# 15 Reducing Herbivory Using Insecticides

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## 15.1 Summary

Insecticides are a vital tool for manipulating insect herbivory, but limitations of the method can result in erroneous conclusions about the relationships among herbivores, plant population dynamics, plant community composition and ecosystem processes. In particular, direct effects of insecticide applications on plants or ecosystem processes, effects on non-target organisms and indirect effects via plant competition may cause ecologists to misjudge the importance of insect herbivores in ecosystems. A survey of published studies showed that most investigators considered some of the more likely artifacts, but few were thorough in testing for such artifacts. Data on insect damage and insect abundance are particularly useful for establishing a causative role for insect herbivore suppression in insecticide effects.

## 15.2 Basic Concepts

Insecticides are an important tool for studying the role of insect herbivores in terrestrial ecosystems. Because insect herbivores are typically small and mobile, physically excluding them from replicated experimental areas in the field is difficult. The main methods of physical exclusion of aboveground insect herbivores (cages, netting and screens) also exclude larger herbivores, such as mammals, which can make it difficult to assess the role of insect herbivores independently (but see Schmitz, Chap. 14, this Vol.). In addition, any method of physical exclusion may change microclimate and light levels. Physical exclusion of belowground herbivores in field experiments is more problematic. So long as ecologists are careful about the inferences they draw from insecticide experiments and are mindful of the limitations of the method, chemical exclusion of insects remains one of the most valuable methods to investigate the role of insects in terrestrial ecosystems.

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## 15.3 Using Insecticides to Infer the Role of Herbivores

Applications of insecticides can reveal the role of insect herbivores in an unmanipulated ecosystem by examination of the assembly, dynamics, structure and functioning of an ecosystem with insect herbivores absent or present at low densities. Still, there are some inherent difficulties in determining the relationships among components in an intact complex system by examining the same system with a single component removed. These include multiple potential paths of causation as well as emergent properties or higher-order interactions in complex systems that may be difficult or impossible to infer by analyzing the behaviour of the system with some components missing (Billick and Case 1994). There are, however, some general principles that apply to interpretation of insecticide experiments that have a tradition in the ecological literature and that have a solid conceptual basis.

Increases in peak standing crop with insecticide applications are usually equated with an effect of insect herbivores on net productivity in the unmanipulated system (Fig. 15.1). In the short term, such increases give insight into the magnitude of the effect of insect herbivory on net productivity within the existing suite of plant species present at the start of the study. The magnitude of the response of net plant productivity to insect exclusion with insecticides

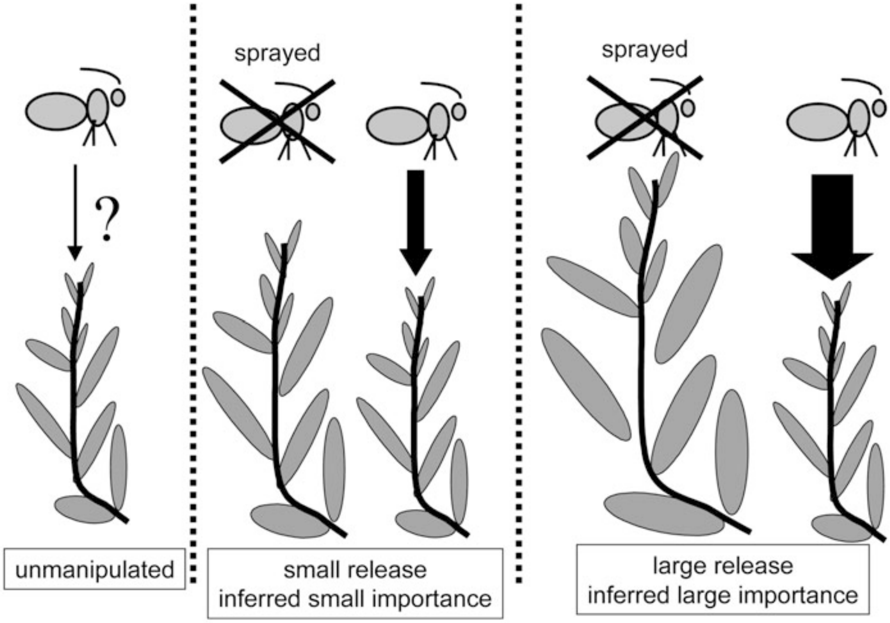

**Fig. 15.1.** Ecologists infer the importance of herbivores in an unmanipulated ecosystem by measuring the response to herbivore removal

should be positively related to the magnitude of net productivity reduction due to insect herbivores in the unmanipulated ecosystem.

If relative impacts of herbivores on plants differ (see below) and insect suppressions continue long enough for plant species composition to respond, changes in productivity may also reflect the indirect effects insect herbivores have on net productivity by favouring or excluding plant species that differ in attributes such as nutrient use efficiency (Crawley 1997; Wardle 2002). Changes in plant species composition with insecticide application are often used to infer relative impacts of insect herbivores on different groups or species of plants when insects are present (Fig. 15.2). Depending on the study, this may include investigations into the relative impact of insect herbivores on different functional groups of plants (i.e. grasses vs. forbs) or different species of plants. Stronger responses of plant mortality, growth and/or reproduction to suppression of insect herbivores (i.e. releases) are equated with relatively larger negative impacts of insect herbivores on plants in the absence of sprays. Decreases in plant performance with insect herbivore suppression are attrib-

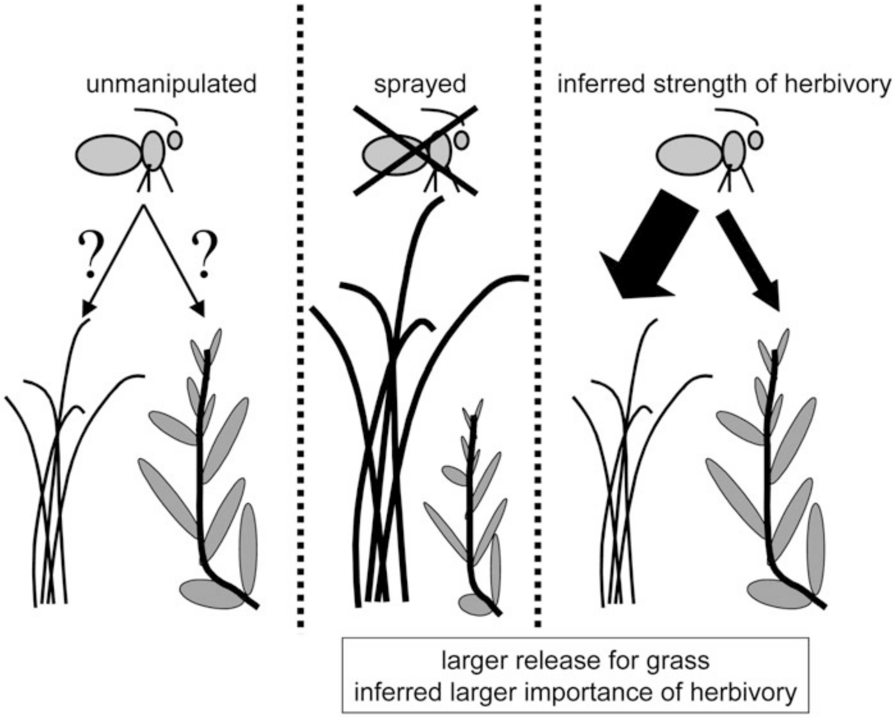

**Fig. 15.2.** Ecologists infer the relative impact of herbivores on different species of plants in an unmanipulated ecosystem by measuring their responses to herbivore removal. In the *middle section*, the large increase in the grass when herbivores are removed suggests that herbivores have a larger impact on the grass in the unmanipulated system

uted to negative indirect effects of herbivore removal via releases of competitors that are larger than the direct positive effects on the plant itself. Changes in plant growth and survival often are used to infer impacts of insect herbivores on plant population dynamics. If insect herbivores have similar influences on different groups or species of plants, whole community removals of insect herbivores will not lead to changes in plant community composition, which may result in the erroneous conclusion that they do not have strong interactions with plants in the unmanipulated community, even when the effects on individual groups or plants are large (Fig. 15.3). In such communities, however, there may be a strong response of peak standing crop or net plant productivity to insect exclusion. Indeed, there is an inverse relationship in grasslands between the strength of the responses of standing crop and species composition to exclusion of grazing mammals, with composition responses dominating at higher productivity (Chase et al. 2000).

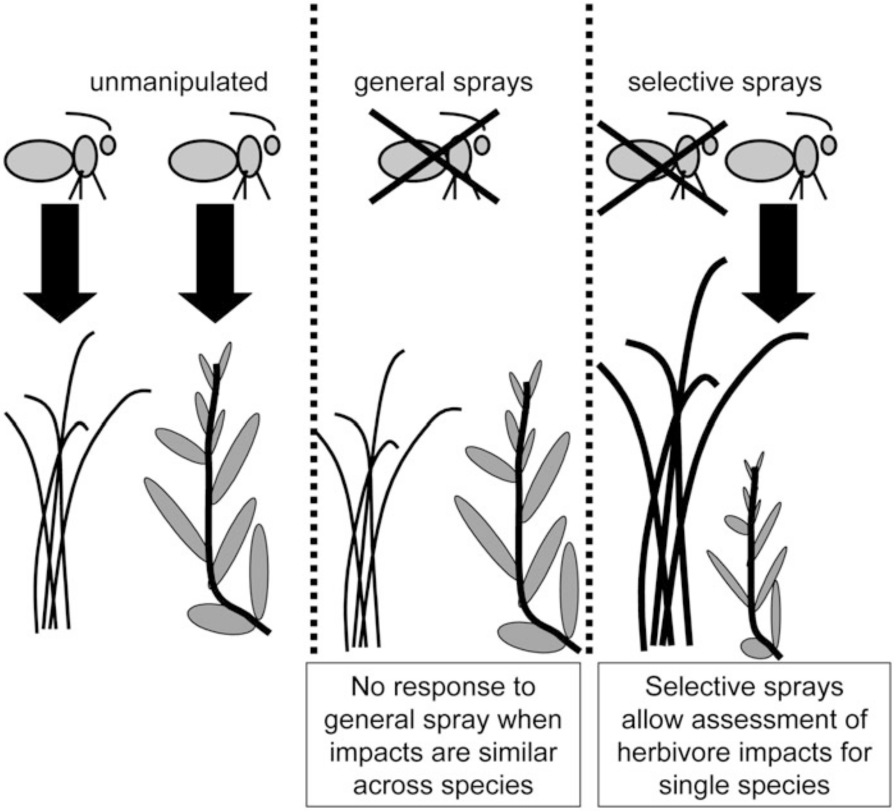

**Fig. 15.3.** Insecticide applications to whole communities versus individual species of plants may give different insights into the role of herbivores

More selective removals of insect herbivores from single species or groups of plants within an ecosystem may give a different picture from whole-system manipulations of insect herbivores (Siemann and Rogers 2003). The response of a single species of plant to whole community insect suppressions is proportional to the difference between its herbivore load and the herbivore loads of other plants in the community, while its response is proportional to the absolute herbivore loads of the other plants in the community if a single plant is grown in a herbivore-free state (Fig. 15.3). The use of methods other than general plot-wide applications has the potential to expand the inferences ecologists can draw from studies using insecticides to exclude insect herbivores.

## 15.4 Ghost of Herbivory Past

Herbivore suppression experiments may miss the effects of herbivory if a herbivore is able to reduce a host plant to low densities and/or restrict its distribution ('Ghost of Herbivory Past', Carson and Root 2000). For example, a beetle introduced to control St. John's Wort (*Hypericum perforatum*) drove the formerly abundant plant to shaded refugia where the plants suffered less attack (Harper 1977). A typical insect exclusion experiment in which plots are located independent of *Hypericum*'s distribution and randomly assigned to insecticide or control treatments could lead to the faulty conclusion that insect herbivores are not important in determining local plant community composition. Similar effects of herbivores on the distribution of their host plants have been shown for other species (e.g. Louda and Rodman 1996). In general, if experiments are short term or have plots containing few individuals of herbivore-susceptible plants at the start of the experiment, even large effects of herbivores on plant growth, survival and reproduction may be statistically undetectable.

To test how the number of replicates and the duration of a herbivore exclusion experiment might influence the likelihood of detecting a significant herbivore effect, we performed computer simulations of herbivore exclusion experiments where insecticide and control treatments were randomly allocated to field plots. We calibrated the model with demographic data on *Solidago canadensis* (formerly *S. altissima*; mortality and rhizome production) from long-term experiments with insect herbivore manipulations (Cain et al. 1991; Carson and Root 2000). We varied four starting conditions (*Solidago* density, strength of release from herbivory, number of experimental replicates, duration of experiment, Fig. 15.4A). At high densities of *Solidago* such as occur in the northeast United States (up to 20 plants m$^{-2}$, Carson and Root 2000), effects of herbivore suppression would be detected even in short-term experiments with modest decreases in mortality and increases in rhizome

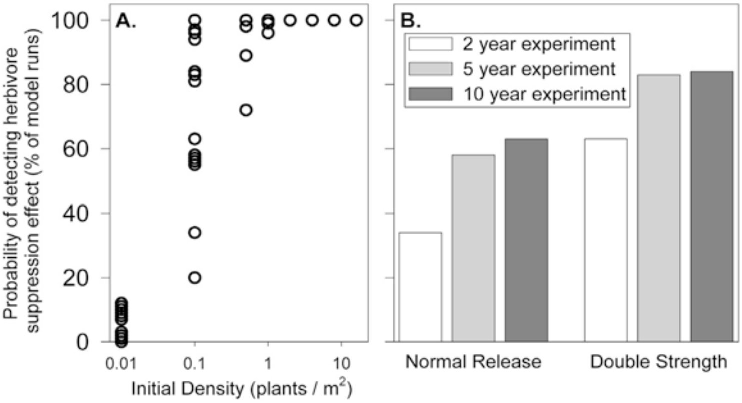

**Fig. 15.4.** Simulated experimental herbivore removal experiments. **A** Probability of detecting a significant effect of herbivores on plant population dynamics depended on the strength of release, number of experimental replicates and duration of study. **B** When host plants are at low densities (0.1 plants $m^{-2}$), a five-replicate study would often miss strong responses of individual plants

production with herbivore suppression (Fig. 15.4A). However, at the densities at which *S. canadensis* occurs in prairies in the midwestern United States (approximately 0.1 plants $m^{-2}$), even a 10-year, five-replicate field experiment with 5×5-m plots would miss the response of herbivore suppression 40 % of the time (Fig. 15.4B). The sensitivity of the model outcome to initial density (Fig. 15.4A) suggests that typical insect herbivore exclusion experiments may be appropriate only for detecting responses of plant species that occur at high densities (i.e. dominant taxa) unless experiments are run with many replicates for many years. If the effect of herbivores on a rare plant is the object of investigation, it may be advisable to add plants to plots (i.e. phytometers) or to locate plots in areas where the plant is present at higher densities.

## 15.5 Artifacts of Method May Masquerade as Release from Herbivory

### 15.5.1 What Types of Artifacts Are a Concern?

Because insecticides are deposited on plants and are toxic to insects, the primary way that insecticide applications are expected to alter ecosystems is through reductions in the population densities and feeding activities of herbivorous insects. However, insecticides may also have direct and indirect effects on other components of ecosystems and may therefore change plant

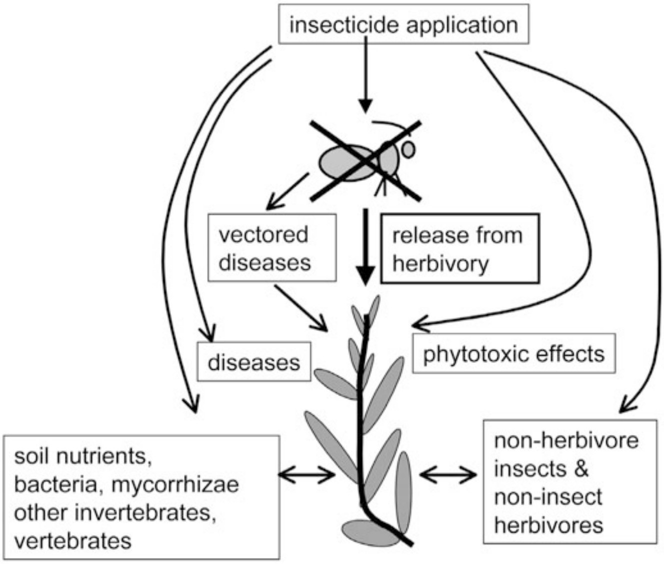

**Fig. 15.5.** Insecticide applications may affect ecosystems by a number of mechanisms

species composition and/or ecosystem functioning (Fig. 15.5). For instance, some insecticides may directly change the plant community because they are toxic to plants at some application rates and increase their mortality, decrease their growth or inhibit seed germination. Insecticides may also be toxic to or may change the activity of other components of the ecosystem such as non-herbivorous insects, non-insect herbivores, bacteria or fungi. Depending on the chemical composition of an insecticide and the inactive ingredients in the formulation, insecticide application may provide limiting nutrients. These side effects of insecticides are of concern, because they may make it difficult to attribute observed differences in ecosystem functioning between sprayed and unsprayed plots to the action of insect herbivores. Investigators can maximize their insights into the role of insect herbivores in terrestrial ecosystems by collecting appropriate data, performing additional studies if possible and considering alternative explanations.

## 15.5.2 Overview of Published Studies

We searched the literature for ecological studies in which insecticides were used in order to examine the relationship between insect herbivores and plant fitness, population dynamics, community structure or ecosystem processes. We generated an initial set of articles by searching for the words 'insecticide', 'insecticides', 'insecticidal' and 'exclusion' in the abstracts of articles in the following journals: *American Journal of Botany* (1914–Jan 2002), *American Nat-*

*uralist* (1867–Sept 2002), *American Midland Naturalist* (1909–July 2002), *Biotropica* (1969–June 2002), *Bulletin of the Torrey Botanical Club* (1870–1996), *Conservation Biology* (1987–Oct 2002), *Ecological Applications* (1991–Aug 2002), *Ecological Monographs* (1931–Aug 2002), *Ecological Entomology* (1991–Oct 2002), *Ecology* (1920–Sept 2002), *Environmental Entomology* (1991–Feb 2002), *Functional Ecology* (1987–Oct 2002), *Journal of Applied Ecology* (1964–Aug 2002), *Journal of Ecology* (1913–Oct 2002), *Journal of Tropical Ecology* (1985–Sept 2002), *Journal of Animal Ecology* (1932–Sept 2002), *Journal of the Torrey Botanical Society* (1997–Sept 2002), *Oecologia* (1991–Sept 2002), *Oikos* (1988–Aug 2002), *Plant Ecology* (1997–July 2002), *Vegetatio* (1991–1996). We read these articles and kept those that employed insecticide treatments in order to investigate the role of insects in determining ecosystem functioning, plant community composition or diversity or plant population dynamics. In total this represented 66 articles. This is not an exhaustive search of the literature for ecological studies that employed insecticides. Rather, it represents a body of articles that allows us to investigate the inferences ecologists draw in such studies and their consideration of potential methodological artifacts.

We classified each article with respect to the following criteria (see Appendix): (1) What response variable was the focus of the study? (2) What type of insecticide was used? (3) Were insect damage or insect abundance quantified? (4) Were toxic effects of insecticide on germination, plant survival or plant growth considered? (5) Was greater toxicity to higher trophic levels of insects considered? (6) Was toxicity to detritivorous insects, soil microbes or mycorrhizae considered? (7) Were fertilization effects of insecticide considered?

### 15.5.3 Quantification of Herbivore Damage

Additional data can clarify whether a reduction in insect herbivory is the mechanism underlying a plant or ecosystem response to insecticide application. In particular, it is critical to collect data on insect herbivore abundance and insect damage to plants in experimental units where insecticides have been applied and compare these units to those to which insecticides have not been applied. If a species or group of plants performs better in plots where insecticide has been applied, insect damage should be lower on insecticide-treated plants if reductions in insect herbivory are responsible. These types of data may be most appropriate for chewing or mining insects where damage can be carefully quantified. A large response of plants to insecticide application without documented decreases in insect damage makes it difficult to have confidence that reduced insect herbivory is the cause. On the other hand, collecting data on the abundance of insect herbivores can be useful for some groups, especially Hemipterans, which often can be easily counted on a plant but for which the damage cannot be as easily quantified independent of their abundance or plant vigour. As for insect damage data, insect herbivore abundance, due to changes in activity or in situ population densities, should be lower on insecticide-treated plants than on untreated plants if insect herbivores are driving plant responses to insecticide application. Of the studies we reviewed, 55 and 41 % of studies collected data on herbivore damage and abundance, respectively.

### 15.5.4 Phytotoxic Effects

Responses of plants, plant communities and ecosystems to insecticide applications may reflect toxic effects of insecticides on plants (i.e. phytotoxic effects). In particular, plants that decrease in abundance or vigour with insecticide applications may be more sensitive to toxic effects and plants that increase with applications may be less sensitive. In this case, an investigator could attribute differential responses of plants to insecticides to differences in the strengths of their releases from herbivory, when they may actually indicate differences in their susceptibility to phytotoxic effects of the insecticide sprays. In the extreme, phytotoxic effects could depress overall ecosystem productivity, but it is unlikely that an insecticide licenced for application in agricultural or horticultural settings would be that toxic to plants at recommended application rates. It is more likely that variations in the magnitude of toxic effects on different plant species may cause changes in species composition.

Phytotoxic effects could include suppression of germination or decreases in survival, growth and/or reproduction. For insecticides registered in the United States, the current requirement for labels is that they report phytotoxic effects if 'more than 25 percent of terrestrial plants show adverse effects on plant life cycle functions and growth such as germination, emergence, plant vigour, reproduction and yields when tested at the maximum label application rate or less' (Environmental Protection Agency 40 CFR Part 159, Reporting Requirements For Risk/Benefit Information). In the European Union, regulations under consideration call for reporting of phytotoxicity data when there is 'more than 50 % effect for one or more species at the maximum application rate' (Guidance Document on Terrestrial Ecotoxicology Under Council Directive 91/414/EEC, European Commission on Health and Consumer Protection). Toxic effects are usually for the product applied alone, with recommendations for applying products in combination based on chemical characteristics of active ingredients. The literature is one resource for ecologists to address the issue of phytotoxic effects.

Another way to disentangle phytotoxic effects and releases from herbivory is to conduct experimental toxicity trials in controlled conditions. For experiments with factorial treatments (such as a fungicide treatment), phytotoxicity trials should also be factorial in case sprays are more toxic in combination.

For instance, in one study pesticide sprays reduced seed germination in combination even though neither had a detectable effect when applied alone (Gange et al. 1992). A rigorous way to conduct these experiments is with a gradient of application rates that include concentrations less than and greater than the field application rates (i.e. perform a dose response experiment).

To test for phytotoxic effects on germination, seeds could be treated with the insecticides and germination rates measured with or without insecticide application. Differential suppression or stimulation of germination among plant species could potentially drive changes in species composition. This particular type of artifact would be a concern in studies at the community or ecosystem level that are of sufficient duration to have recruitment of new plants from seed. Twenty-eight percent of such studies we reviewed considered effects of their insecticide applications on seed germination rates. We did not find any examples of experiments that tested the effects of insecticide sprays on germination in field conditions.

To test for phytotoxic effects on survival, growth and reproduction, plants should be treated with insecticide in conditions of constant, ideally low, insect herbivory. This may be accomplished by growing plants in controlled laboratory or greenhouse conditions where herbivory is extremely low independent of insecticide applications. If plants are grown in pots where roots can be quantitatively recovered, measuring root mass in addition to aboveground mass is desirable in order to test for phytotoxic effects on root mass as well as possible changes in the relative allocation of growth above ground vs. below ground in response to sprays. This may be particularly valuable if field experiments only measure aboveground biomass or growth. In studies at the community or ecosystem level, phytotoxic effects on survival, growth or reproduction could obscure the relationship between a plant's response to insecticide applications and the relative importance of herbivory for that plant species. In studies of the responses of a single species to insecticide application, phytotoxic effects could lead to an underestimation of the release from herbivory, with the indirect positive effect via reduced insect herbivory being obscured by a direct negative effect. Of the studies we reviewed, 58 % of the studies of plant communities, 29 % of the studies of ecosystem processes and 44 % of the studies of individual plant responses considered toxic effects of insecticides on plant growth, survival or reproduction. Only 52 % of these studies conducted experimental tests of their insecticide applications on the species of plants in their studies or referenced literature for the species they studied. The rest cited toxicity data for other species of plants, typically agricultural crops. Many ecologists suppress insects throughout the growing season, resulting in more applications per year than the experiments they reference.

Overall, ecologists have given insufficient attention to the possible role of phytotoxic effects in their studies. This is not to say that they are likely to have compromised many studies, but rather that greater attention to this possibility would strengthen the causal link from insecticide applications to insect herbivore exclusion to plant and ecosystem responses. In particular, we would suggest caution for studies in which application rates or frequencies are greater than those recommended on the product label and for studies of plants for which no recommendation for closely related species is given on the product label.

### 15.5.5 Insecticides May Be Toxic to Several Groups of Insects

Insecticides may change plant composition or productivity by changing the abundance or activities of insects and non-insect arthropods that are not herbivores, such as pollinators, predators, parasitoids and detritivores. Some relevant data on toxicity to pollinators is readily available because insecticides list their toxicity to honeybees (*Apis mellifera*) on their label in Australia, the United States and in most European countries. Still, this may not predict lethal affects on other pollinators that differ in behaviour, physiology or size (Johansen 1972) and does not predict sublethal effects such as lower visitation rates (NRCC 1981). There is little evidence that plant populations or communities are pollinator limited, but reduced pollinator activity may impact the reproductive output of individual plants.

Differences in the susceptibility of insect herbivores and higher trophic levels (predators and parasitoids) to insecticide applications and variable rates of recolonization or population regrowth following applications can obscure the path from insecticide application to plant responses. In the extreme, insecticides may increase insect herbivore abundance if they are more toxic to predators or parasitoids than to insect herbivores (Spencer and Norman 1952). Of the studies we reviewed, 36 % discussed the relative toxicity of their insecticide treatments to herbivores vs. predators or parasitoids. Data on toxicity to higher trophic levels is rarely on a product label, but this information can be found in the literature for many insecticides (Coats et al. 1979 is a good example). Recently adopted guidance documents in the European Union recommend reporting of toxic effects on a standard parasitoid and predator arthropod species [*Aphidius rhopalosiphi* (Hymenoptera, Braconidae) and *Typhlodromus pyri* (Acarina: Phytoseiidae)], but unfortunately no insect predator is tested. Nevertheless, it is not just toxicity per se that is important for insecticide effects on higher trophic levels, but also the level of exposure. A substance that is potentially toxic might not reduce the population size of a predator and parasitoid when it is present only in minute quantities in living herbivores and is not taken up directly from the plant. Conversely, even a low level of toxicity might have great effects on higher trophic levels when exposure is high. Data on the relative toxicity of insecticides to herbivores vs. predators and parasitoids will assist ecologists in choosing an insecticide that is highly toxic to the herbivores they wish to control while simultaneously limiting experimental artifacts mediated through changes in other insect groups.

### 15.5.6 Effects of Insecticides on Non-Arthropods

Insecticides may alter the feeding choices of non-arthropod herbivores. Some pesticides, such as nicotine (insecticide), thiram (fungicide) and ziram (fungicide), are sold to discourage mammal browsing. DDT has been used as both an insecticide and a rodenticide. Some insecticides are marketed to repel (Proxpur) or kill (Fenthion) birds . However, the effect of most insecticides on the palatability of plants to non-arthropod herbivores is unknown. Thus, changes in non-arthropod activity are a possible artifact of insecticide applications in ecological studies. One way to limit such artifacts is to avoid insecticides that are known repellents or that are known to be extremely lethal to non-arthropods. Vertebrate feeding may influence insect herbivores by stimulating plant regrowth and increasing palatability (Du Toit et al. 1990; Bailey and Whitham 2002) or may decrease palatability by inducing defence production (Young and Okello 1998; Shimazaki and Miyashita 2002). In some cases, the defence compounds produced in response to vertebrate browsing may attract specialist insect herbivores (Martinsen et al. 1998). Changes in vertebrate feeding rates might reflect a direct effect of insecticides on vertebrate feeding activity or they may reflect changes in vertebrate feeding in response to reduced insect herbivory. For ecosystems where mammal herbivory is less important, these concerns may not be applicable. It is advisable to collect data on feeding rates of non-arthropod herbivores if possible to quantify their contribution to changes in plants or ecosystem processes.

Insecticides may also have effects on the survival and feeding activity of slugs and snails which may often be important herbivores (Crawley 1997). Some compounds have both molluscicidal and insecticidal activity (e.g. bendiocarb, methiocarb, Azinphos-methyl) and caution should be used in interpreting results when such compounds are used. However, since they belong to two widely used classes of insecticides (carbamates, organophosphates) changes in mollusc feeding are a potential issue for many studies.

### 15.5.7 Effects of Insecticides on Soil Organisms

Insecticides may be toxic to soil organisms that are critical for soil nutrient cycling or above-/belowground interactions. One group of bacteria that are a particular concern, with regard to producing spurious effects of insecticides, are those responsible for nitrogen transformations. In one study of the effects of 54 pesticides on denitrification and nitrification in the soil, 6 significantly stimulated denitrification, 8 significantly inhibited denitrification and 19 significantly reduced nitrification (Pell et al. 1998). There is a potential for such effects to masquerade as effects of insect herbivores on nutrient cycling via changes in their host plants. Since these same changes in soil nutrients may themselves change plant growth and survival, disentangling the chain of cause and effect may be difficult. Of the studies we reviewed, 22 % considered effects of insecticide application on the soil biota. Currently, there is no requirement for effects on soil organisms or soil nutrient cycling to appear on product labels so the main source of such information is the scientific literature. Recently adopted EU guidance documents recommend testing of pesticides for toxic effects on earthworms, standard soil arthropods (collembolans or mites) and rates of litter decomposition, soil nitrification and carbon mineralization (Guidance Document on Terrestrial Ecotoxicology Under Council Directive 91/414/EEC, European Commission on Health and Consumer Protection). Consideration of effects would strengthen all studies of insect herbivores, but it is especially important in studies on belowground herbivores in which insecticide is soaked into the soil or incorporated into the soil at the beginning of the study.

Some insecticides, especially those in the carbamate and organophosphate classes, are also nematicides. In studies that use insecticides that are also nematicides, there is the potential to overestimate the importance of insect herbivory because observed releases reflect both insect and nematode impacts. Three insecticides used in the studies we reviewed are also registered as nematicides: aldicarb, carbofuran and isazophos. In one study using aldicarb the effect of insecticide application is attributed entirely to insect suppression (Norris 1997). In all the other studies using these compounds, effects of insecticide application on plants are more properly ascribed to the combined effect of belowground insect herbivore and nematode suppression (all of the carbofuran and isazophos studies). More generally, because interactions in the soil food web are important for ecosystem processes but are largely unexplored (Wardle 2002), it is difficult to foresee how much the measured response variables such as plant biomass or plant species composition are influenced by alterations in the soil food web. For aboveground manipulations, it is possible to reduce the effects on the soil food web by minimizing the amount of insecticide that enters the soil.

### 15.5.8 Nutrient Inputs May Facilitate Plant Growth

Many insecticides may contain significant concentrations of limiting nutrients (Table 15.1). In particular, carbamates, organophosphates and pyrethroids often contain significant concentrations of nitrogen, and organophosphates always contain phosphorus. For some classes of insecticides, every compound that has been used in ecological studies is free of nitrogen and phosphorus (chlorinated hydrocarbons, flavonoids and organochlorines). The only other

**Table 15.1.** Properties of insecticides used in surveyed ecological studies. Number of times used represents the number of papers in our literature survey that used the chemical. Percentages of nitrogen and phosphorus are percent by weight of active ingredient. Amounts of nitrogen (*N amt*) and phosphorus (*P amt*) (in mg $m^{-2}$ $year^{-1}$) are at the maximum recommended rate or the maximum rate used in a paper we reviewed

| Chemical | Class | No. of times used | N (%) | P (%) | N amt | P amt |
|---|---|---|---|---|---|---|
| Aldicarb | Carbamate | 1 | 14.73 | 0.00 | 29.60 | 0.00 |
| Carbaryl | Carbamate | 7 | 6.96 | 0.00 | 22.28 | 0.00 |
| Carbofuran | Carbamate | 4 | 6.33 | 0.00 | 12.66 | 0.00 |
| Endosulfan | Chlorinated hydrocarbon | 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| Rotenone | Flavonoid | 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| Aldrin | Organochlorine | 2 | 0.00 | 0.00 | 0.00 | 0.00 |
| Chlordane | Organochlorine | 5 | 0.00 | 0.00 | 0.00 | 0.00 |
| DDT | Organochlorine | 2 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lindane | Organochlorine | 2 | 0.00 | 0.00 | 0.00 | 0.00 |
| Acephate | Organophosphate | 1 | 7.65 | 16.92 | 10.19 | 22.53 |
| Azinphos-methyl | Organophosphate | 2 | 13.24 | 9.76 | 27.41 | 20.21 |
| Chlorpyrifos | Organophosphate | 9 | 3.99 | 8.84 | 3.20 | 7.07 |
| Diazinon | Organophosphate | 3 | 9.21 | 10.18 | 14.73 | 16.29 |
| Dimethoate | Organophosphate | 7 | 6.11 | 13.52 | 40.32 | 89.20 |
| Fenitrothion | Organophosphate | 1 | 5.05 | 11.18 | 16.17 | 35.76 |
| Fonofos | Organophosphate | 1 | 0.00 | 12.58 | 0.00 | 10.06 |
| Isazophos | Organophosphate | 1 | 13.39 | 9.88 | 133.94 | 98.77 |
| Malathion | Organophosphate | 10 | 0.00 | 9.38 | 0.00 | 11.72 |
| Omethoate | Organophosphate | 1 | 6.57 | 14.53 | 16.43 | 36.34 |
| Deltamethrin | Pyrethroid | 1 | 2.77 | 0.00 | 0.05 | 0.00 |
| Esfenvalerate | Pyrethroid | 1 | 3.34 | 0.00 | 0.33 | 0.00 |
| Fenvalerate | Pyrethroid | 3 | 3.34 | 0.00 | 1.11 | 0.00 |
| Fluvalinate | Pyrethroid | 2 | 5.57 | 0.00 | 0.07 | 0.00 |
| Permethrin | Pyrethroid | 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| Resmethrin | Pyrethroid | 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pyrethrum mix | Pyrethroid | 1 | NA | NA | NA | NA |

elements present in the active ingredients of any product used in ecological studies are C, H, Cl, O, F, Br and S, none of which is typically a limiting nutrient in terrestrial ecosystems. Even at the maximum rates applied in ecological studies, the amounts of nitrogen and phosphorus added were small. The maximum amounts were 130 mg $m^{-2}$ $year^{-1}$ for nitrogen and 100 mg $m^{-2}$ $year^{-1}$ for phosphorus (isazophos; as used by Wardle and Barker 1997). Background rates of nitrogen and phosphorus cycling in terrestrial ecosystems are typically two and one order of magnitude higher, respectively, than even these amounts (Schlesinger 1997). Assessment of fertilization effects would be easier if investigators report their application rates in terms of active ingredient per plant or unit area per year. Based on maximum recommended application rates for the compounds used by ecologists in the studies we surveyed, we do not think that direct nutrient enrichment effects are an important source of artifacts in ecological studies with insecticides. Nevertheless, it is a good idea to calculate the amounts of nitrogen and phosphorus supplied to the system and to compare it to the natural pools of these nutrients.

Insecticides are usually applied in a mixture of inactive ingredients. For foliar applications, the main inactive ingredient is usually water often with a small amount of surfactant which aids dispersion of the water. In every study we examined, plants not treated with insecticide were sprayed with water to account for the water applied to insecticide-treated plants or plots. We do not think that small amounts of surfactant (i.e. soap) are likely to contribute to major methodological artifacts. For soil applications to control below-ground herbivores, insecticides are sometimes applied as a solution soaked into the soil. In all studies using this method, appropriate water-only controls were used. Some chemicals (especially chlorpyrifos) are applied as granules. These granules typically are composed of a low concentration of active ingredient (5 % or less) and a large proportion of sometimes specified inert ingredients. These materials are typically organic materials with low concentrations of nutrients, such as ground corn cobs or nut shells. The mass of inert ingredients is usually less than 5 g $m^{-2}$ per application. Such a small amount of low nutrient organic material represents a small input.

### 15.5.9 Insect-Vectored Diseases

Removal of carbon and nutrients is not the only means whereby insect herbivores impact plant growth and survival. For instance, many important plant diseases are vectored by insects, especially viral diseases (Perring et al. 1999). Extremely large effects of insect suppression on plant survival with slight changes in herbivore damage and abundance are one indication that insect-vectored diseases may be magnifying the effect of insect herbivore suppression. Unfortunately, the most common vectors for viral diseases are sucking feeders (Perring et al. 1999), making it difficult to independently quantify herbivore consumption and host plant responses. Some diseases have characteristic symptoms which allow the investigator to associate mortality with disease (Mitchell 2003) and draw more accurate conclusions about the role of insect herbivores in the ecosystem. Insecticides that rapidly kill or repel herbivorous insects and those with residual action are those most likely to reduce the transmission of insect-vectored viral diseases. Synthetic pyrethroids are a class of insecticidal compounds that are particularly effective at reducing viral spread (Perring et al. 1999). Other diseases may not be vectored by insects but may opportunistically infect weakened plants and magnify the effect of insect herbivory on plant performance. Fungal diseases are more likely to fall into this category. Factorial insecticide and fungicide experiments have the potential to help tease apart the relationships among insect herbivory, fungal diseases and plant performance.

Insecticides may also influence the susceptibility of plants to fungal pathogens that are not vectored by herbivores. Mostly this is not due to the active ingredient itself, but to the surfactants used in many formulations. A proper control should therefore include spraying of the surfactant.

### 15.4.10 Community-Level Artifacts

One major drawback in the vast majority of toxicity studies is that the toxic effects are investigated in single-organism studies, e.g. by rearing sprayed and unsprayed plants in the absence of herbivores in the greenhouse, or by directly exposing a particular insect to the active substance. Because interactions in the aboveground and belowground food webs are complex, it is generally difficult to extrapolate from such single-organism studies to community-level effects. For example, if an annual plant shows a significant 5 % reduction in seed set when sprayed, this may or may not have consequences for plant species composition in the longer term. To estimate community-level effects, community-level experiments should be performed. For example, entire plant communities could be grown in the greenhouse, or transplanted from the field, and the similar ecosystem variables could be measured in the greenhouse and in the field. For community transplants, a single insecticide spray may be sufficient to eliminate the resistant herbivore insect community. Thereafter, only one group of replicates would be subjected to further spraying while the control group would only receive the first spray. While such an approach is easier for some ecosystems than for others, it would possibly be more conclusive than single-organism studies. Another advantage might be the reduced effort needed to assess side effects. For example, even when the ecosystem under consideration consists of only 20 higher plants, it would be extremely time-consuming if not impossible to test each of these plants and the majority of soil organisms one-by-one in isolation, let alone in two-species combinations. We recommend that community-level tests for insecticide effects should become more common in ecological studies.

## 15.6 Are There Better Types of Insecticides?

There are several classes of insecticides that have not been used in ecological studies. These include antibiotic insecticides that are applied as a bait. They have the advantage of low toxicity to non-target organisms, but they must be consumed by the herbivore in order to be effective. They may be ineffective in small plots with high rates of recolonization and they are unlikely to be effective against a broad spectrum of insects with varied feeding habits. Insect growth regulators have many of the same advantages and disadvantages. Some insecticides are toxic to other groups of organisms such as fungi (dinitrophenol pesticides) or plants (arsenic pesticides), or are non-selective (methyl bromide), which limits their use in ecological studies of insect herbivory. Some classes of insecticides, such as formamidine insecticides (also known as amidine insecticides), have not been used although there do not appear to be any distinct reasons why they have been avoided by ecologists. Ecologists utilize a diversity of insecticides (Table 15.1). The list of products used will likely expand, but the new insecticides will demand the same caution in use and interpretation of results as those currently available. The ultimate aim, however, should be to use insecticides that are as selective as possible. Combining selective insecticides would allow us to draw inferences about the role of different groups of insect herbivores, and of the role of herbivores on particular plants in the community.

## 15.7 Conclusions

Ecologists should show caution in interpreting chains of causation from insecticide application to plant and ecosystem responses without careful examination of intermediate steps in the process. In particular, data on herbivores and herbivory are critical to any argument that insecticide treatments are impacting plants or ecosystem processes via changes in herbivory. Direct toxic effects of insecticides on plants and effects on soil nutrient cycling may also weaken the inferences ecologists can draw in their studies. Insecticides will continue to be a valuable tool for ecologists who study insect herbivores in terrestrial ecosystems.

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## Appendix: Results of Surveyed Studies

| Author | Year | Q1[a]: object | Q2[b]: insecticide | Q3a[c]: dam | Q3b[d]: abund | Q4a[e]: germ | Q4b[f]: surv | Q4 c[g]: growth | Q5[h]: preds | Q6a[i]: det | Q6b[j]: micro | Q7[k]: fert |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agnello et al. | 1996 | IG | Chlorpyrifos, Methomyl | Yes | Yes | No | No | No | No | No | No | No |
| Barrett | 1968 | ER | Carbaryl | No | No | Exp | Exp | Exp | Exp | Exp | No | No |
| Brown | 1993 | ER | Permethrin | No | Yes | No | No | No | Lit | No | No | No |
| Brown and Gange | 1989a | SR, CC | Chlorpyrifos/Dimethoate | No | No | Lit | Lit | Lit | No | No | Lit | Lit |
| Brown and Gange | 1989b | SR, CC | Chlorpyrifos | No | No | Exp | Exp | Exp | Lit | Lit | Lit | No |
| Brown et al. | 1987 | IG, IR | Malathion | No | No | No | Exp | Exp | No | No | No | Exp |
| Brown et al. | 1988 | IG, PG, SR, CC | Malathion | No | Yes | Lit | Lit | Lit | Exp | Lit | Lit | Lit |
| Cain et al. | 1991 | IG, IR | Fenvalerate | No | Yes | Lit | Lit | Lit | No | No | No | Lit |
| Calvo-Irabien and Islas-Luna | 1999 | IS | Monocrotophos | Yes | No | No | No | No | No | No | No | No |
| Cantlon | 1969 | PG | Malathion, DDT, Aldrin | No | No | No | No | No | No | No | No | No |
| Carson and Root | 1999 | CC, CP | Fenvalerate | Yes | Yes | Lit | Lit | Lit | No | No | No | No |
| Christensen and Whitham | 1993 | IR, IG, IS | Dimethoate | Yes | No | No | No | No | No | No | No | No |
| Cohen et al. | 1994 | HR | Deltamethrin | No | Yes | No | No | No | Exp | No | No | No |
| Dempster | 1968 | ER | DDT | No | No | No | No | No | Lit/exp | Lit/exp | Lit | No |
| Dominguez and Dirzo | 1994 | IR, IG, IS | Omethoate | Yes | No | Exp | Exp | Exp | No | No | No | Exp |
| Donaldson | 1997 | ER, PG | Malathion | No | No | No | No | No | No | No | No | No |
| Edwards et al. | 1968 | HR, ER | Dichloropropene, Formalin, Aldrin | No | Yes | No | No | No | Exp | Lit | Lit | No |
| Edwards et al. | 1979 | HR | Fonofos | No | Yes | No | No | No | No | No | No | No |
| Fox and Morrow | 1992 | IG | Carbaryl | Yes | No | No | Lit | Lit | No | No | Exp | No |
| Fraser and Grime | 1997 | CP, ER | (Chlorpyrifos/Diazinon), (Dimethoate/Permethrin) | Yes | No | Exp | Exp | Exp | No | No | No | Exp |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Funderburk et al. | 2000 | IG | Lambda Cyalothrin, Spinosad, Aldicarb, Phorate | Yes | Yes | No | No | No | No | No | No | No |
| Ganade and Brown | 1997 | CC, IR, IG, SR | Chlorpyrifos | Yes | No | Lit | Lit | Lit | Lit | Lit | Lit | Lit |
| Gange et al. | 1989 | IG | Malathion | No | No | Lit | Lit | Lit | No | Lit | Lit | No |
| Gange et al. | 1992 | IR | Chlorpyrifos, Dimethoate, Iprodione | No | No | Exp | No | No | No | No | No | No |
| Gange et al. | 1989 | IR, IG, IS | Malathion | Yes | No | No | No | No | Lit | No | No | No |
| Hartley | 1998 | IG | Resmethrin | Yes | No | No | No | No | No | No | No | No |
| Ingham et al. | 1986 | ER | Carbofuran | No | No | No | No | No | Exp | Exp | Exp | No |
| Kaitaniemi et al. | 1998 | IG | Fenirothrion | Yes | No | No | No | No | No | No | No | No |
| Kelly and Dyer | 2002 | PG, IG, IR, IS | Orthene | Yes | No | No | No | No | Lit | No | No | No |
| Kleintjes | 1997 | IG | Phosphamidon | Yes | Yes | No | No | No | Exp | No | No | No |
| Louda | 1982 | IS, PG | Malathion, Lindane | No | No | Lit | Lit | Lit | No | No | No | No |
| Louda | 1982 | IR, PG, IS | Malathion, Lindane | No | No | No | No | No | No | No | No | No |
| Louda | 1984 | IG, IR | Rotenone | Yes | Yes | No | No | No | No | No | No | Lit |
| Louda and Potvin | 1995 | IG, IS, IR | Lindane | Yes | No | No | No | No | No | No | No | No |
| Louda and Rodman | 1996 | IG, IS, IR, PG | Pyrethrum | Yes | No | Lit | Lit | Lit | No | No | No | Lit |
| Malone | 1969 | ER, SR, PG, CC | Diazinon | No | No | No | No | No | Lit/exp | Exp | No | No |
| Maron | 1997 | IS | Malathion | Yes | No | No | No | No | No | No | No | No |
| Martens and Boyd | 2002 | IG | Aldicarb | Yes | No | No | No | No | No | No | No | No |
| Masters et al. | 2001 | HR, IG, IR | Chlorpyrifos | Yes | Yes | Lit | Lit | Lit | Lit | No | Lit | Lit |
| McBrien et al. | 1983 | PG, CC | Carbaryl, Malathion | No | Yes | No | No | No | No | No | No | No |
| McNaughton | 1970 | IG | Dimethoate | No | No | No | No | Exp | No | No | No | No |
| Messina et al. | 2002 | | Malathion | Yes | Yes | No | Lit | Lit | No | No | No | Lit |
| Müller-Schärer and Brown | 1995 | PG, IG | Dimethoate, Chlorpyrifos | Yes | Yes | No | No | No | No | No | No | No |
| Norris | 1997 | CC, IG, PG | Aldicarb | Yes | No | No | No | No | No | No | No | No |
| Palmisano and Fox | 1997 | PG, IG, IR, IS | Lindane, Carbaryl | Yes | Yes | No | No | Exp | No | No | No | No |
| Parker et al. | 1984 | ER | Chlordane | No | Yes | Exp | Exp | Exp | Exp | Exp | Exp | Exp |
| Paynter et al. | 1998 | IS, IR, PG | Tau-Fluvalinate, Azinphos-methyl | Yes | No | Exp | Exp | No | No | No | No | Exp |

**Appendix** (*Continued*)

| Author | Year | Q1[a]: object | Q2[b]: insecticide | Q3a[c]: dam | Q3b[d]: abund | Q4a[e]: germ | Q4b[f]: surv | Q4 c[g]: growth | Q5[h]: preds | Q6a[i]: det | Q6b[j]: micro | Q7[k]: fert |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Perfecto | 1990 | HR, ER | Carbofuran, Chlorpyrifos | Yes | Yes | No | Exp | Exp | Exp | No | No | No |
| Pysek | 1992 | IG, IR, IS | Metathion | Yes | No | No | No | No | No | No | No | No |
| Rees and Brown | 1992 | IG | Dimethoate, Chlorpyrifos | Yes | No | Lit | Lit | No | Lit | Lit | Lit | No |
| Risch et al. | 1986 | ER | Carbaryl | No | Yes | No | No | No | Exp | Exp | No | No |
| Root | 1996 | IG, IR | Fenvalerate | Yes | Yes | Lit | Lit | Lit/exp | No | No | No | Lit |
| Root and Gowan | 1976 | IG, HR | Carbaryl, Carbofuran | Yes | Yes | No | No | No | Exp | No | No | No |
| Santos and Whitford | 1981 | ER | Chlordane | No | Yes | No | No | No | No | Exp | Exp | No |
| Santos et al. | 1984 | ER | Chlordane | No | Yes | No | No | No | Lit | Exp | Exp | No |
| Santos et al. | 1981 | ER | Chlordane | No | Yes | No | No | No | No | No | No | No |
| Seastedt et al. | 1983 | IG, PG | Carbaryl | Yes | No | No | No | Exp | No | Exp | No | Exp |
| Sessions and Kelly | 2002 | CC, IG | Fluvalinate | Yes | No | No | No | No | No | No | No | No |
| Shure | 1971 | ER, SR, CP, PG, IR | Diazinon | No | No | Exp | Exp | Exp | Exp | No | No | No |
| Siemann and Rogers | 2003 |  | Esfenvalerate | Yes | Yes | No | Exp | Exp | Lit | Lit | Lit | Lit |
| Strong et al. | 2000 | HR, IG | Resmethrin | Yes | Yes | No | No | Lit | No | No | No | Lit |
| Traveset | 1994 | IR | Endosulfan | Yes | No | No | No | No | No | No | No | No |
| Wardle and Barker | 1997 | CP, SR, CC, IG | Isazophos | Yes | No | No | No | No | No | No | Exp | No |
| Weary and Merriam | 1978 | ER | Carbofuran | No | No | No | No | No | Lit | Exp | No | No |
| Whitford et al. | 1981 | ER | Chlordane | No | Yes | No | No | No | No | No | No | No |
| Whittaker and Warrington | 1985 | IG | Malathion | No | No | No | No | No | No | No | No | No |

[a] *Q1*: What type of plant response variable was the focus of the study? *IG* Individual plant growth; *IS* individual plant survival; *IR* individual plant fitness/reproduction; *PG* plant population growth; *SR* plant community diversity (species richness); *CC* plant community composition; *CP* plant community productivity; *HR*, herbivore response; *ER*, ecosystem response

[b] *Q2*: What type of insecticide did they use? (active ingredients)

[c] *Q3a*: Did they quantify changes in insect damage with insecticide treatments?

[d] *Q3b*: Did they quantify changes in insect abundance with insecticide treatments?

[e] *Q4a*: Did they consider effects of insecticide on germination? *Lit* Yes, using a citation of another study; *Exp* yes, by performing their own tests; *No* no

[f] *Q4b*: Did they consider toxic effects of insecticide on plant survival?

[g] *Q4c*: Did they consider toxic effects of insecticide on plant growth?

[h] *Q5*: Did they consider greater toxicity to higher trophic levels?

[i] *Q6a*: Did they consider greater toxicity to detritivorous insects?

[j] *Q6b*: Did they consider effects on soil microbes (especially for nitrification) or mycorrhizae?

[k] *Q7*: Did they consider fertilization effects of insecticide?

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