INSECT – PLANT INTERACTIONS
INSECT – PLANT INTERACTIONS

2 broad categories of interactions

I. Herbivory (phytophagy)

leaf chewing, sap sucking, seed predation, gall inducing, leaf mining

II. Insect-plant mutualism

pollination and plant-insect food for defense relationships

What had that flower to do with being white
The wayside blue and innocent heal-all?
What brought the kindred spider to that height,
Then steered the white moth hither in the night?
What but design of darkness to appall?
If design govern a thing so small. – Robert Frost, Design
4.24. The phylogeny of living and extinct insect orders of insects used in this book, based on various sources (see text). Colors denote most major lineages; darker colors indicate the known extent of fossils.
RADIATIONS OF PHYTOPHAGOUS INSECTS

~ 10 – 25 % of tropical foliage is consumed by insects (not counting eating flowers, roots, stems, wood, seeds and fruit)

In temperate deciduous forests phytophagous insects comprise:
~25% of all arthropod species
~50% of arthropod biomass
~75% of arthropod individuals

In grasslands 10 – 75% of herbivory is by insects (vertebrates account for 15-35%)
Table 2.1 Numbers of herbivorous species in different insect orders. (Data from various sources)

<table>
<thead>
<tr>
<th>Insect order</th>
<th>Total no. of species</th>
<th>Herbivorous species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coleoptera</td>
<td>349000</td>
<td>122000</td>
</tr>
<tr>
<td>Lepidoptera</td>
<td>119000</td>
<td>119000</td>
</tr>
<tr>
<td>Diptera</td>
<td>119000</td>
<td>35700</td>
</tr>
<tr>
<td>Hymenoptera</td>
<td>95000</td>
<td>10500</td>
</tr>
<tr>
<td>Hemiptera</td>
<td>59000</td>
<td>53000</td>
</tr>
<tr>
<td>Orthoptera</td>
<td>20000</td>
<td>19900</td>
</tr>
<tr>
<td>Thysanoptera</td>
<td>5000</td>
<td>4500</td>
</tr>
<tr>
<td>Phasmida</td>
<td>2000</td>
<td>2000</td>
</tr>
</tbody>
</table>
For extant species, phytophagous insects comprise ~43% of all insects.

Primarily from:
- Lepidoptera
- Coleoptera
- Hemiptera
- Orthoptera
- Hymenoptera
RADIATIONS OF PHYTOPHAGOUS INSECTS

Lepidoptera – largest lineage of plant-feeding organisms;
basal leps are detritivores (some phytophagous);
all others comprise a monophyletic group whose larvae are phytophagous (a few revisions to detritus and a few groups have become parasitoids and predators)
RADIATIONS OF PHYTOPHAGOUS INSECTS

Coleoptera – “Phytophaga” - Chrysomelidae, Curculionoidea, Cerambycidae …
RADIATIONS OF PHYTOPHAGOUS INSECTS

**Hemiptera** – Ancestrally all were phytophagous, virtually all Sternorrhyncha and Auchenorrhyncha are herbivores as are many families of the Heteroptera.
Orthoptera – ~95% of orthopterans are herbivores. Closely related to the Phasmatodea all of which are herbivores

Fossil evidence suggests orthopteroid herbivory began in the Carboniferous – oldest living lineage of phytophagous insects
Hymenoptera – Ancestrally all hymenopterans were phytophagous

Basal hymenopterans all eat plants

Secondary plant feeding by larval Cynipidae (galls), chalcid wasps (breeding w/in seeds), and assorted other groups like leaf-cutter bees and ants (although leaf-cutter ants use plants to grow fungus)
RADIATIONS OF PHYTOPHAGOUS INSECTS

Many other orders of insects contain herbivores.
Among the smaller phytophagous lineages:

Thysanoptera – ancestral diet fungus but herbivory evolved several times.
Phytophagy evolved several times in Diptera including, Cecidomyiidae (gall midges – largest herb lineage in flies), tephritoid fruit flies, agromyzid leaf miners, various Anthomyiidae and many families in Cyclorrhapha.
The host plants for these previous groups are primarily angiosperms. This may be due to the biomass and species dominance of angiosperms (i.e. the availability) or this may reflect the fact that angiosperms are more digestible and have higher nutritive value than gymnosperms.
Effects of plant-feeding insects are immense and have been taking place since the Devonian – 400 mya!! Most certainly since the Carboniferous (300 mya)
4.24. The phylogeny of living and extinct insect orders of insects used in this book, based on various sources (see text). Colors denote most major lineages; darker colors indicate the known extent of fossils.
• Modern non-insect hexapods and apterygotes scavenge in the soil and leaf litter on decaying plant material

• Earliest true insects probably fed similarly

• These habitats brought insects into close proximity to plant parts (i.e. roots, storage organs)

• Specialized use of plant shoots arose later in the phylogeny (~300 mya)
Feeding on plants presents problems not experienced by either scavengers living in soil, or by predators

1. To eat shoots insects must gain and retain attachment plant (not a trivial issue)

2. Exposed on plant tissue may subject insect to greater desiccation

3. A diet of plant tissue (excluding seeds) is nutritionally inferior in proteins, sterol and vitamin content compared to food of animal or microbial origin

4. Plants are not passive recipients of herbivory
   Physical defense (spines, spicules)
   Chemical defense (repel, poison, reduce digestibility or somehow interfere with insect behavior and/or physiology
Plant defenses against herbivory

Chapters 3, 5 and 6, respectively), which are interrelated as shown in Figure 1.1. These pathways are ubiquitous and the first products formed in quantity can be considered primary metabolites. Thus, palmitic acid (1.2) is the primary metabolite of the acetate-malonate pathway, other fatty acids and their derivatives being secondary metabolites.

\[ \text{CH}_3(\text{CH}_2)_{14}\text{COOH} \]

palmitic acid

(1.2)

The terpenoids can be chemically and biochemically divided into classes depending on the number of C₅ isoprene units they contain, each class being derived from a primary metabolite precursor biosynthesised by the acetate-mevalonate pathway. Thus, geranyl pyrophosphate (1.3) is the primary metabolite from which the monoterpenoids are derived, farnesyl pyrophosphate (1.4)
### Table 3.1 Some nitrogen-based toxins in plants

<table>
<thead>
<tr>
<th>Class of compound</th>
<th>Example(s)</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-protein aminos</td>
<td>DOPA in <em>Macura</em> seed</td>
<td>Insects, espec. brush-tailed bees</td>
</tr>
<tr>
<td>acids</td>
<td>β-Cyanotatin in <em>Vicia</em> seed</td>
<td>Fatal dose in rats 200 mg/kg; body weight</td>
</tr>
<tr>
<td>Cyanogenic glycosides</td>
<td>Linamarin and lotaustratin in <em>Lactuca</em> sativa</td>
<td>Unusual; fatal dose of HCN in man 20-50 mg</td>
</tr>
<tr>
<td>Glycosinolates</td>
<td>Sinigrin in <em>Brassica</em></td>
<td>Cattle and insects</td>
</tr>
<tr>
<td>Alkaloids</td>
<td>Senecionin in <em>Ragwort</em></td>
<td>Spec. cattle</td>
</tr>
<tr>
<td>Peptides</td>
<td>Arsanilic acid in Arsanilic acids</td>
<td>Mammals; not birds</td>
</tr>
<tr>
<td></td>
<td>Anthracene in <em>Aconitum</em></td>
<td>LD₅₀ in rats 750 mg/kg</td>
</tr>
<tr>
<td>Proteins</td>
<td>Apetin in <em>Apocynum crenatum</em></td>
<td>Lethal dose in man 0-5 mg; <em>Bristle</em> beetles</td>
</tr>
</tbody>
</table>

### Table 3.2 Some non-nitrogenous toxins in plants

<table>
<thead>
<tr>
<th>Class of compound</th>
<th>Example</th>
<th>Toxicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terpenoids</td>
<td><em>Taxus</em> in <em>Cinnamomum</em></td>
<td>Insects, birds</td>
</tr>
<tr>
<td>Sesquiterpene lactones</td>
<td><em>Hymenaea</em> in <em>Hymenaea</em> adonias</td>
<td>Livestock and insects</td>
</tr>
<tr>
<td>Cardiac glycosides</td>
<td><em>Osabina</em> in <em>Oscilina</em></td>
<td>Heart poison, LD₅₀ in rats 17-2 mg/kg</td>
</tr>
<tr>
<td>Sapotoxins</td>
<td><em>Medicago</em> in <em>Medicago</em> sata leaves</td>
<td>Fish, insects</td>
</tr>
<tr>
<td>Pyrrolizidine</td>
<td><em>Xanthotoxin</em> from <em>Pantsoa</em> sativa</td>
<td>Insects</td>
</tr>
<tr>
<td>Isoflavonoids</td>
<td>Rotenone in <em>Derris</em> root</td>
<td>Mainly insects and fowl</td>
</tr>
<tr>
<td>Quinones</td>
<td><em>Hypericin</em> in <em>Hypericum</em> perforatum leaves</td>
<td>Mammals, especially sheep</td>
</tr>
<tr>
<td>Polysaccharides</td>
<td><em>Oenanthotoxin</em> in <em>Oenanth</em> croceae roots</td>
<td>Mammals</td>
</tr>
<tr>
<td>Aflatoxins</td>
<td>Aflatoxin B₁ in <em>Aspergillus flavus</em> infection on peanut</td>
<td>Birds and mammals</td>
</tr>
</tbody>
</table>

### Figures

**Fig. 3.3** Some characteristic alkaloids of plants

**Fig. 3.4** Some non-nitrogenous plant toxins
3

1 $R = CH_3$
2 $R = H$
RADIATIONS OF PHYTOPHAGOUS INSECTS

Given these hurdles to herbivory, plants represent an adaptive free zone. Those that have jumped the hurdle have radiated…
Herbivory

• Plants are suboptimal food
  – Dilute nutrients in indigestible structural compounds (e.g. cellulose, lignin).
  – Secondary metabolites cause toxicity (qualitative) or indigestibility (quantitative).
  – Spines or pubescence on stems and leaves
Selection Pressure Exerted By Herbivorous Insects on Plants

- Resistance vs. Defense
- Plant apparency hypothesis
  - ‘Apparent plants’ → quantitative defense (tannins)
  - ‘Non-apparent plants’ → qualitative defenses (alkaloids)
- Resource availability hypothesis
  - Availability of resources determines amount and type of defense
Plant-insect associations from the Early Miocene of the Most Basin in North Bohemia—Paleoecological and palaeoclimatological implications

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ABSTRACT

Terrestrial plants and insects account for the majority of the Earth’s biodiversity today, and herbivorous interactions are dated back more than 400 million years. However, investigation of their associations remains in its infancy in Europe. The Miocene is characterized by palaeogeographic re-organization due to the collision of the African with the Eurasiatic plates. The Miocene’s enormous impact on global climatic conditions, and thus on European palaeoenvironment, resulted from a series of episodes of major glaciations in the Early Miocene after the initial cooling and ice sheet formation during the Oligocene. More than 3500 plant remains showing various kinds of feeding damage were available for the present study. These traces are crucial for demonstrating insect feeding effects. The presented study consists of a data set including 132000 plant remains from the Most Basin, Slovakia, which were studied and compared with the European Miocene grasshopper and palaeoecological records. The datasets were used to evaluate the environmental conditions of the time, providing information on plant and insect diversity, as well as on the diversity of herbivore feeding patterns. The results indicate that the Early Miocene climate was characterized by a warm climate with high levels of precipitation and vegetation diversity, as well as a high diversity of herbivore feeding patterns, which suggests a high diversity of plant and insect species and damage types.

1. Introduction

The ecology of plant-insect associations is a significant aspect of modern ecological research. Consequently, studies of insect herbivory on fossil leaves provide crucial information on the ecology of feeding associations and the distribution of plants and insect herbivores that cannot otherwise be obtained separately from the record of plant macrofossils and insect body fossils. Because fossilized plant remains and leaf-insect assemblages can help to understand plant and insect interactions, it is essential to examine how factors like global warming and cooling affect insect herbivory.

The Earth’s climate was gradually cooling during the Tertiary (the last 65 My). This trend was punctuated by three more abrupt cooling steps (e.g., Zachos et al., 2001). Paleoecological indicators suggest that the Early Miocene was a time of rapid climatic change, which initiated in the Late Oligocene (Eyre et al., 2007), resulting in a decrease in global sea level by nearly 10 m during this time (Berggren et al., 1995; Berggren, 2002). Subsequently, in the Miocene important vegetation changes resulted from this altered global climate (Uchron et al., 2011), and it remains unclear whether these changes were mainly triggered by Burtin et al. and later expansion of the Antarctic continental ice-sheet (Barber and Thomas, 2001). Subsequently, in the Miocene important vegetation changes resulted from this altered global climate (Uchron et al., 2011), and it remains unclear whether these changes were mainly triggered by Burtin et al. and later expansion of the Antarctic continental ice-sheet (Barber and Thomas, 2001). Subsequently, in the Miocene important vegetation changes resulted from this altered global climate (Uchron et al., 2011), and it remains unclear whether these changes were mainly triggered by Burtin et al. and later expansion of the Antarctic continental ice-sheet (Barber and Thomas, 2001). Subsequently, in the Miocene important vegetation changes resulted from this altered global climate (Uchron et al., 2011), and it remains unclear whether these changes were mainly triggered by Burtin et al. and later expansion of the Antarctic continental ice-sheet (Barber and Thomas, 2001).
Types of Herbivory – Chewers

Chewers - Most diverse of the leaf-chewing insects are the Coleoptera and Lepidoptera.

Other important groups--Orthoptera, Hymenoptera, Phasmatodea

Insects eat leaves, roots, shoots, stems, and flowers or fruits

Chewing insects possess mandibulate mouthparts.
Mandibles serve to cut and grind food

Mandibles are highly sclerotized to reduce wear

High silica content and cellulose can act as resistance to herbivory
Mining and Boring

Insects live between the two epidermal layers of a leaf; damage appears as tunnels, blotches, or blisters

Independently evolved in four orders: Diptera, Lepidoptera, Coleoptera and Hymenoptera

Different species may excavate different layers of leaf parenchyma or reside in particular leaf parts

Proc. Natl. Acad. Sci. USA
Vol. 91, pp. 12278–12282, December 1994
Evolution

Ninety-seven million years of angiosperm–insect association: Paleobiological insights into the meaning of coevolution

(Cretaceous/Graciariidae/Nepaticidae/Magnoliidae/platanoid)

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Contributed by D. L. Dilcher, August 8, 1994
Mining and Boring

Stem mining
stem boring
plant boring
stalk boring
wood borers
fruit borers

Economically damaging
Types of Herbivory – Sap-sucking

Drain plant resources by tapping into xylem and phloem

Can retard growth and lead to overall lower biomass

Often transmit diseases

Hemipterans exemplify this strategy (haustellate mouthparts)
Types of Herbivory – Sap – sucking

Serve to pierce plant tissues and suck liquid food

Labium modified into a sheath enclosing stylet maxillae

Stylets pierce cuticle and can change orientation

Food channel empties into cibarial cavity
Stylet pathway is mostly extracellular

Locating suitable feeding site is a tedious task

Aphids ~4 hrs to find suitable phloem
Sucking insects utilize several kinds of plant fluids

Aphids, mealybugs, Cicadellidae, Psyllidae – Phloem cells

Sub order – Heteroptera and scale insects – Parenchyma
Many plants support both mandibulate and haustellate insect species

**CHEWERS**
No relative size restrictions
Heavy mechanical damage
Faced with indigestible compounds and toxins

**SUCKERS**
Restricted to a relatively small size
Avoid mechanical damage (but still damaging)
Avoid indigestible compounds and most toxins
Xylem less suitable
Types of Herbivory – Gall makers

Galls consist of pathologically developed cells, tissues or organs of plants that have arisen by hypertrophy and/or hyperplasia as a result of stimulation from foreign organisms.

Orders that make galls:
- Hemiptera – Sternorryncha
- Diptera – Cecidomyiidae, Tephritidae, Hymenoptera – Cynipoidea
Covering-coccoids, cynipids
Filz-cynipids
Roll and fold-aphids
Pouch-psyllid
Mark-sawflys
Pit
Bud and Rosette
Galls may be **determinate** (distinct tissue layers) or **indeterminate** (undifferentiated masses of cells).
DEFINITIONS

Monophagous – Insects that in nature occur only on one or a few closely related plant species
Polyphagous

*Ceroplastes sinensis*
200 sp host plants
From >50 families
Table 2.3 Percentage of insect species within taxonomic groups that feed on plants within a single plant genus, or within a single plant family, or on more than one family of plants. Note that the first five groups of insects comprise small insects compared to the other groups. The correlation between size and host-plant range, however, is low. Many examples exist of closely related similarly-sized insects that show large differences in extent of host-plant ranges. NA = Data not available. (Source: modified from Mattson et al., 1988)

<table>
<thead>
<tr>
<th>Insect group</th>
<th>% of species feeding on</th>
<th></th>
<th></th>
<th></th>
<th>No. of species</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One plant genus only</td>
<td>One plant family</td>
<td>More than one</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>only</td>
<td>plant family</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Psyllidae</td>
<td>94</td>
<td>3</td>
<td>0</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>Aphidinae</td>
<td>91</td>
<td>7</td>
<td>2</td>
<td></td>
<td>445</td>
</tr>
<tr>
<td>Scolytidae</td>
<td>59</td>
<td>38</td>
<td>3</td>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Diaspididae</td>
<td>58</td>
<td>8</td>
<td>34</td>
<td></td>
<td>64</td>
</tr>
<tr>
<td>Thysanoptera</td>
<td>56</td>
<td>15</td>
<td>29</td>
<td></td>
<td>88</td>
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<tr>
<td>Nymphalidae</td>
<td>56</td>
<td>11</td>
<td>33</td>
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<tr>
<td>Lycaenidae</td>
<td>55</td>
<td>14</td>
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<td>Pieridae</td>
<td>33</td>
<td>53</td>
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<tr>
<td>Papilionidae</td>
<td>25</td>
<td>21</td>
<td>54</td>
<td></td>
<td>89</td>
</tr>
<tr>
<td>Other Macrolepidoptera</td>
<td>17</td>
<td>23</td>
<td>60</td>
<td></td>
<td>430</td>
</tr>
</tbody>
</table>
COEVOLUTION


• Many plant taxa manufacture novel secondary compounds that are mildly noxious.

• Some insect taxa feed on plants with the compounds and reduce plant fitness.

• Mutation/recombination introduce more toxic plant compounds.

• Insect feeding is reduced and toxicity in plants is selected for.

• The plant taxon goes through adaptive radiation.

• Insects evolve tolerance of or attraction to the novel compound and tend to specialize on plants with that toxin. The insect taxon goes through adaptive radiation.

• The cycle is repeated, resulting in more phytochemicals and more feeding specialization.
Tritrophic view of specialization

The top-down view holds that specialists are better able than generalists to utilize plant chemical or physical characteristics as defenses against enemies (Brower 1958, Atsatt 1981, Bernays 1988, Bernays and Cornelius 1989, Bernays and Graham 1988, Jones et al. 1989, Dyer and Floyd 1993, Dyer 1995).
HSS
BOTTOM-UP CASCADE
OFAN
Other significant models

ENEMIES
G
A

HERBIVORES
H
F

PLANT CHEMISTRY
I
J

PLANT BIOMASS
E
D

RESOURCES

TROPHIC CASCADES MODELS
Omnivory
IGP
Nonlinear trophic structure
Functional trophic levels
Donor, transmitter, receiver
Detrital food webs
Community-wide cascades

Troubles and enhancements....