Chapter 2
Insects as Beneficials

The benefits that insects offer to nature and humans are as diverse as they are inestimable. Insects pollinate plants, thus enabling many cycles to take place in our ecosystem in the first place. They are growth accelerators and make an essential contribution to the diversity of species and habitats.

Insects are the main food source for many animals. Especially, birds and freshwater fish cannot survive without them. Insects, therefore, play a key role in numerous food chains.

For humans, insects produce important foodstuffs and help to improve hygiene. They even support us in the battle against themselves and also promote our economy and our society with numerous services.

2.1 Insects Pollinate Plants

> By linking the lives of plants and animals, flower pollination is the most significant key function in all terrestrial ecosystem.[1]

2.1.1 Pollination

Among plants, a basic distinction is made between three groups: mosses, ferns, and spermatophyte. Because of pollination, the latter are also called seed plants. The pollen is either deposited on the open, "naked" ovule (gymnosperms, 1000 species) or on the protected, "covered" stigma of the carpels (angiosperms, 295,000 species). The gymnosperms include, e.g., evergreens such as conifers, and the angiosperms include, e.g., deciduous trees, grasses, and other flowering plants.

[1]Bundesamt für Naturschutz (BfN) (2009).

H.-D. Reckhaus, *Why Every Fly Counts*, Fascinating Life Sciences,
DOI 10.1007/978-3-319-58765-3_2

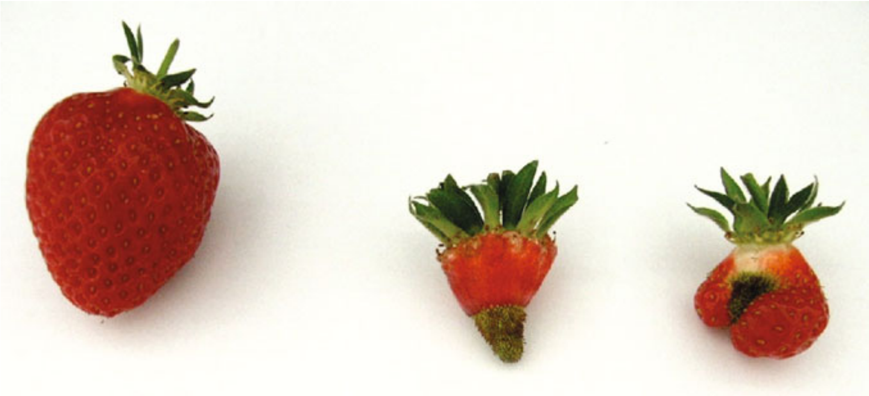

Fig. 2.1 Fruit development depending on the type of pollination. *Picture* © Kristin Marie Krewenka

Plants with hermaphroditic flowers are self-pollinating. However, cross-pollination (xenogamy) is always more successful. It can take place through water, wind, and animals. With wind pollination, large amounts of pollen must be produced, so it can be deposited on the open stamens and stigmas. Figure 2.1 illustrates the effects of the different types of pollination: The strawberry on the left is cross-pollinated by insects. In the middle is a strawberry that must pollinate itself, and on the right, a self-pollinating fruit, that is, also cross-pollinated by wind. Full fruit development is only possible through cross-pollination by insects (cf. Fig. 2.1).

In the following, we will focus on the angiosperms, which represent the largest class with more than 85% of all plants.[2] Angiosperms attract animals with scents and colors. The animals, mainly insects, crawl into the flower to reach the nectar produced in the receptacles of the flower. In the process, pollen remains on the insects' bodies and is transported to the next plant. On their quest for more food, the insects crawl again into the bottom of the next flower. This is how pollination takes place: The pollen is deposited on the sticky ovaries (Fig. 2.2).

To reach the female ovules that are located deep in the flower, the pollen deposited on the ovary forms a tube. This tube grows through the ovary and the style and when it reaches the ovule, it releases the sperm cells. Fertilization takes place through the fusion of the sperm cell with the existing ovum (zygote) (Fig. 2.3).

The zygote grows into the seeds, and the ovary develops into a fruit, and the petals fall off. New plant growth occurs when the seeds are ripe and are spread: The fruits fall down or are eaten by animals, and the seeds are then excreted together with their feces at a different location.

[2] Jaksic-Born et al. (2006, p. 36).

Fig. 2.2 Fruit and vegetables often rely on insect pollination. *Picture* © Stefanie Salzer-Deckert

Fig. 2.3 There would be no cocoa without pollination by midges. *Picture* © Tim Reckmann/pixelio.de

The processes of pollination and fertilization are very successful, because plants and animals have adapted to one another over the course of time. For fertilization to be successful, a suitable sperm cell must be received, i.e., a cell from a plant of the same species.

Because of the species-specific structure of their flowers, plants form highly variable arrangements of the anthers filled with pollen, pistils, and receptacles. Not just any insect is able to pollinate every plant or is able to reach the nectar (cf. Fig. 2.4). This is how plants attract specific insects that, due to their anatomy, are able both to reach the anthers with their bodies and to deposit the pollen on the pistil of the next plant of same species.

In terms of the attracting effect they have on pollinators, plants are specialized with species-specific colors and scents in order to differentiate themselves from other plants. As a result, the animals always prefer the same plants, called flower constancy, as shown in the examples in Fig. 2.4[3]:

- Carthusian pink attracts mainly butterflies that have a particularly long and thin proboscis. No other insect species would be able to penetrate the plant's elongated and narrow flower tube.
- Bumble bees also have a long proboscis; however, compared to other insects, they are very big and require a suitable landing place. The broad flower shape of yellow archangel is optimally adapted to this.
- In contrast, bees have a short proboscis. Blackthorn offers a good landing place and only slightly recessed receptacles.
- Flies are especially attracted by bad odors. Hogweed makes use of this fact and emits carrion-like smells. Insects with short mouth parts visit their shallow flower umbels.

Some plants intensively support the pollination and fertilization process. For example, the horizontal anthers of lupines, filled with pollen, are designed in such a way that they are emptied when an insect visits the flower due to a small upward opening. The insect is literally bombarded with pollen in the process. In contrast, the extensive horizontal stamens of the barberry are sensitive to contact and bend inward when an insect touches them. The insects are embraced and, therefore, impregnated with pollen.

Arum is also impressive, attracting flies and beetles with fecal and carrion scents. Because of its smooth walls, the animals fall from the elevated flowers deep into the receptacle. The plants hold onto the insects for a day or two. This ensures that the transported pollen actually reaches the stigma of the pistil. Finally, the plant's own anthers are opened and the insects are dusted with pollen. The locking bristles that prevented the insects from escaping then wilt and release them.

[3]Jaksic-Born et al. (2006, p. 38).

Fig. 2.4 Different flowers and their pollinators. *Pictures* Drawings © Klett; Plant photographs: top down: CC by anro, free photographs, Maja Dumat, Matt Lavin/all by flickr.com

2.1.2 Plants and Their Pollinators

Angiosperms are mostly pollinated by insects[4]:

- Crucifers: e.g., cabbage, radish, rapeseed, mustard, cress, and horseradish.
- Faboideae: e.g., black locust, broom, lupine, pea, clover, bean, and lentil.
- Lamiaceae: e.g., marjoram, summer savory, peppermint, thyme, sage, and lavender.
- Umbelliferae: e.g., parsley, dill, fennel, caraway, carrot, and celery.
- Rosaceae: e.g., rose, cinquefoils, strawberry, raspberry, blackberry, pear, apple, plum, and cherry.
- Asteraceae: e.g., aster, daisy, lettuce, sunflower, chamomile, dandelion and yarrow.
- Solanaceae: e.g., potato, tomato, squash, and tobacco.
- Sweet grasses: e.g., rye, wheat, oats, barley, rice, corn, and sugar cane. They mainly spread their pollen through the wind.
- Musaceae, which are pollinated by animals such as bats and humming birds.
- Liliaceae: e.g., tulip, asparagus, chive, leek, garlic, onion, and grass lily. They are usually pollinated by insects.

The most important animal plant pollinators are the insects. The most significant insect for crop plants is the European honey bee (*Apis mellifera*).[5] Together with other honey bees and wild bees (25,000–30,000 species), they pollinate most plant species.[6] There are also more than 150,000 fly species as well as butterflies, moths, beetles, and midges that are busy with pollen transport. For example, the flowers of the cacao tree are so tightly arranged that only small midges (*Ceratopogonidae*) are able to pollinate them (cf. Fig. 2.3). But pollen is also transported to other plants by vertebrates such as bats and nonflying mammals such as monkeys, rats, squirrels, and various bear species such as the coati and birds such as humming birds, sunbirds from the sparrow group, and a few parrot species.[7] An example for this is pineapple guava (feijoa), an important and widespread plant used for feed and medicinal purposes, which is exclusively pollinated by birds. Popular in Asia for its fruits, the durian tree is propagated thanks to pollination by bats.

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[4]Leins and Erbar (2008).

[5]In this book, the Latin names of the arthropods are written in italics in parentheses if they serve as a direct translation of the previously mentioned English designation. If they are written without parentheses, they specify the previously mentioned (super-ordinated in biological systematics) term. Example: The ichneumon wasp *Anagyrus lopezi*. *Ichneumonidae* is the name of a family of the Hymenoptera, in which the species *Anagyrus lopezi* is classified.

[6]Klein et al. (2007a).

[7]Food and Agriculture Organization of the United Nations (FAO) (2008).

2.1.3 Flies, the Unknown Pollinators

Flies (*Brachycera*) are generally not considered as pollinators, even though their special features compared to bees have a direct positive effect on the pollinating capacity:

- Because of the small size, they do not need as much space to land and penetrate into the flowers. Flies actually pollinate a multitude of small, inconspicuous plants on the forest floor.
- Flies are not as sensitive to temperature as bees, and for this reason, they mainly pollinate plants where bees are hardly found or not at all. Examples of this are cool, arctic, and alpine regions.
- As a matter of principle, flies require less energy than bees and can, therefore, be more active. Studies have shown that in certain regions, flies pollinate at least as many plants as bees.

In cooler regions, plants even offer flies insulation. The flowers are about five degrees warmer than the surroundings. The flies visit the flower, warm themselves up, and then fly directly to the next plant. This results in a particularly high pollinating performance.

Flies feel comfortable on and in the large flowers of the plants. They often visit specific plants to mate. As a spin-off, intense pollination takes place.

More than 100 fruits are significantly dependent on pollination by flies. For example, the protein- and vitamin-rich berries of the papaya plant in North America are mainly pollinated by dung flies and carrion flies.

Flies, in particular hover flies (*Syrphidae*), ensure the development of economically relevant tropical fruit such as mango, paprika, or pepper. Fennel, coriander, caraway, onions, parsley, and carrots would also not exist in the forms and quantities they do today if it were not for flies.

Fruit-bearing plants from the rose family in the western hemisphere are at least partly pollinated by flies: apple, pear, cherry, apricot, strawberry, and various other berry species (cf. Fig. 2.2). Studies in Europe have shown that flies even visit up to 80% of all plants.

Meanwhile, agriculture makes active use of the pollination potential of flies: The greenbottle fly (*Lucilia caesar*) is commercially bred and used for plant pollination especially in seed breeding operations.[8] It mainly pollinates cauliflower, head lettuce, carrots, asparagus, and onion.

[8] Künast (n.d.).

2.1.4 The Value of Insect Pollination

Numerous plants depend on insects, and, therefore, so do most other animals, the food and animal feed production industry as well as the overall functioning of ecosystems.[9] The facts on pollination by insects demonstrate this impressively[10]:

- 90% of wild plants worldwide benefit from insects.[11]
- 85% of all fruit-bearing plants in Europe are pollinated by insects.[12]
- 75% of all crop plants worldwide grow with the support of insects.
- 75% of the 124 most important fruit-bearing plants in the world cannot ripen without insects.[13]
- 35% of all crop plants worldwide are pollinated by insects.[14]

If one were to calculate the value of all crops that depend on pollination by insects, the economic value of the pollination service provided can be estimated at more than 320 billion US dollars. This value has been continuously increasing in the last two decades; at the beginning of the 1990s, it was still just under 200 billion US dollars.[15]

However, if one were to ask how much effort would have to be made to pollinate plants with alternative methods without insects, the value would be much higher. In South America and Asia, some plants are already being pollinated by hand due to the lack of insects.

Without pollination, the entire animal kingdom would lose their main food source. The animal populations would decrease drastically, and there would be a strong shift in the ecological balance.

The consequences and the resulting costs for humans would be immense, especially with regards to securing the food supply: Not only would prices increase for many foods of plant origin.[16] There would also be much less meat, since, e.g., cattle and sheep eat alfalfa and clover, which are pollinated by insects.[17]

In a long-term study, it was demonstrated that agricultural production would decrease by 5–8% without insects. This drop does not seem drastic, since most

[9]Greenpeace e.V. (2013, p. 3 ff).

[10]Klein et al. (2007b).

[11]Bawa (1990). And: Kremen et al. (2007a).

[12]Williams (1994). And: Aizen et al. (2009a).

[13]Roubik (1995). And: Aizen et al. (2009a).

[14]39 of the 57 most important forage crops are pollinated by insects. The pollinated plants correspond to 35% of the global food production. However, the plants are not exclusively pollinated by insects, so that the fraction of insects is lower than 35%. Klein et al. (2007c).

[15]Lautenbach et al. (2012).

[16]Kremen et al. (2007b).

[17]Berenbaum (2001, p. 14).

plants do not depend exclusively on insects as pollinators. Only approximately, ten percent of the overall agricultural food production depends exclusively on insects.[18] The three most important crops, rice, corn, and wheat, do not depend on insects for their pollination.

It should also be mentioned that plants that are pollinated by insects produce food, that is, particularly rich in nutrients and vitamins. The absence of insects would, therefore, have a direct effect on our nutrition and health.[19]

If insects were missing, plants would no longer be pollinated and could no longer propagate themselves, or not as well. The services provided by plants for the environment would then also be lacking[20]:

- Food for insects, birds, mammals, etc.
- Contribution to biodiversity.
- Flood and erosion protection.
- Climate regulation.
- Water purification.
- Nitrogen fixation.
- Carbon sequestration.

Pollination, therefore, has an effect on the overall environment. It is a decisive ecosystem function.

2.2 Insects Accelerate Plant Growth

Insects act as a growth accelerator. They produce fertilizer, decompose harmful substances, and till the soil.

The interaction between plants, soil-related animals, and microorganisms significantly promotes the biological weathering of soils.[21] Plants, the majority of which are pollinated by insects, penetrate into cracks with their roots and loosen the soil. After flowering, the petals, leaves, and other dead organic materials such as needles and branches fall onto the ground, where they are broken down by animals and especially insects. The material is either eaten or used for building nests (primary consumer). The feces from the first consumers are then eaten by secondary consumers and excreted again. The repeated further utilization takes place progressively deeper in the soil, until microorganisms and fungi perform the final decomposition of the material and inorganic compounds are produced through mineralization, which in turn serve as nutrients for plants.

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[18]Aizen et al. (2009b).

[19]Ibidem.

[20]Greenpeace e.V. (2013, p. 3 ff).

[21]Schulbiologiezentrum des Landkreises Marburg-Biedenkopf (2001, p. 5 ff).

In 1 m^2 of forest soil, there are generally two million active organisms, including approx. 50,000 insects.[22] The soil-bound insects mainly include the following[23]:

- Beetles, e.g., ground beetles, featherwing beetles, and weevils.
- Orthopterans, e.g., crickets (mole crickets).
- Flies, e.g., the larvae of crane flies and midges.
- Hymenoptera, such as spider wasps, bees, and ants.
- Springtails, e.g., the snow flea.

Ants play a special role in terms of soil cultivation. Their nests are relatively large with 500,000–800,000 animals. They loosen and mix the soils by building nests, break down material, and make it available for smaller organisms and excrete nitrogen-rich feces, since they mainly feed on insects. Strong ant colonies can devour up to 100,000 insects per day.

Excrements are the best possible fertilizer for plants. Research has determined that insect feces in the forest soil can account for up to five percent of the carbon, potassium, nitrogen, sodium, and calcium as well as more than eight percent of the phosphorus.[24]

2.3 Insects Promote Biodiversity

Only multifarious natural habitats can also be resistant habitats. As the world's largest animal class with more than one million species, insects make a significant contribution to the biodiversity of our planet.

> Biological diversity – of ecosystems, species and genes – is the natural capital of the Earth. With vital services such as providing food, CO_2 sequestration as well as ocean and water regulation, which represent the basis for economic prosperity, social well-being and quality of life, it is an essential element for sustainable development. Beside climate change, the loss of biological diversity represents the greatest global threat to the environment and leads to considerable economic and welfare losses.[25]

In recent decades, biological biodiversity has decreased significantly. Several thousand animals and plant species disappear every year[26]:

- From 1970 to 2006, the overall vertebrate population dropped by one-third.[27]
- From 1980 until today, bird populations in Europe decreased by 50%.

[22]Schulbiologiezentrum des Landkreises Marburg-Biedenkopf (2001, p. 15 ff).
[23]Beller (2006).
[24]Berenbaum (1997, p. 160).
[25]Europäische Kommission (2010).
[26]Convention on Biological Diversity (2010, p. 24).
[27]Convention on Biological Diversity (2010, p. 9).

- More than 40% of all birds and all amphibians are endangered.
- One quarter of all plants are threatened with extinction.[28]
- Worldwide, almost one-third of the species recorded by the International Union for Conservation of Nature are endangered today.

In Germany, 26% of the 3000 ferns and flowering plants and 36% of indigenous animal species are endangered.[29] Even among the assessed vertebrates, 43% are on the Red List of endangered species.[30] The diversity indicator published by the German Federal Agency for Nature Conservation shows that diversity has decreased by more than 35% from 1970 to 2010.[31]

The rate of species extinction in recent years by far exceeds the natural conservation rate. The United Nations estimate an excess of 100- to even 1000-fold.[32]

Insects play a prominent role for the necessary strengthening of biological diversity and, therefore, the vitality of nature. Insects are small, very mobile, and reproduce rapidly, are particularly adaptable and can penetrate into practically any ecological niche. Together with their large number of species, they are in a unique position to significantly influence biodiversity compared to other animals and plants.

Insects maintain the balance in the cycle of feeding, digestion, and decay. They decompose substances that are harmful to other organisms. And they incite the flora and fauna to respond to the intelligence of insects with increasingly better strategies. Insects can, therefore, be considered as a key element for biodiversity.

2.4 Insects Connect the Food Chain

Insects are an important element of the food chain, or rather of food webs. The trophic relationships between the organisms are not linear. The interactions between the individual participants (such as predators, parasites, food sources, and competitors) in the biocenosis create a complex network of dependencies.[33] Insects, therefore, have a significant influence on the abundance and species diversity of other organisms. They are the main source of food for many animal species and at the same time, predators of other insects and microorganisms from lower trophic levels.

Most vertebrates such as birds, freshwater fish, reptiles, amphibians, and various mammals depend on insects as a food source. Among birds, mainly insectivorous passerine birds, which include songbirds such as swallows, mocking birds, tits, and

[28] Ibidem.

[29] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (2007).

[30] Bundesamt für Naturschutz (2012).

[31] Deutsche Bundesregierung (2012).

[32] Millennium Ecosystem Assessment (2005).

[33] Townsend et al. (2003).

nuthatches, are real insect lovers: These birds, native to all of Europe and Russia, feed almost 100% on insects. For example, the common swift feed on more than 500 species of insects such as aphids, hymenopterans such as bees and ants, beetles, flies, and arachnids. Breeding pairs feeding their young collect up to 40,000 insects per day.[34] Mocking birds also care for their young intensively. In the first twelve days after hatching, the nestlings are given about 150 insects feeding per day. During this time, the young mocking birds each gain five grams of weight every day, corresponding to the required feeding of more than 1000 small insects per day and per animal.[35] For their own survival, the adult animals consume about ten percent of their body weight and, therefore, far more than 1000 insects per day.

The nestlings can even eat beetles that have a hard chitin outer shell. For this purpose, e.g., tits add small rocks when they feed their young, which crush the chitin armor of the beetles.[36] Up to 97% of tits' and other songbirds' nutrition consists of insects from the spring to the beginning of summer, and then they prefer plant seeds.[37]

Woodpeckers are very special insect gourmets.[38] For example, the three-toed woodpecker feeds practically only on bark beetles, eating more than 3000 larvae per day during the winter.

Green woodpeckers have a very special relationship with ants: The birds regularly sit on anthills, where they are sprayed with formic acid and even hold ants in their beaks and rub them on their wings and other body parts. Formic acid acts as a disinfectant, and it is, therefore, assumed that the woodpeckers use this to protect themselves from bacteria and parasites.

Ants are also the main food source for raising young, especially for the green woodpecker. The nestlings have an enormous appetite. The average daily nutritional requirement per animal is as follows:

- Days 1–10: 15 g.
- Days 10–20: 39.5 g.
- Days 20–30: 49.3 g.

Seven young woodpeckers, therefore, consume the surprising amount of 1.5 million ants and their pupae in the first 30 days of their lives.[39]

Their hunger does not diminish in the winter: Green woodpeckers then dig tunnels up to 85 cm long to reach the inside of the anthills.

In contrast, the sapsuckers in North America reach their prey more easily. They peck holes in trees until liquid emerges from the wound through the sap-conducting

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34 Bosch (2003). And: Bauer et al. (2011).

35 Adult thrushes required approx. 10% of their bodyweight in food per day. This corresponds to approx. seven grams and therefore about 1000 small insects. Melde (1991).

36 Löhrl (1991, p. 99).

37 Löhrl (1991, p. 97).

38 Wimmer and Zahner (2010).

39 Korodi Gal (1975). In: Bauer and Glutz von Blotzheim (2001).

bast fiber under the bark. The woodpeckers wait for a little while and then lick up the sugary and sticky sap, which has, meanwhile, accumulated insects such as flies and midges.

Insects also play a key role in the water. Up to 90% of the diet of freshwater fish consists of insects.[40] This also applies for predatory species such as trout, salmon, and perch, which feed on other fish as adults. In the first months, in addition to zooplankton, they feed almost exclusively on the insect larvae of chironomids, mayflies, and caddis flies.[41] Figure 2.5a, b illustrate the feeding preferences of fish depending in their size.[42] The example of the salmon species lavaret shows that fish also become insect lovers at a later time in their development.

For the USA alone, the economic value of insects for the fishing industry was calculated to be at least 224 million US dollars. This represents the revenue, that is, generated with harvested freshwater fish every year.[43]

Amphibians spend their larval stage in the water, where they mainly feed on insect larvae. For example, the diet of the fire salamander, endemic to all of Europe, consists of up to one-third insects.[44] The alpine salamander hunts for ants even to an elevation of 2500 m.[45] But also, the amphibians themselves can fall victim to insects. The larvae of dragonflies, caddis flies, and other large insects eat tadpoles.[46] As adults, the surviving frogs later feed almost exclusively on insects.[47] They are not picky in their food selection. Marsh frogs, for example, feed on various diptera and ground beetles, ants, weevils, cockchafers, hornets, and spiders in one day. Biologists even observed how a frog devoured 19 large meal beetle larvae in succession.[48] Tree frogs also eat wasps, bees, and ants.[49] Once, 117 ant heads were counted in the feces of a tree frog.[50]

Finally, many mammals also feed on insects, e.g., hedgehogs, moles, and shrews, which are grouped in their own order as “insectivores.” For example, in areas with low worm populations such as pine forests, 90% of the diet of moles consists of the larvae of beetles such as longhorn beetles or diptera.[51] Since the

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[40]Berenbaum (2001, p. 18).

[41]Eckmann and Schleuter-Hofmann (2013).

[42]Capinera (2010).

[43]Losey and Vaughan (2006).

[44]Klewen (1991, p. 79 ff).

[45]Klewen (1991, p. 124 ff).

[46]Grosse (1994, p. 169 ff).

[47]Kuzmin (1995).

[48]Günther (1990).

[49]Grosse (1994, p. 89 ff).

[50]Grosse (1994, p. 90).

[51]Witte (1997, p. 105 ff).

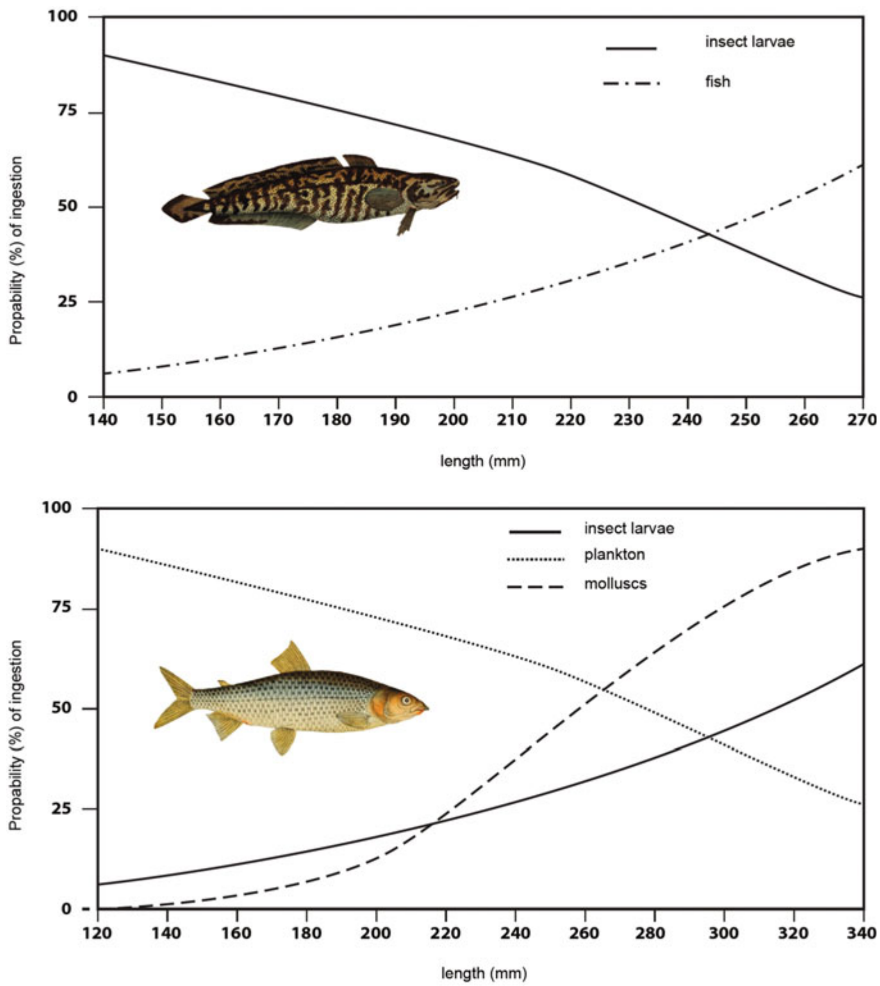

Fig. 2.5 **a** Burbot (Lota lota). Fraction of various foods consumed by fish depending on their body size. *Source* Capinera (2010). **b** Lavaret (Coregonus Lavaretus). Fraction of various foods consumed by fish depending on their body size. *Source* Capinera (2010)

daily food requirement for an adult mole is approx. 50 g of biomass, they consume several tens of thousands of insects per day.[52]

European bats feed exclusively on insects, spiders, and other arthropods. They require between 20 and 30% of their body weight in food on a daily basis, which

[52]Witte reports that the food demand of a mole can be estimated at 62.6% of its bodyweight. From this, the author calculated that with an average weight between 60 and 150 grams, moles must ingest approx. 50 grams of biomass. Witte (1997, p. 102).

represents up to 5000 adult midges for the greater horseshoe bat.[53] The bats hunt for their prey at night at elevations between 0.5 and 8 m and feed almost exclusively on diptera such as flies and midges, butterflies (*Lepidoptera*), net-winged insects (*Neuroptera*) such as green lacewings and antlions, and booklice (*Psocoptera*).[54]

2.5 Insects as the Most Important Element of Nutrition

The Food and Agriculture Association of the United Nations (FAO) has already been studying insect-based nutrition since 2003.[55] In its report from 2013, insects are described as a significant contribution to global food security, income maintenance particularly in developing countries, and improving the general environmental situation.[56]

2.5.1 Insects as Food

Compared to meat from other animals, insects have less of an impact on the environment. Their production requires less feed and emits less climate-damaging gases. For example, the FAO calculated that insects produce one kilogram of insect mass for two kilograms of feed, in contrast, cattle require eight times as much. Pigs produce ten to one hundred times more greenhouse gases than mealworms. Insects need much less water and can be bred more efficiently. For this reason, insect breeding can become an alternative, eco-friendly protein source for developed countries and a source of income for the poor, even in more arid regions. This makes the animals interesting for development policies.

Insects are considered to be a very healthy food source. They are rich in proteins, vitamins, and nutrients, and contain lots of fiber and micronutrients, such as iron and magnesium, and very little fat.[57] For example, 100 g of mealworms or green ants contain between 200 and 1200 calories, and many other edible insects contain 20–75% of protein.[58] Depending on the insect species, 100 g can partially cover the daily requirements for a 25-year-old man: potassium 25%, sodium 65%, calcium

[53]Schober (1998, p. 29).

[54]Schober (1998, pp. 94 and 67 ff).

[55]An overview of the activities is provided by: Food and Agriculture Organization of the United Nations (2013, p. 35 ff).

[56]Food and Agriculture Organization of the United Nations (2013, p. 24 ff).

[57]A good overview of the excellent nutritional value of insects can be found in: Food and Agriculture Organization of the United Nations (2013, p. 162 ff).

[58]Food and Agriculture Organization of the United Nations (2013, p. 68f).

15%, phosphorus 80%, and magnesium 35%.[59] In addition, numerous insects were found to contain vitamins A, B1, B2, and E.

In a direct comparison between industrially bred mealworms and cattle today, insects prove to be the more efficient food alternative. Although beef contains ten percent more protein, it also contains 20% more fat. In contrast, mealworms are richer in vitamins and minerals such as copper, sodium, potassium, iron, and zinc.[60]

Insects have been used as food since more than 2000 years. More than 1900 different insects are consumed by about two billion people today in South Asia, South America, and Africa. Edible insects are also found in Europe, e.g., in France, Italy, and Spain.[61]

2.5.2 Insects as Feed

The Food and Agriculture Association (FAO) calculated that in the year 2050, mankind's demand for food will be about 70% higher than today.[62] This calls for a greater supply of meat, poultry, and fish. The farms need more feed, i.e., more cereals, fishmeal, fish oil, and soya beans. However, these are becoming increasingly scarce, which causes the prices to rise. Already today, feed accounts for 60–70% of the total production costs. In the last ten years, the global prices for cereals and fishmeal have doubled. The international wholesale price of fishmeal, an important basic product, has increased in the last ten years by 250% and reached 1764 US dollars per ton.[63]

The FAO expects a further increase in prices. Accordingly, the search for alternatives is urgent. Insects can assume an important role as a feed substitute or supplement for fish and other animals. Studies were able to prove that, e.g., silk moth larvae (*Anaphe panda*), mealworms (*Tenebrio molitor*), and locusts (e.g., *Oxya fuscovittata* and *Acrida exaltata*) are able to replace feeds such as fishmeal and soya beans.[64]

Particularly in the poultry industry, grasshoppers (e.g., crickets), cockroaches, beetles, flies, and many other insects are added to the animal feed. In Africa and especially in Asia, the larvae of the common housefly (*Musca domestica*) are wide-spread: These consist of 54% pure protein and can, therefore, replace expensive fish feed for breeding chicken. Studies were able to prove that feeding

[59]Food and Agriculture Organization of the United Nations (2013, p. 73).
[60]Food and Agriculture Organization of the United Nations (2013, p. 178 ff).
[61]Food and Agriculture Organization of the United Nations (2013, p. 9 ff).
[62]Wissenschaftlicher Beirat der Bundesregierung Deutschlands (2011).
[63]Tschirner and Simon (2015).
[64]Food and Agriculture Organization of the United Nations (2013, p. 207 ff).

with larvae increases the meat quality and the growth of the chicken by up to 15%[65] and reduce the use of medication.[66]

The Organization for Economic Cooperation and Development (OECD) expects that the consumption of fish will even exceed that of meat and poultry, except in Africa. This development is opposed by the limited catch in natural waters. The critical minimum population of fish for regeneration has already been reached today. Since the 1990s, the annual catch has been constantly at a level between 85 and 90 million tons. Until the year 2022, the OECD forecasts a slight increase to 95 million tons.[67]

Insects play a key role for the global fish supply. In their natural environment, particularly freshwater fish prefers to eat insects and other arthropods. Especially larvae, bugs, fleas, and worms are on the menu. However, insects play an even more important role in the growing aquaculture industry (cf. Fig. 2.6). Because of the legal prohibitions on increasing the catch since the 1980s, this controlled breeding of fish, mussels, crabs, and other aquatic animals in artificially built watercourses experienced strong growth. In the last 30 years, it grew by about eight percent on average.[68]

While aquaculture produced 17 million tons at the beginning of the 1990s, it was already 32 million tons in the year 2000 and about 63 million tons in 2012, of which more than 80% was produced in Asia alone. For the year 2022, the OECD expects about 81 million tons. This then corresponds to half of the total fish consumption, which is estimated at 161 million tons. Today, the proportion of farmed fish already lies at more than 40%.[69] The OECD, therefore, declared aquaculture to be a significant source of human nutrition.[70] Because of their high nutritional value and the relatively cheap sourcing, insects are a popular feed used in aquaculture. To attract additional insects, e.g., lamps are hung over the water.[71]

2.6 Insects Help Considerably with Hygiene

What happens with the cow pats on our pastures? Insects that feed on dung, and therefore get rid of manure, are called coprophagous. Some of them lay their eggs directly in the dung and live there; others dig tunnels to a depth of up to ten centimeters and pull the dung in with them. Scarabs (*Scarabaeidae*) carry it several meters away to be able to consume it in peace away from competitors.

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[65]Food and Agriculture Organization of the United Nations (2013, p. 95).

[66]Food and Agriculture Organization of the United Nations (2013, p. 91).

[67]OECD, Food and Agriculture Organization of the United Nations (2013, p. 194 ff).

[68]Maribus et al. (2013).

[69]OECD, Food and Agriculture Organization of the United Nations (2013, p. 194 ff).

[70]OECD, Food and Agriculture Organization of the United Nations (2013, p. 196).

[71]Food and Agriculture Organization of the United Nations (2013, p. 198 ff).

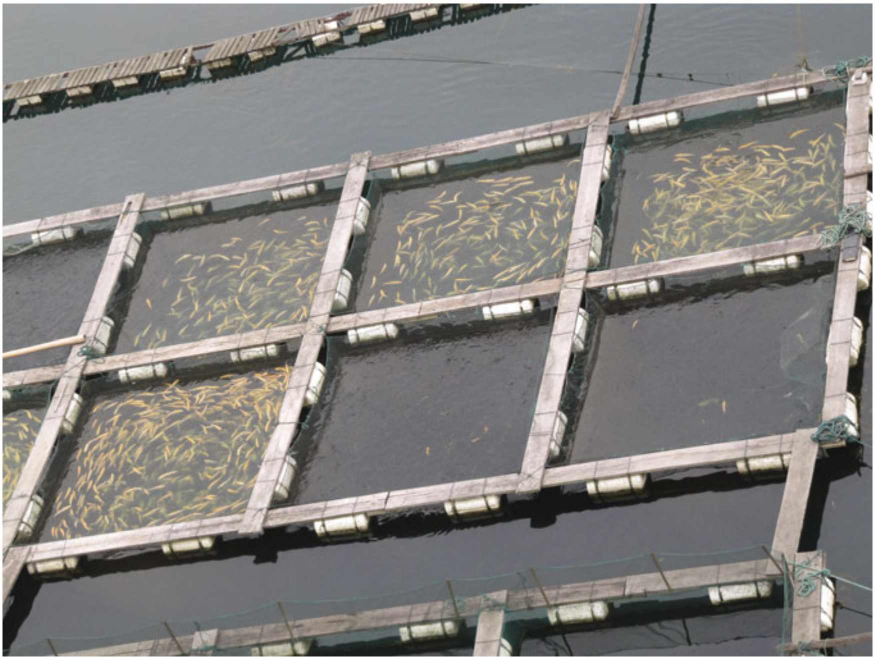

Fig. 2.6 Aquaculture is an important food source for human nutrition. *Picture* CC by IvanWalsh.com

But even for insects that are specialized for dung, the introduction of agriculture in the eighteenth century came too fast: Big problems arose because the import of livestock and animal breeding developed faster than the insects, and therefore also the manure heaps. For example, Australia established an official "dung beetle project" to import 46 different insect species specialized in consuming cow pats from South Africa, Europe, and Hawaii in the hope of regaining control of the situation.[72]

At the end of the 1990s, Christopher O'Toole calculated that without insects, a manure heap covering an area of 1.2 million km^2 would be produced every year in Australia.[73] One cow can produce a dozen cow pats in a day, which would correspond to a weight of almost 5000 kg per year.[74] What would the world look like if it were not for coprophagous insects? And how much money would it cost to remove and dispose of this hazardous waste?

[72]Bornemissza (1976). Cited in: Food and Agriculture Organization of the United Nations (2013, p. 5).

[73]O'Toole (2000, p. 205).

[74]Berenbaum (2001, p. 18).

Midges and flies clean our water. The widespread mosquitoes from the *Culicidae* family need humid areas for their development. The larvae filter food particles out of the water and, therefore, make a considerable contribution to increasing water quality.[75]

Mayfly larvae from the *Hexagenia* genus take care of the floor properties in watercourses: They dig larger tunnels, pulling contaminated material and water into the ground and bringing up clean subsurface material. With their mixing activity, they degrade toxic substances and, therefore, improve water quality.[76]

Hazardous wastes are also no problem for insects. The larvae of the black soldier fly (*Hermetia illucens*), which are considered a valuable food source due to their high calcium content, decompose sensitive substances such as nitrogen (more than 70%), phosphorus (52%), and other substances such as aluminum and chromium and lead by up to 93% and even transform them into high-quality biomass.[77]

Blowflies produce the enzyme collagenase, as do only very few insects, making them capable of decomposing even the toughest substances. Clothes moths, carpet, and skin beetles produce the enzyme keratinase, which decomposes proteins such as skin, hair and nails.[78]

2.7 Insects as Inexpensive Biocide Alternatives

Insects can be used very effectively for insect control (cf. Fig. 2.7). Farmers in China already knew this more than 2000 years ago.[79] They hung the nests of weaver ants from the species *Oecophylla smaragdina* in their citrus trees to keep away or control plant-eating insects such as jewel bugs. Weaver ants are very good defense specialists: With more than 30 neurological substances, they have very special alarm pheromones and react with intense vigilance and aggressiveness.

Because of the natural dependencies in ecosystems, insects generally only become a plague when there are human interventions or foreign insects are introduced. Nonnative insects can be controlled by their natural enemies, which are previously imported from the native distribution range. This type of biological insect control was used for the first time over a greater distance in the year 1762. At the time, a passerine bird called myna from India was introduced to control locusts on Mauritius.[80]

Insects were transported across the continents to control pests for the first time at the end of the nineteenth century. In the year 1885, the cottony cushion scale

[75]Radtke (1999).

[76]Berenbaum (1997, p. 379).

[77]Food and Agriculture Organization of the United Nations (2013, p. 203).

[78]Berenbaum (2001, p. 20).

[79]O'Toole (2000, p. 200).

[80]Berenbaum (1997, p. 230).

Fig. 2.7 Media sensation in Thailand: The wasp Anagyrus lopezi is supposed to keep the agriculturally disastrous cassava mealybug in check. *Picture* CC by CIAT, flickr.com

(*Icerya purchasi*), which was introduced from Australia almost 20 years earlier, became a serious threat to the entire citrus fruit crop in the USA. They sought for natural enemies of the pest in Australia and finally found a suitable insect with the ladybug *Rodolia cardinalis*. Several specimens were imported, which rapidly spread on the trees infested with scale. Affected citrus farmers used the beetle across the land. Within one year, the sector had been saved, and the yields rose from 700 to 2000 freight cars.[81]

An exceptional example from the present is the control of the cassava mealybug (*Phenacoccus manihoti*) in Africa.[82] In the year 1973, the mealybug was introduced unnoticed on cassava cuttings from South America to Zaire. The mealybug, which can spread over a distance of up to 300 km per year, rapidly became an existential problem in Zaire. It destroyed 80% of the cassava harvest, which serves as a staple food south of the Sahara. The whole nation was threatened by famine. Large-scale applications of insecticides in Zaire and in neighboring countries made the problem worse: The high toxicity of the active substance dichlorodiphenyltrichloroethane (DDT) and improper application resulted in numerous cases of poisoning and local

[81]Berenbaum (1997, p. 230 ff).

[82]Cerutti (2011, p. 37 ff).

environmental destruction. It would have taken too long to breed cassava varieties that are resistant to mealybugs. To remedy the situation, biological control was finally considered, led by the entomologist Hans Rudolf Herren. After a two-year search in South America, Herren found the harmful mealybug in Paraguay and, therefore, also its natural enemies. Studies on more than twelve endemic ladybugs and parasitic wasps that appeared to be possible enemies demonstrated that the parasitic wasp *Anagyrus lopezi* was suitable to control the mealybugs. Herren imported the insect and bred it in greenhouses. From 1982 to 1992, he released about 1.6 million parasitic wasps in 30 African countries.

The cassava program designed by Hans Herren

> therefore preserved the most important food source for 200 million people. By preventing the pending famine, he probably saved the lives of 20 million people. The biggest biological pest control program until now, with a relatively low expense of 20 million dollars, brought an estimated benefit of 14 billion dollars for the African agricultural sector according to the Consultative Group for International Agricultural Research – a balance that is probably unique in the crop protection business.[83]

Biological crop protection does not have any resistance is inexpensive and ecologically compatible. Meanwhile in the USA, more than 2300 species have been introduced for research and control purposes.[84] Also in Europe, this type of natural insect control is becoming increasingly important. Although hardly any biological insect control was practiced in Germany at the beginning of the 1980s, today it reaches almost 100% of the cultivated areas in greenhouses for tomatoes, cucumbers, beans, and lettuce, 20% of the cut flowers and 70% of the potted plant cultivation. In the open field, the proportion is significantly lower, but still reaches approx. 30% in, e.g., corn or pome fruits.[85] While the market only offered three beneficials at the beginning of the 1980s, today more than 50 insects are bred specifically for insect control and are sold commercially.[86] The most widespread beneficials in Germany are the marmalade hoverfly (*Episyrphus balteatus*), the aphid midge *Aphidoletes aphidimyza*, the native seven-spot ladybug (*Coccinella septempunctata*), the common green lacewing (*Chrysoperla carnea*) as well as ichneumonid, braconoid, and chalcid wasps, e.g., from the genus *Trichogramma*.

In addition to crop protection, insects are also increasingly being used worldwide for storage protection. For example, the parasitoid wasp *Laelius pedatus* is used against the globally distributed skin beetle. In tropical regions, the cabinet beetle (*Trogoderma granarium*) destroys up to 20% of the food reserves. The larvae are particularly resistant to low temperatures and dryness, and are increasingly resistant to insecticides. The fact that the larvae are capable of surviving in a dormant stage for up to four years under favorable conditions makes controlling them even more

[83]Cerutti (2011, p. 70).
[84]Berenbaum (1997, p. 232).
[85]Jehle et al. (2013, p. 33 ff).
[86]Schneller (2009).

difficult. In Europe, the cabinet or museum beetle (*Anthrenus museorum*) is found more frequently, infesting all sorts of wool products in homes and industries.[87]

Although parasitic wasps are very small, they can attack caterpillars that are several centimeters long. For example, the four-millimeter-long parasitic wasp *Habrobracon hebetor* stings, e.g., the 2.5-cm-long flour moth, paralyzing it and then laying its eggs in the outer skin. The hatching wasp larvae suck out the insides of the moth larvae and then pupate to develop into adults. Only 0.4 mm long, the parasitic wasp *Trichogramma evanescens* does not even allow the moth larvae to develop. It lays its eggs by injecting them directly into the moth eggs. In Europe, the two are industrially bred together with the beetle-specialized parasitic wasps *Anisopteromalus calandrae* and *Lariophagus distinguendus* and used very successfully for storage protection.[88]

If herbicides cannot be sprayed against weeds, e.g., because animals are grazing on the field, this service can also be performed by insects. A prominent example is the control of St. John's wort in the 1940s in the USA.[89] About 8000 km^2 of high-quality pasture was covered with the weed. The animals died because the leaves of St. John's wort contain the toxic substance hypericin. It was known that the Australian leaf beetle *Chrysolina quadrigemina* feeds exclusively on this plant. For this reason, 5000 beetles were imported from Australia, which reproduced rapidly and freed the whole area of the weed. By investing a few thousand dollars, the country was saved and livestock breeding could resume its operations.

Insects can also be used preventatively to control or keep away other insects. Specialized beetles and flies, which mainly feed on manure heaps and therefore "dispose" of them very efficiently, keep other insects away that do not process this biomass as rapidly. An example of this is the black soldier fly (*Hermetia illucens*): It degrades manure heaps so rapidly that 94–100% less normal flies were found compared to a decomposition process without the soldier fly.[90]

A few bred insects can fight against many natural insects. A well-known method is the release of sterile males into nature so that they reproduce with natural females. The females are then not capable of reproducing, causing the entire brood to be reduced or die. For example, this prevented great damage in the USA and in Central America that would have been caused by the New World screw-worm fly (*Cochliomyia hominivorax*) and the Mediterranean fruit fly (*Ceratitis capitata*).[91]

However, anthropogenic use of nonnative insects to control other exotic insects or foreign plants is still always an intervention in an established habitat. The deployed biological opponents should ideally first eliminate the target organisms and then at best eliminate themselves. However, if the deployed parasite survives, it

[87]Al-Kirshi (1998).

[88]Bär (2009).

[89]Berenbaum (1997, p. 189).

[90]Myers et al. (2008).

[91]Food and Agriculture Organization of the United Nations (2013, p. 215).

looks for other food sources and, therefore, causes a new ecological imbalance. Due to the initial lack of natural enemies, it can develop rapidly and also cause great damage.

In the 1950s, the sugar grower association in Hawaii regularly imported parasitic wasps (*Ichneumonidae*) from China and the USA. The wasps were supposed to curb butterfly larvae that destroy the sugarcane plants. They were successful, but they settled in permanently and then decimated other insect species. A study from the years 1999 and 2000 demonstrated that about eight percent of the more than 2000 butterflies collected were infected by the parasitic wasps that were introduced 50 years before.[92] Today, the natural opponents are considered to be the main reason that the numbers and the populations of the butterfly species on the entire island have decreased dramatically. With the reduction in insects, a decrease in bird populations that feed on butterfly larvae has also been observed, as well as for the Hawaiian hoary bat, which feeds preferentially on adult moths.[93]

The tachina fly *Compsilura concinnata* has established itself in the USA for even longer than the wasps. A moth species introduced from Europe to Boston in 1868, the gypsy moth (*Lymantria dispar*), caused damage to the forests in New England. As a large-scale insect egg collection initiative as well as the use of insecticides did not help, the agricultural officials decided in 1905 to import natural enemies of the tree pest from its native region. The tachina fly was known for being specialized for the moth and capable of successfully controlling it.

However, the fly felt more at home in the USA than they thought. In addition to the tree pests, it was also interested in many other butterfly species and, therefore, reduced the moth population less intensively. Although nine other parasitic insects were introduced in addition to the tachina fly, the gypsy moth continued to spread to the south and in the Midwest of the USA and is still a significant plant pest today (cf. Figs. 2.8 and 2.9). The annual damage is estimated at far more than 100 million US dollars.[94] A reliable control method has still not been found.[95] The tachina fly also still feels at home in its new surroundings today. It feeds on more than 180 butterfly species and is held responsible for the reduction of numerous butterfly species that are not harmful to plants.[96]

The correlations involved in biological crop protection can also be complex. Since the 1970s, two knapweed species (*Centaurea maculosa* and *Centaurea diffusa*) grow in North America and cause damage to agriculture. In the state of Montana alone, approx. 80,000 km^2 was infested with the weed originating from Europe.[97] The European fruit flies *Urophora quadrifasciata* and *Urophora affinis* were imported for control. The insects lay their eggs in the buds of the plants, and

[92] Henneman and Memmott (2001).

[93] Peck et al. (2008).

[94] Aukema et al. (2011).

[95] Tobin et al. (2012).

[96] Elkinton and Boettner (2004). Also: Wagner (2012).

[97] Story (1984).

Fig. 2.8 Defoliation of entire landscapes caused by the gypsy moth caterpillar (Pennsylvania, 2007). *Picture* CC 3.0 by Dhalusa, Wikimedia

Fig. 2.9 Wasp Aleiodes indiscretus parasitizes a gypsy moth caterpillar. *Picture* CC by U.S. Department of Agriculture, flickr.com

their larvae then eat the flower organs and. therefore, successfully reduced the weed populations. Unfortunately, it had not been considered that the endemic deer mouse liked the previously unknown larvae so much that between 50 and 90% of their diet now consisted of the introduced insects.[98] Because of the lack of development of the insects, the weed is still a problem for agriculture today. Now they also have to worry about the rising mouse populations: Areas with fruit flies record three times denser populations of deer mice.[99] The mice can be dangerous for humans as they carry the highly contagious hantavirus. Since 1993, more than 600 infections and 200 deaths have been recorded in the USA.[100]

To be successful, biological insect control and biological crop protection require extensive knowledge about the insects, the plants, and the entire biotope in which the insects should be deployed. For example, intensive preparation was required before Hans Herren was able to use the parasitic wasp *Anagyrus lopezi* native to South America for the targeted control of the cassava mealybug in Africa. Because he wanted to prevent the possible spreading of the wrong parasite, Herren performed investigations in English greenhouses to see which insects were most suitable. Before he imported the selected insect species, he first bred several generations in quarantine to prevent the introduction of diseases.[101]

The use of insects for biological control requires lots of preliminary work. However, if the right natural opponent is found, its use is more targeted, effective, inexpensive, and environmentally compatible than the use of conventional biocides.

2.8 Insects Support the Economy and Society

With their diverse characteristics, insects can be considered as a key element for our ecological and economic cycles.[102] They not only pollinate plants but also provide an attractive feed for animals in agriculture. They are also directly suitable for human nutrition. The breeding of insects can satisfy the increasing demand for food in the future and also become a bigger industrial sector for traditional agriculture. Insects close the matter cycle by processing wastes created by human consumption and using them as new breeding sites.

Insects also promote science and support textile production. They support medical science by pollinating medicinal plants, strengthening our immune system, and healing wounds. Moreover, insects produce substances for the chemical industry and help criminologists to solve crimes.

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[98] Pearson et al. (1999).

[99] Pearson and Caalawy (2006).

[100] Centers for Disease Control and Prevention (2015).

[101] Cerutti (2011, p. 45 f).

[102] Peters (2013).

Science

Moths can smell up to 100 times better than humans, ants can carry many times their own body weight, midges resist the force of large raindrops with ease, and beetles orient themselves reliably without an electronic navigation system by looking at the stars.[103] The study of insects can be of great benefit to us humans.

Why do fireflies glow? Can we draw any benefits from this process? The fireflies from the *Lampyridae* family have a special enzyme that transforms their luciferin into light using oxygen. American researchers are now attempting to reconstruct the firefly's genetic material using computers, print the DNA sequences, and use laser technology to cut the sequences in such a way that they can be implanted in plants. The glowing plants should then allow for saving of artificial light.[104]

Ants, bees, wasps, and termites live in communities of 10,000 up to several millions individuals. From research on the social habits of these insects, we can gain valuable information to generate good coexistence in our society.[105]

Insects are also used by science as useful animals. The fruit fly *Drosophila melanogaster* has been used for many years for genetic experiments. Because of its small size compared to laboratory rats and guinea pigs, their use is much more efficient, as they cost less and reproduce more rapidly.[106]

Textile Production

Without insects, we would be standing around quite naked. This refers not only to silk, which is produced by only a few insects. Without the active participation of insects, cotton plants would also not thrive. The same is true for leather, since the animals whose skin is used to produce leather depend on forage plants—and these in turn depend on the work of insects.[107]

Silk has been known since more than 5000 years, but the secret of its production was closely guarded by the Chinese until 300 years before Christ. All caterpillars produce silk, but the caterpillar of the silk moth (*Bombyx mori*) masters this art best. In just one minute, it can spin a thread up to 800 m long, which represents nothing more for it than producing saliva. Silk has excellent characteristics: It insulates and absorbs very well, is not flammable, and is very tear-resistant. Today, more than 90,000 tons of silk are produced by insects annually.[108]

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[103]The dung beetle *Scarabaeus satyrus* uses the sun as orientation in the daytime, and the moon at night. Researchers were now able to observe that on moonless nights, the beetles are capable of orientating themselves using the stars in the Milky Way. Source: Dacke et al. (2013).

[104]Glowing Plant (2015).

[105]There are numerous publications on this topic. A few representatives are mentioned here: Hölldobler and Wilson (2013). And: Wilson (2013). And: Werber (2013).

[106]Berenbaum (2001, p. 20).

[107]Berenbaum (2001, p. 18).

[108]Yong-Woo (1999).

Medical Science

Humans have been using natural medicinal plants and herbs for thousands of years. The plants are used directly or processed into foodstuffs or medicine. Most healing plants would not survive without pollination by insects. Examples include the following: valerian, lavender, lemon balm, eucalyptus, chamomile, St. John's wort, and sage.

For the majority of the Earth's population, such herbal substances are the only medicine available. Especially in developing countries, there is often a lack of financial means for medication and medical infrastructure. In Africa, for example, 80% of the people depend on natural medicinal plants.[109] But also in many other countries, medicinal plants and herbs are of great importance. In China, for example, 30–50% of the overall medical treatment consists of natural substances.[110]

Because of the growing population in developing and threshold nations as well as in Japan and China, the demand for medicinal plants is on the rise. Chronic illness and rising health costs are inciting more and more people in the USA, Europe, and Australia to resort to traditional medicine, at the center of which are medicinal plants. More than 100 million people in Europe use traditional medicine today. In some Asian countries, 86% of people reach for alternative healing methods, in Canada it is 70%, and 75% of people infected with HIV around the world.[111] The global market for medicinal plants has been growing for years at about ten percent per year and amounts to about 100 billion US dollars today.[112]

In addition to the pollination of medicinal plants, insects also support medical science by strengthening our immune systems and healing our wounds. For example, the poison from honey bees has already been used against the joint disease arthritis since 1930. This therapy is considered to be much more effective than treatment with conventional medication.[113]

Already at the end of the eighteenth century, it was observed during the armed conflicts that wounds infested with fly larvae healed particularly well. At the beginning of the twentieth century, the scientific foundation for biosurgery had been laid. The larvae of different carrion, flesh, and blow flies (*Calliphoriden* species) feed on dead tissues. Since they are hardly interested in healthy tissues, they clean the wounds and get rid of infection. Because of the appearance of multiresistant germs, for which medical science has no reliable treatment, maggot therapy has been regaining importance in recent years. Today, the larvae of the green bottle fly *Lucilia sericata* that are suitable for this therapy are bred industrially and distributed worldwide.[114]

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[109] Vasisht and Kumar (2004).

[110] WHO (2003).

[111] WHO (2013).

[112] Own calculation based on Vasisht and Kumar, who already indicated a global market volume of 60 billion US dollars in 2004. Vasisht and Kumar (2004). And: WHO (2003).

[113] O'Toole (2000, p. 209).

[114] Rufli (2002).

Chemistry

Plant lice cause considerable damage. However, the same lice are also of economic use: The skin of mealybugs is used for the production of wax, and scale insects provide resin. The scale insect *Laccifer lacca* is particularly well known.[115] After mating, it produces a resinous secretion, which is nothing other than stock lac or raw lac. After grinding, washing, and filtering, the well-known "shellac" is produced. This substance has excellent properties: very good adherence to many surfaces, good thermal plasticity, and low sensitivity to many solvents. In addition, compared to synthetic resins, shellac is biodegradable. The product is found in many forms today and is used for insulation, denaturation, and sealing: in electrical devices, shoe polish, hair spray, nail polish, floor polish, printing ink, etc. Shellac factories worldwide produce approx. 30,000 tons of the versatile material annually. German companies alone produce more than 3000 tons of shellac-based lacquer annually.[116] For the production of one kilogram, 300,000 scale insects are required.[117]

Scale insects are also useful dye producers. The scale insect *Kermes vermilio* was already being sold 3000 years ago, because it could be used to produce a pretty shade of red. At the end of the sixteenth century, the louse *Dactylopius coccus* from Central and South America dominated the market. Still today, it is used to produce the particularly intense color "carmine red", mainly for the cosmetic and food industries.[118]

Insects even produce oil: The black soldier fly (*Hermetia illucens*) can transform feces into biodiesel. They deposit their larvae in manure heaps, which then feed on the manure and grow. Depending on the type of manure—whether it is from sheep, swine, or even poultry—the fat from the larvae produces between 36 and 91 g of biodiesel per kilogram of manure.[119]

Criminology

Numerous insects feed on flesh. These species are called necrophagous and include flies such as blowflies, house flies and flesh flies, and beetles such as skin beetles and carpet beetles. These insects prefer different types of food and are, therefore, attracted in different ways. For example, odors that form directly after the death of an organism through fermentation processes attract flesh flies. Then the fatty acids are released, which signal a close food supply for skin beetles. Cheese flies are attracted later, then moths, and finally mites. Since this process takes place in a precise sequence with known time frames, entomologists can calculate when the organism actually died. This form of evidence has already been used in criminology since the middle of the nineteenth century and is firmly established today.

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[115] Berenbaum (1997, p. 179 ff).

[116] Verband der deutschen Lack- und Druckfarbenindustrie e.V. (2014).

[117] Markus (2014).

[118] Ibidem.

[119] Food and Agriculture Organization of the United Nations (2013, p. 93).

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