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Review

Reducing the global environmental impact of livestock production: the minilivestock option

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ABSTRACT

Livestock production is among the most ecologically harmful of all anthropogenic activities. It has massive direct and indirect contributions to global warming besides causing widespread ecodegradation in other ways. But livestock production cannot be reduced because, as it is, the global demand for animal protein is far higher than the supply. Whereas in developed countries people get about 95 g of protein per day in their diets, of which nearly 60% is made up of animal protein, in developing countries the protein intake is only about 45 g/day and of it a mere 15% is made up of animal protein. This gap in the availability of animal protein for a large fraction of the world's population who desires it, is continuing to increase because of the increased globalization-induced rich-poor gap across the world.

Besides the fact that conventional ways of animal protein production using livestock—chicken, goat, pork, beef—are highly eco-degrading; in terms of availability of pasture lands as well as enhancement in productivity of edible zoomass with inputs from science and technology, the upper limits of animal protein production have already been reached. The ocean-based food production has similarly reached unsustainable levels. As a consequence, now onwards the demand will increasingly outstrip supply.

In this backdrop it is essential that we look at the potential of minilivestock, especially insects. As brought out in this paper, human beings have evolved as entomophagous species and there are even suggestions that some of the special proteins and other constituents present in the insects might have helped the human brain to develop as rapidly as it did to enable its evolution into *Home sapiens*. Moreover, several species of insects are prized delicacies in advanced countries like Japan, Australia, and Europe. Hence, insects are not restricted to being 'subsistence food' of grossly impoverished people as one might imagine though a lot of species do help the world's poor to survive. If other virtues of insects are considered— especially their high food-to-zoomass conversion efficiency, quick growth rate, enormous variety, and world-wide distribution—their potential as a much more sustainable source of animal protein than conventional livestock would become obvious.

1. Introduction: adverse impacts of livestock

Despite technological advances occurring hand-in-hand with the increasing portability of technological and managerial knowledge (made possible by information technology and globalization), nearly a billion people—or one in every eight—are going hungry in the world (FAO 2014a, b). As human populations increase, and towns expand into cities and cities into mega-cities, there will be increasing reduction in agricultural land while the demand to produce more food will continue to increase.

If the challenge to produce, in general, more food at lesser strain to the environment is going to get bigger with time, an even more daunting challenge is to provide the world with adequate quantities of animal protein (Pimentel and Pimentel, 2008). This challenge is made bigger by the fact that, on one hand, a large section of the global population gets much less animal protein than it desires while, on the other hand, it requires much more energy, land, and water to produce animal protein compared to equivalent quantities of other forms of food (Pimentel and Pimentel, 2003, 2008; Steinfeld et al., 2006). There is much more extensive harm to environment—in terms of soil

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erosion, water resource depletion, pollution, global warming, and loss of bio diversity—than the production of equivalent quantities of other forms of food (Pimentel et al. 1975; Steinfeld et al., 2006).

1.1. Impacts on land-use and biodiversity

According to the Food and Agriculture Organization (FAO, 2006), the livestock sector utilizes and impacts, through grazing and feedcrop production, as much as 3.9 billion hectares of land, or 30% of the non-polar terrestrial surface on the planet. In these areas, more often than not, livestock are a major source of land-based pollution, releasing huge quantities of nutrients and organic matter, pathogens and drug residues onto soil and into rivers, lakes and coastal zones (Aarnink et al., 1995; Losey and Vaughan, 2006; Fiala, 2008). Each of the over 100 million head of cattle in production in the USA generates about 9000 Kg of solid waste per year (Losey and Vaughan, 2006), heavily burdening the earth's environment. There are sharp land-use changes necessitated by livestock production because forests and other landscapes have to be converted to pastures and fodder-generating monocultures. (van Huis et al., 2013). Indeed livestock exert impacts on vast landscapes, altering them unrecognizably (Abbasi and Abbasi, 2010a). Convertion of natural habitats into lands suitable for just a few plant and animal species plays havoc with the region's biodiversity (Fig. 1). About 70% of the previously forested land in the Amazon basin has been converted to pastures, and much of the remaining 30% into croplands, for livestock feed (van Huis et al., 2013).

Overall, as much as 78% of the world's agricultural land and 33% of the world's cropland goes in the service of livestock production (Steinfeld et al., 2006).

1.2. Contribution to global warming

Livestock production is a major contributor to global warming: 35–40% of global anthropogenic methane and 9% of global anthropogenic CO_2 emission are caused by it (Steinfeld et al., 2006; Fiala, 2009; Tauseef et al., 2013). This is induced by deforestation for pasture and feedcrop land, pasture degradation, and livestock-related direct emission. Enteric fermentation and manure, together, constitute 80% of the methane emission (Abbasi et al., 2013; Tauseef et al., 2013).

Livestock activities also contribute substantially to the emission of nitrous oxide which is the most potent of the three major greenhouse gases (GHGs): 65% of global N_2O anthropogenic emissions. They form 75–80 percent of all agricultural emission. Current trends suggest that this level will substantially increase over the coming decades (Tauseef et al., 2013).

Emissions from livestock manure and urine cause 64% of global anthropogenic ammonia emission (Aarmink et al., 1995). Although not a GHG, NH_3 indirectly contributes to N_2O emission as it is converted to N_2O by specialized soil bacteria (Wrage et al., 2001).

Overall, raising, maintaining and utilizing livestock contribute about 18% of total anthropogenic greenhouse gas emission, second only to the top global warming sector: energy. Arguably, agriculture is the leading cause of anthropogenic climate change (Sachs, 2010), and the biggest source of global pollution (Abbasi and Abbasi, 2010b). Livestock contribute a lion's share to the adverse impacts of agriculture (Pimentel et al., 1975; Pimentel and Pimentel, 2008).

1.3. Stress on water and soil resources

The water used by the livestock sector is more than 8% of the global human water use. The major part of this is water used for

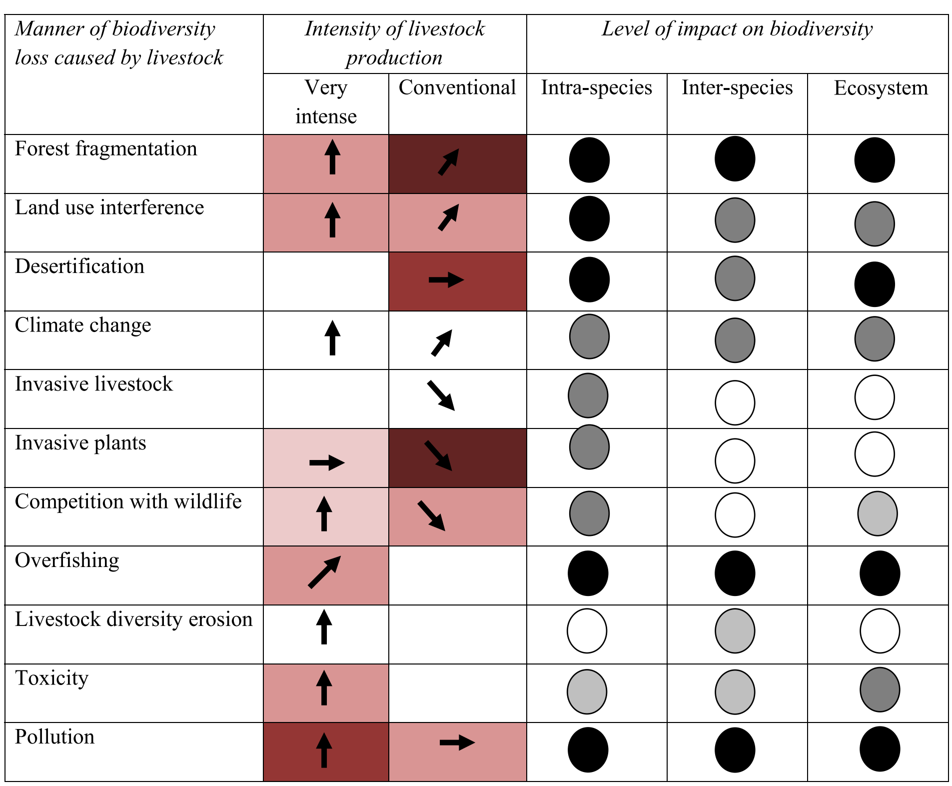

Fig. 1. Impact matrix of livestock production on biodiversity ■ Very strong ■ strong ■ Moderate □ Week. Slanted arrows show decreasing or increasing effect; vertical arrows represent rapid increase and horizontal arrows indicate a constant rate of impact (adapted from FAO, 2006).

feed production. In comparison, the global share of water used for industry, drinking and servicing is just 0.1%. According to estimates of Pimentel (1997), it takes 500–2000 L of water to produce a Kg of potato, wheat, rice, or soybeans while it takes about 43,000 L of water to produce one Kg of beef. Similarly large quantities of energy and grain is required to produce meat as compared to other forms of food (Chapagain and Hoekstra, 2003; Mekonnen and Hoekstra, 2010; Pimentel and Pimentel, 2008). By an estimate livestock in USA consume more than 7 times as much grain as is consumed directly by the entire American population (Pimentel and Pimentel, 2003; Belluco et al., 2013). The impact of livestock production on degradation of land and soil erosion is equally severe.

1.4. Rising demand for livestock

As may be seen from Fig. 2, the use of animal protein increases with the income level of people. Now that two of the world's most populous countries—China and India—are advancing economically, their demand for livestock is sharply rising (Figs. 3 and 4). The trend in other advancing countries like Brazil, Russia, and South Africa is similar. Hence the demand for livestock—and consequently livestock production—is going to increase sharply and is expected to.reach 465 million tonnes, or double the 2000 figure, by 2050 (FAO, 2006). This may take the highly stressed global ecosystem ever closer to the tipping point. As it is, one in every six of the over 6000 million people on Earth die from hunger or malnourishment because they cannot afford even plant-based food (FAOSTAT, 2014). Protein hunger exacerbates calorie malnutrition—when a body faces a calorie deficit it converts protein into calories. The reverse of it, viz. Conversion of calories into protein, is not possible. Due to this most of the instances of protein deficiency occur in regions of the world which are already suffering from calorie deficit (Altschul, 1974; Pimentel et al., 1975).

2. Minilivestock: a viable option

'Minilivestock' is the word given to the small-sized organisms, especially insects, which can be husbanded, and gainfully consumed by humans, just as 'macrolivestock'—or conventional livestock comprising of fowl and larger animals—is presently husbanded and consumed (Paoletti et al., 1995; Premalatha et al., 2011). As is brought out in the following sections, minilivestock used to provide parts of human diet for millions of years and has the potential to significantly alleviate the shortage of animal protein with which the world is suffering (Pimentel and Pimentel, 2003, 2008).

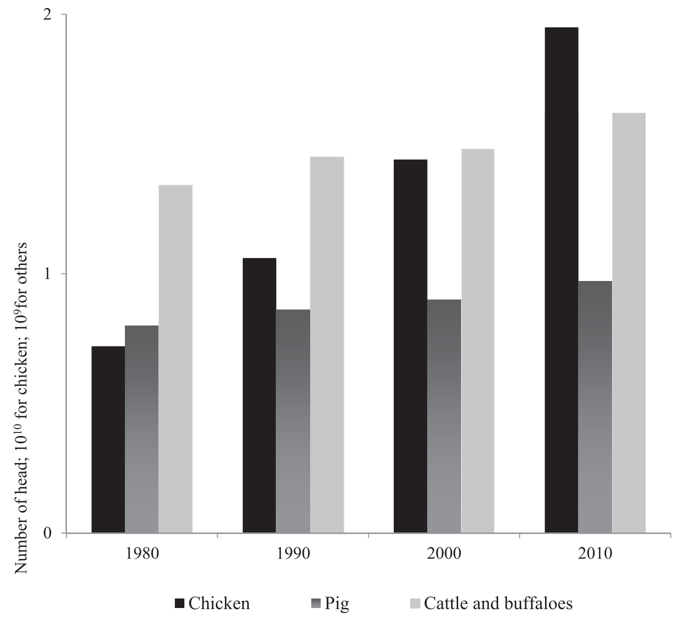

Fig. 3. Rising trend in world livestock production (based on data from FAOSTAT, 2014).

2.1. Entomophagy—a brief history

Repugnant as it may sound to many a present day human being, insect-eating—or 'entomophagy'—has been a part of human existence for millions of years (DeFoliart, 1999; Kinyuru et al., 2010). Archeological evidence as well as analyses of fossilized feces reveal that mankind has evolved as an insect-eating species (Madsen and Schmitt, 1998; Ramos-Elorduy, 2009). Termites were among the preferred group of insects eaten by pre-historic humankind and there is evidence that bones were used by *Australopithecus*

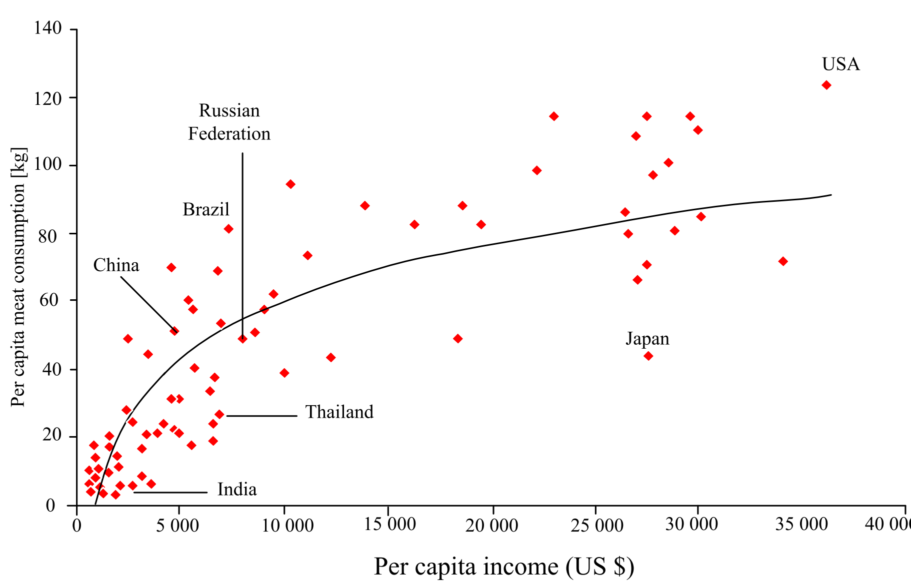

Fig. 2. How livestock demand increases with the economy (FAO, 2006).

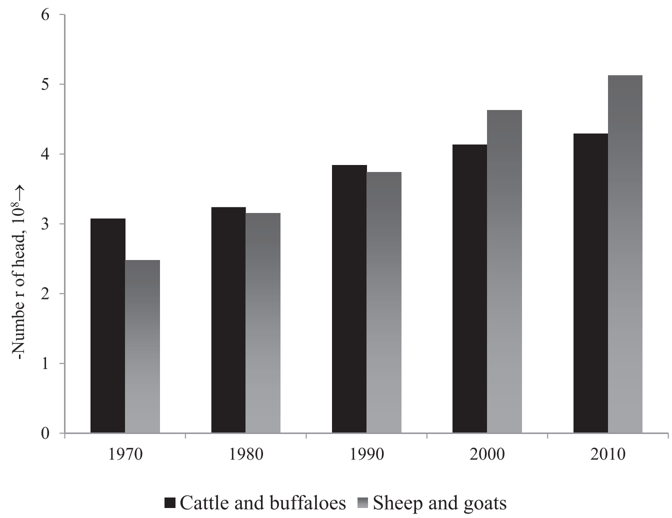

Fig. 4. Sharply rising production of livestock in India and China (based on data from FAOSTAT, 2014).

robustus—a precursor of *Homo sapiens*—in harvesting termites for over a million years (Blackwell and d'Errico, 2001; van Huis, 2003). In other ways, too, evidence is mounting that humankind has been an insect eating genus down to the present day *H. sapiens* (Brothwell and Brothwell, 1998; Mc Grew, 2014; Sutton, 1990) and that the nutrient content of insect-based diets might have played a role in promoting the development of the human brain (Fontaneto et al., 2011; Raubenheimer et al., 2014). The high 13C/12C and Sr/Ca ratios found in the dental enamel of Paranthropus and Australopithecus indicate insect-rich diet (Sponheimer et al., 2005; Mlcek et al., 2014) of the pre-historic humankind. In more recent periods, the Greeks and the Romans were familiar with entomophagy (Harris, 1985), so were the Aztecs, the Egyptians, and numerous other cultures (Bodenheimer, 1951; Premalatha et al. 2011; Van Itterbeeck and van Huis, 2012). Five species of insects and their products were consumed in the Alpine region of North-East Italy until as recently as about 30 years ago (Dreon and Paoletti, 2009). In some parts of Italy and Croatia, cheese maggot remains a delicacy (Overstreet, 2003; Raubenheimer and Rothma, 2013). Even otherwise vestiges of anthropoentomophagy exist firmly in several parts of the world, notably the Americas, southeast Asia, and Africa. In 88 countries of these regions about 1700 species of insects are eaten by humans (Raubenheimer and Rothman, 2013). As inventory by Jongema (2012) lists 2163 species of insects as having been found edible (Shockley and Dossey, 2014). Nor is it always a 'poor man's subsistence food' even in the post-modern world but is also, at many places, a highly prized and coveted delicacy. Indeed some of the costliest food in Japan, China, Australia and other countries is based on insects (Paoletti and Dreon, 2005).

It is believed that the advent of organized religions during the last 3500 years caused the decline of entomophagy as it diverted a major proportion of global population away from entomophagy (Premalatha et al., 2011; van Huis, 2013). This was because in some religions the adherents are advised to eat only certain kinds of red or white meat (which all but excludes insects) while in some other religions eating of any form of animal protein is discouraged. Religious literature of Christian, Jewish, and Islamic faiths do suggest the use of insets as human food, especially locusts (van Huis et al., 2013), but prominence is given to macrolivestock and entomophagy rapidly declined among the adherents of these faiths. The colonization of Asia, Africa, and the Americas during the few previous centuries as also spread of ethnic Europeans (who had long back abandoned insect-eating) in Australia eroded anthropoentomophagy in those regions (Ramos-Elorduy, 2009). In recent decades the impact of globalization and the concomitant spread of a certain kind of fast-food 'culture' has further weaned a large number of protein-hungry people of the third world away from entomophagy (Ayieko et al., 2012; Obopile and Seeletso, 2013; Van Huis et al., 2013). Those who still practice it are increasingly shy of admitting to it (Looy and Wood, 2006; Looy et al., 2013) and seem inclined to give it up for fear of being perceived as 'uncivilized' (Meyer-Rochow and Chakravorty, 2013; Looy et al., 2013). How irrational and 'fashion-driven' the avoidance of entomophagy is, is reflected from the fact that the world relishes honey which is basically insect vomit while feeling queasy at the prospect of eating insects. Conventional livestock can pose risk of life-threatening diseases like the bird flu and can be a source of gastero-intestinal problems, allergies, and endocrine disruptions, yet are popularly perceived as 'safe' and 'clean' while for no justifiable reason insects are perceived as unsafe and dirty in comparison. A lot of authors blame the attitude of opinion-makers in economically advanced 'western' countries for it, where disgust and loathing for insects is prevalent. In films made for mass-viewing, and in other forms of popular art, insects are almost always portrayed as monstrous creatures who will harm the humankind if not destroyed. The 'colonizing of popular imagination' by this 'western' attitude is believed to have increasingly driven people away from entomophagy (Belluco et al., 2013; Looy et al., 2013; Raubenheimer and Rothman, 2013). What has shaped this 'western' attitude is itself a mystry (Looy et al., 2013) because the reasons behind the disgust and disdain for insects—the tendency of some species to bite or generate pungent smells; the association of some species with decadence and disease; and the perceived 'monstrosity' of insect forms, movements and lifecycle—are familiar to entomophagous people as well. But they have overcome them just as non-vegetarians overcome the traditional vegetarians' abhorrence for animal flesh. Interestingly several 'western' authors have pioneered the documentation and promotion of entomophagy (Packard, 1877; Holt, 1885; Howard, 1916). In the wake of the food shortage caused by World War I, Howard even gave demonstrations on preparing and eating insect-based dishes in order to attract people towards entomophagy (Shockley and Dossey, 2014). Later Bodenheimer (1951) produced a definitive review of entomophagy literature. But all those efforts had little impact on the 'western' abhorrence for entomophagy. What is beyond a shadow of doubt is that by omitting insects from their diets and relying solely on conventional livestock, billions of human beings have adversely affected global food availability while seriously jeopardizing the earth's ecosystem. Possibly their own health as well.

Even as, now, entomophagy is primarily practiced by economically weaker people in most countries, yet in North-Eastern India, South-East Asian countries, and in parts of Australia and Europe, some of the insect species are highly prized and form part of elite cuisine (DeFoliart, 1999; Ramos-Elorduy, 2009; van Huis, 2013). For example certain species of wasps, bamboo caterpillars, cricket, and locusts are sold as delicacies in expensive restaurants in Thailand as they do in less priced food shops there. Termite queens are considered exquisite food and are served on special occasions in several parts of Africa (Owen, 1973). Annual sales of edible ants in China reaches $ 100 million. Locusts are called 'aerial shrimps' and consumed with relish in some parts of Pakistan and in the Arabian countries (DeFoliart, 2002). Silkworms are often reared more for human consumption than silk-making in northeast India (Sarmah, 2011).

Among the luxury food items in Japan is the rice-field grasshopper, or *inago* (Nonaka, 2009). So are canned wasps; a 65 g can sells for over USD (US dollar)10 (Paoletti and Dreon, 1995). Some species of wasps are even more expensive and sell at over USD 20 for 100 g (Ramos-Elorduy, 1997). Upmarket restaurants in Mexico charge over USD 25 per plate of *escamoles* (pupae of an ant species) and *gusanos* (butterfly larvae). When exported to Canada escamoles (*Liometopum* spp) achieve an even greater return of USD 50 for a 30 g can (almost two dollar per gram). There are on-line shops like *Thailand Unique* selling 'variety packs' which cover cooked grasshoppers, weaver ants and dung beetles as well as insect mix with bamboo worms and silkworm larva (Mitsuhashi, 2010). The queen brood of Asian weaver ant *Oecophylla smaragdina* sells at twice the price of beef and nearly thrice the price of chicken in Thailand (Offenberg, 2011). It is also a part of traditional medicine in India and China (Kumari and Kumaran, 2009). Several initiatives, such as the one by Arnold van Huis of Wageningen University (Fig. 5) are being made in Europe and USA to popularize entomophagy. In the UK one can now buy 70 g of weaver ant pupae online for about USD 10 and in the Netherlands 35 locusts can be had online for about USD 15 (Van Huis et al., 2013). Websites and blogs devoted to entomophagy are coming up in increasing numbers.

It can be said that if 'western' influence had earlier played a major role in the decline of entomophagy, the same influence is now providing strong thrusts towards the revival of entomophagy (Polis, 2011; Bednarova et al., 2013, 2014; Megido et al., 2014; van Huis et al., 2013; Lensvelt and Steenbekkers, 2014; Verbeke, 2015). Several entomophagy cookbooks have been published, including *Entertaining with Insects* (Taylor and Carter, 1976) and the *Eat-a-Bug Cookbook* (Gordon, 1998, 2013). Books published with catchy titles like *Creepy Crawly Cuisine* (Ramos-Elorduy and Menzel, 1998), *Man Eating Bugs*: *The Art and Science of Eating Insects* (Menzel and D' Aluisio, 1998), and *Edible Bugs*: *Insects on Our Plate* (Peterson, 2012) represent other efforts to popularize entomophagy (Shockley and Dossey, 2014). Research on consumer acceptance is being done to identify strategies for promoting entomophagy (Megido et al., 2014; Lensvelt and Steenbekkers, 2014; Mlcek et al., 2014; Turkez et al., 2014).

Fig. 5. A dish of dough stuffed with worms, eggs, cream and cheese being prepared at a cooking school at Wageningen, The Netherlands (above), and an insect-based food-spread ready for the party (below). Images are courtesy of Arnold van Huis, Wageningen University.

3. Special attributes of insects as human food

There are several advantages associated with the farming and use of insects as a source of human food as compared to conventional livestock.

3.1. Cleaner source of food

There is a common perception that insects harvested from the open are 'dirty' while lobsters, chicken, goats etc, even when they are raised without quality control (as happens commonly in developing countries), are 'cleaner' (Martins and Pliner, 2005; Van Huis et al., 2013). The implication is that the flesh of the insects harvested from the wild is likely to be more contaminated than the flesh of the freely foraging conventional livestock. The reality is opposite: a lot of insect species are strict herbivores who graze upon a few species of plants and do not dwell in polluted habitats. In that sense many of the insect species have much cleaner eating and living habits than the supposedly healthier and prized source of non-vegetarian food: lobster, fowl, pork and even rumen (Bukkens, 1997). Hence insect flesh is not likely to carry any greater risk of contaminants than the flesh of the conventional livestock; perhaps much lesser. For example the grasshopper—an acclaimed delicacy—is one of the cleanest of animals because of the exclusively plant-based feed it lives on (Holt, 1988); chicken raised on a predominantly grasshopper diet are considered tastier and fetch a much higher price than chicken price than chicken raised on commercial feed (DeFoliart, 1997). A number of insects are plant-specific; they consume only a few species of plants which makes it easier to control the quality of their feed than is possible with some of the macrolivestock like chicken and lobster which are much less selective with their foraging. Some insect species feed on only one, or a few related species, of plants for their entire life span (Lindroth, 1993). This makes it possible to rigorously control what they eat, and consequently the quality of protein they provide, much more easily than is possible with even farmed macrolivestock.

3.2. Greater energy efficiency

For every kilogram of vegetation consumed, more animal protein is generated by insects than by conventional livestock (Gullan and Cranston, 2005; van Huis, 2013). Meat production, in particular, consumes great energy as it takes 10 times more plant nutrients to produce meat than equivalent quantities of insect protein (Nakagaki and deFoloart, 1991; Smil, 2002). This is because insects are able to transform phytomass into zoomass much more efficiently than conventional livestock (Nakagaki and DeFoliart, 1991). A substantial contribution to this energy efficiency comes from higher edible weight fraction of insects. For example 80% of a cricket is edible as compared to 58% of chicken and 40% of beef (Nakagaki and DeFoliart, 1991; van Huis, 2013).

Moreover, insects are *poikilothermic*—they can change their body temperatures to match that of the surroundings. Due to this insects have to spend much less part of their food energy and nutrients in maintaining their body temperature than the warm-blooded livestock have to (Lindroth, 1993; Oonincx et al. (2010) This further enhances the overall energy efficiency of insect-based protein production.

3.3. Greater reproductive thrust

Insects reproduce much faster, and also grow to adulthood much faster, than conventional livestock. For example each individual produces thousands of offsprings compared to just a few that are produced by conventional livestock. And these offspring reach adulthood within a matter of days compared to months taken by fowl and years by the rumens. Hence a much higher rate of protein production can be achieved with insects.

3.4. Greater diversity

Compared to chicken and mammals, much greater biodiversity and variety exists in the insect world. Insects are the biggest animal group on earth; the single class of *insecta* has more species than all the species of all other classes of animals combined. Indeed insects constitute as much as 80% of the animal kingdom with more than a million species (Capinera, 2008). Hence a much wider choice of edible species is available. Also, every region has its share of a large number of endemic insect species which thrive on local vegetation. Due to this, insect-based protein production can be achieved with much lesser strain on biodiversity. By several estimates over 2000 species of insects have already been found suitable for human consumption in comparison to just a few dozen species of higher animals, and many more may qualify (Heinrich and Prieto, 2008; Jongema, 2012; Rumpold and Schlüter, 2013; Meyer-Rochow and Chakravorty, 2013). Semi-domestication of some of these species can further reduce impact on biodiversity by easing pressure on those species' natural populations (Paoletti and Dreon, 2005).

3.5. Lesser requirement of minimum essential space for husbandry

Insects can be reproduced and reared in much smaller spaces than is essential for conventional livestock. For example crickets can be reared in a kitchen corner by devoting no bigger space for it than is required for an average-sized fridge. On the other side of the scale large, mechanized, facilities can be, and are, set up for mass production. Indeed cricket farming which is common in Thailand, Vietnam, and Lao PDR, is mostly done in backyards of households with inexpensive materials (Van Huis et al., 2013). Concrete rings of approximately 0.5 m height and 0.8 m diameter, or plastic bowls, are commonly used for the purpose. The containers have a layer of rice chaff placed at the bottom. Poultry feed, vegetable and flower waste, and grasses are used for nourishing the produce (Yhoung-Aree and Viwatpanich, 2005; van Huis et al., 2013).

Oonincx and de Boer (2012) have estimated land requirement, over the product's life cycle, for the production of insect (mealworm) protein in comparison to equivalent quantity of milk/pork/chicken/beef protein. They find that for every hactare (ha) of land required to produce mealworm protein, 2.5, 2–3.5, and 10 ha are needed for milk, pork/chicken, and beef protein respectively. These figures will differ for different insect species but they do provide a broad indication that the land area required to produce insect-based protein is significantly lesser than the land area needed for macrolivesotck.

3.6. Saving on grain while facilitating pollution control

A major advantage with insects as protein source is that insects can be reared on a myriad of biodegradable waste. As De Foliart (1989) had observed, for practically every substance of organic origin, there are one or more species of insets specialized in feeding upon it. If an organic waste happens to carry the risk of pathogens and contaminants—such as manure—the insects reared on it may not be directly utilizable for human consumption but can be made to contribute, with due quality control, indirectly to human diet by use as poultry or fish feed. In this manner insects may reduce the demand on foodgrain for livestock feed and free that much extra foodgrain for human consumption. The significance of this aspect can be gauged from the fact that 60 percent of the total cost of raising farm animals is incurred on the feed of which a major portion comes from foodgrain. In the USA about 91percent of the estimated 27.1 million tons of cereal, legume, and vegetable protein that is otherwise fit for human nutrition, is fed to livestock every year. In return only 5.3 million tons of animal protein is obtained (Pimental et al., 1975). Studies reported so far reveal that insect-based feed is as good, or better, than conventional feed for chicken and fish (Ramos Elorduy et al., 2002; Ijaiya and Bko, 2009; Das et al., 2010; Halder, 2012).

Herbivorous insects can be reared for direct human consumption on leaf litter and on biomass of invasive plants like salvinia and water hyacinth (Abbasi and Nipaney, 1986). This further reduces the need to commit foodgrain for producing animal protein. Moreover, reliance on minilivestock serves the cause of pollution control and environmental protection because a lot of biodegradable waste—including biomass of invasive plants which the invasives generate at the expense of other species of plants—can be gainfully utilized (Abbasi and Abbasi, 2010a). Otherwise these waste streams either consume large quantities of energy and other resources in their treatment or, if left untreated, seriously pollute the environment.

An example of the possible gains in terms of pollution control that can be accrued from the use of biowastes as insect feed is the culturing of black soldier fly *(Hermetia illucens)* larvae on animal manure. Besides converting the nutrients contained in the biowaste to more prized zoomass, worth over ten times in value, they also reduce the bulk of the waste, thereby reducing its transportation costs and the associated carbon footprints (Tomberlin and Sheppard, 2001; Sheppard et al., 2008). Fish offal can also be used in culturing the black soldier fly larvae (St-Hilaire et al., 2007), which have been found to support good growth in chicks, pigs, and fish (Pimentel et al., 2004; Sheppard et al., 2008). Mealworms have been similarly grown on waste products of low nutritive value to generate growth-promoting feed for broiler chicken (Ramos Elorduy et al., 2002).

3.7. Lesser direct GHG emissions

Apart from indirectly benefiting global warming amelioration, insects also help the cause by lesser direct GHG emission than produced by conventional livestock. Oonincx et al. (2010) report that GHG emission of four of the five insect species studied by them was much lower than documented for pigs and for ruminants: the CO_2 production per Kg of body mass gain (BMG) of the insects (337 g/Kg) could be as low as 39% of the CO_2 production per Kg BMG of pigs and 12% of that of cattle. On the other hand the average daily mass gain (ADMG) of the insects, which is indicative of protein production efficiency of livestock (4–19.6 %) was 25% higher than the ADMG of pigs and 600% higher than the ADMG of cattle. Pound to pound, the insect species also gave off lesser NH_3 (3.0–5.4 mg/kg BM/day) than is reported for conventional livestock. For example NH_3 emission by a pig is 8–12 times more than by a cricket and upto 50 times more than a locust (Oonincx et al., 2010; Oonincx and de Boer, 2012).

All-in-all, the insects studied by Oonincx et al. (2010) had a higher relative growth rate and emitted lower amounts of GHG and NH_3 than has been reported for conventional livestock, especially cattle. In a follow-up study, which compared the global warming potential, energy use, and land use of mealworm production with corresponding quantities of milk/pork/chicken/beef production, Oonincx and de Boer (2012) found that milk and chicken have a footprint about twice as large as mealworm while pork and beef had much larger footprints (Table 1). Earlier Chopgain and Hoeckstra (2003) have shown that the water use in mealworm production is also lower (Table 1). The net environmental impacts can be several times lesser if organic waste is used as mealworm feed in comparison to a feed consisting of mixed grains and carrot, which was used in the production of mealworm assessed in Table 1.

3.8. As much or better nutritive value

A recent compilation by Rumpold and Schlüter (2013a), augmented by us with reports from Xia et al. (2011), Ayieko et al. (2012), Kinyuru et al. (2013) Bednarova et al., 2014; Chakravorty et al., 2014; and Dzerofos and Witkowski, 2014; reveals that of the 249 species of edible insects belonging to 9 orders that have been assayed for their nutritive value, 83% have protein content greater than 40% of their body weight, and 43% have protein content greater than 60% of their body weight (Fig. 6a). Majority (72%) of the species were also rich in lipid content, possessing >40% of lipids in their bodies (Fig. 6b). Nearly a third of the species had 30% or more of both proteins and lipids. In an earlier study by Ramos Elorduy and Pinto (1990), which had assessed 94 species of insects that are commonly consumed as human food, 50% had a higher caloric value than soybeans; 87% were superior to maize; 63% were superior to beef, and 70% were better than fish, lentils, and beans. Only 9 of the species analyzed contained less than 30% protein. In another study on eight of the insect species eaten in Thailand, all were found to contain over 37.5% protein, four of the species contained over 50% protein (Raksakantong et al. 2010).

These findings, and those of others, (Banjo et al., 2006; DeFoliart et al., 2009; Cerritos, 2009) reveal that the level of proteins and fats in the insect species is generally high, above those of traditional sources of protein such as meat, dairy products and some nuts.

An even more important attribute of insect-based protein is that it is not only high in quantity but quality as well (DeFoliart, 2002). It contains all indispensable amino acids in favorable proportions (Chen et al., 2008) and is more easily digestible by the organisms that consume it than the proteins of macrolivestock. For example 82–90% of the protein contained in grasshoppers and termites is easily digestible (Kinyuru et al., 2010). It is also very low on cholesterol (Ritter, 1990; Ekpo et al., 2009). The digestibility of insect protein, especially after removing the exoskeleton, is higher than most vegetable-based proteins, too (Finke, 2004). Some species, such as mealworm *(Tenebrio moliter)* and super worm (*Zophabas atratus)* have high protien-purine ratios and make a diet suitable for patients suffering from hyperuricemia or gout (Bednarova et al., 2014).

In a study on weanling rats it was observed that the proteins contained in meals of cricket (*Acheta domesticus* and *Anabrus simplex*) were equal or superior to soy protein as an amino acid source (Finke et al., 1989). Growing performance and carcass quality of broiler chicks 2009). The protein content of the chick muscle remained constant even as the lysine and tryptophan content increased. This was, apparently, possible due to the optimal amino acid profile, high protein content (64%). and high protein digestibility (98.5%) of the larvae. The removal of chitin via an alkaline treatment further improved the nutritional quality of the insect protein in terms of increased protein digestibility and amino acid availability when fed to rats.

All-in-all, edible insects in general and species from the order Orthoptera (grasshopper, cricket, locust) in particular, are rich in proteins (Rumpold and Schlüter, 2013a). The nutrient quality of

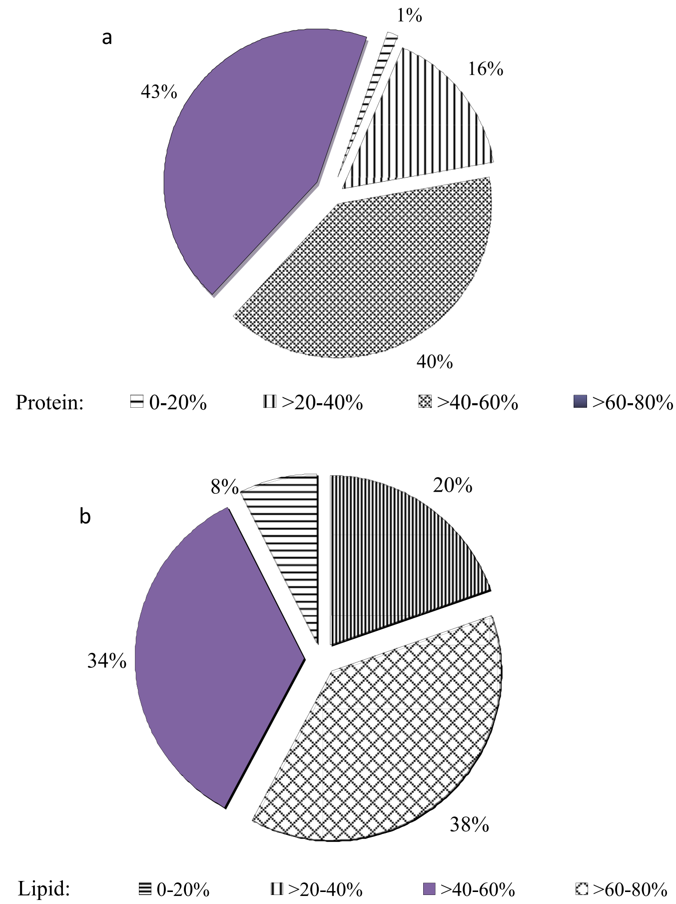

Fig. 6. Protein (a) and lipid (b) content in terms of percent of body weight in 249 species of insects. Boxes show ranges of protein/lipid and the pie diagram gives percentage of insect species bearing those ranges. Based on data culled from Rumpold and Schlüter (2013a), Xia et al.,. (2011); Ayieko et al. (2012); Kinyuru et al. (2013); Bednarova et al. (2014); Chakravorty et al. (2014); and Dzerofos and Witkowski (2014).

Table 1
Resource use and global warming potential (GWP) of mealworm production in comparison with traditional protein sources, compiled on the basis of Oonincx and deBoer, (2012); and Chopgain and Hoeckstra (2003).

Protein source	Energy (MJ/Kg edible protein)	Land (m^2/kg edible protein)	Water (L/kg live weight)	GWP (kg CO_2-eq/kg edible protein)
Mealworms reared with mixed grains and carrot	173	18	–	14
Mealworms reared without energy inputs and on organic waste	0.29	0.04	2.5	0.06
Beef	177–273	142–254	9700	77–175
Pork	95–237	46–63	2800	21–54
Chicken	80–152	41–51	1500	19–37
Milk	36–144	33–58	800	25–39

their protein content can be further improved by the removal of the bulk of chitin. Most edible insects provide satisfactory levels of the required essential amino acids as benchmarked by WHO (2007).

The fatty acids of insects are generally comparable to those of poultry and fish in their degree of unsaturation, but contain more polyunsaturated fatty acids, PUFA (Defoliart, 1991). In contrast, beef and pork contain very little PUFA, while the less favorable MUFA make up the greatest portion of their fatty acid content.

Yhoung-aree et al. (2010) report that cricket and scarab beetles have a fatty acid ratio of 1:1:1 (PUFA:MUFA:SFA) being optimal for an adequate fat uptake. In general the average ratio of SFA to UFA in insects falls between 0.43 and 0.79, showing that unsaturated acids predominate in the fatty acid spectra of edible insects (Rumpold and Schlüter, 2013a) thereby enhancing the insects' nutritional value.

Most species of insects are rich in minerals and vitamins too, but due to large inter-species variations in the mineral or vitamin profiles—as happens with conventional food as well—certain combinations should be eaten to ensure that all nutritional requirements are optimally fulfilled (Banjo et al., 2006; Cerritos, 2009; Rumpold and Schlüter, 2013a). It is believed that bioavailability of iron, zinc and other metals is better in insect-based food than in plants (Christensen et al., 2006) even as insects are generally lean in calcium and potassium (Rumpold and Schlüter, 2013a). Among other distinguishing features of insect-based nutrition is that insects can provide some of the essential polysaturated fatty acids (PUFA) that cannot be *de novo* synthesized by macrolivestock (Fontaneto et al., 2011). Moreover the nutrient content of insects is highly dependent on the feeds, making it possible to tailor the insect zoomass production to meet specific dietary requirements of humans, such as a diet low on sodium or cholesterol (Ritter, 1990; Penino et al., 1991; Ekpo et al., 2009). There is evidence that a shift from entomophagy to 'modern' foods in some regions was accompanied by a general deterioration of the concerned people's health (Ramos Elorduy, 1997). Given that protein content of most insects is as high as of beef yet the fat content of most insects is much lower, insect-based diet is likely to reduce obesity without generating protein deficiency.

4. Insect farming

If insects are harvested from nature with unsustainable intensity, it would have the same negative effects in terms of habitat destruction and loss of biodiversity as overfishing is known to cause (Schabel, 2010). Hence insect farming must be practiced for sustainable promotion of entomophagy. Some species, notably silkworm and honey bee have been domesticated since antiquity, primarily for the production of silk, honey, and wax, but the two species have been eaten as well (Bodenheimer, 1951). Cochineal (*Dactylopius coccus*) has been cultured for the natural red dye it yields (Aldma-Aguilera et al., 2005). Van Itterbeeck and van Huis (2012) have conjectured that semi-cultivation of insects has occurred throughout history on the basis of selective doctoring of the environment. They have given three prominent examples of this: (*a*) harvesting of edible eggs of aquatic hemipterans from artificial oviposition sites created in lakes in Mexico; (*b*) deliberate cutting of palm trees in the tropics to trigger egg laying by palm weevils (*Rhynchophorus* spp.) and the subsequent harvesting of larvae; and (*c*) manipulation of host tree distribution and abundance, shifting cultivation, implementing fire regimes, managing host tree preservation, and manual introduction of caterpillars to a designated area to promote the abundance of arboreal, foliage-consuming caterpillars in sub-Saharan Africa. Another example is planting of maize in Thailand to attract and feed locusts which are then harvested for human consumption (Hanboonsong, 2010).

More recent examples of insect farming for food production include that of the house cricket, the palm weevil and the giant water bug in Thailand, and water beetles in China (Jäch, 2003; van Huis, 2013). The combined produce of several cottage industries can add up to big figures, for example 400 families in two of the villages in Thailand are known to have produced upto 10 metric tons of cricket in the peak growing season, some of which is exported (Johnson, 2010).

Mass rearing of insects on an industrial scale so far has been principally for use as livestock feed or biological pest control (Singh, 1994). Recently Rumpold and Schlüter (2013b) have authored a concept paper on what it will take to mass produce and process insects for human consumption. It builds upon similar other attempts by Kok (1983), Kok et al. (1988), Sileshi and Kenis (2010), Klunder et al. (2012), and others, as detailed in Section 7.1. The possibility that some of the organic wastes can become raw materials is particularly appealing.

5. How safe are insects as food?

One of the most feared disease vectors is an insect—mosquito. Some of the insects are known to cause painful bites and some emit pungent chemicals. How safe, then, are insects as human food?

Out of a million plus species of insects that exist, some are surely unfit for human consumption. Hence any new species should be carefully vetted before it is added to the human menu. But the record of safety associated with the 2000-odd insect species that have been consumed so far is comparable, or perhaps better than, the record of more widely accepted items of food. There has not been any instance of an insect carrying any virus comparable in deadliness with the bird-flu virus that has been carried by chicken. Nor have there been instances of mass food poisoning involving insect-based food as grave in terms of number of people involved or the severity of the impact, as the instances involving conventional food. Indeed, direct zoonosis from insects to humans, comparable in spread and severity with bovine tuberculosis, salmonellosis, or influenza A (bird flu) has not yet emerged even though zoonotic agents such as bacteria, viruses, parasites, and fungi can be transmitted by insects as do conventional foods if proper hygine is not maintained (Kruse et al., 2004; Rumpold and Schlüter, 2013b). As for allergic response, insects do induce it in some people, but so do very many food items prized by those who abhor insects. Indeed the eight items of food which account for about 90% of allergic reactions in humans are also among the most widely consumed: milk; eggs; peanuts; tree nuts such as almonds, cashews, walnuts; fish especially bass, cod, flounder; shellfish, including crab, lobster, and shrimp; soya; and wheat (Cianferoni and Spergel, 2009). It is estimated that 6–8% of children and 4% of adults in the USA suffer from food allergy (Pereira et al., 2005; Venter and Pereira, 2008). Approximately 30,000 anaphylactic reactions and possibly 200 deaths each year in the USA are caused by allergic response to one of these 8 food items (Yocum et al., 1999; Cianferoni and Spergel, 2009). Anaphylactic reactions are highly traumatizing as they sequentially lead to difficulty in breathing, swelling of the mouth and throat, drop in blood pressure, loss of consciousness, and if not controlled, even death (Sampson et al., 1992). Upto 5% of the world's population—or upto 350 million people in the world—have allergy to one or other of these common food items. State-of-the-art reviews by Belluco et al. (2013). Rumpold and Schlüter (2013a) and van Huis (2013) indicate that, in totality, insects are no more hazardous as human food than conventional livestock. Studies *vis a vis* antinutrients also show insects to be comparable with conventional food which is popularly perceived to be more healthy and wholesome than insect-based food (Kiatbenjakul et al., 2015; Tang et al., 2015).

6. Promise and challenges

From the foregoing it emerges that revival of antropoentomophagy and its large-scale deployment holds promise of enhancing the availability of much sought-after animal protein while at the same time doing it at lesser cost to the environment than is entailed in the husbanding of macrolivestock. Due to their ability to convert various types of wastes into feed or food, use of insects can even directly help the cause of pollution control. But how realizable is this promise? As of now we do have several indicators that point towards a favorable answer but there is only very little quantitative information at hand to back the expectation.

6.1. Challenges associated with mass production of insects for human consumption

Extensive experience already exists on mass production of insects in industrial plants for use as feed or as biological pest control agents (Paoletti and Dreon, 2005; Hwangbo et al., 2009; van Huis et al., 2013). For example a facility at Okinawa, Japan, produces 6 million larvae of melon fly *Bactrocera cucurbitae* per day (Mitsuhashi, 2005). It is a largely automated system with centralized controls much like any other sophisticated food industry. Oonincx and de Boer (2012) describe a facility in the Netherlands, which produces about 0.1 million Kg/year of mealworms, utilizing a 588 m^2 area. The feed consists of mixed grains and carrots that are grown off site for feed. The top 10 cricket producers in the United States of America (USA) together generate approximately 2 billion head of cricket annually, amounting to about 1.36 million kg of zoomass. Similar quantities of feeder mealworms are also likely being produced per year in the USA (Shokley and Dossey, 2014). Additionally, many more small companies are producing, collectively, hundreds of millions of insects per year. Mass production of biological crop protection agents and pollinators (bees and bumblebees) has been going on for some decades; the first factory to mass produce screw-worm on an artificial diet was set up in 1936. From then onwards considerable expertize has also been generated on large-scale rearing of insects, with tailored diets, to serve as biological weapons (Singh, 1994; Rumpold and Schlüter, 2013b). Insects have also been reared for the *in vivo* production of pathogenic nematodes and viruses (van Huis et al., 2013).

The collective experience of these endeavors reveals that the challenges associated with mass production of insects appear no bigger than the ones that are encountered by any food or feed industry. Prevention of biological contamination, especially of disease vectors that can infest the product, is the greatest concern alongside contamination of chemicals that can adversely effect the consumers of the product (Klunder et al., 2012). If a breach occurs, the consequences can be disastrous as had happened with the Dutch company Kreca engaged in mass producing cricket (*A. domesticus*). In the year 2000, 50% of the cricket population died within a few hours due to what was suspected as a densovirus attack. A die-off of this magnitude was unprecedented and was attributed to the fact that since Kreca was relying on a single species, its product was vulnerable to population crash like all other monocultures are. The company now rears three species of cricket instead of one and has not experienced again the kind of crisis it had faced in 2000 (van Huis et al., 2013).

Studies done so far indicate that even though insects are liable to be infected with pathogens, such pathogens are taxonomically separate form vertebrate pathogens and are generally harmless to humans and macrolivestock (Jensen et al., 1977; Vega and Kaya, 2012). But insect flesh can get infected during handling and storage with pathogens that can effect humans in the same way as macrolivestock flesh does (Banjo et al., 2006; Klunder et al., 2012). The risk, though, can be minimized with preservation methods that are simple and inexpensive (Klunder et al., 2012).

Nadeau et al. (2014) have estimated that 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 (FAO, 2014a, b). If even half the production can be done using organic waste as feed, about 1600 ha—or 0.0003% of the almost 5 billion hectares of agricultural land in the world—would be needed to produce all of the energy required to erase the abovementioned deficit. The estimate assumes no land use for the production of organic waste streams because they are the byproduct of primary food crops and other processes.

It must be emphasized that even if mass production of insects for food may not entail any greater risk than mass production of macrolivestock does, it would nevertheless need massive investments in process design and implementation because the system components needed for breeding, rearing, and processing minilivestock are essentially different from the ones that are in place for macrolivestock-based food production. Rumpolt and Schlüter (2013b), Klunder et al. (2012) and Shokley and Doessey (2014) have addressed some of these issues in recent reviews, presenting models of likely production processes, discussing factors that may improve profitability, and dwelling upon safety aspects.

6.2. Need for standards to regulate quality of insect-based food

At present there are no standards in existence to define and regulate the quality of insect-based food. What regulations pertaining to food administration that do exist only provide for levels of certain insects, admissible in grains and other items of food, when the insects are inadvertently brought into these items. Hence setting of the required standards is a priority in the quest of promoting anthropoentomophagy.

6.3. Safeguards against unsustainable harvesting from the wild

Another major concern that will have to be addressed when promoting anothropoentomophagy is to safeguard against uncontrolled harvesting from the wild. In regions where anthropoentomophagy is prevalent, such as in Mexico, several insect species are already under threat due to excessive harvesting (Ramos Elorduy, 2006). Unscrupulous gatherers are known to even chop down host trees to make gathering of the guest insects easier (Vantomme et al., 2004; Dzerefos et al., 2013).

Insects provide essential ecosystem services, notably pollination, scavenging, soil-working, wildfire protection and pest control, which are of enormous value. According to an estimate of Losey and Vaughan (2006), the contribution of insects in just four of the many ecosystem services they provided in the USA—dung burial, pest control, pollination, and wildlife nutrition—is worth over $ 60 billion per year. The contribution of ants and termites in processing and rejuvinating the world's soils would be worth much more (Premalatha et al., 2013), so is the contribution of numerous insect species on several fronts. Hence it is of crucial importance that their collection for human consumption does not override their regeneration capacity.

Collection can interfere with, as well as exacerbate, the effect of natural predation. This may endanger population viability (Choo, 2008). In turn, the reduced population of a given species can adversely effect its predators. Hence a reduction in the numbers of a few insect species may have cascading effect on populations of other insect species as well as on their predators and preys, and affect ecosystem function.

The stability and regeneration of edible insect populations can also be threatened by improper collection practices (Latham, 2003; Illgner and Nel, 2000; Ramos Elorduy, 2006). For example, collection of mature insects before their first mating or before they lay eggs can lead to very quick decline of their population (Cerritos, 2009).

Prevention of uncontrolled harvesting acquires additional importance because already insect populations are under pressure due to anthropogenic habitat destraction, pesticides, and pollution in most parts of the world (Morris, 2004; Losey and Vaughan, 2006). This directly influences the abundance and distribution of insect population (FAO, 2011).

Untill the advant of modernity, insect collection was done with traditional knowledge. As people depended largely on food available close to their dwellings, traditional practices of food gathering, including insect harvesting, were always geared towards ensuring optimal regeneration, hence sustainability. In modern and postmodern times traditional practices have been abandoned and insect collection is often indiscriminate; hence unsustainable (Choo, 2008; Chakravorty et al., 2013).

In contrast to indiscriminate harvesting, controlled collection of insects can be hugely beneficial. For example those of edible insects that harm agricultural crops, if collected for use as food or feed, can save that much pesticide use while providing valuable protein. This measure of insect collection can, at times, enhance the gains from agriculture manifold. By an estimate of De Foliart (1997), a farmer can get three times more value form his field of corn if he harvests and sells, instead of killing with pesticides, the grasshoppers that infest his crop. In most situations undesirable populations of insects can be gainfully controlled by collection and use thereby not only saving upon the cost of pesticides but also the harm to environment that pesticides cause in the course of their production and subsequent dispersal.

6.4. Precautions necessary when consuming potentially toxic insects

The insects which are regularly consumed by humans include species like stinkbug *(Encosternum delegorguei)* of which defense mechanism consists of exuding pungent fluids and flying into the hunter's eyes (Dzerefos et al., 2013). Some other species like *Zonocerus veviegatus* also either have toxic exhudates or contain chemicals in some of their body parts which can cause toxicity. Practices already exist to eliminate this risk while cooking such insects for food (Barreteau, 1999; Morris, 2004), or eating them directly (Zagrobelny et al., 2009), but risk does exist that if safeguards are not observed due to ignorance or carelessness, some harm may ensue. The repercussions can be serious - for example if hair of caterpillars are not burnt off before eating the caterpillars, the resulting toxicity may be significant (Muyay, 1981), and consumption of excessive quantity of scarab beetles may cause severe enough constipation to require surgical intervention because the beetle's indigestible chitinous remains can accumulate inside the human gut (Kuyten, 1960). While taking note of these risks, it must also be remembered that consumption of macrolivestock is not free from serious risks either. Very painful and debilitating diseases are caused in the course of eating red or white macrolivestock meat if the latter happens to be contaminated with pathogenic organisms or xenobiotics (Zagrobelny et al., 2013). Insects, too, bioaccumulate pesticides and heavy metals as macrolivestock does but most macrolivestock species being higher in food chain than insects are likely to carry this risk in a greater measure. Some of the adverse impacts of insects are due to over-consumption; otherwise some of the constituents that cause harm can actually be beneficial if eaten in moderation. For example limited consumption of insect-based chitin can improve the human immune system (Muzzarelli, 2010).

6.5. Overcoming food taboos

Whether a substance has desirable taste and flavor or not is more a matter of perception than the innate properties of that substance. The adage 'one man's peach is other man's poison' holds true. The perception, in turn, is influenced by culture and fashions. Untill a few decades ago an invitation to partake raw fish would have been considered crass and uncouth in India and many other parts of the world. But in the present era *Sushi* is a prized delicacy across the world. It would be revolting to hear that the vomit of some insects can be delicious, and very shocking to learn that most of us do relish an insect's vomit. The fact, as stated earlier, is we do indeed consider honey a delicacy even though it is essentially bee's vomit.

Given that most of food taboos are irrational there is no reason why the negative perception of a section of the world population towards entomophagy will not change once the benefits of entomophagy become better known and insect-based delicacies come into global fashion. There are indications that conscious efforts towards promoting entomophagy are likely to cause a change in public perception for the better (Bednarova et al., 2013; Medigo et al., 2014).

7. Conclusion

Production of animal protein employing livestock is among the most global warming and eco-degrading of anthropogenic activities. As demand for animal protein is sharply rising while the availability of land and other resources to meet the demand is falling, it is becoming increasingly difficult to supply the rising global population with the desired quantities of animal protein. In this context 'minilivestock', which mainly consist of insects, can be a viable option. Humankind has evolved as an insect-eating genera for millions of years and despite an erosion of anthropo entomophagy after the advent of major organized religions, over 2000 species of insects continue to be eaten by people in 88 countries of the world. Apart from offering numerous advantages over conventional livestock production—including greater diversity, energy efficiency, reproductive thrust, and cleaner production—insects are also highly nutritious. As a source of safe and wholesome food insects are comparable, perhaps better, than items like milk, eggs, nuts and soya which are prized all over the world. If a larger populace can shift, even partially, from conventional livestock to minilivestock, it would enable the world to achieve much greater quantities of animal protein production at much lesser carbon footprint and other environmental costs.

It should also be emphasized that even though the minilivestock option is hugely promising, exercising it is not free from uncertainties and challenges. From the limited quantitative information that is presently available, it appears that the challenges may not be too difficult to overcome.

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