Mass Production of Beneficial Organisms

Invertebrates and Entomopathogens

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Chapter 18

Insects for Human Consumption

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18.1. INTRODUCTION

The utilization of insects as a sustainable and secure source of animal-based food for the human diet has continued to increase in popularity in recent years (Ash et al., 2010; Crabbe, 2012; Dossey, 2013; Dzamba, 2010; FAO, 2008; Gahukar, 2011; Katayama et al., 2008; Nonaka, 2009; Premalatha et al., 2011; Ramos-Elorduy, 2009; Smith, 2012; Srivastava et al., 2009; van Huis, 2013; van Huis et al., 2013; Vantomme et al., 2012; Vogel, 2010; Yen, 2009a, b). Throughout the world, a large portion of the human population consumes insects as a regular part of their diet (Fig. 18.1). Thousands of edible species have been identified (Bukkens, 1997; Bukkens and Paoletti, 2005; DeFoliart, 1999; Ramos-Elorduy, 2009). However, in regions of the world where Western cultures dominate, such as North America and Europe, and in developing countries heavily influenced by Western culture, mass media have negatively influenced the public's perception of insects by creating or reinforcing fears and phobias (Kellert, 1993; Looy and Wood, 2006). Nonetheless, the potentially substantial benefits of farming and utilizing insects as a primary dietary component, particularly to supplement or replace foods and food ingredients made from vertebrate livestock, are gaining increased attention even in Europe and the United States. Thus, we present this chapter to describe this emerging field at all levels, including historical, cultural, agricultural, industrial, and food science perspectives. To accomplish this, the chapter covers the topic of human entomophagy via the following subtopic categories: (1) historic and cultural precedents for insects as food; (2) the nutritional and human health value of insects; (3) insects as a sustainable protein and a secure source of human food; (4) current examples of mass-produced insects with potential as human food; and (5) potential products and byproducts from mass-produced food or feed insects. The definition of entomophagy is the dietary consumption of insects by any organism, but it is commonly used to refer specifically to the human consumption of insects. Thus, throughout this chapter we will use the term "entomophagy" interchangeably with and in referring only to the dietary consumption of insects by humans.

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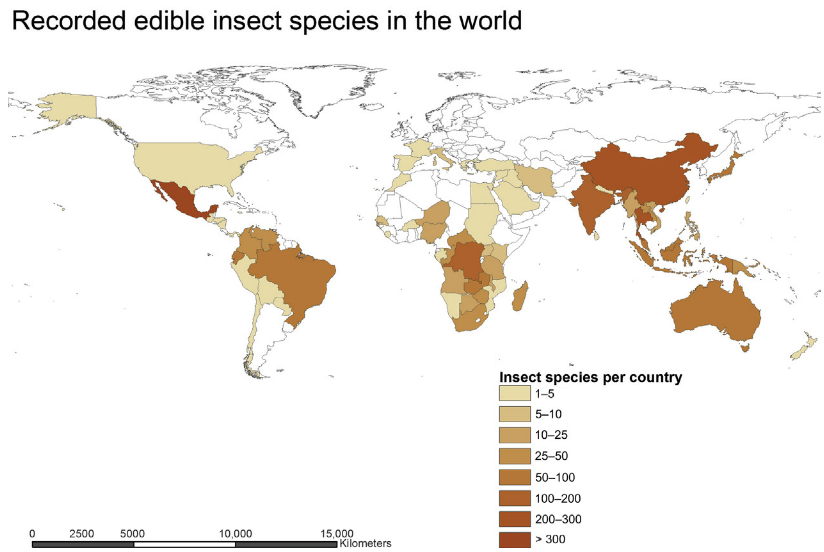

FIGURE 18.1 Edible insects of the world by biogeographical realm. *Wageningen University Laboratory of Entomology (2012).* (For the color version of this figure, the reader is referred to the online version of this book.)

18.2. HISTORIC AND CULTURAL PRECEDENTS FOR INSECTS AS FOOD

Many species of insects are important natural resources. Insects can be consumed as food for humans and animals alike and used for either self-sufficiency or commercial food products in many parts of the world. The use of edible insects varies by local preference, sociocultural significance, and region (Fig. 18.1). Edible insects are often regarded as cultural resources reflecting a rich biodiversity. As well, people who eat insects have established a broad variety of methods for their collection and preparation (Nonaka, 2009).

Wageningen University's Laboratory of Entomology's 2012 inventory of edible insects worldwide listed 2163 species that were reported in the literature as being consumed by humans (Fig. 18.2) (Jongema, 2012). Using the biogeographical realms proposed by Udvardy, high insect consumption of ~350 to ~700 edible insect species can be observed in the African, Neotropical, Oriental, and Palearctic Realms (Figs 18.3 and 18.4). There are several major orders of insects utilized in entomophagy worldwide, including Lepidoptera, Hemiptera, Coleoptera, Diptera, Orthoptera, and Hymenoptera. Worldwide, the three most common orders of insects eaten by humans are Lepidoptera (36 families and 396 species), Hemiptera (27 families and 222 species), and Coleoptera (26 families and 661 species). It is interesting to note that at the species level, the insect families that are most commonly consumed by humans worldwide are the Coleoptera, with the Scarabaeidae

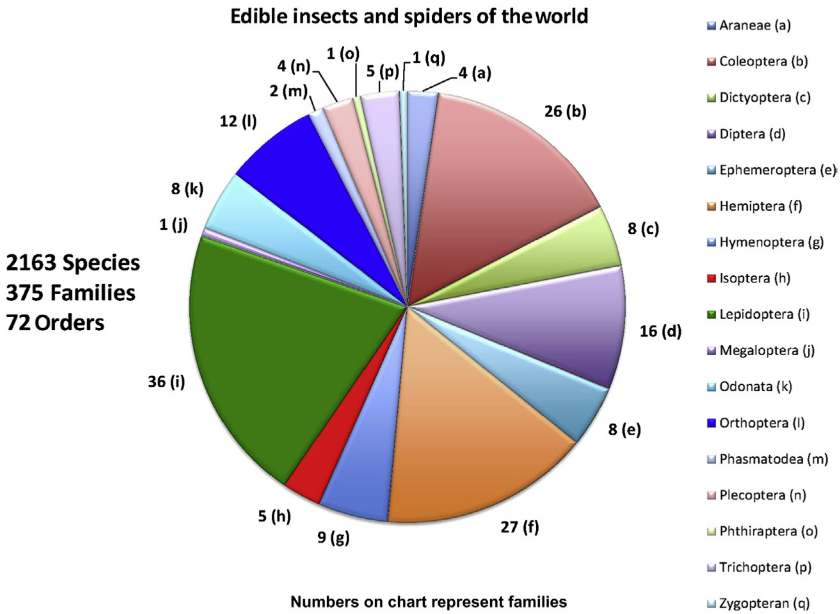

FIGURE 18.2 Edible insects and spiders of the world. *This chart is based on data from Wageningen University Laboratory of Entomology (2012).* (For the color version of this figure, the reader is referred to the online version of this book.)

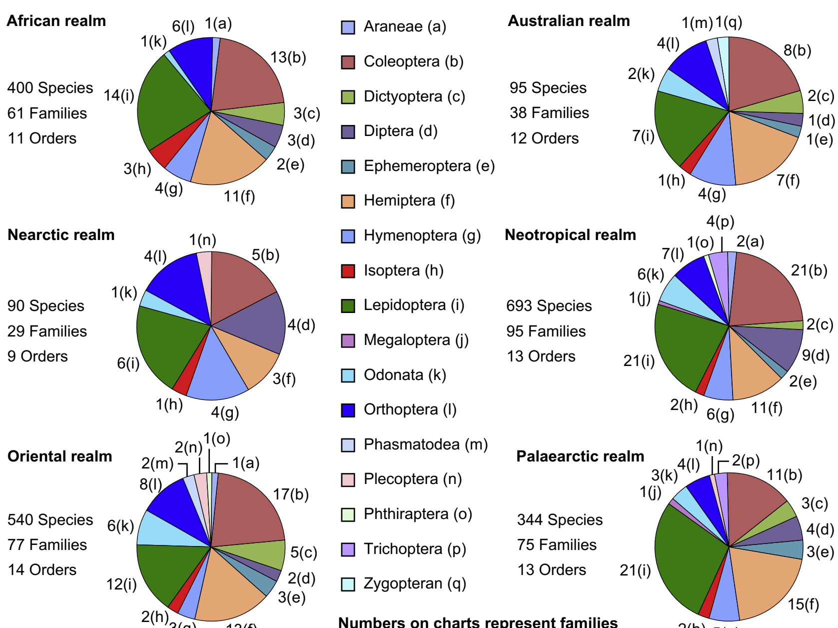

FIGURE 18.3 Edible insects and spiders by region. *This chart is based on data from Wageningen University Laboratory of Entomology (2012).* (For the color version of this figure, the reader is referred to the online version of this book.)

FIGURE 18.4 Terrestrial biogeographic realms of the world M.D.F. *Udvardy (1975)*.

(247 species), Dytiscidae (55 species), and Cerambycidae (129 species) being the most commonly eaten families of insects. As for Lepidoptera, the most commonly consumed families are Saturniidae (109 species), Hepialidae (47 species), and Sphingidae (36 species). Among Hemiptera, the most commonly edible families are Cicadidae (70 species), Pentatomidae (31 species), and Belostomatidae (17 species) (Jongema, 2012).

The following list outlines edible insect species consumed by humans by biogeographical realm, from those with the highest to the lowest frequency: Neotropical (639 species), Oriental (540 species), African (400 species), Palearctic (344 species), Australian (95 species), and Nearctic (90 species) (Fig. 18.4). More specifically, in the Neotropical realm, 13 orders, 95 families, and 693 species of insects are edible. As for the Oriental realm, 14 orders, 77 families, and 540 species of insects are incorporated into human diets. In the African realm, 11 orders, 61 families, and 400 species of insects are eaten. In the Palearctic realm, 13 orders, 75 families, and 344 species of insects are edible. In the Australian realm, 12 orders, 38 families, and 95 species of insects are consumed by humans. Last, in the Nearctic realm, nine orders, 29 families, and 90 species of edible insects have been documented in the literature (Fig. 18.4) (Jongema, 2012). This information is consistent with Western bias and Western influence against entomophagy, with the Nearctic and Australian realms consuming the lowest number of species of insects. It is estimated that as much as 80% of the world's population eats insects intentionally, and 100% do so unintentionally (Srivastava et al., 2009).

18.2.1. History of Human Insect Consumption

An 1877 book by Alpheus Spring Packard dedicated a chapter to edible insects, describing insects such as grasshoppers of the East, eaten by Arabs and in other parts of Africa, and collected by scorching their wings with fire during flight. Packard then described bees and ants eaten in Mexico and used in Sweden

to flavor brandy, and discussed the Chinese eating silkworms and the larvae of hawkmoths. Last, he discussed the palm weevils eaten in the West Indies (Packard, 1877). Another book, titled *Why Not Eat Insects?*, is one of the earliest entomophagy-related publications in the United States. In that book, author Vincent M. Holt shares his angst about "a long-existing and deep-rooted public prejudice" to insects as food (Holt, 1885). In a 1916 publication, Leland Ossian Howard and members of the Bureau of Entomology and the Bureau of Biological Survey discussed practical suggestions concerning any new cheap foods such as insects (Howard, 1916). During World War I, food prices worldwide were increasing, and many nations were facing very serious shortages. He and his colleagues prepared and personally ate various edible insect dishes. Howard concluded that colleges of agriculture, with their departments of home economics and entomology, were in an excellent position to conduct entomophagy research (Howard, 1916). In a review of the early literature, Friedrich Simon Bodenheimer's book *Insects as Human Food* cites more than 500 entomophagy references, from prehistory to the 1950s (Bodenheimer, 1951; Dufour, 1990). These studies revealed that many of the primitive peoples of Africa, Asia, and America were underfed or lived on unbalanced, unsatisfactory diets, with a serious shortage of animal fats, animal proteins, and carbohydrates. To date, Bodenheimer's book remains the most comprehensive review of historical entomophagy literature.

18.2.2. Overview of Insect-Eating Cultures in Modern Times

Entomophagy is accepted and practiced by many cultures around the world and constitutes a major source of nutritious food for many people (DeFoliart, 1995; Nonaka, 2009; Ramos-Elorduy, 2009) (Fig. 18.1). It exists in both protocultures and formal cultures (Ramos-Elorduy, 2009). The traditional use of insects as food continues to be widespread in tropical and subtropical countries, and it provides significant nutritional, economic, and ecological benefits for rural communities (Figs 18.3 and 18.4). As many as 3071 ethnic groups in 130 countries (Ramos-Elorduy, 2009) utilize insects as essential elements of their diet (FAO, 2008; Srivastava et al., 2009; Yen, 2009a, b). Many of the poorest populations in the world routinely eat insects as part of their diet, particularly in Africa, Asia, the Neotropics, and the Palearctic (Figs 18.3 and 18.4) (Gahukar, 2011; Manary and Sandige, 2008; Nonaka, 2009; Ramos-Elorduy, 2009). A study in Kenya, where malnutrition is prevalent, found that wheat buns enriched with insects were actually preferred by the locals over ordinary breads (Gahukar, 2011).

Recently, there has been increasing interest in entomophagy in the United States and Europe (FAO, 2008; Gahukar, 2011; Polis, 2011). However, European populations and European-derived populations in North America historically have placed taboos on entomophagous eating practices and continue to do so. Multiple attempts by entomologists have been made to make insects more broadly appealing. A popular example is Ronald Taylor's (1975) book *Butterflies in My Stomach*, and the accompanying recipe guide, *Entertaining*

with Insects (1976) (Taylor, 1975; Taylor and Carter, 1976). Several subsequent entomophagy cookbooks have been published, including *Insectes à croquer (Insects to Munch)*, produced by the Montreal Insectarium; and *Cuisine des insectes: À la découverte de l'entomophagie*, by Gabriel Martinez, a French culinary guide offering professional cooking advice. Others, such as the humorous *The Eat-a-Bug Cookbook*, offer readers familiar American recipes such as pancakes, pizza, and alphabet soup altered with the addition of edible invertebrates (Gordon, 1998). Due to recent popularity and interest in entomophagy in the United States, a second edition of *The Eat-a-Bug Cookbook* was released in 2013 (Gordon, 2013). Edible insects are also featured in Peter Menzel and Faith D'Aluisio's photo-essay volume, *Man Eating Bugs: The Art and Science of Eating Insects*, including diverse entomophagy scenes and dishes from around the globe (Menzel and D'Aluisio, 1998). Julieta Ramos-Elorduy's *Creepy Crawly Cuisine* is an introduction to the world of edible insects, complete with recipes and photographs (Ramos-Elorduy and Menzel, 1998). It includes a historical look at the use of edible insects in indigenous cultures and provides information on where to obtain insects and how to store and prepare them. *Het insectenkookboek* or *The Insects Cookbook* was recently published in The Netherlands and features various insect recipes (van Huis et al., 2012). *Edible Bugs: Insects on Our Plate* by Chad Peterson was published in 2012 and is available as an electronic book (Peterson, 2012).

18.2.3. Cultural Acceptance of Edible Insects

In Western-dominated cultures, people are accustomed to eating and willing to eat food items that they perceive as safe and are inherently unafraid of. Eating insects for nutrition is not imperative for most people in the United States and Western Europe, who may have many food options. However, there have been recent advancements in edible insect research in Europe. In The Netherlands a project entitled Sustainable Production of Insect Proteins for Human Consumption investigates the industrial extraction of insect protein to be incorporated into a range of food products. Likewise, cultural acceptance of edible insects in the United States is slowly becoming more prevalent. Although entomophagy may be informally observed in the United States, there is still an attitudinal barrier to the use of insects as human food. During 2011, entomophagy appeared almost weekly in newspapers, magazines, and blogs (Cruz and Johar, 2012). The *Huffington Post* reported insects as the number-one food trend of 2011 (Polis, 2011). Edible insects can also be found in a few restaurants in the United States in Arizona, California, and New York (Oaxaca, Toloache, Typhoon, and Bugs), as well as in food carts (Don Bugito, Jungle George's Exotic Meats, and Bugs) (Table 18.1). Worldwide, there are also entomophagy-based businesses, including Hotlix, Edible Unique, Thailand Unique Edible Insects/Bugs, All Things Bugs, Edible Insectivor, Deli Bugs, Insectes Comestibles, Lazybone, World Entomophagy, BugMuscle, and Chapul. In addition, there are numerous

TABLE 18.1 Additional Entomophagy Resources

Books and Cookbooks	**URL**
Creepy Crawly Cuisine	NA
Eat-a-Bug Cookbook	NA
Butterflies in My Stomach	NA
Entertaining with Insects	NA
Insectes à croquer (Insects to Munch)	NA
Cuisine des insects: À la decouverte de l'entomophagie	NA
Edible Bugs: Insects on Our Plate	NA
Het Insectenkookboek or *The Insects Cookbook*	http://www.uitgeverijatlas.nl/result titel.asp?id=3368
Cicada-licious	http://www.newdesk.umd.edu/pdf/cicada%20recipes.PDF
Man Eating Bugs	http://www.menzelphoto.com/books/meb.php
Websites, Activists, and Informal Educators	**URL**
All Things Bugs	http://www.allthingsbugs.com/
Food-Insects	http://www.food-insects.com/
Insects are Food	http://insectsarefood.com/
World Entomophagy	https://worldento.com/
David George Gordon	http://www.davidgeorgegordon.com/
Small Stock Foods	http://www.smallstockfoods.com
MiniLivestock	http://minilivestock.org/
Girl Meets Bug	http://girlmeetsbug.com/
Entom Foods	http://entomfoods.com/
Eating Bugs (from the Manataka American Indian Council)	http://www.manataka.org/page160.html
Food Insects Newsletter (through 2009)	http://www.hollowtop.com/finl html/finl.html
Food Insects Newsletter (2010 through present)	http://www.foodinsectsnewsletter.org/

Continued

TABLE 18.1 Additional Entomophagy Resources—cont'd

Websites, Activists, and Informal Educators	**URL**
Edible Forest Insects: Humans Bite Back (February 2010)	http://www.fao.org/docrep/012/i1380e/i1380e00.pdf
National Geographic, "Bugs as Food: Humans Bite Back"	http://news.nationalgeographic.com/news/2004/04/0416_040416_eatingcicadas.html
International	**URL**
Ento Cargo Collective	http://cargocollective.com/ento
Food Factory Foundation	http://www.foodfactoryfoundation.org
UN Food and Agriculture Organization, Edible Forest Insects	http;//www.fao.org/forestry/65422/en/
Heifer International: Extra Crunch with Lunch	http://www.heifer.org/media/world-ark/archives/2011/fall/extra-cruch-with-lunch
Entomophagy in Japan (2009)	http://tonymcnicol.com/2009/03/15/entomophagy-in-japan/
Food, Supplements, and Vendors	**URL**
All Things Bugs	http://www.allthingsbugs.com/
Chapul	http://chapul.com
Don Bugito	http://www.donbugito.com
World Entomophagy	https://worldentocom/
Bugmuscle	http://www.bugmuscle.com
Insectes Comestibles	http://www.insectescomestibles.fr/
Edible Unique Bugs and Gourmet Exotic	http://www.edibleunique.com/
Hotlix	http://www.hotlix.com/
Thailand Unique Edible Insects/Bugs	http://www.thailandunique.com/store/edible-insects-bugs-c-1.html
Edible Insectivore	http://www.edible-shop.com/shop/insectivore/
Deli Bugs	http://www.delibugs.nl/
Lazybone	http://lazyboneuk.com/categories/Edible-Insects-/

websites and blogs devoted to entomophagy, including Food-Insects, Insects Are Food, All Things Bugs, World Entomophagy, David George Gordon, Small Stock Foods, MiniLivestock, Girl Meets Bug, Entom Foods, Eating Bugs (from the Manataka American Indian Council), *Food Insects Newsletter*, Entomophagy in Japan, National Geographic's "Bugs as Food: Humans Bite Back," the Bay Area Bug Eating Society, the Ento Cargo Collective, the Food Factory Foundation, the UN Food and Agriculture Organization, Edible Forest Insects, Heifer International, Extra Crunch with Lunch, Insect Europe, and Harvesting of Insects in South Africa and Japan: Indigenous Knowledge in the Classroom. For a complete list of websites associated with entomophagy books, cookbooks, websites, activists and informal educators, and blogs; international entomophagy; entomophagy food and supplement products; and insect vendors, refer to Table 18.1.

18.2.4. Social Change, Food Choice, and Perceptions

In areas where entomophagy is not prevalent, food choice and food habits are driving forces of acceptance. Lewin (1952) first researched food habits in the 1940s during World War II, when there were food shortages and increased food costs. He described methods to integrate cultural anthropology, psychology, and sociology into the concepts of group decision making and ultimately social change. Group decision making lies at the interface of many basic problems of group life and individual psychology, and it addresses the relationship of motivation to action with the effect of a group setting on the individual's readiness to change or to keep certain standards. Lewin (1943) observed that the subjects in his study had a desire to be educated about the new food sources and food item alternatives (such as changing sirloin and ribeye to liver and hearts). They also wanted to discuss difficulties in preparation, the concept of group decision making in a household, ideas for presenting the new food to the family, and determining success after the food had been introduced in the home. Lewin (1943) discussed the techniques utilized to change food habits, such as lecture or group discussion or decision making, which were perceived as essential components by the study participants. Similar methods could be used for action research into changing group opinions of food habits and choices related to edible insects. In order to accomplish this, we need a better understanding of the fundamental problems of action research, namely, how to change group conduct in a way that persists (Lewin, 1952).

In order for entomophagy to be popularly accepted, the concepts of group decision making and social change theory must be utilized and further researched. The perceived issue of edible insects being associated only with poor countries, as a low-status problem, must be eliminated (Lewin, 1943). Lewin's food habits research can be the basis for future entomophagy research in the United States related to cultural acceptance of edible insects, relying on the fields of adult education, psychology, and entomology from a multidisci-

plinary approach. However, for social change to occur so that entomophagy can be accepted in the United States, we must simultaneously decrease the fears and phobias associated with insects while increasing the public's positive perception of insects. Food neophobia (fear of new foods) prevents people from trying new foods, such as insects (Birch, 1999). Phobias such as these need to be addressed for insects to be accepted and incorporated into Western-dominated diets.

Another entomophagy barrier to overcome is the public's perception of invertebrates. Kellert (1993), in his invertebrate perception study, proposed the use of psychological attitude scales in relation to people's perceptions toward invertebrates. Basic attitudes toward invertebrates were summarized by nine scales: aesthetic, dominionistic, ecologistic, humanistic, moralistic, naturalistic, negativistic, scientistic, and utilitarian (Kellert, 1993). This study found that a more positive view of invertebrates was observed when participants were presented with taxa that possessed aesthetic value (e.g. butterflies) or practical value (e.g. bees). It is interesting to note that the most common order of insects eaten by humans worldwide is Lepidoptera (butterflies and moths) (Fig. 18.2). Variation in the results may be attributed to an innate learning disposition, the association of many invertebrates with disease and damage, the ecological scale between us and them, the relative abundance of insects, the lack of a sense of identity and consciousness among invertebrates, the presumption of mindlessness among invertebrates, and the radical autonomy of invertebrates from human control.

Kellert's psychological attitude scale has been widely utilized in animal perception research by multiple disciplines, including entomology and psychology. Looy and Wood (2006) studied the psychology of entomophagy, which examined whether educational bug banquets influenced attitudes toward invertebrates. There is a general informal consensus among entomophagy educators and activists that incorporating edible insects into entomology outreach programs as a form of informal education to introduce the general public to entomophagy may be vital to the acceptance of entomophagy (Looy and Wood, 2006).

18.3. NUTRITIONAL AND HUMAN HEALTH VALUE OF INSECTS

The United Nations (UN) has placed heavy emphasis on alleviating hunger and malnutrition in children. Two of their eight Millennium Development Goals (MDGs), set to be achieved by 2015, are directly related to this area: The first MDG is to "eradicate extreme poverty and hunger," and the fourth is to "reduce child mortality rates'' (Dossey, 2013). Here, we present a number of assets that insects provide to improve sustainable access to highly nutritious food, as well as how insects can help alleviate world hunger. Number 7 on the MDG list is "ensuring environmental sustainability'' (Dossey, 2013). The tremendous benefits of insects in ensuring environmental sustainability are discussed in this chapter.

18.3.1. Animal- versus Plant-Based Food and Protein

Animals, which include insects, are important or even the sole sources of numerous necessary nutrients for humans. Some important examples of these are the eight essential amino acids ("complete" protein), vitamin B_{12}, riboflavin, the biologically active form of vitamin A (retinol, retinoic acid, and retinaldehyde), and several minerals (Bukkens, 1997; Bukkens and Paoletti, 2005; Hoppe et al., 2008; Michaelsen et al., 2009; Singh and Singh, 1991; Yen, 2009a, b). In particular, it is broadly accepted that animal-sourced dietary protein is superior to that derived from plants (Babji et al., 2010; Hoppe et al., 2008; Michaelsen et al., 2009; Singh and Singh, 1991). Animal-based food is important for the nutritional status, growth, and recovery rate as well as cognitive performance of undernourished children (Michaelsen et al., 2009; Neumann et al., 2003). Even small amounts of animal-sourced food ingredients, such as insects, can substantially improve nutrient adequacy (Michaelsen et al., 2009). A review by Michaelsen et al. (2009) cites numerous benefits of animal-sourced foods in general and particularly their importance for children suffering from malnutrition. Specifically, they recommend that these foods contain at least 25–33% animal-sourced food ingredients to significantly improve growth rate. Most ready-to-use therapeutic food (RUTF) used to treat malnutrition in children is "lipid based" in order to provide high energy content (Manary and Sandige, 2008). Michaelsen et al. (2009) recommend a diet, including animal sources of eicosapentaenoic and docosahexaenoic acids, for children born undernourished and at low birth weight.

As described in this chapter, insects can be grown highly efficiently in many areas not amenable to dairy cattle and, thus, help to provide a robust alternative to milk as well as a potential alternative income source for farmers. Consequently, insects are likely the best source of animal-sourced food for people in much of the world.

18.3.2. Nutrient Content of Insects

Insects present a substantial, yet extremely underexplored, alternative opportunity to provide much-needed animal-sourced nutrients, particularly to the developing world. Several authors have examined the nutritional value of insects and their role in human nutrition (Banjo et al., 2006; Bukkens, 1997; Bukkens and Paoletti, 2005; DeFoliart, 1992; Finke, 2002, 2004, 2005, 2012; Jokthan et al., 2007; Michaelsen et al., 2009; Ramos-Elorduy, 1997, 2008, 2009; Ramos-Elorduy and Menzel, 1998). Hundreds of insect species have been formally studied for nutrient composition. Most nutrition studies analyze insects for moisture, protein, fat, ash, and fiber. Insects are generally high in protein and fat at levels comparable to those of milk and meat such as beef (Table 18.2). A review by Bukkens concludes that the amino acid composition of insects compares favorably with the reference standard recommended by the UN Food and Agriculture Organization (FAO), World Health Organization (WHO), and

TABLE 18.2 Nutritional Content of Insects Compared with Other High-Protein Foods

Insect or Food Item	Protein (g/kg)	Fat (g/kg)	Calories (kcal/kg)	Thiamin (mg/kg)	Riboflavin (mg/kg)
Black soldier fly*	175	140	1994	7.7	16.2
House fly*	197	19	918	11.3	77.2
House cricket**	205	68	1402	0.4	34.1
Superworm**	197	177	2423	0.6	7.5
Mealworm**	187	134	2056	2.4	8.1
Giant mealworm**	184	168	2252	1.2	16.1
Waxworm**	141	249	2747	2.3	7.3
Silkworm**	93	14	674	3.3	9.4
Beef†	256	187	2776	0.5	1.8
Milk powder‡	265	268	4982	2.6	14.8

**Finke (2012).*
***Finke (2002).*
†Current USDA National Nutrient Database for Standard Reference.
‡From the US Dairy Export Council website.
Beef: ground, 75% lean meat and 25% fat, patty, cooked, broiled, milk, whole dry powder (black soldier fly = Hermetia illucens larvae; house fly = Musca domestica adults; house cricket = Acheta domestica adults; Superworm = Zophobas morio larvae; mealworm or giant mealworm = Tenebrio molitor larvae; Waxworm = Galleria mellonella larvae; silkworm = Bombyx mori larvae).

United Nations University (UNU) (Bukkens and Paoletti, 2005). Insects are particularly high in protein, at levels comparable to those of beef and milk (Table 18.2). House crickets, for example, contain approximately 205 g of protein per kilogram of cricket, while ground beef contains about 256 g per kilogram and whole powdered milk contains about 265 g per kilogram. Some estimate that the digestibility of flour made from insects is as high as 91% (Bukkens, 1997). Protein from various sources, in dried form, is most frequently found in village markets of the developing world. Insects are very high in crude protein, with many species ranging above 60% by dry weight (Bukkens, 1997; Bukkens and Paoletti, 2005). Some insect proteins are equivalent to soy protein, whereas others are superior as a source of amino acids at all levels of intake. Whole insects as a source of protein are of somewhat lower quality than vertebrate animal products because of the indigestibility of chitin. Removal of chitin increases the quality of insect protein to a level comparable to that of products from vertebrate animals (see Section 18.4.3 for more information on insect processing). In general, insect protein tends to be low in amino acids such as

methionine and cysteine, but it is high in lysine and threonine, one or both of which may be deficient in the wheat-, rice-, cassava-, and maize-based diets that are prevalent in the developing world (DeFoliart, 1992).

Insects are also particularly rich in fat (Table 18.2) (Bukkens, 1997; Bukkens and Paoletti, 2005; DeFoliart, 1992; Finke, 2012; Gahukar, 2011) and can supply a high caloric contribution for energy-dense foods (Table 18.2). In the reviews by Bukkens, all insect species were found to be a "significant source of the essential fatty acids linoleic and linolenic acid" (Bukkens, 1997; Bukkens and Paoletti, 2005). Some insects can also provide a higher caloric contribution to the diet than soy, maize, or beef (Gahukar, 2011). Cholesterol levels in insects vary from low to approximately the levels found in other animals, depending on the species and diet. Insect fatty acids are similar to those of poultry and fish in their degree of unsaturation, with some groups being rather higher in linoleic and/or linolenic acids, which are the essential fatty acids (DeFoliart, 1992).

In addition to protein, fat, and caloric content, many insects are particularly high in a number of vitamins, minerals, and other valuable nutrients (Table 18.2). For example, many species are significantly higher in thiamin and riboflavin than whole-meal bread and hen's eggs (Bukkens, 1997; Bukkens and Paoletti, 2005). The retinol (a biologically active form of vitamin A) and beta-carotene content of many insect species is also high, with levels in some species as high as 356 mg/kg and 1800 mg/kg, respectively (Bukkens and Paoletti, 2005). However, currently very limited data are available for vitamin analyses of insects, and more studies are needed.

18.3.3. Global Malnutrition and How Insects Can Help

Malnutrition affects 178–195 million children worldwide (Black et al., 2008). The WHO estimates that malnutrition accounts for 54% of child mortality worldwide (Duggan et al., 2008). Malnutrition results in wasting, a reduced ability to fight infection, impaired cognitive disorders, and other developmental disorders that can be permanent (Victora et al., 2008). About 60 million children suffer from moderate acute malnutrition, and 13 million from severe acute malnutrition (Collins et al., 2006). Malnutrition is a contributing factor in over 50% of the 10–11 million children under the age of 5 years who die from preventable causes each year (Black et al., 2003; Caulfield et al., 2004; Pelletier and Frongillo, 2003; Rice et al., 2000). Fatality rates from severe acute malnutrition have averaged 20–30% since the 1950s (Schofield and Ashworth, 1996). It is estimated that 9% of Sub-Saharan African children and 15% of Asian children suffer from moderate acute malnutrition (Collins et al., 2006).

As mentioned in Section 18.3, the United Nations has established eight MDGs; the first MDG is to "eradicate extreme poverty and hunger," and the fourth is to "reduce child mortality rates'' (Dossey, 2013). Specifically, the goals involve reducing childhood mortality by two-thirds and worldwide hunger by one-half. Indeed, the topic of the potential for insects to contribute to sustainable

human food security has taken the notice of multiple organizations. For example, as mentioned in this chapter, the FAO has taken the initiative and proposed a program of feeding people with alternative food sources, including insects (Gahukar, 2011). Two major meetings on the feasibility and benefits of insects as a food source have resulted from this initiative: (1) a February 2008 workshop in Thailand, which produced an important book in the field called *Forest Insects as Food: Humans Bite Back* (FAO, 2008); and (2) a technical consultation held January 2012 at FAO headquarters in Rome, Italy (Vantomme et al., 2012). At the 2012 meeting, a global summit on insects and food security for 2014 was also proposed. Those in attendance at the 2012 meeting appeared to come away quite optimistic that insect-based food products are indeed an important part of our future. It was also generally recognized that government and industry backing is necessary to support the widespread implementation of insect-based diets.

Malnutrition in developing countries is primarily a problem of protein and calorie deficiency. While the content of particular nutrients and nutrient categories varies widely among the hundreds of species analyzed, insects are in general a very good source of protein, fat, and other nutrients that are valuable to the human diet (see also Section 18.3.2). Additionally, the problem of protein deficiency is one that affects low-income people worldwide. The consumption of some insects can provide both high protein and caloric intake. For example, the nutrient content of the African palm weevil larvae (*Rhynchophorus phoenicis*) was described in a Nigerian study, and they were found to be very high in both carbohydrate and protein (Okaraonye and Ikewuchi, 2008). Because insects are a robust source of animal protein, it is important to improve production and preservation techniques, to market them, and to make them available to all populations (Melo et al., 2011).

Given the fact that insects compare quite favorably in their nutrient content with vertebrate livestock, as described in this chapter, increasing their consumption in places where vertebrate livestock is unavailable or their growth is infeasible can greatly improve the health and nutritional status of a great number of people worldwide. Access to edible insects can be achieved by different methods, including wild harvesting, efficient and/or sustainable farming, or even household rearing or gardening. Insects are much less resource intensive and much more resistant to drought and disease (typically) than cattle and most other vertebrate livestock commonly utilized by humans (see Section 18.4). Research and education programs on insect farming and preparation and on safe selection and preparation of wild-harvested insects are two activities that can greatly improve nutrition and food security worldwide. However, the primary methods of preparing, cooking, or processing insects in many areas of the world, particularly in places where poverty and malnutrition are highest, involve roasting, searing, or frying whole insects. Unfortunately, these methods of processing can remove fat (an important source of calories) and other nutrients, while destroying others or making them indigestible. Education programs on methods of cooking, processing, or preparing insects (either wild harvested

or farmed) for human consumption in places where malnutrition rates are high might dramatically improve the nutritional status and overall health of the people who live there.

Relief foods such as RUTF products present another opportunity to begin utilizing insects as a more sustainable source of animal-sourced nutrition. One reason for this is that it is often highly desirable for organizations or companies to grow these products in the same country where they will be consumed and from ingredients sourced as nearby as possible. Whereas milk powder is almost always imported and is rarely locally available in places where malnutrition is prevalent, many types of insects can be locally farmed or harvested from the wild. There is already at least one US company working on just this sort of product (Crabbe, 2012) (Table 18.1). That firm was awarded a grant from the Bill and Melinda Gates Foundation in 2012 to develop an insect-based RUTF (Crabbe, 2012). If this sort of endeavor is successful, it could substantially improve the prospects of the insect-based food industry by drastically increasing demand for insects reared as human food ingredients for the insect-based RUTF.

Another potentially impactful way in which insects can improve food security is strategic utilization of pest species and/or species of high seasonal or regular abundance. This can not only expand the use of insects (currently an extremely underutilized resource) but also be a safer, cleaner, and more sustainable method of pest control—thus turning the proverbial "lemons into lemonade." For example, insects such as Lepidoptera larvae (caterpillars), locusts and other grasshoppers (Orthoptera), and others tend to be of extremely high abundance in places where effective pesticides are not used. Cerritos and Cano-Santana (2008) found that manual harvest of grasshopper pests reduces the density of grasshoppers and suggests that implementation of this mechanical method of control may be an effective substitute for chemical control (Cerritos and Cano-Santana, 2008). Mechanical control provides general advantages that include (1) a second profitable product, (2) savings realized from the reduced cost of insecticides, and (3) a reduced risk of soil and water contamination by insecticides. This sort of dual-function pest control might be highly amenable to farming in developing nations as well as organic farms in the United States. Even in more modern agricultural settings, if insect pests can be allowed to consume the inedible parts of crop plants, or crops that are otherwise deemed no longer useful as a harvest, they can potentially be an additional crop with value added to the already ongoing farming practice. Other species, while not actual pests, can also be highly abundant at certain times of the year or in periodic outbreaks. Some examples of this include "lake flies" in Africa (Ayieko et al., 2010a; Ayieko and Oriaro, 2008; Ayieko et al., 2010b) and even some walking stick insects (Phasmatodea), which defoliate sections of forest from time to time (Campbell, 1960, 1961; Graham, 1937; Hennemann and Conle, 2008). Thus, more efficient and increased use of abundant insect resources results in the reduction of pesticides and creates new economic opportunities for indigenous people (DeFoliart, 1992).

Some specific studies have already identified cases whereby pest insects can have a substantial positive health impact in areas where malnutrition is high, as well as economic benefits. For example, a grasshopper in Mexico known as *chapulines* (*Sphenarium purpurascens* Charpentier) (see Section 18.5) is controlled by harvesting them as a food item in addition to the crops they attack. This activity provides an annual profit of about $3000 per family and a total of 100 metric tons of edible insect mass (Premalatha et al., 2011). Studies on the nutritional value of edible insects from Mexico and Nigeria revealed that some of the insects, which are pests, also have high nutritional qualities (Banjo et al., 2006; Ramos-Elorduy, 1997). Christensen et al. (2006) identified edible insects as a mineral source in Kenya (Christensen et al., 2006). Deficiencies of important minerals such as iron, zinc, and calcium are often widespread among people in developing countries. These deficiencies are caused by the low availability of these nutrients in staple foods such as cereals and legumes due to the considerable amount of phytic acid and other antinutrients present in these foods and due to the lack of animal foods with higher content and bioavailability of these nutrients (Christensen et al., 2006). Iron and zinc deficiency is widespread in developing countries, especially in children and women of reproductive age. Iron deficiency leads to anemia, reduced physical activity, and increased maternal morbidity and mortality. As a result, entomophagy could prove to be a valuable measure to combat iron and zinc deficiency in developing countries. Some caterpillars have been found to be a rich source of iron, copper, zinc, thiamin (vitamin B_1), and riboflavin (vitamin B_2); 100 g of cooked insect provided >100% of the daily requirement of each of these minerals and vitamins. Iron deficiency is a major problem in women's diets in the developing world, particularly among pregnant women, and especially in Africa (DeFoliart, 1992).

18.3.4. Insects in Medicine and Drug Discovery

Arthropods appear to be a largely unexplored and underutilized source of drugs and drug lead compounds for modern medicine and biomedical research (Alves and Alves, 2011; Dossey, 2010; Ratcliffe et al., 2011; Srivastava et al., 2009; Yi et al., 2010). Insects and other arthropods are used as drugs by many cultures around the world, particularly Korea (Pemberton, 1999), China, Brazil, and India (Dossey, 2010). For example, they appear in pharmacopoeias of Korean traditional medicine, but little was known about their use in modern South Korea. There, most of the arthropod drugs were traditionally collected or reared, but now they are imported, mainly from China. Folk logic appears to be the basis for some arthropod drug uses. However, many of the arthropods have venom and other defensive chemicals, which are biologically active (Dossey, 2010). The South Korean use of arthropods as drugs is due, in part, to more positive attitudes toward these animals compared to many other cultures (Yi et al., 2010). Medicinal use of insects is also prevalent in China. For example,

in a monograph by Read and Li (1931), they describe numerous notes of the ancient Chinese records about insects for medicinal use, as well as their descriptions, habitat, and folklore (Read and Li, 1931).

Like all other organisms, insects and related arthropods mainly utilize chemistry to adapt to their environments in a wide variety of ways, such as for defense against predation or infection, communication and socialization, life cycle development, and surviving environmental conditions. Arthropods harbor a large variety of chemical substances used for these ecological functions, and this is the overarching theme of the field of chemical ecology. However, the fields of pharmacognosy (primarily involved with drug discovery from natural sources) and natural products chemistry have largely ignored insects as a potential source of pharmaceuticals, favoring plants and, more recently, marine organisms instead. Some potential rationale for this bias, such as the relatively larger amounts of material available from plants, their role as primary biosynthetic producers, and the limitations of the minimum amounts of material needed for analysis by standard analytical chemistry techniques, has been discussed in a review article by Dossey (2010) for the journal *Natural Product Reports*. However, Dossey (2010) also points out that recent advances in analytical chemistry technology and instrumental sensitivity, along with the aforementioned biodiversity (see the "Biodiversity" paragraph of Section 18.4) of insects and other arthropods, merits reconsideration of insects as a source of material for natural products. While the potential role of insects in drug discovery, development, and production is fascinating and represents a quite important set of applications for insects (whether farmed, collected, or cultured in the laboratory), it is beyond the scope of this chapter, and we recommend the following review articles for more information on this topic: Alves and Alves (2011), Dossey (2010), Pemberton (1999), Srivastava et al. (2009), Trowell (2003), and Yi et al. (2010).

18.4. INSECTS AS A SUSTAINABLE SOURCE OF HUMAN FOOD

As the human population grows, it is ever more important to sustain rather than increase our levels of consuming and harvesting materials from the earth and its ecosphere. The world adds about 70 million people each year. The United Nations expects the population to grow to more than 9 billion people by 2050, adding approximately twice the current population of China (Dzamba, 2010; Safina, 2011; Vogel, 2010). Humans consume roughly 40% of the biomass that the land and the coastal seas produce (Safina, 2011). Approximately 70% of agricultural land, and 30% of the total land on earth, is used to raise livestock (Steinfeld et al., 2006). Food reserves are at a 50-year low, yet demand for food is expected to increase by 50% by 2030. The historic US drought of 2012 also throws into sharp relief our need for more sustainable agricultural practices (Smith, 2012). We cannot rely on food production strategies utilizing livestock such as cattle to feed our growing population. Insects hold tremendous promise

in addressing this gloomy outlook (Dossey, 2013). Expanding the amount of land used for livestock production is not a feasible or sustainable solution to cover the food and protein needs of the projected increases in population. Therefore, it is important to use sources of high-quality animal protein that reduce the amount of pollution, habitat destruction, and abuse of natural resources. However, new technologies for improving food security, such as producing and processing insects as human food, take time for development and application on a large scale, so it is important to make investments in these innovations sooner rather than later (Gahukar, 2011).

The use of insects as a major human food source presents two important technological challenges: (1) how to turn insects into safe, healthy, and tasty food products; and (2) how to cheaply, efficiently, and sustainably produce enough insects to meet market demand. Many also advocate the wild harvesting of insects as human food as a solution to hunger and global food security. While this may be a reasonable short-term solution in a number of isolated situations in certain localities, we feel strongly that for full realization of the potential benefits derived from utilization of insects as a safe, reliable, and sustainable alternative to vertebrate livestock, the ultimate goal must be the efficient farming and/or mass production of insects. Dependence on wild-harvested insects for feeding large populations involves serious risks, such as overharvesting, ecological damage, and consuming insects contaminated by pesticides, environmental contaminants, and/or exposure to pathogens, parasites, and other disease-causing agents that may exist in the environment but can be eliminated or controlled in farmed or captive-reared stocks. Additionally, data on nutrient content vary widely by species, so using homogeneously farmed stock of individual species provides much greater product quality control (Bukkens, 1997, 2005). As a consequence, this chapter focuses primarily on the latter.

Insects have numerous attributes that make them highly attractive, yet underexplored, sources of highly nutritious and sustainable food (Crabbe, 2012; Dossey, 2013; Dzamba, 2010; FAO, 2008; Gahukar, 2011; Katayama et al., 2008; Nonaka, 2009; Premalatha et al., 2011; Ramos-Elorduy, 2009; Smith, 2012; Srivastava et al., 2009; van Huis, 2013; Vogel, 2010; Yen, 2009a, b). The general categories where insects provide the most substantial benefits for sustainable and secure food supplies are (1) efficiency and (2) biodiversity.

Efficiency. Insects can be produced more sustainably and with a much smaller ecological footprint than most vertebrate livestock such as cattle and swine. They are very efficient at biotransformation of a wide variety of organic matter into edible insect biomass (a high feed conversion ratio) (Nakagaki and Defoliart, 1991; Oonincx et al., 2010). For example, cows consume 8 g of food mass per gram of weight gained, whereas insects can require less than 2 g (Vogel, 2010). This is partly due to insects being poikilothermic ("cold blooded"), thus using less energy for body warmth since they utilize their environment for body temperature regulation (Premalatha et al., 2011). House crickets (*Acheta domesticus* L.) have an "efficiency of conversion of ingested food (ECI) that is twice

that of pigs and chickens, 4 times that of sheep and 6 times that of steer" (Gahukar, 2011). This efficiency can also lead to less usage of pesticides on animal feed, thus providing additional environmental, health, and economic incentives.

In addition to their highly efficient feed conversion ratios and diet variability, insect fecundity, rapid growth rates, and short life cycles add to the greater efficiency with which they can be produced as a human food ingredient compared with vertebrate livestock. Insects tend to reproduce quickly, are highly adaptable, have large numbers of progeny per individual (high fecundity), and have a large biomass. For example, house crickets can lay 1200–1500 eggs in a 3–4 week period (Gahukar, 2011).

Biodiversity. The UN FAO estimates that there are well over 1000 edible insects currently used (Vogel, 2010), and others estimate that number to be over 2000 (Figs 18.1–18.3) (Jongema, 2012; Ramos-Elorduy, 1997, 2009). There are over 1 million species described and 4–30 million species estimated to exist on earth, living in every niche inhabited by humans and beyond (Dossey, 2010). With this diversity and their collective adaptability, they are a much safer source for future food security than are vertebrate animals such as cattle, fowl, or even fish. Development of more diversity in animal livestock and protein sources is critical to human food security going forward. Insects, being the largest and most diverse group of organisms on earth, certainly have a substantial role to play. For example, since there are insects of some sort on nearly every patch of land on earth, chances are that some local species in every area can be farmed as human food without the need to import nonnative species for the same purpose. Since insects are prolific in the wild, they can be readily tapped to replenish gene pools of farmed stock, unlike most terrestrial vertebrate livestock. That capability, along with a reliance on multiple farmed insect species, can greatly reduce the impact of livestock shortages on food security.

18.4.1. Environmental Footprint of Insects versus Vertebrate Livestock

Since, as described in this chapter, about 70% of agricultural land, and 30% of the total land on earth, is used to raise livestock (Steinfeld et al., 2006), increasing the efficiency with which we utilize this land to generate food for the growing population is one of the most effective ways we can reduce our impact on the world's ecosystems. Toward the goal of reducing human contribution to climate change, insects, in addition to possessing a high feed conversion ratio (as described in Section 18.4), also produce lower levels of greenhouse gases (GHGs) (Oonincx et al., 2010). Global average temperature has increased by 1.4 °F over the last century, and it is predicted to continue rising, a trend that is expected to lead to significant negative consequences. Global warming is primarily caused by GHG emissions related to human activity (Smith et al., 2001). The livestock sector contributes about 8.2% of anthropogenic GHG emissions (Takle and Hofstrand, 2008). A recent study by Oonincx et al. (2010) has

demonstrated through rigorous experimentation and measurement that insects give off lower levels of greenhouse gases, such as methane, carbon dioxide, and nitrous oxide, than do cows. Oonincx et al. (2010) quantified the production of carbon dioxide and average daily gain (ADG) as a measure of feed conversion efficiency, and quantified the production of the GHGs methane and nitrous oxide, as well as ammonia, by edible insect species. Results varied considerably by species, but they generally had a higher relative growth rate and emitted comparable or lower amounts of GHGs and ammonia than pigs and much lower amounts of GHGs than cattle (Oonincx et al., 2010). The same was true for carbon dioxide production per kilogram of metabolic weight and per kilogram of mass gain. Additionally, livestock produce large amounts of ammonia, leading to soil nitrification and acidification. The results of this study can be used as basic information to compare the production of insects versus conventional livestock by means of a life cycle analysis (Oonincx et al., 2010). Thus, the data presented in that report add to the already growing amount of research suggesting that insects could serve as a more environmentally friendly alternative to the production of animal protein with respect to GHG and ammonia emissions.

Insect production also uses much less water than production of vertebrate livestock (van Huis, 2013) because insects obtain their water directly from food. Additionally, the higher feed conversion ratios for insects, described in Section 18.4, also contribute to this water use efficiency since a lower feed requirement means less water is used to grow that feed. Lower water usage also reduces the energy needed to pump or recycle more clean water for crops and vertebrate livestock, adding to the benefits of farming insects rather than larger animals. In fact, many insects can be produced with almost no additional feed crop production. For example, many insects, such as the black soldier fly (*Hermetia illucens* L.) (Bondari and Sheppard, 1981; Popa and Green, 2012), can eat organic biomass such as agricultural and food byproducts (see Section 18.5 for more details on the black soldier fly). Such organic biomass could include corn stalks, pulp from fruit-juicing or wine-making operations, expired produce from grocery stores, yeast from wine or beer production, portions of crops that cannot be converted into human food, and other types of clean, safe, and low- or no-value biomass. For simplicity, this type of biomass will be referred to as "agricultural or food byproducts," "nonfood crops," or simply "byproducts.'' Insects are able to convert these byproducts, and other biomass otherwise not useful for human food production such as switchgrass and algae, into edible insect mass. Hence, the production of some insects as human food in many cases may neither require feed to be grown especially for that purpose nor compete with the existing human food supply, unlike vertebrate livestock such as cows and chickens, which are often fed a diet primarily consisting of grain such as corn. In addition to production efficiency, insects may provide nutritional value directly to the consumer more efficiently, per kilogram of foodstuff consumed, than other food resources (Ramos-Elorduy, 2008; Ramos-Elorduy et al., 2008). This adds another level of environmental impact reduction from the use

of insects as human food over other, currently more popular alternatives such as vertebrate livestock. For example, edible insects provide 217–777 kcal/100 g (insects raised on organic byproducts provide 288–575 kcal/100 g), whereas energetic values for livestock are 165–705 kcal/100 g and for vegetables are 308–352 kcal/100 g. Fats provide the majority of the energy necessary for sustaining life. Immature stages of holometabolous insects have high quantities of polyunsaturated fat, which is stored in preparation for the pupal stage when they do not eat and are developing into adults. While the energy contents of edible insects vary according to the species and region found, coleopteran and lepidopteran species tend to provide more energy. Additionally, the energetic cost of collecting edible insects can be lower than that for vertebrates. Hence, insects may efficiently provide the necessary energy for the vital functions of our organism (Ramos-Elorduy, 2008; Ramos-Elorduy et al., 2008).

18.4.2. Insects as Animal Feed

In addition to the tremendous potential that insects hold as primary sources of human food and other directly consumed products, they also present a promising opportunity in their use as intermediate products such as animal feed. Considering the substantial efficiency, sustainability, and nutritional aspects of insects as described in this chapter, the logic easily follows as to how they might provide similar value when utilized in the vertebrate livestock industry, or even in vertebrate animal production at the subsistence level. For example, early stages of poultry, fish, ostrich, and pig, which were raised on insects, had conversion efficiency values of 1.24:1–2.83:1 (Ramos-Elorduy, 2008). Insects fed with biomass such as manure and certain forms of agricultural or other organic waste may not be safe, suitable, or acceptable if used directly as a human food ingredient. However, such insects can be perfectly safe when used as feed for vertebrate animals, such as fish and chicken, which are more commonly eaten by most human populations. Using insects in this way can also provide some of the aforementioned food production sustainability benefits while avoiding social stigmas or food safety concerns. For example, in some studies, insects such as the black solder fly have been explored and developed for chicken and fish feed in a sustainable and efficient nutrient-recycling paradigm due to their ability to be reared entirely on waste such as animal manure and other agricultural or food industry waste streams (Bondari and Sheppard, 1981; Sheppard et al., 1994; St-Hilaire et al., 2007). Indeed, several companies and organizations around the world, even in the United States, are beginning to develop various insects as animal feed. Black soldier fly (discussed in this chapter) appears to be one of the species favored for this type of application. The topic of use of insects as animal feed is fascinating and critical for the larger picture of how insects can greatly improve human food security. This topic is beyond the scope of the current chapter, but the use of insects as animal feed is covered extensively in Chapter 16 of this book.

18.4.3. Considerations for Insect-Based Food Production, Processing, and Safety

The full realization of aforementioned benefits of edible insects requires the development and implementation of food-processing and preparation methods for incorporation of insects into more standard foodstuffs at the large-scale industrial, cottage industrial, as well as household level. While very little if any literature exists on studies demonstrating the capabilities of such food-processing methodologies, we can begin to discuss what the important features to consider are. First, since insects are poikilothermic, and individuals of many species die naturally with the coming of winter (at least in temperate and subtropical zones), a consensus among insect cooks seems to be that the most humane and efficient way to kill them for use in food is by freezing. Subsequently, most insect preparations will likely involve using whole insects or grinding them into a paste or powder.

There are numerous procedures and methods already in existence in the food industry for dealing with pastes, powders, and liquids, so it is likely that little additional innovation, if any, will be developed to feasibly use many of these methods with insects. Also, the chitin in insects is likely undesirable for many food products due to its indigestibility; its possible function as fiber, which limits nutrient absorption; or simply because it adds a disagreeable texture to foods that are ideally low in fiber. Thus, methods that efficiently extract the valuable nutritional content from insects while leaving behind chitin are highly desirable. Additionally, shelf life is an important consideration for any food product. Much research is needed for this aspect of insect-based foods as very little information on insect shelf life is currently available. Nonetheless, some known features of insects may suggest that insect-based food ingredients may have an advantage of longer shelf life than similar noninsect alternatives, particularly for dry products or pastes with high levels of insect content. For example, a number of insects have been shown to contain antimicrobial substances such as peptides, fatty acids and other secondary metabolites (Dossey, 2010; Finke, 2012; Huang et al., 2011), which may lend themselves to extending the shelf life of insect-containing foods. Additionally, the chitin from insects is known to have antimicrobial properties (Tharanathan and Kittur, 2003). Thus, even though in many cases the texture of insect-based foods is improved by removing chitin (as mentioned here), in other food products there may be advantages in leaving the chitin. In those cases, the texture issues with chitin might be alleviated by grinding the insects into a fine powder, while maintaining the fiber and antimicrobial benefits of chitin.

Food safety is one of the most important considerations for developing methods for incorporating insects into any diet. While a good number of people around the world consume insects in large numbers without suffering any adverse health effects, and proper processing and preparation of insects as a food ingredient can alleviate many hazards that insects may present, it is important to point out some potential hazards. Some of those hazards include entomophobia,

nutritional losses, dyspepsia, toxic effects, tumorigenic metabolites, trauma to intestinal mucosa, and allergic reactions (Gorham, 1979). Nearly all food preparations using insects as an ingredient will involve use of the whole insect in some form or another, including its digestive tract and its contents. This is different from most vertebrate livestock-derived food products, in which the intestines and other bacteria-rich portions are removed in early stages of processing the carcass. It has even been suggested that removing the digestive tract ("gutting") of insects is important to prepare them for human consumption, but not if fed to livestock because the livestock benefit from the fiber (Shackleton and Shackleton, 2004). However, robust processing methods and microbial kill-steps, such as pasteurization, will likely mitigate the need for this sort of tedious and inefficient process. Such kill-steps, which eliminate bacteria and other microbes (and their spores) from processed insect material, are quite necessary, and it is highly desirable to incorporate these early in any insect-derived food product operations or protocols. Additionally, as insects become a more popular and widely used food ingredient, regulations on how they are handled will need to evolve, particularly in the United States. The US Federal Food, Drug, and Cosmetic Act of 1976 (FD&C Act) prohibits the "adulteration of any food in interstate commerce" "if it consists of whole or in part of any filthy, putrid, or decomposed substance, or if it is otherwise unfit for food" (Gorham, 1979). Therefore, Title 21, Part 110.110, of the Code of Federal Regulations allows the US Food and Drug Administration to establish maximum levels of natural or unavoidable defects (e.g. insect parts) in foods for human use that present no health hazard; these are known as "Food Defect Action Levels" in the FD&C Act. Finally, educational programs and materials containing protocols, recipes, and methods for safe and effective processing, cooking, and so on can assure the safe and efficient use of insects as food ingredients in general, particularly in the developing world, where more effective food-processing equipment and methods are not readily available (Amadi et al., 2005).

18.5. CURRENT EXAMPLES OF MASS-PRODUCED INSECTS WITH POTENTIAL AS HUMAN FOOD

There are a few large and many small farms in the United States rearing pet feeder insects such as crickets (usually *A. domesticus*), mealworms (larvae of *Tenebrio molitor*), and waxworms (larvae of *Galleria mellonella*). For example, the 10 largest producers of crickets in the United States already collectively produce approximately 2 billion crickets annually. This amounts to about 1.36 million kg (3 million pounds), or 1680 tonnes (1500 tons) of total cricket mass produced each year, assuming a weight of 680 g (1.5 lb) per 1000 crickets. It is likely that similar amounts of feeder mealworms are also being produced at a similar rate. Additionally, there are many more small companies producing from only a few thousand of various feeder species to hundreds of millions of insects per year. Many insect farms in the United States are located in rural

communities and contribute to local economies. Additionally, there is substantial interest in, and new companies being formed for the purpose of, mass producing other feeder insects, such as black soldier flies. The current market for insect farms in the United States currently primarily consists of pet feed (for reptiles and amphibians), fish food, zoos, pest control companies (particularly for biocontrol), research labs, and a handful of aquaculture companies. Here we provide a few prominent examples of insects that are mass reared in the United States, which we feel merit further examination as potential targets for use as insect-based food ingredients.

18.5.1. Orthoptera

Around the world, 12 families and 278 species of crickets, grasshoppers, and katydids are recorded as being consumed by humans. Orthoptera is the fifth most consumed insect order worldwide (Fig. 18.2). Acrididae represent the highest frequency of human consumption (171 species), followed by Gryllidae (34 species) and Tettigoniidae (30 species) (Jongema, 2012).

The house cricket (*A. domesticus*) probably has the longest industry history of any insect mass produced in the United States, with the first large cricket farms having started in the 1940s–1950s. As mentioned in Section 18.5, they are also one of the most commonly mass-reared insects in the United States, with at least 1680 tonnes (1500 tons) being produced annually. House crickets are likely one of the least expensive insects to farm since their mass-rearing methods have been refined for several decades. Their nutrient content is also well established (Table 18.2) (Finke, 2002). Crickets and other insects are proving more efficient and sustainable to produce than several types of vertebrate livestock, including chicken, pig, lamb, and steer (Nakagaki and Defoliart, 1991). Currently, a typical wholesale cost per 1000 feeder house crickets in the United States, which weighs about 453–680 g (1–1.5 lb), is approximately $9–15 (data from personal communications with cricket farm owners). This is the price point even without the considerably larger potential demand for these insects that will arise as insect-based foods become more popular and widespread. Minimal shifts in industry practices would need to occur for prices of crickets marketed for human consumption to become more competitive. As an additional Orthopteran example, in Mexico, the grasshopper called *chapulines* has been documented as being the most frequently ingested insect in regions where it is popular, such as Oaxaca (Ramos-Elorduy et al., 2008). Huge baskets full of these *chapulines* can be found at markets throughout southern Mexico.

18.5.2. Diptera

Flies (order Diptera) are the fourth most consumed insect order by humans, with 16 families and 39 total edible examples documented in the literature (Fig. 18.2) (Jongema, 2012). They are probably the insects with the largest reproductive

capacity, shortest life cycles, and rapid growth rates and that are able to eat the widest variety of organic material as feed input for mass production of insect biomass. These and other features make them some of the most attractive insects for applications to increase world food security from a production perspective. A number of applied laboratories and companies are already beginning to focus on scaling up production of black soldier flies for use as animal feed, composting, waste mitigation, and other nonfood applications (see Chapter 16 for more information on insects used as animal feed). Black soldier fly nutrient content is well established. For example, their larvae are very high in fat and calories (Table 18.2) (Finke, 2012; Popa and Green, 2012), since, like other holometatolous insects, they store it for their immobile noneating pupal development stage. Black soldier fly larvae have very little hard chitin and are easy to process. This means that we can efficiently remove the chitin without losing protein. The black soldier fly is also high in lauric acid (Finke, 2012), a fatty acid with significant antimicrobial activity (Huang et al., 2011) that is typically found in milk (Beare-Rogers et al., 2001). Fly larvae are known to contain other antimicrobial compounds, some of which might improve the shelf life of food ingredients made from them (Dossey, 2010). Additionally, several aspects of this fly give it the potential for highly efficient and sustainable production. Black soldier fly larvae can develop on almost any kind of nontoxic organic matter, including a wide array of agricultural byproducts (Bondari and Sheppard, 1981; Popa and Green, 2012; Sheppard et al., 2002). Thus, their production costs are likely to decrease over time as methodologies for mass rearing and low-cost feed are identified. Additionally, black soldier fly rearing involves several processes that are highly amenable to automation.

Currently, some of the most substantial examples of mass-reared Diptera in the United States and around the world are flies, such as various tephritid fruit flies (family Tephritidae) that are mass reared for sterile male releases. Mass production methods and facility and equipment designs for these insects have been heavily researched and are already very efficient and highly refined. Thus, these production methods could likely be very easily adapted for human food or animal feed applications. These flies are typically produced as pupae, which are irradiated, and then the resulting reproductively nonviable adults are released in orchards and farms in order to reduce wild populations of these pests; this is known as the "sterile insect technique" (SIT) (Dowell et al., 2005). Some of the most prominent examples include the Caribbean fruit fly (or "carib fly," *Anastrpha suspensa* (Loew)), the Mediterranean fruit fly (or "med fly," *Ceratitis capitata* (Widemann)), the Mexican fruit fly (or "mex fly," *Anastrepha ludens* (Loew)), and the oriental fruit fly (*Bactrocera dorsalis* (Hendel)). However, in the United States and many other places, only government facilities produce these insects and only for SIT. As a consequence, the potential of these insects is tremendously underrealized. While regulatory constraints may make actual pest species impractical for commercial production in areas where they are not already established, the methods developed to grow pest species are

easily adaptable to many nonpest species of flies. Thus, commercial enterprises producing these insects as human food, animal feed, or other biomass applications (drugs, biomaterials, neutraceuticals, etc.), even if only in places where these "pests" are already established, can be a tremendous benefit to the local economies of those areas as well as contribute to global sustainability, food security, human health, and technological advances.

18.5.3. Coleoptera

At the species level, the insects most commonly consumed by humans worldwide are the Coleoptera, with 661 documented species being consumed among 26 families (Fig. 18.4). This makes sense, since Coleoptera is by far the largest group of any organism on earth. Scarabaeidae (247 species) demonstrate the greatest diversity, followed by Dytiscidae (55 species) and Cerambycidae (129 species) as being the most commonly eaten by humans (Jongema, 2012). In the United States, mealworms (*T. molitor* L.) and superworms (*Zophobas morio* F.) are currently mass produced for the pet industry as live feeder animals. Their nutrient content is also well established (Table 18.2) (Finke, 2002). Interest in using mealworms and superworms as human food has increased recently in the United States. They are featured as edible insects in many entomology outreach programs and are being purchased by various businesses and incorporated into hard candies as well as baked goods such as cakes, cookies, and cupcakes (see, e.g. http://www.hotlix.com). Mealworms and superworms can be easily reared on multiple types of vegetables and grains by the general public in a small space and are often used as an educational teaching tool in K-12 classrooms to demonstrate complete metamorphosis. Mealworms and superworms may be considered more acceptable for human consumption due to their minimal appendages.

18.5.4. Lepidoptera

Worldwide, more families of Lepidoptera (36) are consumed by humans than any other insect (Fig. 18.2). The most commonly consumed families are Saturniidae (109 species), Hepialidae (47 species), and Sphingidae (36 species) (Fig. 18.4). Their frequency of human consumption is highest in the Neotropical and Palearctic biogeographical realms, where they are the dominant order of insect consumed (Figs 18.3 and 18.4) (Jongema, 2012). In the United States, a commonly consumed Lepidopteran insect by humans is the waxworm (*G. mellonella* L.). They are mass reared for the animal feed industry as well as for fish bait. Their nutrient content is well established (Table 18.2) (Finke, 2002). Due to their holometabolous life cycle and lack of noticeable appendages during the larval stage, they are also a great candidate for roasting, grinding into flour, and incorporating into various food products. They are very high in fat, which makes them an appealing food supplement in resource-limited areas where people are malnourished and underfed.

18.6. POTENTIAL PRODUCTS AND BYPRODUCTS FROM MASS-PRODUCED FOOD OR FEED INSECTS

It is already established that insects can be used as pollinators, biological control agents, vehicles for education and outreach programs, objects of art, pets (particularly in Europe and Asia), and feeder insects for animals (Yi et al., 2010). Indeed, there is also an increasing market for edible insects and insect-based food products worldwide, particularly outside the United States. Some US restaurants, particularly Latin American and Asian restaurants, are now offering insects on their menus (FAO, 2008; Gahukar, 2011). A number of companies, as mentioned in this chapter, are preparing to capitalize on this emerging market in its early stages by being the first food product developers using insects as a primary ingredient in the United States. However, promising technologies for addressing food security and sustainability and meeting new and novel market demands take time to develop, perfect, and bring up to industrial scale. Thus, it is important for these research and industry communities to begin contemplating and developing the most feasible products on which this emerging industry can launch. This chapter has identified prominent examples so far. Once protocols are developed to produce various insect-based food ingredients, they can then be incorporated into numerous consumer items such as "meat" substitutes, protein-fortified bars and nutritional powders, as well as numerous types of snack foods (Dossey, 2013). Section 18.6.1 gives a few examples that we feel merit examination at this time.

18.6.1. Alternative "Meats"

Replacing vertebrate animal meat (muscle and other tissue) in our diet with protein-rich meat-like products derived from insects, the coup de grâce of insects replacing vertebrate livestock, means that our diets do not need to change drastically. We do not need to do without the delicious meaty products that most of us enjoy, including tacos, hotdogs, and breaded meat nuggets (currently made of chicken and fish). With a small amount of innovation, most if not all of these can be made from insects! This can be achieved in part by utilizing processes very similar to those used to make vegetarian or vegan meat substitutes from plant protein (tofu, tempeh, etc.). The internal protein of insects often appears to behave very similar to other proteins and meats when cooked, with similar textures, flavors, and odors. Even many popular vertebrate livestock-derived products such as hotdogs, sausages, ground beef (for tacos, etc.), chicken nuggets, and others often contain substantial amounts of fillers and other nonmeat ingredients as well as seasoning to improve their palatability. Thus, with a little research and development for applying existing meat and meat substitute production methods to mass-produced or mass-farmed insects as starting raw material, many products currently made from vertebrate animals could be made quite easily from insects. Some companies in the United States are already

developing strategies to make these types of insect-derived alternative meat products feasible.

18.6.2. Protein and Nutritional Supplements

In the short term, protein supplements (bars, shakes, powders, cereals, etc.) for athletes and others wishing to increase their protein consumption also present a simple and ripe opportunity for incorporation of insect-derived protein. Much of the protein in these products comes from peanuts or soy. As mentioned in this chapter, animal-derived protein is superior to protein from plants, so the best protein supplements also must include some animal protein. Many of these products contain whey protein derived from milk, which has a much larger environmental footprint to produce than insects. These types of products have a relatively low barrier to entry, since they are very simple to produce and are typically sold to nutrition or environmentally conscience consumers, and the protein they contain is not visibly or gustatorially distinguishable from just about any other protein source (e.g. replacing soy powder with insect powder does not change a product's look, flavor, or texture). As a result, simple strategies to produce powders and pastes from insects can constitute high-quality protein ingredients for high-end protein supplement foods and beverages. Some of the aforementioned companies are already exploring some of these types of products in the United States.

18.6.3. Chitin: Opportunities for New Products from Insects

For many insect-based food products, the chitinous exoskeleton must be removed. This is particularly true for products such as those discussed in this chapter to alleviate malnutrition (RUTF, etc.) and others from which high nutrient absorption efficiency is desired, as chitin can reduce the absorption of some nutrients. However, the leftover chitin from industrial-scale insect-based food-producing operations can itself be a desirable high-value product with a number of additional applications, such as a neutraceutical for reduction of fat or cholesterol, a drug carrier, in agricultural pest control, in water purification, in biodegradable materials and plastic alternatives, as an antimicrobial ingredient in food and other perishable materials, to aid in wound healing, in cosmetics, and in a host of other applications. Indeed, this topic has gained the attention of others who have reviewed the potential applied and industrial value of chitin in greater detail (Je and Kim, 2012; Tharanathan and Kittur, 2003). Marketing chitin as a high-value commodity can help subsidize the budding insect-based food industry, particularly in the United States and Europe. However, the vast majority of chitin currently used for these applications comes from unsustainable harvesting of shrimp that, like much of the ocean's other resources, are constantly being overharvested. As a consequence, chitin from farmed and mass-produced insects, particularly those fed with agricultural or

food byproducts, can present a much more sustainable alternative source of this chitin.

18.6.4. Novelty Products

Of course, the modern paradigm of insect-containing foods and insects as food ingredients, particularly in the United States and Europe, is still various exotic or novelty items that contain only a small amount of whole insects. These types of products can be sold at relatively high prices relative to ingredient costs. Thus, they are a way for the budding insect-derived food product industry to generate revenue while developing cheaper and more mainstream products and allowing cultural acceptance for insect-based foods to increase. On the other hand, as long as novelty or exotic food items containing whole visible insects remain the primary insect-containing foods available on the market, both cultural acceptability and overall market feasibility on a larger scale of insects as a primary food ingredient will continue to be severely limited. Thus, we propose that an increased focus on developing more standard processed insect-containing foods, similar to those that people are already familiar with and enjoy (described in Sections 18.6.1 and 18.6.2), is essential to truly realizing all of the benefits of humans eating insects that are discussed in this chapter.

18.7. CONCLUSIONS AND A CALL TO ACTION

In cultures that eat insects regularly, they are considered beneficial and are viewed as nutritious, medicinal, environmental, and a sustainable and secure food item. Once insects become more widely accepted as a respectable food item in industrialized countries, the economic implications will have a profound positive impact on businesses, industry, governments, and research. Replacing vertebrate livestock-derived foods and food ingredients with those derived from insects will also substantially improve the health of the earth's natural environment. Incorporating insects into Western food habits will increase and diversify food production, increase food supply and availability, as well as meet the nutritional needs of resource-limited households (Yen, 2009a, b). Insects will form a whole new class of foods for low-input small-business and small-farm production, with tremendous potential to be mass produced for human consumption. The future of worldwide acceptance of entomophagy relies on the commercialization of new food products but must be coupled with patents and revised regulations. International trade in edible insects would almost certainly increase as well (DeFoliart, 1992). Currently, insects in places like the United States are still not widely available and come at a high cost as compared to other animal-based food ingredients. However, as the production of insects as human food and animal feed increases worldwide, particularly in the United States, many aspects related to the feasibility of insect-based foods, such as cost, safety, the efficiency of insect mass production, and availability, will improve. The

resulting increase in demand will synergistically drive the status of insects as a standard mainstream food ingredient.

Lewin's *Forces behind Our Food* (1943) gave insight into the food-buying habits of individuals primarily responsible for choosing family foods during wartime, and it can be applied to household and individual food choices today (Lewin, 1943). If the public's positive perception about insects as a mainstream edible food source is our intended outcome, knowledge about why people choose the foods they do is essential while simultaneously addressing the specific processes involved. A multidisciplinary approach is needed to realize the substantial potential benefits of human consumption of insects on a global scale. Engineers are needed to develop appropriate rearing systems for different environments and insects. Food scientists are needed to study the nature of insect foods and nutritional content, the causes of deterioration of insect food products, the principles underlying insect food processing, and the improvement of insect foods. Family and consumer scientists are needed to address the relationship between individuals, families, and communities in relation to food habits and food choices. Nutritionists are needed to advise consumers on insect foods and the nutritional impacts of insect foods on human health. Marketing, promotion, and advertising specialists are needed to promote the nutritional benefits of edible insects while marketing and selling insects for human consumption.

In order to realize their potential as a major source of human food, there are several constraints that must be overcome. These include production cost and efficiency, commercialization, technology, regulation, and social change regarding food habits and food choices. The need for development of multiple-product food–insect systems is pressing (Gahukar, 2011). This is already beginning in the United States and, in its current form, consists of human consumption of edible insects or feeder insects purchased from producers who grow them primarily for livestock and pet food. Although there are several private and public mass insect-rearing facilities in the United States, they do not yet produce insects for human consumption. Limited research and government funding are focused on mass-rearing or mass-processing methodologies of insects for human consumption. However, as mentioned in this chapter, several small companies are beginning to produce food products containing insects as well as develop methods of processing insects for use as safe, efficient food ingredients. There is limited research on insect nutrition, the psychology of insect phobias and fears, as well as insects in food science and engineering. Much of the current entomophagy research is being generated in Europe, Asia, Africa, and Central and South America. Indeed, the call for using insects to improve human food security has become more prominent in the past couple of years as well (Crabbe, 2012; Dossey, 2013; Dzamba, 2010; FAO, 2008; Gahukar, 2011; Katayama et al., 2008; Nonaka, 2009; Premalatha et al., 2011; Ramos-Elorduy, 2009; Smith, 2012; Srivastava et al., 2009; van Huis, 2013; van Huis et al., 2013; Vogel, 2010; Yen, 2009a, b).

Westerners will likely need to be exposed to entomophagy in informal environments such as festivals, fairs, museums, nature centers, parks, and

restaurants as well as formal teaching and research environments in order to be more accustomed to the concept of accepting insects as food. DeFoliart (1999) emphasized that Westerners should become more aware of their negative impact on the global natural environment and their bias against consuming insects, and should increase their acceptance of insects as an alternative food source. At the time of this writing in 2013, we argue that this is even truer. In order to achieve greater recognition of insects as a viable alternative food source, a more positive social attitude about insects as human food must occur. With an increasing human population and environmental degradation, many people face a major problem in obtaining adequate protein levels in their diet. Westernized societies are reluctant to use insects, despite being major consumers of other animal proteins. We now need to consider insects as a source of food for humans in a manner that acknowledges both the role of entomophagy in indigenous societies and the need for Westernized societies to reduce the size of their environmental footprint with regard to food production, in part by replacing vertebrate livestock with insects wherever and whenever possible.

There is a need to eliminate or greatly reduce the Western-driven stigma over the use of insects as food. This will help to provide increased opportunities for research on large- and small-scale mass production as well as optimization of ecological benefits and the nutritional benefits of insects. In our global society, entomophagy must play a role in decision making and policies related to agriculture, nutrition, and food security. In order to realize the potential benefits that insects can provide to our food security as a human food and as animal feed, we call for the following: (1) greater support and attention from government funding, agricultural, and regulatory agencies for research on insect production and use as a human food ingredient; (2) support from industry to provide the means to move insect-based foods and other products from the laboratory to the market; and (3) the establishment of a formal international society, an industry association, and a journal for researchers, academics, industry partners, and other practitioners in the field of food and feed insect production. These will help tremendously in moving this emerging field forward. A formal international society would promote and present how entomophagy research could be beneficial to science, society, and industry and, thus, set the stage for what might be one of the most substantial revolutions in modern agriculture and food production: the human utilization of insects for food.

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