 30 million undescribed insect species. The diversity of insects is highest in the tropics, where the majority of undescribed species are known to be. Most of the unidentified species are small parasitoid wasps parasitizing in other insects. In an animal-like insect, which has a skeleton outside the body, the mechanics of support and growth are such that the animal is limited to a relatively small size. This is compensated for by rapid growth and an enormous number of individuals. Some termite colonies may have a population of over a million, and locust swarms can contain up to a billion individuals. Drastic changes in life conditions of herbivorous insects or the reduced defense of host plants may result in outbreaks of insects. On the other hand, the clearing of forest for agricultural land in the tropics may cause the loss of several insect species every day.

The majority of insects are herbivorous, and high numbers of species in a food web are dependent on autotrophic plants. Consequently, factors that disturb plant physiology have effects on insect fauna relying on plants. A substantial amount of literature indicates that insect herbivore abundance often increases when the host plant is subjected to some abiotic stress. Plant stress-induced alteration in insect herbivores is a result of variation in both plant responses to stress and insect sensitivity to changes in stressed plants. Most air pollutants, such as ozone, fluorides, and heavy metals (see *Environmental Pollution and Function of Plant Leaves*), may disturb the physiology of plants, and in high concentrations they are phytotoxic. Sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) formed in burning processes can also be phytotoxic, but they may also act as fertilizers, when they are source of sulfur and nitrogen for nutrient-deficient plants.

The most important (and globally most evenly distributed) air pollutant released by fossil energy production is carbon dioxide (CO_2). The trend of atmospheric concentrations has increased continuously since records began, and the rates of the late twentieth century are expected to double during the twenty-first century. For plants CO_2 is a source of carbon for photosynthesis. CO_2 has a fertilizing effect on plant growth, since the current atmospheric concentration (about 360 $\mu L\ L^{-1}$) restricts plant photosynthesis. In a higher CO_2 atmosphere plants can allocate more carbon for growth and storage. However nutrients, especially nitrogen, might become growth-limiting in high CO_2 conditions. An increased carbon–nitrogen ratio in plant tissues is one of the most distinctive results of an elevated CO_2 atmosphere for plants. A high tropospheric CO_2 concentration also promotes stratospheric ozone loss, which results in elevated UV-B radiation. Both elevated temperatures and enhanced UV-B radiation are the results of increased levels of gaseous pollutants in the atmosphere. These factors can have significant effects on plant-feeding insects. The type of pollutant determines whether the effect of that pollutant is expected locally or on a wider scale. While concentrations of CO_2 and UV-B exposure are rising globally, local concentrations of oxides of nitrogen and sulfur in Western Europe are declining, although they are still rising in other industrialized areas of the world.

One of the first observations of insect outbreaks on plants exposed to air pollution was an outbreak of the spruce-needle-mining moth, *Epinotia tedella,* in 1831 in a smoke-damaged young spruce stand in Germany. Since then there have been numerous reports of insect damage in forests that have been exposed to SO_2, oxides of nitrogen, fluorides, or heavy metals in the vicinity of industrial areas. Experimental exposures of plants together with insects to pollutants have confirmed that these outbreaks are partly a result of disturbances of the plant capacity for defense against herbivores. Disturbances in the function of ecosystems in damaged areas can also affect the capacity of predators and parasitoids to control the populations of herbivorous insects and mites. Some recent generalizations of plant stress–herbivore responses have been over-simplistic, because the same changes in the plant do not result in uniform responses from all insect herbivores. Knowledge of the food consumption habits of insects is crucial for the evaluation of the response of certain species to pollution stress. Only on very few occasions can the pollution load be so high that it is directly toxic to insects. Accumulating heavy metals and hydrogen fluoride can be directly toxic to herbivorous insects. However, on most occasions the effects on plant-feeding insects are mediated via alterations in the host plants' nutritional quality or its disturbed defenses.

What is known as "industrial melanism," the spread of dark and black insect forms, is a well-known phenomenon in areas subjected to heavy air pollution, mainly SO_2. Melanism has applications in practical bioindication. The phenomenon is expected to be an indication of the increased susceptibility to predation by birds of white forms of insects resting on dark tree trunks. This increased predation affects only adult insects, since at the larval stage many moth species feed on green foliage. However, the increased proportions of melanic forms indicate the disappearance of light-colored epiphytic lichens on tree trunks, rather than the degree of physiological response of trees to pollution. Thus industrial melanism does not directly indicate how herbivorous insects respond to pollution-stressed host plants, since adult moths do not feed on lichens. Also some predatory coccinellid beetles frequently have darker forms at polluted sites. Possibly they are also adapted to the darker color of tree trunks. This article mainly reviews insect responses on plants exposed to air pollutants. Herbivorous mites that feed on plants have a very similar behavior to insects, since they are arthropods morphologically related to insects. Therefore, observations of mite behavior on pollutant-stressed plants are included. The article concludes with a short description of air pollution interaction with plant pathogens. Pathogens inducing plant diseases are also plant parasites whose behavior can be altered on plants exposed to air pollution. In addition to this, the spread of plant pathogens is often related to insects, and thus any disturbance of the insect–host plant interaction may affect the intensity of plant pathogen infections.

2. Ecosystem and Host Plant Level Disturbances in Polluted Areas

When industrial plants or other sources of air pollution are established in areas of clean air, the development of damaged vegetation zones is quickly observed. The damage is caused partly by direct pollutant effects on plant foliage, and partly via roots, when the pollution load (for example, of heavy metals) disturbs the normal function of plant roots. All the vegetation in the immediate vicinity may die if phytotoxic emissions are very high. The *first vegetation zone* consists of badly damaged, but still surviving, plants. The damage to dying trees is often associated with the appearance of cambium-feeding bark beetles. Continuing development of pollution damage may kill these plants, if pollution is not controlled in the future. The *second vegetation zone* is composed of plants that are mainly visibly healthy, but have a disturbed physiology because of pollution stress. In this vegetation zone the numbers of phloem-feeding insects and mining insects are often increased, and their damage to plant foliage could be mixed with pollution symptoms. The *third vegetation zone* is normal healthy vegetation, associated with a background level of air pollutants. Insect outbreaks are only occasional in this zone.

The zonation of insect damage in forests around a pollution source has been observed in several studies. An example of the intensity of conifer needle damage caused by needle-mining moths in a pollution gradient around a pulp mill in central Finland is shown in Figure 1. In the closest vicinity (< 1 km from the pulp mill) trees are heavily damaged by SO_2 pollution, and the numbers of needle miners are lower than in a clean background area. In the second plant damage zone (1–3 km from the pulp mill) moth densities are four to five times higher than in a clean background area. Moth densities decline gradually, reaching background level 8 –10 km from the pollution source.

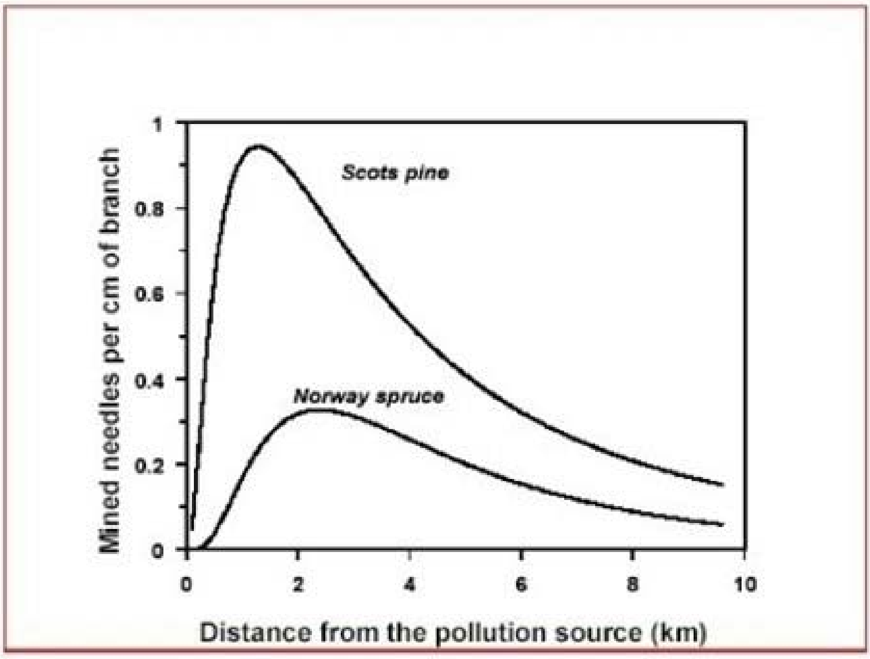

Figure 1. An example of densities in Scots pine and Norway spruce needles showing damage by larvae of needle mining moths in a pollution gradient around a pulp mill

In a plant community resistance to air pollutants is variable. Some plant species or their provenances are more sensitive and they vanish, whereas others are more resistant and may become more dominant. Also the physiological disturbance caused by air pollution to plants that directly reduces their capacity to defend themselves against herbivorous insects affects the ability of plants to compete, and the structure of communities of plants changes. In boreal forests dwarf shrubs that normally dominate the understory of conifer forest are replaced with hay and broad-leaved bushes in polluted areas. These types of disturbances in the function of ecosystems in damaged areas can also affect the capacity of predators and parasitoids to control herbivorous insect populations. Table 1 describes some of the potential interactions between host plant and insect herbivore involved in pollution-induced alterations in polluted environments. The host plant environment is taken to be the whole ecosystem around the target plant. An alteration in volatile organic compound (VOC) emissions from stressed plants might affect the orientation behavior of herbivorous insects that are specialized on a few host plant species. Such insects use specific plant odors to localize the proper host plant species.

Host plant properties		**Insect responses**
A. Host environment		
Dying trees change density and diversity of vegetation resulting in changes in light environment and microclimate.	⇒	Altered host finding, altered efficiency of natural enemies. Alterations in growth rate of herbivores. Disturbances in overwintering due to altered vegetation cover on soil.
B. Host surface properties		
Surface colour and morphology changed due to pollution stress and accumulated pollutant particles.	⇒	Host finding, feeding and oviposition of herbivores is disturbed. Exposure to natural enemies may be changed.
C. Host nutritional value		
Physiological disturbances affect water balance, and levels of sugars and amino acids. Accumulation of pollutants in plant tissues.	⇒	Acceptance, consumption, and growth rate are increased or decreased. Mortality of herbivores may increase. Acceptability to natural enemies may change.
D. Host defense		
Changes in toughness and production of secondary metabolites. Herbivore-induced production of signal chemicals may be disturbed.	⇒	Acceptance, consumption, and growth rate are increased or decreased. Mortality of herbivores may increase. Host finding of natural enemies may be reduced.

Table 1. Potential alterations in host trees and in their environment under pollution stress, and the related response in the function of insects, that may result in increased susceptibility of the host to insect attack

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Biographical Sketch

Dr. J.K. Holopainen was born in 1953 in Kuopio, Finland. He finished his schooling in Kuopio and has studied agricultural and forest entomology, plant pathology, and horticulture at the University of Helsinki. He completed a M.Sc. thesis in Agricultural and Forest Sciences in 1983 concerning natural enemies of cabbage root flies, and a Licentiate thesis concerning predatory ground beetles as natural enemies of pest insects in 1987. He received a Ph.D. in 1990 from the University of Kuopio. His Ph.D. thesis concerned the growth disturbances of Scots pine and the role of *Lygus* bugs as inducers of deformed growth. Since then he has held several research positions in the Academy of Finland, in the University of Kuopio and at Agrifood Research Finland. Currently he is Academy Research Fellow studying air pollution and global change effects on the interactions between plants, herbivores, and their natural enemies. His scientific work has been mainly in the fields of applied entomology and applied ecology, including several publications about air pollution effects on insects and the secondary chemistry of host plants.