Chapter 3
Welfare Dilemmas Created by Keeping Insects in Captivity

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Abstract The challenging issue of animal welfare has focused mainly on furred and feathered vertebrates. However, unnoticed by most people, literally billions of insects are kept in captivity, in increasing numbers, and traded for a great variety of purposes. Arguably the most successful animals on Earth, insects are ignored or actively disliked by most people. Not just the different appreciation of insects by humans but the diversity of insects, and the diversity of their ecosystem services, shows that a discussion of insect welfare requires different criteria than vertebrate welfare. Their biology is very different, and insects are far less tolerant of suboptimal conditions. As a result, successful insect breeding programmes must necessarily fulfil basic welfare requirements. Insect natural history illustrates the complexity of practical welfare, even without fundamental consideration of insects as animals that have intrinsic value and their own agency, and the extent to which they are conscious or not and may or may not suffer pain. The great variety of insect lifestyles and lack of accessible information about industrial breeding mean that it is impossible to set general standards for insect welfare or provide meaningful evaluations of current practices. The best guidance that can be offered is to 'keep insects under as natural conditions as possible'. However, even this cannot be adhered to. Conditions in live butterfly exhibits involve compromises. Insects released in billions as biocontrol agents often involve x-ray sterilisation or transgenic procedures and pose environmental risks. For insects bred for human food and animal feed, euthanasia is a pressing issue. Numerous questions and ethical and welfare dilemmas are raised. Despite this, formulation of an Insect Welfare Charter based on respect, and the need to pay more attention to insects, is encouraged, preferably also addressing insects living in the wild.

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C. Carere, J. Mather (eds.), *The Welfare of Invertebrate Animals*, Animal Welfare 18,
https://doi.org/10.1007/978-3-030-13947-6_3

3.1 Introduction

At first mention, insect welfare in captivity sounds a highly specialised subject, relevant to few people. Moreover, while trillions of organisms, not just insects, are killed by habitat destruction, pesticide use and other human activities, concern for captive insects might seem naïve or even a dishonest distraction. Who cares about insects anyway? However, encouraging more respect for insects in general could create better awareness of the many insects in captivity and vice versa, as well as the damage being done to the biosphere by relentless growth in resource consumption. When the facts are set within an ecological framework, the subject becomes relevant not only to scientists and philosophers but also the public. Yet, as we explore below, the issue reveals numerous paradoxes and ethical dilemmas.

While discussing in some detail welfare of bred butterflies—'good' insects for most of us—we mainly consider the multiple uses for which insects are nowadays kept in captivity and bred in billions and the diverse welfare factors involved. Although the issues go well beyond natural science, insights from insect physiology, behaviour and ecology are essential for proper understanding.

Cultural differences affect attitudes towards insects. In advanced economies, these differences are multifold, non-homogeneous and conflicting. Here we take a largely European perspective. We have also chosen a focus on commercially used insects in captivity. Working at the interface between philosophy, natural sciences and the humanities, our arguments necessarily range from 'soft' to 'hard'.

We do not have space to address all of the rich and complex aspects of insect welfare in depth or comprehensively. We needed to restrict citations to a minimum and—whenever possible—we preferably quote recent reviews. Unfortunately, numerous current issues are not dealt with in formal publications, and relevant discussion is often only available from web or grey literature sources. A major problem is the lifestyle diversity of species in captivity in combination with a lack of sufficiently detailed information necessary to permit assessment of their living conditions. Our contribution thus illuminates the breadth or dimensions of the subject but cannot provide proper welfare analyses. Needless to say, insects are animals, and welfare issues discussed for vertebrates are applicable to insects, too—however, insects are in many respects very different. Although final answers to the numerous questions raised cannot be given, we hope to stimulate discussion by providing an overview together with relevant basic ecology and entomology. We also highlight various 'insect welfare dilemmas' that arise in this context.

Terminology

To appreciate the text, it is necessary to comment on two terminological matters: (1) We differentiate various ways of keeping insect in human custody and call it *rearing* when early instars of insects are collected in the wild and kept in captivity until adulthood; *breeding* when several generations are continuously kept in captivity; *farming* when insects are kept outdoors but on plants especially provided for them—in the literature these terms are not uniformly, often synonymously, used; and also 'culturing' (which implies breeding) and 'raising' (which implies rearing).

(2) We here subdivide antagonists (natural enemies of animals) into *predators* (which kill and typically feed on more than one, mostly non-specific prey), *parasites* (which live in or on one or more hosts and do some harm but without necessarily killing them), *parasitoids* (in which each larva feeds on or in a single (typically specific) host, which usually dies as a result) and *pathogens* (protozoans, fungi, bacteria and viruses that cause diseases—in many cases these are transmitted by parasites).

3.2 Insects Around Us and Our Attitudes Towards Them

Everybody during his or her life kills many insects, intentionally and unintentionally. Who will not smite a biting mosquito? As individuals we kill insects when driving a car or playing on a meadow; as societies we destroy habitats of insects and kill many in the course of pest management—not only target species but also uncounted numbers of nontarget, often beneficial ones ('collateral damage' on a vast scale). Even vegetarians (and vegans) among us cannot avoid consuming insects accidentally (Gorham 1979). However, none of these facts invalidates the need to address the issues of insect welfare.

Human attitudes to insects generally seem to fall into three categories:

Dislike: The great majority see insects as bad, dangerous and/or repellent (Kellert 1993)—they are feared or disliked because some sting and transmit diseases, many are annoying and some destroy stored food or clothes, while others are pests in gardens, agriculture and forestry. Many people are phobic of insects and even find them 'revolting' (Lockwood 2013).

Like: A few insects, including colourful butterflies, scarabs, ladybirds and dragonflies, are appreciated and in various cultures receive not only aesthetic appreciation but also have spiritual associations (Hogue 1987; Kritsky and Cherry 2000; Manos-Jones 2000) or are liked for their products (honey) or as 'gardeners' friends'.

Ignorance: The vast majority of insects play no acknowledged role in human life—not even their existence is recognised. Taxonomists have only catalogued a fraction of the several million insect species believed to exist (Stork et al. 2015), and in general very little or even nothing is known of their biology. Admittedly, the majority are small or tiny creatures with a cryptic appearance, often only apparent for short periods of time, or generally not found or seen without special searching and technical aids. This limited knowledge seems largely responsible for the fact that insects do not get the attention they deserve. We share the planet with as few as 5500 species of mammals but over a million insects have already been named and millions more will follow. Insects are different and extremely diverse (see Sect. 3.8), and so unsurprisingly there is much more consistency of opinion regarding vertebrates than insects. Scientific names often reflect human attitudes—beautiful butterflies named after Greek goddesses (e.g. *Troides helena*, *Speyeria aphrodite*), flies named after disagreeable habits (e.g. *Haematobia irritans*, *Calliphora vomitoria*).

We conclude that most humans differentiate between *some* insects but usually consider them only from a personal, anthropocentric view, unaware of their importance in the ecosystems on which all of us depend (Schowalter 2013). Insects play vital roles in ecology and thus—although mostly indirectly—serve human interests ('ecosystem services', e.g. Losey and Vaughan 2006; Stout and Finn 2015). Few insects are in fact dangerous to humans. The biocentric view that *every organism has the right to live* conflicts with the common opinion that *the only good insect is a dead insect*. A unified view has never existed and likely will never be realised, making consideration of insect welfare something of 'a suicide mission' almost bound to end in failure. But a far better informed picture needs to be drawn, because insects are nowadays more relevant to human life than ever before (see Sect. 3.4). We need to pay insects far more respect and far more attention. It is thus good to note that their importance was recognised by the Council of Europe (1986) in their Charter of Invertebrates.

3.3 Insects in Captivity: Historical Changes

Many people worldwide have long made use of insects (Table 3.1), notably opportunistic gathering for food (see Sect. 3.10) and medicine (entomoceuticals; Dossey 2010; Cherniack 2010; Mishra and Omkar 2017a). Only two species have been kept permanently in captivity: about 2500 BCE humans started to use silk and domesticated the silk worm moth (*Bombyx mori*). Even earlier, wild honey was harvested and the honeybee (*Apis mellifera*) subsequently domesticated (see Roffet-Salque et al. 2015), originally for honey and beeswax and recently for assuring pollination in orchards (see Sect. 3.10).

The use of insects as weapons of war, tools of terrorism and instruments of torture has been a practice, even mentioned in the Bible, continued over many centuries (Lockwood 2009, 2012). This represents a transition between wild insects and those held in captivity, and a very obvious connection between welfare and ethics.

Humans live unintentionally with many insects under one roof: silverfish, house flies, cockroaches, meal moths, rice weevils, clothes moths, etc. (Bertone et al. 2016). We now store an increasing diversity of food and other materials in our homes, with the likelihood that additional insect species will become 'uninvited guests'. Such inquilines, like 'pests' in agriculture and forestry, are combated in many different ways.

For many centuries the relations between humans and insects changed little. People did not need to know much about insects because life was largely sustainable (although the word had yet to be coined) and, despite the steady increase in land area transformed for agriculture and forestry, environments remained essentially fully functional for a long time. However, after the mid-eighteenth-century European industrial and agricultural revolutions, followed by the mid-nineteenth-century 'marriage' of science and technology, the situation changed dramatically (White 1967; Berger 1980).

Table 3.1 Necessarily incomplete overview of the diversity of insects kept in captivity, both now and in the past, and the numerous purposes served

Use	Insects	Order	Sample genus	Trade 'product(s)'	Comments	Sample reference(s)
Historic uses						
Special products	Silkworms	LEP	*Bombyx*	Silk from cocoon (pupae)	Pupae also sometimes used as food for farm animals or humans. *Bombyx mori* is domesticated, does not occur in the wild and cannot fly. More recently also 'wild silk' from cocoons of Saturniidae as home industries	
	Honeybees	HYM	*Apis*	Honey, wax, royal jelly	Honeybees are not strictly kept in captivity	
Warfare	Wasps	HYM	*Vespula*		Not only were stinging insects fired into enemy strongholds; bioterrorism also includes insects carrying diseases or causing damage in agriculture	Lockwood (2009, 2012)
Fun	Crickets	ORT	*Gryllus*	Individual adults	Enjoyment of insect song in homes or competitive fights	Judge and Bonanno (2008)
More recent uses						
Research					Uncountable numbers of species and individuals have been and are being reared or bred for studying their physiology, behaviour, genetics, development, etc.	
Hobby	Gentles	DIP	*Calliphora*	Maggots by weight	Maggots bred en masse and traded as bait for fishing	
	Butterflies, moths	LEP	Any	Mainly eggs, pupae, adults in small numbers	Amateur entomologists have long reared insects in captivity for collections; insect lovers also keep various insects as pets, nowadays an increasing trend due to wider availability of interesting exotic species	
	Ants	HYM	*Atta*	individual living queens		
	Beetles	COL	*Pachnoda*			

(continued)

Table 3.1 (continued)

Use	Insects	Order	Sample genus	Trade 'product(s)'	Comments	Sample reference(s)
Feed for small animals	Crickets	ORT	*Gryllus*		Commercial large-scale breeding as food for pets at home, zoos, laboratory animals, etc.	Finke and Oonincx (2014)
	Locusts		*Schistocerca*			
	Mealworms	COL	*Tenebrio*	Larvae by weight		
Medicinal therapy	Blow flies	DIP	*Lucilia*	Maggots in medicinal kits	Maggots clean necrotic flesh from open wounds, releasing antibiotics and promoting healing; applied since middle ages, now on industrial scale	Fleischmann and Grassberger (2003)
Most recent uses						
Entertainment	Butterflies	LEP	*Danaus*	Adult butterflies by dozen(s)	For ceremonial release (in- and outdoors) at weddings, funerals, birthday parties	Pyle et al. (2010)
Education/ edutainment	Grasshoppers	ORT	*Romalea*		Live exhibits as continuous cultures in zoos, museums and butterfly houses	
	Beetles	COL	*Dynastes*			
	Butterflies	LEP	*Morpho*	Pupae by dozen(s)	Live exhibits in zoos, museums and butterfly houses, usually not bred	Boppré and Vane-Wright (2012)
	Butterflies		*Vanessa*	Eggs by dozen(s)	Rearing kits for schools to demonstrate different life stages and metamorphosis	
Conservation	Butterflies and others	LEP	*Lycaeides*		Endangered or locally extinct species are bred in captivity to eventually be released and establish a new population in the field; environmental risks exist re *Wolbachia*	Hughes and Bennett (1991); Pearce-Kelly et al. (2007); Crone et al. (2007)

Pest management	Phytophagous wasps	HYM	*Tetramesa*		Mass-produced parasites for field release to combat exotic weeds, often unsuccessful and associated with environmental risks by influencing nontarget populations	Moran et al. (2014)
	Moths	LEP	*Cactoblastis*			Capinera (2008: 696)
	Phytophagous flies	DIP	*Urophora*			Pearson and Callaway (2003)
	Lacewings	NEU	*Chrysopa*		Biological control of insect pest populations in agriculture and greenhouses but also in households by predators	
	Ladybirds	COL	*Delphastus*			Riddick and Chen (2014)
	True bugs	HET	*Dicyphus*			De Clercq et al. (2014)
	Parasitoid wasps	HYM	*Encarsia*	Infested substitute host or artificial eggs	Industrially mass-bred parasitoids for field release to kill pests or for use in private households against insects feeding on stored products	Sithanantham et al. (2013)
	Fruit flies	DIP	*Ceratitis*	Sterile males	Industrially mass-bred conspecific males for release to reduce fertility of wild females; often in the course of 'eradication programmes'	Krafsur (1998); Dindo and Grenier (2014)
	Blow flies		*Cochliomyia*			Wyss (2000)
Pollination	Solitary bees	HYM	*Megachile*	Pupae	Industrially mass bred for release to pollinate alfalfa	Peterson and Artz (2014)
	Bumble bees		*Bombus*	Queens, international	Pollination of greenhouse or field crops, with various environmental risks such as spread of pathogens	Owen et al. (2016)
Food/protein for humans	Crickets	ORT	*Achaeta*	Adults or powdered specimens	Currently for restaurants or as ingredient of power bars or for insect burgers; in the future to provide basic food and/or to substitute vertebrate meat	van Huis et al. (2013, 2014); van Huis (2015); Shockley and Dossey (2014); Dossey et al. (2016); Mishra and Omkar (2017b)
	Grasshoppers		*Locusta*			
	Mealworms	COL	*Tenebrio*	Larvae or powdered specimens		
Feed for poultry and fish	Saprophagous flies	DIP	*Hermetia*	Puparia or as meal/flower	Saprophagous flies are reared on animal dung and/or organic waste in increasing amounts to recycle it and obtain, at the same time, eco-friendly substitute for fish meal to feed poultry and fish	Khusro et al. (2012); Riddick (2014)
			Musca			Hussein et al. (2017)

COL Coleoptera, *DIP* Diptera, *LEP* Lepidoptera, *HET* Heteroptera, *HYM* Hymenoptera, *NEU* Neuroptera, *ORT* Orthoptera

Modern agriculture and silviculture have created superabundant crops, often in the form of monocultures. Certain formerly unnoticed insects can now multiply rapidly on these resources, and, as a result, they can become pest populations. This has brought us into a new type of conflict with nature—albeit an altered nature largely of our own making. The monocultures, supposedly necessary to feed our burgeoning population, have encouraged the invention and widespread release of poisons (pesticides): insecticides to kill insects directly, as well as herbicides to kill 'weeds'—which for many insects are larval or adult hostplants. Further, keeping stock in large numbers (e.g. sheep, cattle) brings disease-causing and disease-transmitting insects into focus (e.g. flystrike, blue-tongue; see Sect. 3.10).

Over the same time period, more and more people live in cities—currently more than 50%. City dwellers are increasingly alienated from nature, according to some resulting in undesirable psychological conditions such as biophobia (Orr 2004) and 'nature-deficit disorder' (Louv 2005; Dickinson 2013).

Counter-intuitively, these changes have resulted in taking more and more insects into human custody (Table 3.1). Widespread use of non-specific pesticides has enormous impact on nontarget organisms (many of them beneficial) and even entire biocoenoses. The search for more 'environmentally friendly' means of biocontrol *s.l.* includes industrial production of various antagonists (see Sect. 3.10), seen as desirable not only to control outbreaks of native species but also invasive exotics—themselves often moved around as a result of our ever-increasing global trade. Honeybees, in many areas, having become slaves of crop industries, as well as many other pollinators and insects in general are in decline, and a pollinator crisis is being debated (Levy 2011; Martin 2015). We seek to support pollination by breeding huge numbers of solitary bees and bumblebees in captivity for targeted release (see Sect. 3.10).

With the human carrying capacity of the Earth arguably already exceeded, as a result of this overexploitation, we face a food crisis, in particular a lack of protein (Drew & Lorimer 2011). In response, it is suggested we produce insect protein on an industrial scale for food and feed (see Sect. 3.10), and terms such as 'minilivestock' for mass breeding of insects are coined (Defoliart 1995, Paoletti 2004; see Sect. 3.10). More and more species of insects are now used in research, education and art (Table 3.1).

Perhaps reflecting a reaction against our disconnect with nature, an increasing number of people now keep insects as pets, or as a hobby (including 'urban beekeeping'). In pre-industrial societies, this was probably very rare—although, for example, it has been a custom in China since the eighth century to keep crickets as 'pets', to enjoy their singing and especially fighting (Judge and Bonanno 2008). With the arrival of Internet communication and fast courier services, it has become easy to obtain exotic insects for hobby purposes, including walking sticks, beetles, cockroaches, praying mantids, ants and grasshoppers. Interestingly, not only 'nice' insects but also 'interesting' ones are thus taken into human custody. The Internet also provides background information on pet insects, including 'care sheets' aimed at proper husbandry. Many zoological gardens now exhibit some insects too, and over the past 30 years, dedicated live exhibits of butterflies for edutainment (butterfly houses; see Sect. 3.9) have added significantly to the growing number of insects in human care.

3.4 Insects in Captivity: A Necessity?

A list of insects held in captivity and their major uses (Table 3.1) may come as a surprise for many of us because captive insects largely escape our attention. Table 3.1 gives an overview not only of the numerous uses but also the range of insects involved and indicates the diversity of their lifestyles.

The rather small number of species regularly held in captivity belongs to about one third of the 27–30 recognised orders (major groups) of living insects: grasshoppers and crickets (Orthoptera), stick insects (Phasmatodea), cockroaches (Blattodea), plant lice and assasin bugs (Hemiptera), lacewings (Neuroptera), beetles (Coleoptera), true flies (Diptera), butterflies and moths (Lepidoptera) and ants, bees and wasps (Hymenoptera). While the number of species bred does not exceed several hundreds, the number of individuals is in the order of trillions (see Sect. 3.10). The different groups (and usually individual species) have various and often very different lifestyles and require their particular requirements to be met fully if they are to be maintained successfully in confinement (see Sect. 3.8).

For basic research, innumerable species of all kinds have been taken into the laboratory, mostly for limited periods (although *Drosophila* species have been bred for over a century). Because of space limitations, we say nothing further here about the welfare of insects used in basic research (but see Crook 2013).

Great differences in the numbers of insects held captive are due to who keeps them, and their purposes: hobbyists just keep a few individuals for a while, or typically rear a single generation; in contrast, commercial businesses continuously breed insects en masse as feed for zoo and pet animals, silk, education, pest management and pollination. The greatest numbers are (or potentially will be) bred for pest control and obtaining insect protein as food and feed (see Sect. 3.10). To be able to produce chosen insects on an industrial scale, we presume that during the initial search for optimally efficient breeding regimes, huge numbers may be sacrificed (see Sects. 3.9 and 3.11). The number of individual bred insects already exceeds the number of vertebrates held in captivity.

Not many insects currently kept in captivity could readily be substituted without impact on our daily lives, or our environment—even if we would not be directly aware of it. Commercial production of silk from domesticated as well as wild silkworms to make a minority luxury product can be seen as unnecessary because alternative materials are available. However, for the sake of our managed ecosystems and human well-being, breeding certain insects in captivity (and often later releasing them; see Sect. 3.10) has become a necessity and will become even more important in the future.

While the use of commercially produced parasitoids, for example, serves the profit of some farmers (as well as those producing the insects), breeding and releasing antagonists seems, at first sight a least, far healthier for our societies, more sustainable for the environment and more ethical (cf. Pimentel et al. 1980) than application of non-specific insecticides. The only alternative would be largely to abandon monocultures and return to small-scale farming—likely a fantasy in our globalised world, despite possible greater per-hectare productivity, sustainability and conservation potential of the latter (e.g. Perfecto and Vandermeer 2010).

3.5 Human Attitudes to Insects and Insect Welfare

In parallel with increased captive insect breeding, human views about nature in general and animals in particular have been changing. Despite concerns about harm, cruelty and disrespect to animals going back to the philosophers of ancient Greece and long expressed by some eastern religions, in the modern west the term 'animal welfare' only came into common use over the past 50 years. There is public debate about 'humane' keeping of chicken, cattle and other livestock, and zoos are improving their ways of keeping exotic animals to provide their specific requirements (Kohn 1994).

Animal welfare is thus a current issue (see Eadie 2012) receiving more and more public attention. While 'insect' does not appear once in Eadie's overview, to our surprise, in Animal Welfare, a journal published by the Universities Federation for Animal Welfare (UFAW 2017), insects so far seem not to be an issue either.

The conservative philosopher Sir Roger Scruton (1998) has written: '. . . it is only with a certain strain that we can care for the wellbeing of individual insects, even though we recognise that they suffer pain and fear, and are often hungry and in need like the other animals'. Although insects belong to the Kingdom Animalia and are thus undeniably 'animals' in a scientific sense, Scruton accurately describes the *dis*affection many people feel towards them. Speciesism towards insects is thus unlikely to be challenged by anyone other than animal rights activists. And this is enshrined in the laws of many countries which (deliberately) *ex*clude insects (and indeed most animals other than vertebrates) from legislation concerning cruelty and welfare. Before the law of most countries insects are literally of no account.

Sekimizu et al. (2012: 226) suggested using the silkworm moth *Bombyx* for drug testing in Japan, instead of 'sacrificing model animals' such as mice and rats, to circumvent animal welfare requirements. As they put it, '"Animal" addressed in the Act can be defined as a "vertebrate animal". If we can make use of invertebrate animals in testing instead of vertebrate ones, that would be a remarkable solution for the issue of animal welfare'. Clearly Sekimizu and co-authors considered insects—from legal, welfare and perhaps moral, ethical and emotional perspectives—to be qualitatively different from vertebrates.

In contrast and at the same time, slowly and not yet universally, insects are also coming into consideration (Horvath et al. 2013; Broom 2013). Discussion is so far largely limited to the most obvious cases of insects that are either liked (e.g. butterflies) or perceived as 'good' in some way. In particular, extensive discussion about bees, sometimes treated 'unnaturally' and 'disrespectfully' (Imhoof & Lieckfeld 2015), has raised awareness about the treatment of insects in human custody and posed moral and ethical questions. It is a serious issue although parodied by some (e.g. www.insectrights.org). More significantly, the now widespread focus on bees as pollinators to the exclusion of all else runs a real risk of oversimplifying general understanding of ecosystems, with attendant risks for biodiversity (Smith and Saunders 2016).

The exhibition of live butterflies in windowless rooms as objects of art by Damien Hirst at Tate Modern has resulted in some public protest (Nikkhah 2012; Cashell 2009: 159). Increased awareness has also made people reflective about other practices. The traditional way of obtaining silk from silkworm cocoons, involving 'cruel' killing of the pupae by boiling, is now also subject to public criticism, and silk is increasingly questioned by some as an unethical product (Plannthin 2016). The application of pesticides is mainly discussed in relation to harming environments, but the ethics of en masse killing of insects in our environments is also a matter of discussion (e.g. Pimentel et al. 1980; Lockwood 1996; Bentley and O'Neil 1997).

Does the fact that some people condemn the use of silk on grounds of cruelty indicate a fundamental change in (western) perceptions of insects? While a majority of people still do not like 'creepy crawlies' and care little for their welfare, increasing concern is being expressed about human responsibilities towards an ever-wider range of organisms. This has been termed 'ethical extensionism' (Engel 2008; see also Favre 1979; Singer 2011).

Traditionally, Western philosophy generally limited moral concern to living human beings. Extensionists claim this speciesism was based on false understanding of ethics and moral theory and that our concerns should be expanded to include humans yet unborn, arguably all sentient animals and even, according to some, all living organisms. There are two major variants of extensionism—utilitarian and deontological.

As Blackburn (2001) has suggested, 'We are often vaguely uncomfortable when we think of such things as exploitation of the world's resources'. Utilitarian extensionism regards organisms as natural resources which we need to deal with or treat in an ethical manner. This can be reduced to the claim that any organism capable of experiencing pain has an interest in avoiding suffering. According to Singer (1975, 2011), this then requires humans to take account of the interests of all sentient organisms. In our context the question then becomes: are insects sentient, and can they experience pain as a result of human activity (see Sect. 3.7)?

In fundamental contrast, the deontological or rights approach, as advocated by Regan (1983), is based on the notion that all conscious creatures are 'experiencing subjects-of-a-life' (ESLs). Their own welfare and needs are important to them without regard to other organisms, including humans. In effect this is an extension of Kant's respect-for-persons principle (Dillon 2016)—which, if accepted, leads to the conclusion that we have a duty of respect towards all ESLs because of their independent agency and own intrinsic value. Consequently, they should never be treated solely as a means to some (human determined) end (Engel 2008). Or as Samways (2005: 11) has put it, specifically in our context here, 'Do we have the right to assume that insects do not have rights?'

There are further, more nuanced, variants of extensionism, some of which Engel (2008) explores. For example, Paul Taylor's (1986) synthesis leads to an egalitarian biocentric ethic which argues that 'every living organism deserves equal moral consideration' (Engel 2008). By extending such equality to every living being, Engel asks if Taylor has thereby taken extensionism 'to an absurd extreme'. Thus 'Respect for all living things would require settling conflicts between persons and non-persons in ways that are fair to both' (Dillon 2016). This might sound good in theory, but in practice to decide on conflicts that inevitably arise between the supposedly equal interests of different organisms in general, one is reduced to making up more or less *ad hoc* rules (as Taylor himself tried to propose). Do we really need a complex rule book to decide upon the morality of smiting that mosquito? To many people such arcane arguments only seem important to those of us fortunate to live a life of plenty—are we in danger of inventing a 'luxury problem' in more than one sense of the word? So we are left with irresolvable ethical dilemmas.

Another variant (not without its own considerable problems: Sander-Staudt 2017) is 'care ethics'—which seeks to ground moral treatment of animals 'not in rights or utilitarian considerations but in our sympathy for animals and relationships with them. By grounding moral duties in sympathy and relationships, care ethics avoids some of the more problematic elements of other animal welfare positions' (Engster 2006). Donald Broom holds the view that our actions towards others, including other animals, should be based on obligations (cf. Lockwood 1987), stating recently that 'all animal life should be respected and studies of the welfare of even the simplest invertebrate animals should be taken into consideration when we interact with these animals. Even if we do not protect the animals by law, we should try to avoid cutting an earthworm in half, mutilating a snail or damaging the wing of an insect' (Broom 2014: 200). But even if we are willing to accept notions of interests, rights, care ethics or obligations, in the end the question is not, for example, if we should keep insects in captivity at all, or how we might justify which ones we keep and for what purposes, but something far more operational—how and on what basis can we establish appropriate welfare practices when we 'interact' with insects, justifiably or not?

Human Attitudes to 'Nature'

Humankind has not just different attitudes to insects but to nature in general. Not only the beauty or ugliness of different organisms is a matter of individual taste and influenced by culture but also their behaviour. In nature what many westerners would call 'brutal' is common (hunting and killing), and there is much cheating which we do not want as standard for us. We do not need to accept rules of nature as rules for human behaviour, but we do need to acknowledge species-appropriateness. We are a different species!

If we accept that, does respecting organisms in captivity mean taking care of them appropriately, on their own terms so-to-speak, even if this, potentially, is not appropriate for us? Among ourselves we mostly aspire to accept different cultures. So in parallel, don't we have to accept nature even with its often, in our terms, ugly and cruel ways? We have to accept the existence of insects, even 'dangerous' ones, and respect their individual lives. Do we therefore accept that our feelings and values with respect to living conditions and lifestyles are fundamentally different to the reality of insects in the field and that we cannot apply our (culturally determined) views to nature? Or do we want to establish ethical rules superior to 'rules in nature' because of our disgust?

We can change nature significantly, we can even modify organisms genetically—but not the intrinsic rules of life. Nature inevitably entails struggle and competition, and, except within a few social mammals such as monkeys, elephants and cetaceans, the life of the individual largely appears 'unrespected' (see Sect. 3.7). In thinking about insects in captivity—which moreover unlike many vertebrates never become companions, or 'bond' with their captors—to develop any principled ethical basis, we will have to decide between human culture-appropriate vs species-appropriate measures. Thus 'nature', depending on this decision, may or may not offer us a basis for establishing principled, ethical guidelines (see Sect. 3.7).

3.6 What Makes Insects Different, What Differences Occur Among Them, and How Do These Differences Relate to Welfare in Captivity?

Insects have basically the very same functional organisation as ourselves and other vertebrates, including nervous, digestive, respiratory, motor and reproductive systems. But with millions of species and countless trillions of individuals, abounding in every terrestrial ecosystem from the poles to the tropics, including high mountains, and fresh and brackish waters, they are often considered one of the most successful groups of organisms on Earth. What can explain this?

Insects are invertebrates, and, although belonging within the major phylum Arthropoda, they are in many ways incomparable to most other groups of organisms. They share with all arthropods jointed limbs, and their special cuticle confers numerous advantages (Watson et al. 2017). Other factors that arguably contribute to their success include small size (imposed by respiratory constraints and their exoskeletal structure); short generation times (often only days or weeks); high reproductive rate; sophisticated sensory and locomotor abilities (including powered flight in the adults of most species); countless, often specific biotic relationships with plants and other organisms; and metamorphosis (Gullan and Cranston 2010). Mayhew (2007), however, challenged a number of these ideas as lacking decisive evidence—but still accepted 'complete metamorphosis' as one of the most likely key factors. Metamorphosis has many important consequences for insect biology—and thus for thinking about insect welfare.

Metamorphosis In those taxa exhibiting incomplete metamorphosis (hemimetaboly: grasshoppers, cockroaches, lice, etc.), the first instar that hatches from the egg is somewhat like a small adult—but lacks functional wings and genitalia. It then grows through a series of discrete stages ('instars'), each separated by moulting. The last larval moult gives rise to the adult, the final and only stage that can fly and reproduce.

In contrast, in those insects exhibiting complete metamorphosis (holometaboly: butterflies, moths, flies, wasps, beetles, etc.), all the early stages are completely different from the adult. When the final larval instar moults, the adult is not revealed but, instead, a further distinct stage appears, the pupa, which is immobile and does not eat. Inside the pupal exoskeleton, the whole organism is transformed into an adult which, when the process is complete, emerges as a creature radically different from both the larval and pupal stages—not only in appearance but also in biological needs and functionality.

Differentiating between early stages and adults makes us aware that, in holometabolous species particularly, a single individual has in effect several lives, looking and behaving very differently, having different antagonists, often requiring different resources in its different stages (both abiotic and biotic: consider, e.g. the different lives of maggots and the flies they become or caterpillars and butterflies). Keeping insects in captivity therefore poses various welfare and husbandry challenges that are not only different from vertebrates but more complex in addition.

Individuality and insect life cycles René Descartes famously declared that animals are simply machines (Hatfield 2018, see also Hatfield 2008). However, few now consider organisms to be automata—neither are they robots nor, generally, clones. We thus need to consider the needs of individuals and, especially, *individual life cycles*, and not just base discussions of welfare on abstract concepts such as 'species' and 'species-specific differences'. Species can be defined as reproductive communities. However, within a given species, there are heritable as well as environmentally induced differences between populations, and, within populations, differences at the level of the individual are universal. Most (although certainly not all) individual insects are the result of sexual reproduction, and almost all are genetically polymorphic; as a result, even with respect to genetics alone, we can safely assert that the great majority of individual insects are unique. This is to be considered in addition to the 'individuality' issue (e.g. Carere and Maestripieri 2013). Insects, when forming a superorganism, can respect other individuals: *Megaponera* ants after fights with termites rescue their injured sisters (Frank et al. 2017).

3.7 Living in the Wild vs Living in Confinement

Here we address the reality that the welfare of insects in captivity potentially involves a complex mix of issues including stress, loss of individual choice (denial of their agency), suffering, pain, sentience, even aesthetics—and the subjectivity of our individual moral views and how we collectively comprehend the 'nature' of nature itself. This opens a huge debate which can only be touched upon here. Discussion can be intense, emotional and non-objective. As an aid to thought, we offer a few facts or realities that are not well recognised, if recognised at all, in the current welfare and ethics literature.

Stress

Living inevitably involves stress, in whatever way the word is defined (e.g. 'stimulation beyond the capacity for complete adaptation': Broom and Johnson

1993). In the wild, animals experience stress related to abiotic factors, including light, temperature and moisture, in addition to biotic pressures such as obtaining food, defence against enemies and the struggle to reproduce (finding a partner and a suitable host(plant) or substrate)—all usually involving competition. Many of these unavoidable 'natural stresses' are more or less eliminated in well-managed captivity. Confinement can offer optimal abiotic conditions, abundant food and considerable protection from enemies, as well as meet many other basic needs—resulting in high survival rates right through to the adult stage. But such benign conditions are in fact *un*natural. Thus Hoffmann and Ross (2018) comment that 'Laboratory-adapted lines tend to be more sensitive to stress, likely reflecting relaxed selection for stress-related traits' (see also Garnas 2018).

Survival and Reproduction

In nature, biological fitness (contributing to the gene pool of a population through individual reproductive success) is only achieved by relatively few individuals. In an intact ecosystem, all populations are approximately balanced, i.e. they remain quite stable over time even though they undergo fluctuations. Looking at numbers demonstrates the challenge: of N eggs laid by a given female insect, on long-range average only two become parents, whether $N = 50$, 500, 5000 or any other number. Generally, the same is true for offspring of all animals and plants. This implies that, in untouched nature, the vast majority of individuals die or get killed long before they can achieve biological fitness, most serving as food within the ecosystem. In contrast, in captivity the vast majority of individuals survive to adulthood—but we often then deny all of them any chance to reproduce. Is this right, ethically? It is noteworthy that the insects living in human-made monocultures often do, at least for periods, mass reproduce—just as insects in households; an anthropogenic habitat reduces stresses they would naturally experience.

Animal Behaviour and Public 'Taste'

Not everything that animals do (in the wild or captivity) is appealing to us or readily meets our 'standards'. Many if not most of us consider certain hunting strategies or food preferences 'disgusting', even though it is species-appropriate. Infanticide among animals is widespread (Hrdy 1979). Does our tendency to be repulsed by such behaviours relate to welfare? Not directly, but such reactions almost certainly affect public opinion or 'taste'—and ethics, morals and thus welfare may seem as much 'emotional' as simply 'technical', 'scientific' or 'principled' issues.

Insect lifestyles are also more or less likeable/acceptable from a human perspective. Many fly maggots feed on faeces, dead bodies or rotting plant material; praying mantids consume their insect prey without prior killing; and pompilid and sphecid wasps provision their burrows with paralysed spiders or insects, respectively, as food for their developing larvae—this way, the hosts don't decay and their blocked nervous system prevents escape. The grubs of most parasitoid wasps (e.g. Chalcidoidea, Ichneumonidea) feed inside the still living larvae or pupae of butterflies, moths and other insects. What appears disgusting to us is, billion-fold, an everyday reality in nature all around us—many pages could be filled with further examples. Such realities have to be accepted as 'natural'. But do they clash with measures for the welfare of animals held in captivity?

Suffering and Pain

Some of the more grisly insect examples above provoke the question *Does nature inevitably entail suffering and/or pain*? And if so, is this different or not from vertebrates (Elwood 2011)?

As insect physiologist Sir Vincent Wigglesworth (1980) now famously asked: Do insects feel pain? Since pain cannot be measured objectively, it is a matter of continuing debate if, e.g. physical injury, temperature extremes, noise, thirst, hunger, poisoning and/or irradiation cause pain or suffering in insects (e.g. Eisemann et al. 1984; Lockwood 1988; Smith 1991; Elwood 2011; Broom 2013; Sneddon et al. 2014; Tiffin 2016; Adamo 2016).

Many discussions appear human-centred—about what we do, as agents, to insects. The debate has rarely if ever touched on 'natural cruelties' like those briefly mentioned above. Is, for example, moulting of a larva which not only affects the exoskeleton but also internal structures (the fore- and hindgut and entire tracheal system) or the transformation of larval into adult organs inside a pupa which—like the moulting larva—definitely has a functioning, complex nervous system associated with pain and suffering? Should we feel sorry for this struggling, seemingly almost desperate creature—or is it really oblivious to this process and we unjustifiably apply human feelings? The new debates on insect consciousness (e.g. Barron and Klein 2016; Klein and Barron 2016) and emotions (Mendl and Paul 2016) suggest that the neural capacities of insects, and the affective states they may experience, could be far richer and more sophisticated than hitherto believed.

The European Food and Safety Authority (EFSA 2005) lists nonsocial insects in 'Category 2—The scientific evidence clearly indicates, either directly or by analogy with animals in the same taxonomic groups that animals in those groups are NOT able to experience pain and distress'. In light of the above, this EFSA edict seems far from convincing.

Nature Does Not Respect Individuals

Summarising, on an ecosystem level all organisms (including plants) are 'simply' individual entities, potentially providing food for others, nothing less but nothing more. That's how nature works and implies that nature in general does not respect individuals; individuals do not have intrinsic rights (even if we perceive them as having intrinsic value as 'things-in-themselves')—in sharp distinction to our 'intellectualised' values. We give them 'rights'—or not—according to our convictions.

3.8 Peculiar Welfare Standards for Insects?

Living conditions In general, one might think for animal keepers it would be in their own interest to look after their livestock as well as possible—but this is not always the case, particularly when commercial mass breeding is involved. As we all know from the chicken farm debate, animals can be accidentally or even deliberately mistreated without precluding the goal of keeping them. Chickens may have wounds and no feathers and never see natural light—but they can still lay nutritious eggs; farmed mammals may receive inappropriate food but still provide meat.

A general rule seems to be that most vertebrates have a much higher tolerance of poor, species-inappropriate conditions than insects, at least for significant periods of time. In other words, there are fewer options for inappropriate keeping of insects compared to vertebrates; it is thus less likely that insects can be kept alive under 'inhumane' (species-inappropriate) conditions. While most vertebrates can survive—within relatively wide limits—on inadequate food and/or under poor space and unfavourable light and climatic conditions, with insects their plasticity limits are much narrower. Being ectotherms, thermoregulation is more difficult—notably in captivity. Humidity levels can be critical. Many phytophagous species can only eat a very small range of plant species (comparable in this way to, e.g. the giant panda) and so on.

Consequently, to keep insects in captivity, it is generally essential to practise more precise husbandry compared to that needed to maintain vertebrates. Vertebrates can be neglected for days, sometimes weeks, but insects will often die within hours or even minutes if conditions are not right. Good artificial diets for insects, essential for mass breeding (see Sect. 3.10), are notoriously difficult to create (Morales-Ramos et al. 2014a, b), requiring far more precise formulation than the pellets and biscuits produced for, e.g. chickens or dogs.

Veterinary practices Vertebrates face a variety of diseases that are similar or comparable to human illnesses, and a huge discipline (veterinary science) takes care of this with a great repertoire of prophylactic and curative medicines, surgical and other procedures. Medicinal means (vaccinations, etc.) are *always* necessary to keep vertebrates in captivity for prolonged periods, but for insects such means are not available.

Insects are also heavily affected by pathogens (viruses, bacteria, fungi; Rolff and Reynolds 2009; Vega and Kaya 2012; Eilenberg et al. 2015; Maciel-Vergara and Ros 2017). De Goede et al. (2013) conclude that it is 'practically infeasible to provide insects in rearing facilities the freedom from diseases'. Although insect pathology is a growing subject, including the ecology of naturally occurring diseases (e.g. Hajek and Shapiro-Ilan 2018), effective treatment remains almost impossible—prophylactic methods, including hygiene and culling, are the main means for control (Eilenberg et al. 2015). In a valuable review of the threat of viruses to mass-bred insects, Maciel-Vergara and Ros (2017) suggest the possibility of RNA interference and transgenic technologies.

Special manipulations and interventions For some purposes highly unnatural treatments of insects, which can and probably do add very unnatural stresses, are unavoidable to meet the goals of breeding them. To produce infertile individuals for release to control fruit flies, mosquitoes and screwworm, for example, billions of individual insects are subject to various manipulations, including sterilisation by exposure to x-rays (see Sect. 3.10).

These mass release cases present major issues if we wish to approach insect welfare from an extensionist position. From a utilitarian interpretation, we are clearly not taking account of the insects' interests, at the very least with respect to reproduction. From a deontological perspective, we are surely using the insects merely as a means to an end. However, given that we now have technologies to produce, e.g. 115 million screwworms and 5×10^9 medflies per week (Leppla et al. 2014; see Sect. 3.10) with the potential to greatly reduce suffering and save the lives of thousands if not millions of humans and other mammals (many of the latter already in our care), or make a major contribution to environmental health by reducing the need for insecticides, is it ethical *not* to use insects in this way? More generally, should we or should we not trade-off mistreatment and exploitation of one organism versus 'avoidable harm' to another—with or without considerations of human self-interest—representing yet another ethical dilemma?

There are other interventions to consider. For example, selective animal breeding has been practised for many hundreds of years and is generally accepted—but how and in what way does this differ from the production and release of genetically modified organisms (GMOs) using modern biotechnologies (Benedict 2014)—often the subject of heated debate? The existence of GMOs, produced in captivity and then accidentally or purposefully released into the wild, has unknown environmental consequences and raises many ethical issues, not least regarding the organisms themselves (Ormandy et al. 2011; GeneWatch UK 2015) and our relationships with them (Schicktanz 2006).

Context dependency A further complication concerns context-specific behaviour and human self-interest. For example, the green bottle fly *Lucilia sericata* lays its eggs on open wounds, where the larvae normally develop on the necrotic tissues. Sheep are a frequent 'target', and this can result in 'sheep strike'—if the available wound material becomes insufficient to feed all the growing fly larvae, they will invade the living flesh of the sheep and cause injuries so gruesome they can even lead to death (Hall et al. 2016).

Prevention of sheep strike by the use of insecticides is obviously an economic concern as well as a welfare issue for sheep farmers. Further, the same fly species is being used purposefully to heal humans by controlled 'maggot debridement therapy (MDT)'—which is dependent on both the local release of powerful antibiotics by the larvae and their effective 'microsurgery' in cleaning necrotic and infected wounds (Sherman et al. 2000; Fleischmann and Grassberger 2003; Hall et al. 2016). Thus the enemy of the sheep and the farmer can be the saviour of an ulcerated senior citizen. Many people are disgusted by maggots—but in this context they are of great help to us and are even bred industrially for such medicinal use and disease management (see Sect. 3.10). All these conflicting human values and interests affect our approach to the welfare of maggots bred in captivity.

Do the ends ever justify the means? Paradoxically, some ethical questions become even more acute where we can be confident that the overall environmental consequences are likely to be minimal. In reviewing the great potential for 'gene drive' genetically engineered mosquitoes (e.g. Carvalho et al. 2014; Hammond et al. 2016) in the 'war' against malaria, Eckhoff et al. (2017) call for 'the development of a robust governance framework codesigned by all interested parties'. However, it is not at all clear if the mosquitoes let alone the plasmodia they may carry are to be included as parties with interests (sensu Singer 2011).

What Standards Can Be Established?

The above suggests that setting general (or principled, ethical) standards for insect welfare in captivity is an impossible task. Due to the functional diversity of insects, and the wide range of purposes addressed by keeping them, generalised criteria cannot be formulated—simply there is no 'model insect' with respect to development, food, behaviour, ecology, etc. from which general conclusions could be drawn. More specialised husbandry is nearly always necessary to keep insects successfully—which means that the possibilities for 'chronic' mistreatment of captive insects are, fortunately and incidentally, reduced (although unintended killing is all too easy). Keeping insects in captivity depends on replication of the key conditions, requirements and processes they experience in the wild. To show proper respect, this means setting aside any idea about applying 'human standards' in favour of delivering species-appropriate and species-specific welfare. A rule 'keep insects under as natural conditions as possible', taking species-appropriateness into account, looks to be about the best guidance that can be offered—even though, as already discussed, perfectly 'natural' stresses are relieved and new stresses induced—and in some circumstances, 'mistreatment' may be justified if the ends arguably preclude terrible suffering or death for other organisms. This further underlines the conclusion that personal feelings about what might or might not seem 'natural' or desirable for us, or any feelings of disgust and repulsion, cannot play a role in setting welfare standards for insects.

The 'Five Freedoms': A Way Forward?

The 'Five Freedoms' approach to animal welfare developed in the 1960s as a result of growing concerns over farm animals such as chicken and veal calves being mass bred in intensive confinement (FAWC 2009). The Five Freedoms (FF) can be summarised as freedom from thirst, hunger and malnutrition; from thermal and physical discomfort; from pain, injury and disease; from fear and distress; and freedom to express normal behaviour (Webster 2016).

De Goede et al. (2013, see also Erens et al. 2012) recently considered extending the FF framework to the management of mass-bred insects. As they discussed, while several of these freedoms can be helpful in addressing care-standards for insects, freedom from contracted diseases, as we have already noted, is unrealistic due to the lack of veterinary procedures, and freedom to express normal behaviour is very difficult to implement—not least because so many mass produced insects are first subject to manipulation (e.g. sterilisation) and then released. Moreover, there is evidence that just the process of breeding or even simply rearing insects in confinement can alter behaviour (e.g. Jandt et al. 2015). De Goede et al. (2013) also point out that the Five Freedoms are essentially about ethical standards rather than science-based prescriptions for actual welfare—although there have been proposals to make the FF approach operational, such as the 2004–2009 EU WelfareQuality project (e.g. Botreau et al. 2007).

Others have called for more positive ‘five domains’ or ‘quality of life’ approaches to animal welfare (Green and Mellor 2011; Mellor and Webster 2014), or welfare founded on capacity for change (allostasis), leading to ‘a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity’ (Korte et al. 2007). Thus the concepts of animal welfare are becoming more diverse and more nuanced (Hagen et al. 2011; Maple and Perdue 2013; Plannthin 2016). Even so, Webster (2016) reaffirms FF principles as ‘timeless’ and ‘a memorable set of signposts to right action’. Thus the Five Freedoms, as De Goede et al. (2013) have suggested, appear to offer the most appropriate framework to advance welfare principles and practices for the mass breeding of insects (cf. Taponen 2015). We next look at a specific example where the Five Freedoms could be used for welfare guidance in the future.

3.9 Butterflies in Captivity: What for and How?

Tropical butterflies are addressed as an example for insect welfare, being well-liked and the most widely known insects held in captivity. This involves all life stages, with the adults being used in various ways. Despite our reservations about generality, many of the issues are relevant for other insects—some of which are now mass produced in billions (see Sect. 3.10).

Although most consider adult butterflies beautiful, their early stages are often viewed as ugly ‘worms’. But ‘What the caterpillar calls the end, the rest of the world calls a butterfly’ (Lao Tse). While caterpillars serve few if any human utilitarian needs (but see Sect. 3.10), the butterflies they become are used in live butterfly exhibits (butterfly houses, butterfly zoos) for edutainment, outdoor and indoor release at events, souvenirs and raw materials for artworks. These uses are partly conflicting with respect to the ‘moral domain’.

Mass Production of Butterfly Pupae

Mass production of butterflies mainly happens in tropical countries. Annual global production of live butterfly pupae as a cash crop represents a multimillion dollar industry, with numerous stakeholders (Boppré and Vane-Wright 2012). Producers vary from single individuals to small- to medium-sized businesses (‘butterfly farms’). Trading is usually done by dealers who ship pupae internationally.

Factors affecting welfare include food, water, temperature, light, humidity, density, antagonists and hygiene. Different butterflies require more or less different conditions and treatment at all life stages (eggs, each of the several larval stages, pupae, adults). While most butterfly larvae live individually and can become cannibalistic if crowded, some species have gregarious larvae, thriving and even pupating in groups. Some 200 (1%) of the 20,000 world butterfly species are bred commercially, although about only 30 account for the majority.

How the many hundred butterfly farmers handle their cultures is uninvestigated and unmonitored. Some raise larvae in cages or boxes on cut foodplants; others keep larvae under ‘sleeves’ on living trees. Several manuals provide information on the basic biology and keeping conditions of commonly bred species (e.g. Stone and Midwinter 1975; Venters and Rogers 2001; Harberd 2005; Aisi et al. 2007; Montero 2007), but they do not address welfare. Even so, it is reasonable to assume all early stages, and those adults needed to found the next generation, are generally well treated—otherwise the farmers would not get enough healthy pupae to sell (see Sect. 3.6). Butterflies (in contrast to many other insects) do not lay eggs in unsuitable conditions, in particular without having species-specific hostplants available. Larvae will fall ill and die if they do not get correct or sufficient food. The same is true if they are forced to live too densely, suffer inappropriate physical conditions or are exposed to predators and parasitoids.

However, species-inappropriate treatments almost certainly occur at least occasionally within the butterfly house industry, notably during the ‘self-training’ phase that most novice breeders go through—but this cannot be chronic; otherwise insufficient pupae would be produced for sale. Nevertheless, with continuous breeding diseases often build up, and so rigorous hygiene is essential (Lees 1989). Failure can lead to 100% mortality—but such events are not reported and escape analysis. If breeders are happy to get much less than 90% of eggs or larvae through to the pupal stage, then conditions for welfare are definitely wrong.

If butterfly producers consistently and repeatedly rear from gravid females taken from the wild instead of breeding from their captive stock, this is not sustainable, and there is thus environmental concern. However, with respect to the lives of the individual insects once in captivity, the welfare issues are the same.

Shipping of Butterfly Pupae

Shipping creates potential for mistreatment. However, perhaps even more than at the breeding stage, it is in the dealers economic interest that pupae reach customers in good condition. There is now much experience on shipping pupae successfully, and welfare does not appear to be a significant issue.

Live Butterfly Exhibits

Butterflies are generally seen as beautiful and harmless and thus have greater potential for creating environmental awareness than other insects. Butterfly houses have become popular because they delight and entertain people, young and old. They can then also make visitors aware of the ecological diversity of insects, and how invertebrates play key roles in the ecosystems on which we depend. In other words, butterfly houses can offer an entertaining yet revelatory introduction to ecological literacy and the needs for conservation (Boppré and Vane-Wright 2012).

For this ‘edutainment’ to be realised, butterfly houses need not only to be well organised with respect to education but also care for their live butterflies properly. Adult butterflies have quite different requirements to their larvae, with fundamental consequences for welfare. Several countries have established rules on how a butterfly house must be run and which species can be exhibited; however, these focus solely on 'security' (environmental safety) (USDA 2002) and do not address welfare.

As natural as a butterfly house might look and feel (tropical plants, high temperature and humidity), it is an artificial environment. When you want to entertain, educate and raise ecological awareness, you need a variety of species (small, large, colourful, cryptic, etc.), and these are typically derived, as are the plants, not only from different habitats but even different continents: they don't occur together in nature or represent a natural community. This is practically unavoidable: few species can be bred reliably in large numbers, and many are unsuited for displays since they do not behave well in confinement (e.g. sitting in corners or flying incessantly against the glass).

Even so, each butterfly species will have its own requirements. Thus, a live butterfly exhibit must provide diverse structures with sunny and shady, warmer and cooler areas, to simulate different natural habitats (forests/open areas). Unavoidably, the light regime (day-length, light quality) is very different for tropical species brought to temperate latitudes, including artificial lights. Whether this is stressful is unknown and, as far as we are aware, uninvestigated. Diurnal variations in temperature and humidity are difficult to match with each species' natural preferences, all with unknown consequences for stress and longevity.

Food is a critical issue. Of the species usually exhibited, some require nectar, others rotten fruit. For nectar feeders, suitable flowers (with relatively simple floral structure that allows butterflies to access the nectar easily, i.e. daisies or verbenas rather than exotic orchids) cannot be provided to offer sufficient nectar for numerous butterflies in confinement. The usual solution is 'artificial feeders' offering sugar water. These can supply the butterflies' basic needs for water and energy. In nature, nectar feeders use a wide variety of flower species—in contrast to their larvae, which are much more specific. More important than the particular sugars offered is the structure of the feeder, because this determines accessibility. Viscosity can be a major problem. The butterfly proboscis is like a drinking straw—from personal experience everybody knows that a larger diameter straw is needed for a smoothie than a soda! Due to evaporation the viscosity of sugar solutions offered in exhibits can change quickly from being acceptable to lethal—death can ensue if the proboscis becomes clogged with crystallising sugars as a feeder dries up.

Fruit feeders rarely visit flowers or take artificial nectar, but in butterfly houses they often do, seemingly in desperation—because fruit is often not provided in an appropriate state. Fresh bananas look nice, but they do not feed a butterfly—rotten, fermenting bananas look bad, but they offer just what a fruit-feeding butterfly needs. Other fruit also has to be overripe and decaying—but citrus is not appropriate even though it may be visited for lack of anything better.

In summary, although a compromise, the abiotic conditions for butterflies in a butterfly house can be made 'as natural as possible'. From an ecological perspective, the butterflies are, in effect, sacrificed. Keeping them under unnatural light, temperature and humidity regimes and food-supply conditions, almost certainly results in some kind of stress which they have no opportunity to avoid. Females need specific host plants for egg-laying which cannot be provided because it is too difficult or expensive, or resultant early stages have to be culled to stop them eating too much, starving, spoiling the plants and producing excrement—this last a potential source of infection. Is a gravid female unable to lay her eggs stressed, or even in pain? On the other hand, adult butterflies in well-managed captivity are not usually exposed to antagonists, and so have the chance to live longer than in nature.

In contrast to breeding, if due to poor welfare adult butterflies in an exhibit do not live as long as they could, they can easily be replaced by new individuals. Thus for butterfly exhibitors, there is less pressure than for breeders to exercise good husbandry because the additional cost of replacement is marginal. Indeed, it will often be more cost-effective to replace than practice good welfare. This can be to the financial benefit of the breeders and traders too—but not the interests of the insects themselves. The educational value could also be compromised if visitors see moribund butterflies.

Event Releases of Butterflies

To 'bring colour' to a party or celebration (birthday, wedding, funeral), the release of living butterflies has become fashionable (Pyle et al. 2010). These are normally produced by different breeders to those producing pupae for butterfly houses: they use far fewer species, and the insects are shipped not as pupae but as adults.

At first glance, release of butterflies appears benign. Suppliers even justify it on the grounds that it will increase local butterfly numbers—what could be nicer than that? However, much depends on which butterflies are released, when and where. Will they find food, partners and hostplants? Or do they cause environmental harm if released beyond their natural range, with the risk of introductions and detrimental interactions with the local fauna? Even when the same species occurs locally, rarely will the released butterflies be genetically the same as the native population, also with potentially negative consequences (Pyle 2010). The educational benefits appear minimal if non-existent, especially if we conclude that butterflies are simply being sacrificed for human vanity. Releases of living butterflies within meeting rooms, auditoriums, clubs and other such spaces are arguably unethical with respect to the plight of the insects.

Breeding Insects to Supply Adult Deadstock

This affects butterflies, various giant moths (Saturniidae), stick insects, beetles, etc., in the context of production for collectors, souvenirs and artwork. The welfare issues are comparable to those described for butterfly farmers, together with the problems of euthanasia. The ethical issues relate to extensionism—clearly these are purely utilitarian activities, lives taken as a means to an end (collecting and decorative arts).

3.10 Industrial Mass Production of Insects: What for?

Butterflies represent the tip of the iceberg on welfare and husbandry of insects in captivity. They are an interesting example because they are liked insects, but the vast majority of insects currently kept in captivity are (to most) unappealing creatures that the average person never encounters—yet they are produced in billions! This 'industrial entomology' can only be sketched here, but it has to be addressed because of a variety of potential welfare issues and its exceptional magnitude. If insects suffer from stress, the high density at which they are raised (e.g. crowding effect: Weaver and McFarlane 1990; Morales-Ramos and Rojas 2015), necessarily exceeding the highest densities that occur in the wild by far, would definitely be an issue. In addition there are major ethical conflicts between 'big business', benefits for humanity and ecosystem health, versus mass generation and use of insects with little or no regard for their lives, welfare or interests.

Insects for Release to Suppress Pest Populations

The greatest numbers of insects currently mass generated in captivity are produced to control pest populations affecting agriculture, forestry and farm animals or exotic species or vectors of human diseases. A large diversity of taxa are targets. More than 200 species of natural enemies are commercially available for biological control (van Lenteren 2012b) but 'data ... are very hard to obtain' (van Lenteren 2012a). To suppress Mediterranean fruit fly (*Ceratitis capitata*) populations, to give one example only, a single facility produced a maximum of 5,000,000,000 flies per week (Leppla et al. 2014). Some species are produced by private companies for sale and others by state agencies for 'eradication programmes'.

Schneider (2009) provides an overview on principles and procedures for breeding high-quality insects and discusses, inter alia, insectary design, genetics, abiotic conditions, nutrition, pathogens and quality control. Further overviews on mass breeding techniques/technologies (see 'entotechnology', Kok 2017) include Leppla and Ashley (1978), Parker (2005), Cáceres et al. (2012), Carvalho et al. (2014) and Cortes Ortiz et al. (2016). However, with respect to breeding technologies actually employed by commercial companies or public institutions, little is publicly known.

Generally, two approaches to pest management are served by mass-bred insects:

Release of bred parasites, predators and parasitoids: These are primarily targeted against exotic weeds (e.g. Moran et al. 2014) and early instars of mostly phytophagous insect pest populations affecting horticulture, agriculture and forestry. Predators commercially bred are, for example, ladybird beetles (Coleoptera) (Riddick and Chen 2014) or true bugs (Hemiptera: Heteroptera) (De Clercq et al. 2014). Parasitoids affect mostly insect eggs or larvae and belong to various families of wasps and flies (e.g. Braconidae, Aphelinidae, Trichogrammatidae, Tachinidae) (e.g. Boivin et al. 2012; Sithanantham et al. 2013; Dindo and Grenier 2014; Wang et al. 2014). Usually, 'augmentative biological control' (van Driesche et al. 2008) is practised: the beneficial organisms are necessarily released periodically since they do not usually establish in the field.

Release of bred sterile males: These are produced (Parker 2005) and released to reduce female fertility of target species (autocidal control; sterile insect technique; sterile insect release method, SIRM; Krafsur 1998; Wyss 2000; Dyck et al. 2005). Target species are numerous but mainly belong to four families of Diptera: fruit flies (Tephritidae), the maggots of which infest fruit preharvest, mosquitoes (Culicidae) carrying virulent human diseases such as malaria, and blow flies (Calliphoridae) and flesh flies (Sarcophagidae) the maggots of which (sometimes fatally) parasitise livestock, wild mammals and humans (flystrike and myiasis; Hall & Farkas 2000). In addition to the parasitoids, in the case of fruit fly control, use can also be made of irradiated hosts for breeding and for release in the field for monitoring purposes (Cancino et al. 2012).

Both approaches involve the release of tens of thousands to millions of individuals (King et al. 1985; Leppla et al. 2014; Skoda et al. 2018). Industrial production necessitates the establishment of 'biofactories' (Leppla et al. 2014) employing automated processes with complex engineering and mostly using factitious food or artificial media ('diets') as substitute food (e.g. Singh 1977; Grenier 2009; Riddick 2009; Panizzi and Parra 2012; Parra 2012; Morales-Ramos et al. 2014a, b; Cohen 2015). Nowadays, silkworms are also produced on artificial media (Hamamura 2001). Antibiotics are often added to insect diets to prevent diseases, but many insects depend, to varying degrees, on symbiotic bacteria (Duron and Hurst 2013), and artificial diets might have hidden (sublethal) effects for development and/or vitality (e.g. Thakur et al. 2016). From a welfare perspective, feeding captive insects on artificial diets saves lives of their natural prey or hosts, with which, however, mass production would neither be practical nor economic. SIRM typically requires x-ray irradiation of the living insects—does this involve stress, pain, discomfort and/or suffering?

A modification of SIRM involves transgenic technologies (Benedict 2014; Li et al. 2014) to create genetically modified insects, obviating the need for x-ray sterilisation. The mass-produced insects carry altered genes that will kill offspring or confer female sterility after mating with wild conspecifics. This has the potential to suppress target insect populations over the scale of years, but requires continuing release as dispersal and/or natural selection will overcome the induced extreme maladaptation (see, e.g. Carvalho et al. 2014; Hammond et al. 2016; Eckhoff et al. 2017). The ethical, welfare and environmental issues of such techniques do not appear to be addressed at all.

Insects as Food

Insects serve as basic food for innumerable (insectivorous, entomophagous) animals, from other insects to mammals, and provide supplementary food for people, mainly in tropical countries. Traditionally worldwide more than 1500 species (Ramos-Elorduy 2005; cf. Yen and Van Itterbeeck 2016), from caterpillars to grasshoppers, beetle grubs, wasp maggots and adult termites, are opportunistically harvested in the wild and used as food ('anthro(po)entomophagy') for millions of people, partly also taken into human custody (farming) and representing a significant food source for rural people including economic benefits (e.g. Ramos-Elorduy 1996, 2005, 2009;

Ramos-Elorduy et al. 2011; Thomas 2013; Makhado et al. 2014; Chakravorty 2014; Baiyegunhi and Oppong 2016; Feng et al. 2018). For most species, traditional extraction of insects as extra food for a small local community has a quantitative limit set by the need for sustainability, not overharvesting a target species and thus risking its local extinction (Yen 2009; see also Secretariat of the Convention on Biological Diversity 2001 and Münke-Svendsen et al. 2018). However, outbreaks providing huge numbers of edible insects can occur—e.g. at Lake Victoria tiny midges (Chaoboridae) appear in clouds stretching many miles and are harvested to produce 'kungu cake' (Capinera 2008: 2384). Unfortunately, such traditional foods can nowadays be quite unhealthy, such as mopane worms (Lepidoptera: Saturniidae—*Imbrasia belina*), recently found to have high concentrations of heavy metals (Greenfield et al. 2014).

In the West, although the idea of insects as food has long been given serious consideration (e.g. Bodenheimer 1951; Zumpt and Schimitschek 1968; DeFoliart 1989), it currently enjoys very active promotion by several NGOs—including the Food and Agriculture Organisation of the United Nations (FAO; van Huis et al. 2013)—as well as the media, and is advocated by an increasing number of authors (Ramos-Elorduy 1996, 2009; Paoletti 2004; van Huis 2013; van Huis et al. 2013; Shockley and Dossey 2014; Evans et al. 2015; van Huis et al. 2015; Vantomme 2015; Dossey et al. 2016; Payne et al. 2016; Mishra and Omkar 2017b; van Huis and Tomberlin 2017). They state that with insect protein, the impending food crisis can be combated, and since insects produce protein in an environmentally more friendly and sustainable way than traditional stock (cattle, pigs and chickens), insect protein would, in addition, help reduce the ever-increasing stress on our environment.

If a move from insects as *supplementary* food 'for some' to insects as *basic* food 'for many' is seen ethically as an excellent idea, too, we have to ask: which insect species would be suitable for being mass produced to feed millions of people more or less regularly/continuously, and how can mass production be done in an eco-friendly way at affordable prices? Then the question on welfare of insects in such breeding facilities comes even more sharply into focus, while similar to the mass breeding of wasps and flies (above), it brings an extra dimension: the tiny wasps and flies mass produced for pest management are generally considered as 'un-nice', while many of those under discussion as food are much larger and would be considered by many as 'nice'.

Currently, limited mass production of mealworm beetle larvae (*Tenebrio*) (Grau et al. 2017), crickets (*Acheta, Brachytrupes, Gryllus*) and grasshoppers (*Locusta*) for human consumption and non-local trade is practised. They serve to supply restaurants specialising in insect cuisine and the production of lollypops with 'worms'; 'real crickets and worms, dipped in a chocolate coating'; and insect powder, insect bars, insect snacks and insect hamburgers (see Internet for products and prices). This is a new business idea to make money with 'specialities', 'trendy food' or 'novelties' for people who can afford such extras. The current scale of operation is, however, far too small, and the effort and costs involved far too great to serve food security and/or reduce dependence on the admittedly unsustainable production of vertebrate protein—all of which would potentially be an ethical justification for human use of insects as food (facile arguments about environmental benefits, however, play a big role in marketing). Rather, the scale appears similar to breeding insects as food for pets and zoo animals—there the effort (and consequently the price) is high and only worthwhile because there is no practical substitute. Whether such breeding is always 'eco-friendly' or not is an unanswered question.

To market insects in the West for food as a way to educate people to overcome disgust towards them distracts from the importance of the subject, simply because insect protein-containing food can be produced like vegetarian 'hamburgers', where taste and structure can be engineered to simulate beef or other conventional meats. Then it can no longer strictly be called entomophagy—which in the future will not and cannot mean consuming 'entire insects'.

Critical assessments with respect to the practicability of real mass production (Leppla 2009; Sileshi and Kenis 2010; Maciel-Vergara and Ros 2017; Kok 2017) are scant although, from an entomological/natural history perspective, it is not surprising that mass production of insects for food and feed is not (yet?) properly established. In contrast to the examples of mass production of predators, parasitoids or sterile males (above), the biology of (most of) the wild species used for human consumption is generally different. The majority do not develop continuously (that is why harvesting from the wild is always a seasonal affair). To have sufficient food for the species to be mass produced, to manage disease risks (Eilenberg et al. 2015) and to maintain the necessarily complex technology require much effort, and probably huge investment and operating costs. Mass production should not have an ecological footprint greater than the savings gained by using insects instead of vertebrates. Also killing methods (see Sect. 3.11) for currently millions, eventually trillions of insects require consideration.

In conclusion, only a very limited number of non-saprophagous species are, perhaps, suited for continuous, eco-friendly industrial mass production of insect protein. Considering insect lifestyles, and taking into account what was said above about insect generally low tolerance of non-near-optimal conditions (see Sect. 3.6), mass production of insects for human food on an industrial scale is, positively expressed, a great challenge. That no 'big player' in the food industry has yet built or commissioned biofactories for producing and mass marketing insect protein (cf. Kok 2017: 171) seems to support our scepticism.

Many additional issues, some of which are now being debated, are in need of much further research. These include and range from food safety and hygiene (Belluco et al. 2013; EFSA 2015; Grabowski and Klein 2017) to potential health benefits from insect metabolites (Roos and van Huis 2017; Lee et al. 2017). Effects of harmful insect metabolites (Blum 1994) seem to gain little attention as do those related to long-term consumption of particular insect species as a primary food source. A basic complication, or even an obstacle, is the diversity of adaptations insects exhibit, which not only manifest in their visible appearance but—even more so—in hidden characters. There is no 'model species' stakeholders of entomophagy could study to gain reliable, transferable insights.

Insects as Feed and Decomposers

The supply of live insects as feed for pets or small animals in zoos is a long-established practice. Numerous zoos and households are supplied with mealworms, crickets, locusts and other insects for this purpose. There are no data on the magnitude of the industry, but, as it is possible to buy live insects off-the-shelf in almost any pet shop, and they are widely available on the Internet, it is clear that many millions of individual insects are involved annually. Sold by weight and generally transported in densely packed containers without food, the prices per gramme are high compared with human foodstuffs. This is economically sustainable because, to feed many captive insectivorous animals, as already noted, there are no practical alternatives.

Insects as feed for poultry or aquaculture to some extent parallels the issue of insects as human food but, although a more advanced practice, there are still problems (Rumpold and Schlüter 2013; Makkar et al. 2014; Henry et al. 2015; Lundy and Parrella 2015; Smetana et al. 2016). Despite all the brilliant advantages, the conclusion of Józefiak et al. (2016) '... legislation barriers in the European Union, as well as relatively high costs and limited quantity of produced insects are restrictions in the large-scale use of insect meals in poultry nutrition' likely holds true not only for insects as feed but also for insects as food. Even so, the French agro-industrial company Ynsect produces 'over one tonne of proteins and derivatives, lipids and chitin and derivatives per day' (PRO*te*INSECT 2016) using robotics and automation to farm mealworm.

The stock example is the black soldier fly larva (BSFL, *Hermetia illucens*), in many ways a unique animal (Müller et al. 2017). The larvae are bred on manure or organic waste and are already successfully used for aquaculture and animal feed (although there are limitations: Barragán-Fonseca et al. 2017), as well as for composting (e.g. Riddick 2014). Breeding BSFL for feed is in many ways comparable to what happens in a garden compost heap, just on a larger scale. With respect to welfare, the saprophagous lifestyle of BSFL makes a huge difference in comparison to insects with more demanding lifestyles. Does the gain from decomposing organic human waste also add to the 'ethical dimension'? Ideas for using BSFL go far beyond feed—'bioconversion of organic wastes into biodiesel via insect farming' is a proposal (Surendra et al. 2016; Leong et al. 2016).

If hygiene problems (see EFSA 2015) can be solved, BSFL might also be suited as food for humans. Several other Diptera with a saprophagous lifestyle (e.g. house flies, *Musca domestica*; Hussein et al. 2017) could play a big future role too. Intrinsic problems with keeping such species are much reduced compared with phytophagous and carnivorous insects. However, diseases and antagonists can still be a welfare as well as a practical problem: recently, an established BSFL production in West Africa was hampered by a pupal parasitoid, which reduced future broodstock by almost 72% (Devic and Maquart 2015). This clearly exemplifies the ever-present risks of operating large-scale breeding facilities—but such incidents are rarely reported.

Insects as Pollinators

Pollinators are now mass produced in captivity for targeted release. Originally bumblebees were bred and traded for pollination of plants in greenhouses (Velthuis and van Doorn 2006). Commercial bumblebee breeding farms now also produce insects for release into the wild for pollinator supplementation, and bumblebees have become subjects for domiciliation and domestication. 'Bombiculture' (Kwon 2008) is a growing issue because, with decline of the honeybee, pollination of crops by other insects needs to be assured. The emergent industry trades several *Bombus* species and subspecies globally, in increasingly large numbers. For example, in 2006 'approximately one million colonies [of *B. terrestris dalmatinus*] were transported across 57 countries . . . 16 of which [were] outside its native range' (from Ings 2006, not seen, as reported in Owen et al. 2016). In parallel, 'raising bumble bees at home' is also promoted (e.g. Strange 2015). Long before, the solitary alfalfa leafcutting bee (*Megachile rotundata*) was mass-produced and released specifically for pollination of alfalfa (Pitts-Singer and Cane 2011; Peterson and Artz 2014), a leguminous plant used for feed and fertilisation.

As in the cases of mass-bred insects for pest management, mass-bred pollinators are also released into the wild, with potential consequences for wild insects and our responsibilities towards them. The associated problems are multifold (see, e.g. Winter et al. 2006; Dafni et al. 2010; Goulson 2010; Graystock et al. 2013, 2016; Manley et al. 2015; Cameron et al. 2016; Gisder and Genersch 2017; Pirk et al. 2017; Tehel et al. 2016) and cannot be discussed here in detail, in particular because of the complexity and numerous gaps in knowledge.

3.11 Welfare and Ethics of Industrial Mass Production of Insects

Ethical concern for the insects themselves does not in general appear to be a significant matter in the literature on insect mass production. As Gjerris et al. (2016) note, in the context of mass producing insects for food and feed, ethical issues concerning insect welfare are hardly addressed. Not only 'the keeping' needs to be assessed ethically but also all the associated logistics (packing, shipping, methods of release, killing, etc.). As noted by Plannthin (2016), the stresses associated with the annual long-distance movements of huge numbers of honeybees across the USA by truck (Bond et al. 2014) can only be guessed at—but recent research suggests this may really be one of the factors responsible for honeybee colony failure (Simone-Finstrom et al. 2016; see also Perry et al. 2015). With respect to the ever-increasing trade in large numbers of living insects for feeding small animals, stress and welfare have never been addressed. It is not obvious how the practice could be improved practically—even though the shipping methods seem far from ideal and the fate of unsold, unused or uneaten individuals is unknown.

The welfare, breeding conditions and killing of insects currently produced for human consumption are not transparent, or the information available is too scant for serious comment; an example from the homepage of a commercial dealer of insect food is ‘They [crickets] are fed a healthy diet of mixed grains and vegetables and raised in clean hygienic conditions. In addition they are also fed on a unique food blend specially developed for crickets’. Nevertheless one should ask: is mass production of animals for making novelty snacks marketed on the basis of amusement really justifiable? It does not show respect towards insects.

However, even details on how insects are kept and mass produced in biofactories cannot be analysed because, due to competition, suspicions, ‘trade secrets’ and so forth, methods and outcomes are not shared or published. As Erens et al. (2012) report, ‘breeders [understandably] prove reluctant in sharing information on their techniques’. See also Dobermann (2017) for valuable insights into the tension between research and business in the development of insects for food and feed.

One of the major uses of mass-produced insects is biocontrol. We tend to believe that the use of supposedly species-specific parasitoids is more benign and ‘better for the environment’ than chemical control, because of the social and environmental costs of the latter (Pimentel et al. 1980). However, in a broad-ranging review, Lockwood (1996) stated ‘With biological control there is the potential for a single, poorly conceived introduction to forever damage the well-being of an entire ecosystem. Perhaps no other human activity has the potential for a single individual [human] to undertake such a spatially, temporally, and ecologically devastating course of action’. Biocontrol thus represents a particularly powerful example of where we cannot consider the welfare of insects in captivity as an issue that ends at the biofactory door: our responsibilities if we resort to such powerful technologies are protean, extending even to the whole biosphere.

Are insects produced for insect restaurants and as expensive ‘special’ food (with no significant impact on overall human food supply) to be treated, ethically or with respect to welfare, in a different way to those (eventually) produced en masse to overcome hunger and/or to provide more eco-friendly protein? Are those to feed animals (e.g. pets, poultry, fish) to be treated differently from those for human consumption? Brando and Harfeld (2014) raise similar ethical questions and dilemmas about zoos and zoo animals: discrepancies between animal-friendly values for welfare of the animals exhibited *versus* disregard for welfare issues affecting the origins of protein (meat and fish) offered at zoo restaurants—and fed to the zoo animals themselves (including mass produced insects).

It does not need much imagination to realise that industrial mass production of insects cannot be done ‘as natural as possible’. Do for insects artificial diets taste different than natural food?—and even if not, do they cause stress during digestion or modify quality/vitality? Dozens of such questions can be raised but they cannot be answered. Answers, actually, would not help much for ethical evaluation since there is no general foundation for insect welfare and, as already discussed, developing such a baseline is difficult to imagine or even impossible because of insect diversity.

Despite all of these uncertainties, our statement that insects hardly tolerate mistreatment (see Sect. 3.8) would appear to hold in particular for mass breeding.

This receives some support from the work of Portilla et al. (2014) who, in life-table studies of some mass-bred insects, found high reproductive rates on artificial diets, even including the case of specialised Colorado beetle predator *Perillus bioculatus* (Hemiptera: Pentatomidae) when fed on factitious prey. However, in a wide-ranging review of aphid parasitoids used in biological control, Boivin et al. (2012) comment on a variety of physiological, nutritional and natural selection problems associated with meeting the developmental needs of such parasitoids—which inter alia can lead to a loss of efficiency when released (due to inappropriate selection effects when bred at very high density). Artificial diets can reduce the quality of the adults (Grenier and DeClerq 2003), and genetic adaptation to captivity as well as loss of biological fitness and inbreeding depression can occur (see Gilligan and Frankham 2003; Boivin et al. 2012; Hoffmann and Ross 2018). Nevertheless, one can assume that when millions of individuals are being bred, the conditions must be species-appropriate or very close to it. Even so, during the research to find appropriate food mixtures/artificial diets and/or operational technologies for keeping the insects, likely mistreatments are unavoidable. Again, we face a lack of data for analysis. Although these problems do not directly affect issues of welfare in captivity, the possible effects on wild populations when potentially huge numbers of 'substandard' individuals are released are unknown. Again, if we choose to adopt these powerful technologies, our responsibilities cannot end at the biofactory gates.

Given the human misery caused by malaria, it seems unlikely that many of us would protest against the successful use of such technology on the grounds of insect welfare. Thus any exhortation to keep insects under 'as natural conditions as possible' could be set aside if the benefits of breeding in unnatural conditions or subject to genetic engineering are seen as ethically justifiable in their application—in other words, 'the ends do justify the means'. Even so, it is almost certainly the case that, in accordance with Albert Schweitzer's 'reverence for life' principle of ethics and the *Ahimsa* doctrine of Jainism, some people would not agree with such manipulations, even when the goal is to save human lives. Moreover, in many such cases, even the ends may be in conflict: releasing millions of insect parasitoids for biological control can cause ecological harm to nontarget species and whole ecosystems and thus become a threat to biosecurity and wider human interests.

Euthanasia

Despite their various uses, including ecological roles (e.g. pest control, pollination), in very many cases, keeping insects eventually means killing them. Emotionally, taking the life of a beautiful butterfly for many of us (but not all: Knutsson 2016) is quite a different issue than killing a tiny mosquito or the puparium of a fly. As said above, whether we like it or not, we inevitably destroy a lot of insects during our lives (see Sect. 3.2). But a difference remains between unintentional killing of some and intentional killing of many (notwithstanding that intensions and intentionality represent major issues in moral philosophy that we cannot address here).

In addition to mechanical killing of individuals, the main mass killing options are using a gas (e.g. hydrogen cyanide, ether, ethyl acetate; these 'anaesthetic' methods should be followed by, e.g. freezing: AVMA 2013), heat (e.g. boiling water, the traditional method for silkworm pupae) or cold (rapid or slow freezing). There is debate about which is ethically 'best'. As insects are ectotherms and naturally become torpid at lower temperatures, freezing might seem more humane than gassing—but this relates to the question of feeling pain which remains unanswered (see Sect. 3.7). Freezing after cooling without prior anaesthesia, often advocated, is considered an unacceptable method for ectothermic vertebrates (AVMA 2013: 78), and this view has now been extended to invertebrates including insects (Pellett et al. 2013). Simply due to the very high numbers involved, killing insects for food and feed requires new ways.

However, guessing which is 'best' on the basis of human experience, even something akin to emotional transference, without underlying physiological and neurological knowledge is in the end inadequate and potentially misleading. As Cooper (2011) and others have pointed out, more research is needed to help ensure that, even at the point of death, insects in captivity 'are handled with the respect due to any living creature' (Murray 2012: 44).

3.12 Insect Welfare in Captivity vs in the Wild

While the majority of animals currently considered in the context of welfare are domesticated races of vertebrates not found in the wild, there are many (e.g. birds and reptiles kept as pets) that do have natural populations. But *all* insect species in human custody (other than the silkworm and honeybee) occur in the wild. Trying to keep insects in captivity in as 'humane', natural or species-appropriate way as possible has a logical consequence—we also have to pay respect and give attention to insects living in natural habitats: on the one hand to learn about their life in the wild and on the other because many wild populations are in effect in human custody due to our now major and relentless impacts on the biosphere.

Risks of Mass Releases

It follows that the issue of insect welfare cannot be restricted to husbandry in captivity only, but must include environmental issues too. When insecticides are sprayed against pest populations of insects, are we primarily concerned with our own welfare, insect welfare and/or the health of the environment as a whole? When herbicides are used, are we concerned that food for insects is destroyed? And insects as food for vertebrates? If we release pollinators, parasitoids and sterile flies—what about their individual fate and welfare, what if they mate with wild relatives? Thus from an ethical perspective, we also need to consider ecological harm.

While we are not able to address this additional dimension adequately here, we wish to make the point that ethical and welfare issues still arise even if we accidentally—let alone purposefully—release insects bred in captivity into the general environment. Even giving 'harmless' insects like butterflies their 'freedom' by opening the butterfly house doors would not be an unquestionably 'noble' act. Quite the opposite in most cases—more akin to the problems of captive mink release by animal rights activists (e.g. Macdonald and Burnham 2010). Risks of mass releases include aspects of biosecurity, nontarget risks, epigenetic effects, inbreeding depression, etc. GeneWatch UK (2015) published evidence that genetically modified (GM) insect factories could spread antibiotic-resistant bacteria into the environment, posing a risk not only to environmental but directly to human health.

3.13 Is There a Need for Legislative Regulations on the Welfare of Insects in Captivity?

More and more states including the European Union enact regulations in the context of animal welfare. There are laws prescribing conditions under which meat and eggs may be produced. How to keep vertebrates in zoos is regulated. How familiar pets such as dogs, cats and various birds are kept is usually seen as a private matter—but if cruelty is demonstrated, legal action can be taken. Because of various risks including the potential for poor husbandry, some countries have considered bans on keeping reptiles and other exotic pets in private (e.g. UK: CDP 2015).

For insects, there are hardly any regulations regarding their welfare (the recent Dutch Animal Act is a rare exception: Wet Dieren 2013; De Goede et al. 2013). Conservation laws restrict collecting certain species in the wild (e.g. the butterfly *Parnassius apollo* is legally protected in at least 19 European countries: Nakonieczny et al. 2007), and this normally includes prohibition of keeping early stages and adults in captivity. Sooner or later, however, the welfare of captive insects will come to the attention of legislators in more countries than just the Netherlands. What general criteria could or should be applied? As outlined above, from a purely scientific point of view, little general advice can be given. Perhaps legislation regarding the release of reared or bred insects, however produced, might be easier to address.

Even if not entirely logical or even enforceable, a law can act as a signal to make people think and might thereby contribute to awareness of the need to respect nature in general and individual organisms in particular. But if anything well-considered is to be done with regard to legislation, it will require an interdisciplinary approach involving the humanities as well as sciences.

3.14 Some Conclusions and Perspectives

In view of the worldwide general decline of insect species (Sánchez-Bayoa and Wyckhuys 2019) and numbers due to human destruction of natural habitats, land use change, water and air pollution, use of herbicides (reducing hostplant availability) and insecticides (which always kill many nontarget species) and even genetically engineered insects, when you take into account global climate change as well, discussing welfare and husbandry of the *relatively* few insect species humans keep in captivity may seem trifling, even irrelevant. Moreover, very large-scale uses of insects without defensible utilitarian justifications appear to be rare.

There are plenty of research deficits (cf. van Huis 2017), and some of the common general problems (inbreeding depression, diseases, environmental safety, etc.) of the mass breeding industries for edutainment, pest management, food, feed and pollination should be tackled cooperatively.

Be that as it may, faced with evaluating welfare of insects in captivity, we find that their vast diversity, uncertainties regarding susceptibility to stress and pain and widely divergent attitudes of people force us to conclude that any attempt to lay down general 'rules' is practically impossible. In the foreseeable future, there will be no consensus on how we should address insect welfare. We have focused here on the intrinsic peculiarities of insects which affect their keeping in captivity—in part because, for a critical assessment about how they should be kept, there are few if any data available for evidence-based analyses. Theoretical discussions can and should be pursued—but even if we had relevant data, we believe we would still face ethical dilemmas and have to go into value theory (axiology). As De Goede et al. (2013: 241) comment '. . . the idea that we are required to give insects moral concern by analogy with "higher animals" may be hard to accept. We therefore argue that not only scientific evidence, but also consensus on the moral status of insects is needed'. Such complexity requires holistic approaches capable of including such issues as integrity (Singer 1975; Regan 1983), consciousness, mind and even spirituality, as well as systems ecology (e.g. Capra and Luisi 2014). Some of these and other ethical challenges are well reviewed by Röcklinsberg et al. (2017).

Theoretical discussions aside, the reality is that with the massive and continuing growth in the 'human enterprise'—encouraged by global economic expansionism and many religious traditions alike—we now face a desperately urgent need to reassess our relationship with 'nature'. Pragmatism and education (Mather 2011) are probably now more effective than ethics in discovering or rediscovering that respect for nature and all life forms is almost certainly the only secure long-term 'solution'. For example, although Adamo (2016) recently concluded that the evidence that insects experience pain is 'weak' (but see also Klein and Barron 2016), Lockwood (1987, 1988) counselled that we 'refrain from actions which may be reasonably expected to kill or cause nontrivial pain in insects when avoiding these actions has no, or only trivial, costs to our own welfare'. Lockwood went on to quote Robert L. Rabb (in Perkins 1982): 'The use of [technological] power is a tremendous responsibility and must be done without arrogance and with a subtle sensitivity, if not a reverence, for the value of all life'.

We conclude that our general attitude towards insects as 'living things' is crucial, regardless of whether the insects are in captivity or not. Perhaps an excellent step would be to create an international Insect Welfare Charter—a framework that could be used to evaluate our current and future 'handling' of insects, based on species-appropriateness and respect towards all organisms and considering environmental issues, too. It could, at least, also generate more respect for insects and the ecosystem services they provide and would perfectly complement the EU's Charter of Invertebrates (Council of Europe 1986).

Acknowledgements We thank Ottmar Fischer and Philipp Klein for interesting discussions and comments on an earlier draft of the manuscript. Several colleagues, including Donald Broom, Martin Hall and Paul Williams, helped us with literature, for which we are very grateful. We also thank the reviewers and editors for suggestions that have led to improvements in the text.

References

Adamo SA (2016) Do insects feel pain? A question at the intersection of animal behaviour, philosophy and robotics. Anim Behav 118:75–79

Aisi C, Hudson M, Small R (2007) How to ranch and collect insects in Papua New Guinea. Available online: www.geog.cam.ac.uk/research/projects/insectfarming/InsectManual.pdf (last accessed 25-05-2017)

AVMA (American Veterinary Medical Association) (2013) AVMA guidelines for the euthanasia of animals. Available online: www.avma.org/KB/Policies/Documents/euthanasia.pdf (last accessed 25-05-2017)

Baiyegunhi LJS, Oppong BB (2016) Commercialisation of mopane worm (*Imbrasia belina*) in rural households in Limpopo Province, South Africa. For Policy Econ 62:141–148

Barragán-Fonseca KB, Dicke M, van Loon JJA (2017) Nutritional value of the black soldier fly (*Hermetia illucens* L.) and its suitability as animal feed—a review. J Insects Food Feed 3:105–120

Barron AB, Klein C (2016) What insects can tell us about the origins of consciousness. Proc Natl Acad Sci USA 113:4900

Belluco S, Losasso C, Maggioletti M, Alonzi CC, Paoletti MG, Ricci A (2013) Edible insects in a food safety and nutritional perspective: a critical review. Compr Rev Food Sci Food Saf 12:296–313

Benedict MQ (ed) (2014) Transgenic insects. Techniques and application. CABI, Wallingford

Bentley JW, O'Neil RJ (1997) On the ethics of biological control of insect pests. Agric Hum Values 14:283–289

Berger J (1980) Why look at animals? In: Berger J (ed) About looking. Writers & Readers, London, pp 1–26

Bertone MA, Leong M, Bayless KM, Malow TLF, Dunn RR, Trautwein MD (2016) Arthropods of the great indoors: characterizing diversity inside urban and suburban homes. PeerJ 4:e1582

Blackburn S (2001) Ethics, a very short introduction. Oxford University Press, New York

Blum MS (1994) The limits of entomophagy: a discretionary gourmand in a world of toxic insects. Food Insect Newsl 7:2–12

Bodenheimer FS (1951) Insects as human food. Junk, The Hague

Boivin G, Hance T, Brodeur J (2012) Aphid parasitoids in biological control. Can J Plant Sci 92:1–12

Bond J, Plattner K, Hunt K (2014) Fruit and tree nuts. Outlook: economic insight. U.S. pollination-services market. Special Article/FTS-357SA/September 26, 2014. United States Department of Agriculture. Available online: www.ers.usda.gov/webdocs/publications/37059/49131_special-article-september_-pollinator-service-market-4-.pdf?v=41911 (last accessed 25-05-2017)

Boppré M, Vane-Wright RI (2012) The butterfly house industry: conservation risks and education opportunities. Conserv Soc 10:285–303

Botreau R, Veissier I, Butterworth A, Bracke MBM, Keeling LJ (2007) Definition of criteria for overall assessment of animal welfare. Anim Welf 16:225–228

Brando S, Harfeld JL (2014) Eating animals at the zoo. J Crit Anim Stud 12:63–88

Broom DM (2013) The welfare of invertebrate animals such as insects, spiders, snails and worms. In: Kemp TA, Lachance M (eds) Animal suffering: from science to law. Intern Symp Paris, Èd Yvon Blais, pp 135–152
Broom DM (2014) Sentience and animal welfare. CABI, Wallingford
Broom DM, Johnson KG (1993) Stress and animal welfare. Springer, Dordrecht
Cáceres C, Rendjón P, Jessup A (2012) The FAO/IAEA spread sheet for designing and operating insect mass-rearing facilities. FAO, Rome
Cameron SA, Lim HC, Lozier JD, Duennes MA, Thorp R (2016) Test of the invasive pathogen hypothesis of bumble bee decline in North America. Proc Natl Acad Sci USA 113:4386–4391
Cancino J, Ruiz L, Viscarret M, Sivinski J, Hendrichs J (2012) Application of nuclear techniques to improve the mass production and management of fruit fly parasitoids. Insects 3:1105–1125
Capinera JL (ed) (2008) Encyclopedia of entomology. Springer, Heidelberg
Capra F, Luisi PL (2014) The systems view of life: a unifying vision. Cambridge University Press, Cambridge
Carere C, Maestripieri D (eds) (2013) Animal personalities: behavior, physiology, and evolution. University Chicago Press, Chicago
Carvalho DO, Nimmo D, Naish N, McKemey AR, Gray P, Wilke ABB, Marrelli MT et al (2014) Mass production of genetically modified *Aedes aegypti* for field releases in Brazil. J Vis Exp (83), e3579
Cashell K (2009) Aftershock: the ethics of contemporary transgressive art. Tauris, London
CDP (2015) Exotic pets trade. Debate Pack (CDP 2015/0124). House of Commons Library, London. Available online: http://researchbriefings.parliament.uk/ResearchBriefing/Summary/CDP-2015-0124#fullreport (last accessed 25-05-2017)
Chakravorty J (2014) Diversity of edible insects and practices of entomophagy in India: an overview. J Biodivers Biopros Dev 1:124
Cherniack EP (2010) Bugs as drugs, part 1: insects. The "new" alternative medicine for the 21st century? Altern Med Rev 15:124–135
Cohen AC (2015) Insect diets: science and technology. CRC, Boca Raton
Cooper JE (2011) Anesthesia, analgesia, and euthanasia of invertebrates. ILAR J 52:196–204
Cortes Ortiz JA, Ruiz AT, Morales-Ramos JA, Thomas M, Rojas MG, Tomberlin JK, Yi L et al (2016) Insect mass production technologies. In: Dossey AT, Morales-Ramos JA (eds) Insects as sustainable food ingredients: production, processing and food applications. Academic, London, pp 153–201
Council of Europe (1986) Recommendation No R(86)10 of the Committee of Ministers to Member States concerning the Charter on Invertebrates. J Appl Ecol 24:315–319. Available online: https://rm.coe.int/16804bb7c8 (last accessed 25-05-2017)
Crone EE, Pickering D, Schultz CB (2007) Can captive rearing promote recovery of endangered butterflies? An assessment in the face of uncertainty. Biol Conserv 139:103–112
Crook RJ (2013) The welfare of invertebrate animals in research: can science's next generation improve their lot? J Postdoc Res 1:9–20
Dafni A, Kevan P, Gross CL, Goka K (2010) *Bombus terrestris*, pollinator, invasive and pest: an assessment of problems associated with its widespread introductions for commercial purposes. Appl Entomol Zool 45:101–113
De Clercq P, Coudron TA, Reddick EW (2014) Production of heteropteran predators. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 57–100
DeFoliart GR (1989) The human use of insects as food. Bull Entomol Soc Am 35:22–35
DeFoliart GR (1995) Edible insects as minilivestock. Biodivers Conserv 4:306–321
De Goede DM, Erens J, Kapsomenou E, Peters M (2013) Large scale insect rearing and animal welfare. In: Röcklinsberg H, Sandin P (eds) The citizen, the market and the law. Academic, Wageningen, pp 236–242
Devic E, Maquart P-O (2015) *Dirhinus giffardii* (Hymenoptera: Chalcididae), parasitoid affecting black soldier fly production systems in West Africa. Entomologia 3:284

Dickinson E (2013) The misdiagnosis: rethinking "nature-deficit disorder". Environ Commun 7:315–335
Dillon RS (2016) "Respect". In: Zalta EN (ed) The Stanford encyclopedia of philosophy (Winter 2016 edition). Available online: https://plato.stanford.edu/archives/win2016/entries/respect/ (last accessed 25-05-2017)
Dindo ML, Grenier S (2014) Production of dipteran parasitoids. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 101–144
Dobermann D (2017) Insects as food and feed: can research and business work together? J Insects Food Feed 3:155–160
Dossey AT (2010) Insects and their chemical weaponry: new potential for drug discovery. Nat Prod Rep 27:1737–1757
Dossey AT, Morales-Ramos JA, Rojas MG (2016) Insects as sustainable food ingredients: production, processing and food applications. Academic, New York
Drew J, Lorimer D (2011) The protein crunch. Civilisation on the brink. Print Matters Planet, Noordhoek, South Africa
Duron O, Hurst GDD (2013) Arthropods and inherited bacteria: from counting the symbionts to understanding how symbionts count. BMC Biol 11:45
Dyck VA, Hendrichs J, Robinson AS (eds) (2005) Sterile insect technique: principles and practice in area-wide integrated pest management. Springer, Dordrecht
Eadie EN (2012) Understanding animal welfare. An integrated approach. Springer, Berlin
Eckhoff PA, Wenger EA, Godfray HCJ, Burt A (2017) Impact of mosquito gene drive on malaria elimination in a computational model with explicit spatial and temporal dynamics. Proc Natl Acad Sci USA 114:E255–E264
EFSA—European Food and Safety Agency (2005) Aspects of the biology and welfare of animals used for experimental and other scientific purposes. EFSA J 3:292
EFSA—European Food and Safety Agency (2015) Risk profile related to production and consumption of insects as food and feed. EFSA J 13:4257
Eilenberg J, Vlak JM, Nielsen-LeRoux C, Cappellozza S, Jensen AB (2015) Diseases in insects produced for food and feed. J Insects Food Feed 1:87–102
Eisemann CH, Jorgensen WK, Merritt DJ, Rice MJ, Cribb BW, Webb PD, Zalucki MP (1984) Do insects feel pain?—A biological review. Experientia 40:164–167
Elwood RW (2011) Pain and suffering in invertebrates. ILAR J 52:175–184
Engel M Jr (2008) Ethical extensionism. In: Callicott JB, Frodeman R (eds) Encyclopedia of environmental ethics and philosophy, vol 1. Macmillan, Detroit, pp 396–398
Engster D (2006) Care ethics and animal welfare. J Soc Philos 37:521–536
Erens J, van Es S, Haverkort F, Kapsomenou E, Luijben A (2012) A bug's life. Large scale insect rearing in relation to animal welfare. VENIK, Wageningen
Evans J, Alemu MH, Flore R, Frøst MB, Halloran A, Jensen AB, Maciel-Vergara G et al (2015) 'Entomophagy': an evolving terminology in need for review. J Insects Food Feed 1:293–305
FAWC—Farm Animal Welfare Council (2009) Farm animal welfare in Great Britain: past, present and future. Available online: www.gov.uk/government/publications/fawc-report-on-farm-animal-welfare-in-great-britain-past-present-and-future (last accessed 25-05-2017)
Favre DS (1979) Wildlife-rights: the ever-widening circle. Environ Law 9:241–281
Feng Y, Chen X-M, Zhao M, He Z, Sun L, Wand C-Y, Ding W-F (2018) Edible insects in China: utilization and prospects. Insect Sci 25:184–198
Finke MD, Oonincx D (2014) Insects as food for insectivores. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 583–616
Fleischmann W, Grassberger M (2003) Maggot therapy: a handbook of maggot-assisted wound healing. Thieme, Stuttgart
Frank ET, Schmitt T, Hovestadt T, Mitesser O, Stiegler J, Linsenmair KE (2017) Saving the injured: rescue behaviour in the termite hunting ant *Megaponera analis*. Sci Adv 3:e160218
Garnas JR (2018) Rapid evolution of insects to global environmental change: conceptual issues and empirical gaps. Curr Opin Insect Sci 29:933–101

GeneWatch UK (2015) Genetically modified insect factories: a new source of superbugs? Available online: http://www.genewatch.org/uploads/f03c6d66a9b354535738483c1c3d49e4/Antibiotic_GWbrief_fin.pdf (last accessed 25-05-2017)
Gilligan DM, Frankham R (2003) Dynamics of genetic adaptation to captivity. Conserv Genet 4:189–197
Gisder S, Genersch E (2017) Viruses of commercialized insect pollinators. J Invertebr Pathol 147:51–59
Gjerris M, Gamborg C, Röcklinsberg H (2016) Ethical aspects of insect production for food and feed. J Insects Food Feed 2:101–110
Gorham JR (1979) The significance for human health of insects in food. Annu Rev Entomol 24:209–224
Goulson D (2010) Impacts of non-native bumblebees in Western Europe and North America. Appl Entomol Zool 45:7–12
Grabowski NTh, Klein G (2017) Bacteria encountered in raw insect, spider, scorpion, and centipede taxa including edible species, and their significance from the food hygiene point of view. Trends Food Sci Technol 63:80–90
Grau T, Vilcinskas A, Joop G (2017) Sustainable farming of the mealworm *Tenebrio molitor* for the production of food and feed. Z Naturforsch 72:337–349
Graystock P, Yates K, Evison SEF, Darvill B, Goulson D, Hughes WOH (2013) The Trojan hives: pollinator pathogens, imported and distributed in bumblebee colonies. J Appl Ecol 50:1207–1215
Graystock P, Blane EJ, Mcfrederick QS, Goulson D, Hughes WOH (2016) Do managed bees drive parasite spread and emergence in wild bees? Int J Parasitol Parasites Wildl 5:64–75
Green TC, Mellor DJ (2011) Extending ideas about animal welfare assessment to include 'quality of life' and related concepts. N Z Vet J 59:263–271
Greenfield R, Akala N, van der Bank FH (2014) Heavy metal concentrations in two populations of mopane worms (*Imbrasia belina*) in the Kruger National Park pose a potential human health risk. Bull Environ Contam Toxicol 93:316–321
Grenier S (2009) *In vitro* rearing of entomophagous insects—past and future trends: a minireview. Bull Insectol 62:1–6
Grenier S, DeClerq P (2003) Comparison of artificially vs. naturally reared natural enemies and their potential for use in biological control. In: van Lenteren JC (ed) Quality control and production of biological control agents theory and testing procedures. CABI, Wallingford Oxon, UK, pp 115–131
Gullan PJ, Cranston PS (2010) The insects. An outline of entomology. Wiley-Blackwell, Chichester
Hagen K, Van den Bos R, de Cock BT (2011) Editorial: concepts of animal welfare. Acta Biotheor 59:93–103
Hajek AE, Shapiro-Ilan DI (eds) (2018) Ecology of invertebrate diseases. Wiley, Hoboken
Hall MJR, Farkas R (2000) Traumatic myiasis of humans and animals. In: Papp L, Darvas B (eds) Contributions to a manual of Palaearctic Diptera. Sci Herald, Budapest, pp 751–768
Hall MRJ, Wall RL, Stevens JR (2016) Traumatic myiasis: a neglected disease in a changing world. Annu Rev Entomol 61:159–176
Hamamura Y (ed) (2001) Silkworm rearing on artificial diet. Science, Enfield
Hammond A, Galizi R, Kyrou K, Simoni A, Siniscalchi C, Katsanos D, Gribble M et al (2016) A CRISPR-Cas9 gene drive system targeting female reproduction in the malaria mosquito vector *Anopheles gambiae*. Nat Biotechnol 34:78–83
Harberd R (2005) A manual of tropical butterfly farming. Available online: http://www.darwininitiative.org.uk/documents/13005/3192/13-005FRApp7ManualofTropicalButterflyFarming.pdf. Accessed 27 Mar 2019
Hatfield R (2008) Animals. In: Carriero J, Broughton J (eds) Companion to Descartes. Blackwell, Oxford, pp 404–425

Hatfield G (2018) René Descartes. In: Zalta EN (ed) The Stanford encyclopedia of philosophy (Summer 2018 Edition). https://plato.stanford.edu/archives/sum2018/entries/descartes/ (last accessed 23-15-2018)
Henry M, Gasco L, Piccolo G, Fountoulaki E (2015) Review on the use of insects in the diet of framed fish: past and future. Anim Feed Sci Technol 203:1–22
Hoffmann AA, Ross PA (2018) Rates and patterns of laboratory adaptation in (mostly) insects. J Econ Entomol 111:501–509
Hogue CL (1987) Cultural entomology. Annu Rev Entomol 32:181–199
Horvath K, Angeletti D, Nascetti G, Carere C (2013) Invertebrate welfare: an overlooked issue. Ann Ist Super Sanità 49:9–17
Hrdy SB (1979) Infanticide among animals: a review, classification, and examination of the implications for the reproductive strategies of females. Ethol Sociobiol 1:13–40
Hughes DG, Bennett PM (1991) Captive breeding and the conservation of invertebrates. Int Zoo Yearb 30:45–51
Hussein M, Pillai VV, Goddard JM, Park HG, Kothapalli KS, Ross DA, Ketterings QM et al (2017) Sustainable production of housefly (*Musca domestica*) larvae as a protein-rich feed ingredient by utilizing cattle manure. PLoS One 12:e0171708
Imhoof M, Lieckfeld C-P (2015) More than honey: the survival of bees and the future of our world. Greystone, Vancouver
Ings TC (2006) *Bombus terrestris*, humble pollinator or assiduous invader? PhD thesis, Queen Mary College, University of London, UK
Jandt JM, Thomson JL, Geffre AC, Toth AL (2015) Lab rearing environment perturbs social traits: a case study with *Polistes* wasps. Behav Ecol 26:1274–1284
Józefiak D, Józefiak A, Kieronczyk B, Rawski M, Swiatkiewicz JD, Engberg RM (2016) Insects—a natural nutrient source for poultry—a review. Ann Anim Sci 16:297–313
Judge KA, Bonanno VL (2008) Male weaponry in a fighting cricket. PLoS One 3:e3980
Kellert SR (1993) Values and perceptions of invertebrates. Conserv Biol 7:845–855
Khusro M, Andrew NR, Nicholas A (2012) Insects as poultry feed: a scoping study for poultry production systems in Australia. World Poult Sci J 68:435–446
King EG, Hopper KR, Powell JE (1985) Analysis of systems for biological control of crop arthropod pests in the U.S. by augmentation of predators and parasites. In: Hoy MA, Herzog DC (eds) Biological control in agricultural IPM systems. Academic, Orlando, pp 201–227
Klein C, Barron AB (2016) Insect consciousness: commitments, conflicts and consequences. Anim Sentience 2016:153
Knutsson S (2016) Reducing suffering among invertebrates such as insects. Sentience Politics (1):1–18. Available online: https://sentience-politics.org/files/reducing-suffering-invertebrates-6.pdf (last accessed 25-05-2017)
Kohn B (1994) Zoo animal welfare. Rev Sci Tech Off Int Epiz 13:233–245
Kok R (2017) Insect production and facility design. In: van Huis A, Tomberlin JK (eds) Insects as food and feed. From production to consumption. Wageningen Academic, Wageningen, pp 143–172
Korte SM, Olivier B, Koolhaas JM (2007) A new animal welfare concept based on allostasis. Physiol Behav 92:422–428
Krafsur ES (1998) Sterile insect technique for suppressing and eradicating insect population: 55 years and counting. J Agric Entomol 15:303–317
Kritsky G, Cherry R (2000) Insect mythology. Writers Club, San Jose
Kwon YJ (2008) Bombiculture: a fascinating insect industry for crop pollination in Korea. Entomol Res 38:566–570
Lee J, Hwan IH, Kim JH, Kim M-A, Hwang JS, Kim YH, Na MK (2017) Quinoxaline-, dopamine-, and amino-acid derived metabolites from the edible insect *Protaetia brevitarsis seulensis*. Arch Pharmacol Res 40:1064–1070
Lees D[C] (1989) Practical considerations and techniques in the captive breeding of insects for conservation purposes. Entomologist 108:77–96

Leong SY, Kutty SRM, Malakhmad A, Tan CK (2016) Feasibility study of biodiesel using lipids of *Hermetia illucens* larva fed with organic waste. Waste Manag 47:84–90
Leppla NC (2009) Rearing of insects. In: Resh VH, Cardé R (eds) Encyclopedia of insects. Elsevier, Amsterdam, pp 866–869
Leppla NC, Ashley TR (1978) Facilities for insect research and production. USDA Technical Bulletin 1576
Leppla NC, Morales-Ramos JA, Shapiro-Ilan DI, Rojas MG (2014) Introduction. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, New York, pp 1–16
Levy S (2011) What's best for bees. Nature 479:164–165
Li F, Wantuch HA, Linger RJ, Belikoff EJ, Scott MJ (2014) Transgenic sexing system for genetic control of the Australian sheep blowfly *Lucilia cuprina*. Insect Biochem Mol Biol 51:80–88
Lockwood JA (1987) The moral standing of insects and the ethics of extinction. Fla Entomol 70:70–89
Lockwood JA (1988) Not to harm a fly: our ethical obligations to insects. Between Species 4:204–211
Lockwood JA (1996) The ethics of biological control: understanding the moral implications of our most powerful ecological technology. Agric Hum Values 13:2–19
Lockwood JA (2009) Six-legged soldiers. Oxford University Press, Oxford
Lockwood JA (2012) Insects as weapons of war, terror, and torture. Annu Rev Entomol 57:205–227
Lockwood J (2013) The infested mind: why humans fear, loathe, and love insects. Oxford University Press, Oxford
Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. BioScience 56:311–323
Louv R (2005) Last child in the woods: saving our children from nature-deficit disorder. Algonquin, Chapel Hill
Lundy ME, Parrella MP (2015) Crickets are not a free lunch: protein capture from scalable organic side-streams via high-density populations of *Acheta domesticus*. PLoS One 10:e0118785
Macdonald D, Burnham D (2010) The state of Britain's mammals: a focus on invasive species. People's Trust for Endangered Species, London
Maciel-Vergara G, Ros VID (2017) Viruses of insects reared for food and feed. J Invert Pathol 147:60–75
Makhado R, Potgieter M, Timberlake J, Gumbo D (2014) A review of the significance of mopane products to rural people's livelihoods in southern Africa. Trans R Soc S Afr 69:117–122
Makkar HPS, Tran G, Heuzé V, Ankers P (2014) State-of-the-art on use of insects as animal feed. Anim Feed Sci Technol 197:1–33
Manley R, Boots M, Wilfert L (2015) Emerging viral disease risk to pollinating insects: ecological, evolutionary and anthropogenic factors. J Appl Ecol 52:331–340
Manos-Jones M (2000) The spirit of butterflies. Myth, magic, and art. Abrams, New York
Maple TL, Perdue BM (2013) Defining animal welfare. In: Maple TL, Perdue BM (eds) Zoo animal welfare. Springer, Berlin, pp 21–33
Martin C (2015) A re-examination of the pollinator crisis. Curr Biol 25:R811–R826
Mather JA (2011) Philosophical background of attitudes toward and treatment of invertebrates. ILAR J 52:205–212
Mayhew PJ (2007) Why are there so many insect species? Perspectives from fossils and phylogenies. Biol Rev 82:425–454
Mellor DJ, Webster JR (2014) Development of animal welfare understanding drives change in minimum welfare standards. Rev Sci Tech 33:121–130
Mendl MT, Paul ES (2016) Bee happy. Science 353:1499–1500
Mishra G, Omkar (2017a) Entomoceuticals. In: Omkar (ed) Industrial entomology. Springer, Singapore, pp 435–450
Mishra G, Omkar (2017b) Insects as food. In: Omkar (ed) Industrial entomology. Springer, Singapore, pp 413–434

Montero JR (2007) Manual Para el Manejo de Mariposarios. InBio, San José
Morales-Ramos JA, Rojas MG (2015) Effect of larval density on food utilization efficiency of *Tenebrio molitor* (Coleoptera: Tenebrionidae). J Econ Entomol 108:2259–2267
Morales-Ramos J, Rojas MG, Coudron TA (2014a) Artificial diet development for entomophagous arthropods. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 203–240
Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) (2014b) Mass production of beneficial organisms. Invertebrates and entomopathogens. Academic, London
Moran PJ, Goolsby JA, Racelis AE, Cohen AC, Ciomperlik MA, Summy KR, Sands DPA, Kirk AA (2014) Mass rearing of the stem-galling wasp *Tetramesa romana*, a biological control agent of the invasive weed *Arundo donax*. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 145–162
Müller A, Wolf D, Gutzeit HO (2017) The black soldier fly, *Hermetia illucens* — a promising source for sustainable production of proteins, lipids and bioactive substances. Z Naturforsch 72:351–363
Münke-Svendsen C, Ao V, Lach T, Chamnan C, Hjortsø CN, Roos N (2018) An explorative study of the practice of light trapping and the informal market for crickets in Cambodia. J Insect Food Feed 4:61–70
Murray MJ (2012) Euthanasia. In: Lewbart GA (ed) Invertebrate medicine, 2nd edn. Wiley-Blackwell, Chichester, UK, pp 441–443
Nakonieczny M, Kędziorski A, Michalczyk K (2007) Apollo butterfly (*Parnassius apollo* L.) in Europe—its history, decline and perspectives of conservation. Funct Ecosyst Communities 1:56–79
Nikkhah R (2012) Damien Hirst condemned for killing 9,000 butterflies in Tate show. The Telegraph. Available online: www.telegraph.co.uk/culture/culturenews/9606498/Damien-Hirst-condemned-for-killing-9000-butterflies-in-Tate-show.html (last accessed 25-05-2017)
Ormandy EH, Dale J, Griffin G (2011) Genetic engineering of animals: ethical issues, including welfare concerns. Can Vet J 52:544–550
Orr DW (2004) Earth in mind. On education, environment and the human prospect (10th anniversary edition). Island Press, Washington, DC
Owen EL, Bale JS, Hayward SAL (2016) Establishment risk of the commercially imported bumblebee *Bombus terrestris dalmatinu* — can they survive UK winters? Apidologie 47:66–75
Panizzi AR, Parra JRP (2012) Introduction to insect bioecology and nutrition for integrated pest management (IPM). In: Panizzi AR, Parra JRP (eds) Insect bioecology and nutrition for integrated pest management. CRC, Boca Raton, pp 3–11
Paoletti MG (2004) Ecological implications of minilivestock. Potential of insects, rodents, frogs and snails. Science, Plymouth
Parker AG (2005) Mass-rearing for sterile insect release. In: Dyck VA, Hendrichs J, Robinson AS (eds) Sterile insect technique: principles and practice in area-wide integrated pest management. Springer, Dordrecht, pp 209–232
Parra JRP (2012) The evolution of artificial diets and their interactions in science and technology. In: Panizzi AR, Parra JRP (eds) Insect bioecology and nutrition for integrated pest management. CRC, Boca Raton, pp 51–92
Payne CLR, Dobermann D, Forkes A, House J, Josephs J, McBride A, Müller A et al (2016) Insects as food and feed: European perspectives on recent research and future priorities. J Insects Food Feed 2:269–276
Pearce-Kelly P, Morgan R, Honan P, Barrett P, Perrotti L, Magdich M, Daniel BA et al (2007) The conservation value of insect breeding programmes: rationale, evaluation tools and example programme case studies. In: Stewart AJA, New TR, Lewis OT (eds) Insect conservation biology. CABI, Wallingford, pp 57–75
Pearson DE, Callaway RM (2003) Indirect effects of host-specific biological control agents. Trends Ecol Evol 18:456–461

Pellett S, Pizzi R; Trim S, Bushell M, Clarke D, Wood J (2013) BIAZA recommendations for ethical euthanasia of invertebrates. British and Irish Association of Zoos and Aquariums [available to members only]
Perfecto I, Vandermeer J (2010) The agroecological matrix as alternative to the land-sparing/agriculture intensification model. Proc Natl Acad Sci USA 107:5786–5791
Perkins JH (1982) Insects, experts and the insecticide crisis. Plenum, New York
Perry CJ, Søvik E, Myerscough MR, Barron AB (2015) Rapid behavioral maturation accelerates failure of stressed honey bee colonies. Proc Natl Acad Sci USA 112:3427–3432
Peterson SS, Artz DR (2014) Production of solitary bees for pollination in the United States. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 653–682
Pimentel D, Andow D, Dyson-Hudson R, Gallahan D, Jacobson J, Irish M, Kroop S et al (1980) Environmental and social costs of pesticides. A preliminary assessment. Oikos 34:126–140
Pirk CWW, Crewe RM, Moritz RFA (2017) Risks and benefits of the biological interface between managed and wild bee pollinators. Funct Ecol 31:47–55
Pitts-Singer TL, Cane JH (2011) The alfalfa leafcutting bee, *Megachile rotundata*: the world's most intensively managed solitary bee. Annu Rev Entomol 56:221–237
Plannthin D-K (2016) Animal ethics and welfare in the fashion and lifestyle industries. In: Muthu SS, Gardetti MA (eds) Green fashion, environmental footprints and eco-design of products and processes. Springer, Singapore, pp 49–122
Portilla M, Morales-Ramos JA, Rojas MG, Blanco CA (2014) Life tables as tools of evaluation and quality control for arthropod mass production. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 241–276
PRO*te*INSECT (2016) White paper "Insect protein—feed for the future". Available online: www.proteinsect.eu/fileadmin/user_upload/press/proteinsect-whitepaper-2016.pdf (last accessed 25-05-2017)
Pyle M (2010) Under their own steam: the biogeographic case against butterfly releases. News Lep Soc 52:54–57
Pyle M, Jepsen SJ, Black SH, Monroe M (2010) Xerces Society policy on butterfly releases. Available online: www.xerces.org/wp-content/uploads/2010/08/xerces-butterfly-release-policy.pdf (last accessed 25-05-2017)
Ramos-Elorduy J (1996) Insects: a sustainable source of food? Ecol Food Nutr 36:247–276
Ramos-Elorduy J (2005) Insects: a hopeful food source. In: Paoletti MG (ed) Ecological implications of minilivestock. Potential of insects, rodents, frogs and snails. Science, Plymouth, pp 263–291
Ramos-Elorduy J (2009) Anthropo-entomophagy: cultures, evolution and sustainability. Entomol Res 39:271–288
Ramos-Elorduy J, Moreno JMP, Vázquez AI, Landero I, Oliva-Rivera H, Camacho VHM (2011) Edible Lepidoptera in Mexico: geographic distribution, ethnicity, economic and nutritional importance for rural people. J Ethnobiol Ethnomed 7:2
Regan T (1983) The case for animal rights. University of California Press, Berkeley
Riddick EW (2009) Benefit and limitations of factitious prey and artificial diets on life parameters of predatory beetles, bugs, and lacewings: a minireview. BioControl 54:325–339
Riddick EW (2014) Insect protein as a partial replacement for fishmeal in the diets of juvenile fish and crustaceans. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 565–582
Riddick EW, Chen H (2014) Production of coleopterans predators. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 17–56
Röcklinsberg H, Gamborg C, Gjerris M (2017) Ethical issues in insect production. In: van Huis A, Tomberlin JK (eds) Insects as food and feed. From production to consumption. Wageningen Academic, Wageningen, pp 364–379

Roffet-Salque M, Regert M, Evershed RP, Outram AK, Cramp LJE, Decavallas O, Dunne J et al (2015) Widespread exploitation of the honeybee by early Neolithic farmers. Nature 257:226–231
Rolff J, Reynolds SE (2009) Insect infection and immunity. evolution, ecology, and mechanisms. Oxford University Press, Oxford
Roos N, van Huis A (2017) Consuming insects: are there health benefits? J Insects Food Feed 225–229
Rumpold BA, Schlüter OK (2013) Potential and challenges of insects as an innovative source for food and feed production. Innovative Food Sci Emerg Technol 17:1–11
Samways MJ (2005) Insect diversity conservation. Cambridge University Press, Cambridge
Sánchez-Bayoa F, Wyckhuys KAG (2019) Worldwide decline of the entomofauna: a review of its drivers. Biol Conserv 232:8–27
Sander-Staudt M (2017) Care ethics. Internet encyclopedia of philosophy. www.iep.utm.edu/care-eth/ (accessed 25-05-2017)
Schicktanz S (2006) Ethical considerations of the human-animal-relationship under conditions of asymmetry and ambivalence. J Agric Environ Ethic 19:7–16
Schneider JC (ed) (2009) Principles and procedures for rearing high quality insects. Mississippi State University, Starkville
Schowalter TD (2013) Insects and sustainability of ecosystem services. CRC, Boca Raton
Scruton R (1998) Animal rights and wrongs, 2nd edn. Demos, London
Sekimizu N, Paudel A, Hamamoto H (2012) Animal welfare and use of silkworm as model animal. Druc Discov Ther 6:226–229
Secretariat of the Convention on Biological Diversity (2001) Sustainable management of non-timber forest resources.SCBD, Montreal , 30p (CBD Technical Series no. 6)
Sherman RA, Hall MJR, Thomas S (2000) Medicinal maggots: an ancient remedy for some contemporary afflictions. Annu Rev Entomol 45:55–81
Shockley M, Dossey AT (2014) Insects for human consumption. In: Morales-Ramos J, Rojas MG, Shapiro-Ilan DI (eds) Mass production of beneficial insects. Elsevier, Amsterdam, pp 617–652
Skoda SR, Philipps PL, Welch JB (2018) Screwworm (Diptera: Calliphoridae) in the United States: response to and elimination of the 2016-2017 outbreak in Florida. J Med Entomol 55:777–786
Sileshi GW, Kenis M (2010) Food security: farming insects. Science 328:568
Simone-Finstrom M, Li-Byarlay H, Huang MH, Strand MK, Rueppell O, Tarpy DR (2016) Migratory management and environmental conditions affect lifespan and oxidative stress in honey bees. Sci Rep 6:32023
Singh P (1977) Artificial diets for insects, mites, and spiders. Springer, New York
Singer P (1975) Animal liberation: a new ethics for the treatment of animals. New York Review, New York
Singer P (2011) The expanding circle. Ethics and sociobiology. Princeton University Press, Princeton
Sithanantham S, Ballal CR, Jalali SK, Bakthavatsalam N (eds) (2013) Biological control of insect pests using egg parasitoids. Springer, New Delhi
Smetana S, Palanisamy M, Mathys A, Heinz V (2016) Sustainability of insect use for feed and food: life cycle assessment perspective. J Cleaner Prod 137:741–751
Smith JA (1991) A question of pain in invertebrates. ILAR J 33:25–31
Smith TJ, Saunders ME (2016) Honey bees: the queens of mass media, despite minority rule among insect pollinators. Insect Conserv Div 9:384–390
Sneddon LU, Elwood RW, Adamo SA, Leach MC (2014) Defining and assessing animal pain. Anim Behav 97:201–212
Stout JC, Finn JA (2015) Recognizing the value of insects in providing ecosystem services. Ecol Entomol 40:1–2
Strange JP (2015) Raising bumble bees at home. A guide to getting started. Available online: www.ars.usda.gov/ARSUserFiles/20800500/BumbleBeeRearingGuide.pdf (last accessed 25-05-2017)

Stone JLS, Midwinter HJ (1975) Butterfly culture. A guide to breeding butterflies, moths and other insects. Poole, Blandford

Stork NE, McBroom J, Gely C, Hamilton AJ (2015) New approaches narrow global species estimates for beetles, insects, and terrestrial arthropods. Proc Natl Acad Sci USA 112:7519–7523

Surendra KC, Olivier R, Tomberlin JK, Jha R, Khanal SK (2016) Bioconversion of organic wastes into biodiesel and animal feed via insect farming. Renew Energy 98:197–202

Taponen I (2015) Animal welfare in insect farming. Available online: https://ilkkataponen.com/2015/01/04/the-animal-welfare-in-insect-farming/ (last accessed 25-05-2017)

Taylor PM (1986) Respect for nature: a theory of environmental ethics. Princeton University Press, Princeton

Tehel A, Brown MJF, Paxton RJ (2016) Impact of managed honey bee viruses on wild bees. Curr Opin Virol 19:16–22

Thakur A, Dhammi P, Saini HS, Knaur S (2016) Effect of antibiotic on survival and development of *Spodoptera litura* (Lepidoptera: Noctuidae) and its gut microbial diversity. Bull Entomol Res 106:387–394

Thomas B (2013) Sustainable harvesting and trading of mopane worms (*Imbrasia belina*) in Northern Namibia: an experience from the Uukwaluudhi area. Int J Environ Stud 70:494–502

Tiffin H (2016) Do insects feel pain? Anim Stud J 5:80–96

UFAW—Universities Federation for Animal Welfare (2017) www.ufaw.org.uk/the-ufaw-journal/animal-welfare (last accessed 25-05-2017)

USDA—United States Department of Agriculture (2002) Containment guidelines for educational displays of adult,[sic] butterflies and moths (Lepidoptera). Butterfly containment guidelines. Available online: www.aphis.usda.gov/plant_health/permits/downloads/butterfly_containment_guidelines.pdf (last accessed 25-05-2017)

van Driesche R, Hoddle M, Center E (2008) Control of pests and weeds by natural enemies. An introduction to biological control. Blackwell, Oxford

van Huis A (2013) Potential of insects as food and feed in assuring food security. Annu Rev Entomol 58:563–583

van Huis A (2015) Edible insects contributing to food security? Agric Food Secur 4:20

van Huis A (2017) Edible insects and research needs. J Insects Food Feed 3:3–5

van Huis A, Tomberlin JK (eds) (2017) Insects as food and feed. From production to consumption. Wageningen Academic, Wageningen

van Huis A, van Itterbeeck J, Klunder H, Mertens E, Halloran A, Muir G, Vantomme P (2013) Edible insects: future prospects for food and feed security. FAO, Rome

van Huis A, van Gurp H, Dicke M (eds) (2014) The insect cookbook: food for a sustainable planet. Columbia University Press, New York

van Huis A, Dicke M, van Loon JJA (2015) Insects to feed the world. J Insects Food Feed 1:3–5

van Lenteren JC (2012a) IOBC internet book of biological control. Available online: www.iobc-global.org/publications_iobc_internet_book_of_biological_control.html (last accessed 25-05-2017)

van Lenteren JC (2012b) The state of commercial augmentative biological control: plenty of natural enemies, but a frustrating lack of uptake. BioControl 57:1–20

Vantomme P (2015) Way forward to bring insects in the human food chain. J Insects Food Feed 1:121–129

Vega FE, Kaya HK (eds) (2012) Insect pathology. Elsevier, Amsterdam

Velthuis HHW, van Doorn A (2006) A century of advances in bumblebee domestication and the economic and environmental aspects of its commercialization for pollination. Apidologie 37:421–451

Venters N, Rogers L (2001) The butterfly farming library—the commercial butterfly breeders manual and the advanced guide to commercial butterfly production. Available online: www.butterflyboutique.net/pages/manual.html (last accessed 25-05-2017)

Wang Z-Y, He K-L, Zhang F, Lu X, Babendreier D (2014) Mass rearing and release of *Trichogramma* for biological control of insect pests of corn in China. Biol Control 68:137–144
Watson GS, Watson JA, Cribb BW (2017) Diversity of cuticular micro- and nanostructures on insects: properties, functions, and potential applications. Annu Rev Entomol 62:185–205
Weaver DK, McFarlane JE (1990) The effect of larval density on growth and development of *Tenebrio molitor*. J Insect Physiol 36:531–536
Webster J (2016) Animal welfare: freedoms, dominions and "a life worth living". Animals 6:35
Wet Dieren (2013) Wet van 19 mei 2011, houdende een integraal kader voor regels over gehouden dieren en daaraan gerelateerde onderwerpen (Wet dieren). Stb., Den Haag, The Netherlands, 2012: 659
White L Jr (1967) The historical roots of our ecologic crisis. Science 155:1203–1207
Wigglesworth VB (1980) Do insects feel pain? Antenna 4:8–9
Winter K, Adams L, Thorp R, Inouye D, Day L, Ascher J, Buchmann S (2006) Importation of non-native bumble bees into North America: potential consequences of using *Bombus terrestris* and other non-native bumble bees for greenhouse crop pollination in Canada, Mexico, and the United States. A white paper of the North American Pollinator Protection Campaign (NAPPC). Available online: http://cues.cfans.umn.edu/old/pollinators/pdf-BBcolony/2006nonativebee.pdf. Accessed 27 Mar 2019
Wyss JH (2000) Screwworm eradication in the Americas. In: Conference of the OIE 2000, pp 239–244
Yen AL (2009) Entomophagy and insect conservation: some thoughts for digestion. J Insect Conserv 13:667–670
Yen AL, Van Itterbeeck J (2016) No taxonomists? No progress. J Insects Food Feed 2:223–224
Zumpt F, Schimitschek E (1968) Insekten als Nahrung, in Brauchtum, Kult und Kultur. In: Helmcke J-G, Statrck DH, Wermuth H (eds) Handbuch der Zoologie. IV. Band, Arthropoda, 2. Hälfte Insecta. de Gruyter, Wien