Ecology of Food and Nutrition, 00:1–9, 2014

ISSN: 0367-0244 print/1543-5237 online
DOI: 10.1080/03670244.2014.930032

The Potential for Entomophagy to Address Undernutrition

LUC NADEAU
Independent Investigator, Longmont, Colorado, USA

ISAAC NADEAU
Independent Investigator, Madison, Wisconsin, USA

FRANK FRANKLIN
Department of Health Behavior, University of Alabama at Birmingham, Alabama, USA

FLORENCE DUNKEL
Department of Plant Sciences and Plant Pathology, Montana State University, Bozeman, Montana, USA

The use of insects as food for humans has the potential to substantially reduce undernutrition worldwide. The Food and Agriculture Organization of the United Nations estimates that 805 million people are undernourished, with a total food energy deficit of 67.6 billion kcal/day (84 kcal/day/person). Calculations in this article suggest that this deficit could theoretically be reduced or eliminated through edible insect rearing, utilizing organic side streams as feed, on 15,586 to 92,976 ha.

KEYWORDS entomophagy, food security, insects as food, undernutrition

According to the Food and Agriculture Organization of the United Nations (FAO 2014a), 805 million people worldwide are undernourished, defined as "the result of prolonged low levels of food intake and/or low absorption of food consumed." Depth of food deficit describes "how many calories would be needed to lift the undernourished from their status" (FAO 2014b). In 2012–2014, the global food energy deficit was 67.6 billion kcal/day, an average of 84 kcal/day/undernourished person (FAO 2014b).

Address correspondence to Luc Nadeau, 437 Vivian St., Longmont, CO 80501, USA. E-mail: lucanadeau@gmail.com

New agricultural land is scarce, the world population is expected to reach 9 billion by 2050, and a greater proportion of people are eating resource-intensive animal protein than ever before. In addition to meeting the needs of the undernourished today, where will the food come from to feed a growing population with a growing appetite? Furthermore, climate change is affecting food systems worldwide. The contribution of the Working Group II to the recent Fifth Assessment Report by the Intergovernmental Panel on Climate Change (Porter et al. 2014) discusses a broad range of impacts of climate change on food security, including increased crop prices and decreased yields and changes in the abundance and distribution of fisheries stocks. These changes further compound the challenges of feeding the world's hungry and highlight the importance of identifying food sources and production practices that not only make a minimal contribution to climate change but also serve as effective adaptations to the ongoing climate change-induced impacts to the food system. A compelling case can be made that insects are part of the answer.

Over 1,900 species of insects are known to be part of human diets, more than 2 billion people consume insects on a regular basis, and insect eating provides a significant proportion of the animal protein consumed in some regions (DeFoliart 1989; van Huis et al. 2013). The nutrient profiles of many insect species rival or surpass those of conventional livestock, and rearing these insects has a smaller environmental footprint than that associated with rearing conventional livestock. Because entomophagy is widely practiced, and because it compares favorably with the nutrient and environmental aspects of conventional livestock rearing, it has the potential to contribute substantially to reducing undernutrition among an expanding global population. We have examined insect production on both a light-industrial and small-farm scale to calculate the potential for each system to produce enough insects to eliminate the world's food deficit. It is important to note that the calculations provided here are intended to describe the theoretical potential for entomophagy based on the available data. Clearly, insect-eating represents only a partial contribution to the ongoing and multifaceted efforts to reduce hunger.

METHODS

To illustrate the potential for edible insect-rearing projects to address undernutrition, we provide two case studies: a light-industrial mealworm-rearing facility in the Netherlands and a small-scale cricket-farming system in Thailand. We chose these examples because they represent two distinct approaches to insect rearing and serve as potential models for the implementation of similar projects elsewhere in the world. The systems use two different insect species, both of which provide similar nutrient profiles with lower environmental impacts than conventional large livestock.

However, in both cases, insect rearing utilizes relatively high-grade feed (e.g., grains, carrots, high-protein chicken feed). The SUPRO2 program in the Netherlands is currently investigating the efficacy of using organic side streams for insect feed (van Huis et al. 2013). Organic side streams are biowaste from agriculture, forestry, and household processes. The use of organic side streams can theoretically reduce the already low costs and environmental impact of rearing insects and creates a potential income source for the waste-processing service provided by the insects. Our calculations highlight the potential of the large-scale implementation of such systems. However, it is important to note that the efficiency and cost-effectiveness of rearing insects on organic side streams will vary and have yet to be quantified. For example, the nutrient content of insects reared on side streams, the insect biomass produced by the rearing operation, and production costs are likely to vary substantially depending on the available side streams, processing and transportation requirements, and specific insect species reared. Ramos-Elorduy and colleagues (2002) reported energy and protein profiles for mealworms (*Tenebrio molitor*) reared on five organic-waste diets that were comparable to those of a control group reared on an optimal diet. However, the organic waste diets were supplemented to include 20% protein. Nakagaki and DeFoliart (1991) found a highly variable cost per kilogram of crickets (*Acheta domesticus*) produced depending on the feed used. Further research in this area, utilizing organic side streams, could further refine diets nutritionally and economically optimized for insect production (including nutrient profiles).

Light Industrial System: The Netherlands

Van de ven Insectenkwekerij, a facility in the Netherlands, produces 83,200 kg/year of mealworms (the larvae of *Tenebrio molitor* L. and *Zophobas morio* F.) (Oonincx and de Boer 2012). The facility is 588 m^2 in area and uses mixed grains and carrots that are grown off site for feed. Other inputs include egg trays for rearing, gas for heating the facility, electricity, and water. In their lifecycle analysis of the global warming potential (GWP, $CO_{2\text{-eq}}$), energy use, and land use for this facility, Oonincx and de Boer (2012) found that feed accounted for 56% of the GWP, 44% of the energy use, and 99.5% of the land use. Gas and electricity accounted for 43% of the GWP and 56% of the energy use. Even with relatively high contributions to GWP, energy, and land use from feed production and climate control, the production of these mealworms was associated with lower GWP than milk, pork, chicken, or beef (per kg of edible protein); similar levels of energy usage; and far less land use (table 1).

Feed at this facility is relatively high grade and accounts for all but a fraction of the land use and most of the GWP. If organic side streams were used for feed instead, GWP, land use, and energy use could be dramatically

TABLE 1 Environmental Impacts of Insect Rearing Compared with Traditional Livestock

	GWP (kg CO_2-eq/kg edible protein)[1]	Energy (MJ/kg edible protein)[1]	Land (m^2/kg edible protein)[1]	Water (L/kg live weight)[2]
Mealworms	14	173	18	No information
Beef	77–175	177–273	142–254	9, 700
Pork	21–54	95–237	46–63	2, 800
Chicken	19–37	80–152	41–51	1, 500
Milk	25–39	36–144	33–58	800
Mealworms reared without energy inputs and on organic side streams	0.06	0.29	0.04	2.5[1]

[1]Oonincx and de Boer (2012).
[2]Chapagain and Hoekstra (2003).

reduced. Additionally, if such a facility were located in the tropics, the energy used for climate control would likely be greatly reduced, resulting in further reductions in GWP and energy use.

T. molitor provides 2,056 kcal/kg, and *Z. morio* provides 2,423 kcal/kg (Finke 2002). Based on these figures, theoretically, 30.2 million kg of mealworms per day would provide all the energy needed to erase the 67.6 billion kcal/day energy deficit of the world's undernourished (see Supplementary Material for details on calculations). However, it is important to note that the nutritional values of insects are variable, even within a species, depending on life stage and diet and on how the insect is prepared before eating (Ramos-Elorduy et al. 2002). If one assumes that organic side streams for feed would result in only half the production of the high-grade feed used at the Dutch facility, then worldwide, 15,586 ha of such facilities could produce all of the energy needed to erase the world's food deficit (for comparison, this figure represents 0.0003% of the almost 5 billion hectares of agricultural land in the world). These estimates assume no land use for the production of organic side streams because they are the byproduct of primary food crops and other processes.

Small-Scale Farming: Thailand

In northeastern Thailand, there are almost 20,000 small- to mid-scale cricket (*Acheta domesticus* [L.]) farming operations (Hanboonsong, Jamjanya, and Durst 2013). A typical farm uses concrete enclosures, and the largest farms can produce 450–750 kg crickets in each harvest cycle (45 days). Feed is generally high-protein chicken feed replaced with food scraps shortly before harvest. There has not been a lifecycle analysis conducted on all inputs for this type of farming, but feed is half to two-thirds of the production cost. Electricity, water, and packing account for only 1% of total costs. A large farm (60–80 breeding containers measuring 2.5 × 8 × 0.5 m) requires approximately 2–3 hours of labor per day for feeding and maintenance.

One farmer with seven years experience produces 1 kg of crickets per day on 9.64 m^2 (on average, Thai insect farmers have much lower productivity, but this farmer represents the potential in what is a nascent farming process). Adult crickets provide 1,402 kcal/kg (Finke 2002). If farmers produced half the number of crickets using organic side streams for feed, 92,976 ha would be required to rear enough crickets to meet the world's food deficit (0.0019% of the world's agricultural land). Because of seasonality, cricket farmers in Thailand harvest about four times per year, despite a harvest cycle of only 45 days; in areas with less seasonal variability, the number of harvests per year could increase.

DISCUSSION AND RECOMMENDATIONS

Simply eating enough calories may not be enough to eliminate undernutrition. Many insect species are not only energy-dense but also nutrient-dense foods. These foods are comparable, and in some cases superior, to conventional livestock, eggs, and milk in both their energy and nutrient content (table 2). Many insects provide lipids, amino acids, and micronutrients deficient in cereal- and legume-based diets (van Huis et al. 2013). Table 3 illustrates how edible insects might provide some essential amino acids and micronutrients, in addition to calories, to effectively balance the diet of an undernourished person. For example, on approximately 10 m^2 of land, an experienced insect farmer could rear approximately 1,000 g/day of crickets, addressing the calorie needs of a family of five with a total food deficit of 1,500 kcal/day. Importantly, these crickets would also provide the total recommended daily amounts of lysine, methionine + cysteine, tryptophan, zinc, and vitamin B_{12}, in addition to a substantial amount of iron and niacin.

Although food deficits and undernutrition can be described on a global level, addressing them requires an approach that considers regional, national,

TABLE 2 Insect Nutrition Compared with Conventional Livestock Products

	Energy (kcal/kg)	Protein (g/kg)	Fat (g/kg)
Adult cricket (*Acheta domesticus*)[1]	1,402	205	68
Mealworm (*Tenebrio molitor* larvae)[1]	2,056	187	134
Beef, ground, 85% lean, 15% fat, broiled[2]	2,504	259	153
Pork, ham with bone, unheated[2]	1,732	224	92
Chicken[2]	2,186	250	129
Eggs[2]	1,560	120	100
Milk, whole[2]	598	32	33
Fish, tilapia, cooked[2]	1,287	264	26

[1]Finke (2002).
[2]USDA (2011).

TABLE 3 The Potential for Insects to Supplement Diets of the Undernourished

	Amount (g)	Land required to rear in one day (m^2)	Lysine (g)	Methionine + Cysteine (g)	Tryptophan (g)	Iron (mg)	Zinc (mg)	Niacin (mg)	Vitamin B_{12} (μg)
Insect – 300 kcal serving									
Crickets (*Acheta domesticus*)	214	2.06	2.4	1.01	0.28	4.1	14.4	8.2	11.5
Mealworms (*Tenebrio molitor*)	146	0.37	1.5	0.58	0.22	3.0	7.6	5.9	0.69
RDA									
A 55-kg 30-year-old woman			1.65 g/day	0.83 g/day	0.22 g/day	18 mg/day	8 mg/day	14 mg/day	2.4 μg/day
A 12-kg 2-year-old child			0.53 g/day	0.26 g/day	0.07 g/day	7 mg/day	3 mg/day	6 mg/day	0.9 μg/day

Note. Insect nutrition from Finke (2002). RDAs for amino acids are estimates from WHO (2002). Iron, zinc, and vitamin B_{12} RDAs are from NIH Office of Dietary Supplements (2013). Land required for mealworm rearing is based on Oonincx and de Boer (2012). Land required for cricket rearing is from Hanboonsong and colleagues (2013). For both land estimates, the use of organic side streams for feed is assumed. Additionally, in Sub-Saharan Africa, there are many areas in which a food deficit of 300 kcal/person/day is not uncommon. Often, people living in these communities subsist on a diet that is primarily cereal- and legume-based, resulting in deficiencies of the essential amino acids lysine, methionine + cysteine, and tryptophan, as well as deficiencies in iron, zinc, niacin, and vitamin B12. This table illustrates that it is feasible to make up the caloric and nutrient deficiencies of a representative undernourished family with insects alone; however, we are not proposing that insects need be the sole means to addressing these deficiencies. The assumptions in this table are (1) that the farmer is experienced, (2) that the farmer can provide the additional labor needed, (3) that the farmer can process the insects into a daily meal supplement acceptable to young children and adults, and (4) that additional labor and costs are acceptable in obtaining the organic side streams needed to feed the insects.

and even village-level realities. For insects to contribute to reducing hunger, they must provide adequate nutrition and they must be as or more cost-effective as foods with similar nutrient profiles, environmentally sustainable, feasibly grown and processed, and culturally acceptable, including tasting good. There are many indications that insects can meet all of these criteria. As insect-rearing techniques are refined, insects could become even more promising as a food source. In particular, the use of agricultural and other organic side streams may have the potential to simultaneously reduce the costs and lower the environmental impact of feeding the human population. In addition, in certain situations increased mechanization in insect rearing may reduce production and processing costs while increasing overall production.

Given the potential for entomophagy to aid in reducing hunger, we recommend that funding be allocated for the FAO to implement pilot projects in areas with chronically undernourished populations. These projects should be designed to test production processes with the aim of developing best practices that are both broadly applicable and allow for adaptation to local cultural and environmental conditions. The following recommendations represent key considerations in the development of these pilot projects.

- Entomophagy initiatives should prioritize combinations of species, local dietary and cultural preferences, and production systems that maximize the use of existing underutilized side streams as feed resources in specific regions.
- Local food deficits should be matched with insect species with nutritional profiles appropriate to address those deficits.
- Local cultural barriers and traditions regarding insect eating must be adequately understood. Entomophagy is still widely practiced, but it is underutilized or has declined in many areas, often as a result of Western influence (DeFoliart 1999; Durst et al. 2010; Hanboonsong et al. 2013). Local holders of traditional knowledge should be consulted regarding the traditions of entomophagy, including species, preparation, and storage, safety, and strategies for reintroducing insect eating.
- To the extent feasible, particularly in rural and remote areas, insect-rearing operations should be controlled at the household level to encourage household-level autonomy and food security.
- In areas where edible insects can be collected in the wild, insect habitats should be preserved and collecting should be regulated. Additionally, education on sustainable practices for wild harvesting and the importance of intact habitats should be emphasized.
- When introducing non-native food insect species, their potential to disrupt local ecosystems or agricultural systems must be accounted for, and such disruptions must be carefully avoided.

In addition, the cost-effectiveness of larger-scale industrial production and processing of edible insects should be examined. Acute severe protein-energy malnutrition could be addressed by including edible insects as a component of protein/energy supplements produced by aid-giving/developed countries. Thus, it is critical for major providers of food aid, such as the United States, to develop production and processing methods and safety and nutritional standards for the inclusion of insects in human diets where economically feasible. Programs to examine optimal insect production conditions can be conducted in parallel with testing the safety and effectiveness of insect-based foods.

The ongoing challenges of population growth, climate change, land and water availability, and the current rates of undernutrition require novel strategies for food production. Rearing insects for food has the potential to contribute substantially to reducing hunger in an environmentally sustainable manner. Active research programs to refine the most effective models are essential, but given that the effects of climate change on food security are not only a future prospect but a present reality, the currently available techniques and information are sufficient to implement projects to help meet the immediate needs of the hungry.

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