# Silkworm *(Bombyx mori)* Protein Substitution in China: Analysis of Greenhouse Gas Reduction Strategies

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# ABSTRACT

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**1.0 Introduction**

China's ascension as the world's second largest economy has lifted millions into the middle class and more than halved undernourishment in the country.[1] Today, China is in the midst of a "protein transition" as incomes across the country rise, dietary patterns shift, and consumption of meat increases. China consumes nearly 30 percent of the world's meat and over 50 percent of the world's pork, with no plateau in demand forecasted.[2] The Food and Agriculture Organization of the United Nations (FAO) projects that global consumption of meat will increase 76 percent on recent levels by 2050,[3] on the same timeframe as the world population is expected to reach nearly 10 billion.[4] This is not sustainable and poses major environmental challenges globally and for China domestically.

Globally, the livestock sector is already responsible for 7.1 GtCO2-eq a year of greenhouse gas (GHG) emissions—just under 15 percent of the global total, and equivalent to emissions from all the world's vehicles.[5] Meat consumption in the developed world has largely plateaued, but consumption in developing nations continues to rise rapidly. If UN projections for population and meat consumption growth are realized, it will be difficult for the international community to limit the average global temperature rise to two degrees Celsius as affirmed at COP21 in Paris.[6] Although China is not the sole driver of increasing demand for meat—this is a pattern across the developing world—its impact on the global livestock market is unmatched in scope and scale.

China's demand for meat by 2050 is projected to be over four times that of the next fastest-growing consumer, Brazil.[7] Nationally, growing demand for livestock products, and especially pork, threaten food and resource security in a country that is already limited in water quantity and soil quality. The demand for Chinese pork has outstripped domestic supply, leading to a surge in imports. In addition, China, which was once a major soybean exporter, now imports over 87 percent of all soybeans it consumes, with the majority going towards pig feed.[8] As demand increases, China will need to weigh environmental concerns and food security with satisfying a seemingly insatiable demand for pork.

One proposed solution to curb demand for meat in China and around the world is the use of edible insects as an alternative protein source. FAO estimates that entomophagy—the practice of consuming insects—is common for over 2 billion people around the world. Many edible insects are high in protein, fat, minerals, and vitamins on levels comparable to livestock products. In addition, edible insects may have a significantly smaller environmental footprint over traditional livestock products.[9]

China is believed to be one of the oldest civilizations in which entomophagy is practiced. The silkworm was domesticated thousands of years ago in China to produce silk, and silkworm pupae are a byproduct that was traditionally consumed or used for animal feed.[10] China produces over 85 percent of the world's silk (around 170,000 metric tons per year), which requires millions of silkworm cocoons to harvest. As a result, an estimated 1,360,000 metric tons of fresh (340,000 metric tons of dried) silkworm pupae are produced annually as a byproduct of the sericulture sector in China.[11] The volume of China's silk production creates a unique opportunity for the country to reallocate silkworm pupae as a protein replacement.

A series of hypothetical scenarios are evaluated to compare two avenues by which silkworm pupae byproduct from the sericulture industry could be reused as a protein replacement to offset GHG emissions from the livestock sector in China. Scenario A examines the hypothetical reuse of silkworm pupae as a partial protein replacement in the average Chinese diet for the three major animal protein sources: beef, pork, and chicken. Scenario B examines the hypothetical use of silkworm pupae as a partial protein replacement in pig feed for soybean meal. In both scenarios, various silkworm pupae usability rates from the sericulture industry are assessed. The silkworm may offer an opportunity for China to merge traditional knowledge and modern science to meet the food and nutrition challenges of today and the projected demands of tomorrow.

**1.1 Global Impacts of the Livestock Sector on Climate Change**

An analysis of emissions from the livestock sector highlight the significant impacts on global climate change. FAO estimates that GHG emissions from the livestock sector account for 7.1 GtCO2-eq/year, just under 15 percent of total global emissions. This estimate places emissions from the livestock sector on par with global vehicle emissions.[12] The three main sources of GHG emissions are in the form of methane (CH4) at 3.1 GtCO2-eq per year or 44 percent, nitrous oxide (N2O) at 2 GtCO2-eq per year or 29 percent, and carbon dioxide (CO2) at 2 GtCO2-eq per year or 27 percent of total emissions. [13]

The livestock sector consists of a series of complex supply chains, with emissions varying along certain points of production. As outlined in Table 1, feed production and processing (including land use change) is estimated to be responsible for almost half of total emissions (45%), followed by enteric fermentation from ruminants (39%), manure storage and processing (10%), and transportation of animal products (6%).[14] Pound for pound, the global warming potential of methane and nitrous oxide is estimated to be 25 and 300 times higher than carbon dioxide.[15] Nitrous oxide emissions are most prevalent at the feed production stage, while methane emissions are primarily released from enteric fermentation and manure.[16] Emission intensities also vary due to differences in production practices around the world.

Emissions also vary by livestock commodity. As noted in Table 2, beef and milk from cattle are responsible for more than half of total emissions at 41 percent and 20 percent respectively. This is followed by pork (9%), buffalo meat and milk (8%), chicken and eggs (8%), small ruminant meat and milk (6%), and other poultry and mixed non-edible byproducts (8%).[17] The energy required and emissions released in the production of one kilogram of beef (46.2 kg CO2-eq per kg product carcass weight) is the same needed to produce more than 7 kilograms of either pork (6.1 kg CO2-eq per kg product carcass weight) or chicken (5.4 kg CO2-eq per kg product carcass weight).[18] These estimates provide a baseline indication of industry averages that can be used to forecast emissions.

**Table 1: Livestock Supply Chain Emissions**

| Supply Chain Step | Estimated GHG Emissions (Gt CO2-eq/yr) | Percent of Total Livestock Supply Chain Emissions |
|---|---|---|
| Feed Production and Processing (Including Land Use Change) | 3.195 | 45% |
| Enteric Fermentation | 2.769 | 39% |
| Manure Storage and Processing | 0.71 | 10% |
| Transportation | 0.426 | 6% |
| **Total** | **7.1** | **100%** |

*Source: Gerber et al. (2013)*

**Table 2: Livestock Emissions by Product**

| Livestock Product | Estimated GHG Emissions (Gt CO2-eq/yr) | Percent of Total Livestock Emissions |
|---|---|---|
| Beef | 2.911 | 41% |
| Cattle Milk | 1.42 | 20% |
| Pork | 0.639 | 9% |
| Buffalo Meat and Milk | 0.568 | 8% |
| Chicken and Eggs | 0.568 | 8% |
| Small Ruminant Meat and Milk | 0.426 | 6% |
| Other | 0.568 | 8% |
| **Total** | **7.1** | **100%** |

*Source: Gerber et al. (2013)*

FAO projects that global consumption of meat will increase 76 percent on recent levels by 2050,[19] on the same timeframe as the world population is expected to reach nearly 10 billion.[20] This trend is unsustainable considering that the UN estimates total global GHG emissions must fall from 2010 estimates of 49 GtCO2-eq/year to 40 GtCO2-eq/year if global warming is to be stabilized near 2 degrees Celsius.[21] The US Department of Agriculture (USDA) estimates that developing countries will account for an estimated 81 percent of projected growth in global meat consumption during this period due to rising incomes, urbanization, and changes in consumer patterns.[22] Specifically, China's demand for meat by 2050 is projected to be over four times that of the next fasted-growing consumer, Brazil.[23] Therefore, China's demand patterns—accounting for almost a third of total meat and over half of total pork consumption—will have major implications on livestock sector emissions over the next several decades.

**1.2 China's Growing Demand for Pork**

China has witnessed an unprecedented growth in the livestock sector over the past several decades. The average per capita meat consumption in China has quadrupled to 58 kg of meat from 1980 to 2009.[24] Even though share of pork in terms of total meat consumption in China has fallen from 94 percent of all meat in 2000 to 65 percent in 2005, pork remains the principle meat in China. [25] The Chinese Communist Party (CPC) has invested over $22 billion into pork subsidies to ensure stable prices and access for citizens.[26] Demand for pork is unlikely to diminish if the CPC can keep pace with consumption patterns, as evidenced for several key reasons.

First, pork captured the most growth in demand for meat over the past several decades: the Chinese consumed an average 39 kg of pork a year as of 2014. This pattern is expected to continue, with projections indicating that pork will capture 66 percent of additional consumption, despite the diversification of meat sources.[27] Second, pork has special cultural significance in China and signifies wealth and prosperity. During the Cultural Revolution, food rationing was common and the average Chinese ate pork only once or twice a year. During the 1970s, the CPC encouraged the Chinese to "eat meat in revenge" and against past scarcity as part of their reform policies.[28] From a cultural perspective in China, the more wealth someone possesses, the more pork they are encouraged to consume.

Third, estimates suggest that consumption of animal protein in rural China is about 30 years behind urban centers.[29] Increasing the rates of urbanization has been a policy of the CPC for several decades, and the recently released "National New-type Urbanization Plan (2014-2020)" clearly outlines a desire to increase urbanization from 52 percent to 60 percent by 2020.[30] Urbanization has been linked with growth in demand for livestock products, thus it is reasonable to expect that China's urbanization strategy over the next decade will signal further growth in demand for meat.

**1.3 Impacts of Chinese Pork Demand on the Environment and Food Security**

Chinese demand for pork has not been without consequences to Chinese food security and the environment. As China's meat production has shifted from backyard farming to industrialized systems, the amount of feed needed to raise an average pig has increased dramatically. The average pig raised in one of the industrial operation in China consumes 350 kg of feed to reach slaughter weight, while one raised on a family farm consumes only 150 kg, with the rest coming from other household and waste sources. [31]

Over the past several decades, demand for staple feed crops has increased rapidly to meet growing demand for pork and other livestock products. In the 1970s and 1980s, China was largely self-sufficient in the production of soybeans. Today, due to the rising demands for soybeans as the preferred plant-protein in livestock feed, China imports 87 percent of soybean consumption—representing over 50 percent of the total soybean market. Corn, the other major feedstock crop, is following a similar pattern.[32] In addition to importing increasing amounts of feed crops, China has also had to import pork to meet growing demand. Even though Chinese imports are considered negligible in terms of total consumption—in 2014 China imported 775,000 tons of pork from 20 world markets, equating to just over one percent of total demand—they represent a significant portion (11%) of total world exports of 7 million tons.[33] The result is greater vulnerability of China's food security to external forces and market changes.

Perhaps the primary concern of increased pork consumption in China is environmental. Globally, China's need for feed is literally reshaping countries, especially in South America. In Brazil, it is estimated that more than 25 million hectares of land—parts of which were once Amazon rainforest—have been cut to enable cultivation of soybeans.  In Argentina, thousands of hectares of forest have been cut to grow soybeans—total land under cultivation for soybeans has quadrupled since 1990.[34] The United States, Brazil, and Argentina together account for nearly four fifths80% of the world's soybean crop and account for an estimated 90 percent of global soybean exports. Brazil and Argentina are the second and third most important soybean export markets for China, behind only the United States.[35] Chinese demand is driving deforestation and land change on a massive scale to feed their pigs.

Domestically, China's pork and feed demands are causing issues with resource scarcity and pollution. China's national soybean and corn production is unlikely to expand primarily due to shortages of arable land and water in the north, where corn and soybeans have traditionally been grown. In these areas, water tables are dropping at a rate of 3 to 10 feet a year and as a result deserts are expanding in the north and west of the country at a rate of 360,000 hectares a year.[36] This is an alarming trend and only represents a portion of the estimated 4500 liters of water required to produce one kg of pork.[37]

Finally, there are growing concerns about the environmental impacts in China from raising millions of pigs. According to the Wilson Center, the average pig in China produces 5.3 kg of waste each day, which often contain nutrients, heavy metals, and other residue that can leach into the soil or runoff into water sources.[38] As noted above, pig waste also contributes to methane and nitrous oxide emissions, GHGs that are 300 times more concentrated than carbon dioxide. The current model of matching insatiable demand for Chinese pork with increased production is not sustainable considering the toll on natural resources, increasing emissions, and rising pollution.

**1.4 An Alternative Protein Source: Edible Insects**

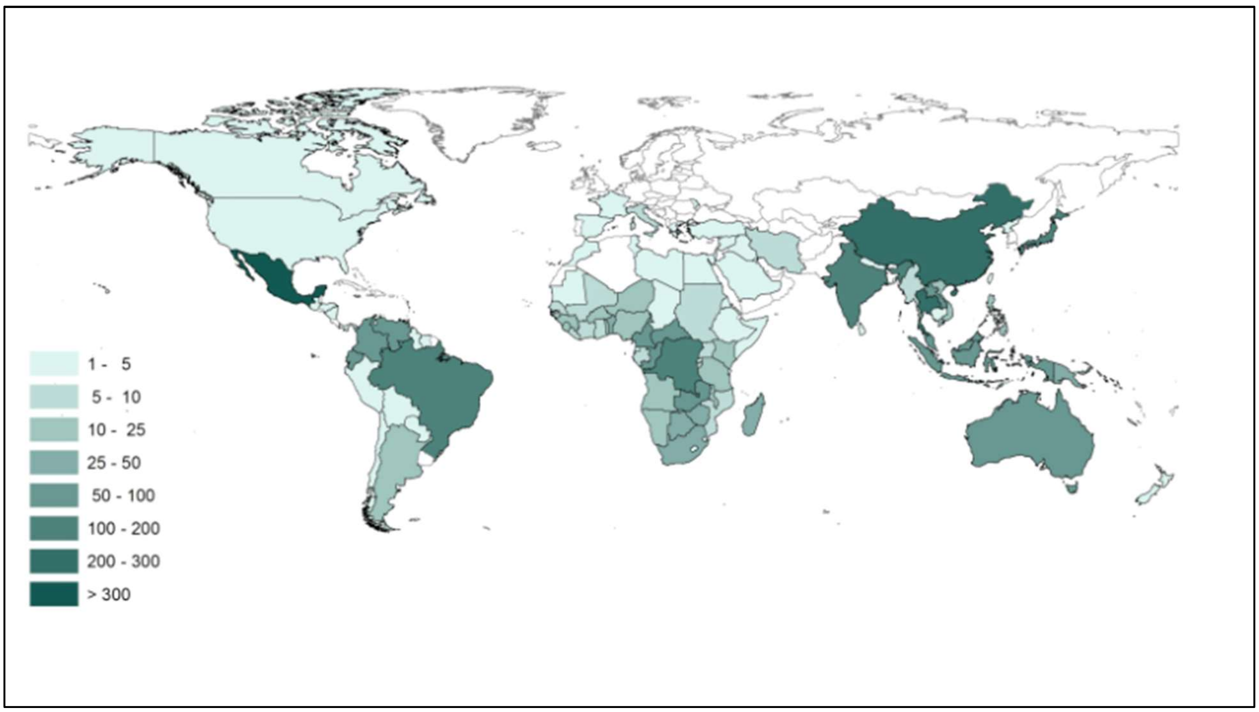
One proposed solution to curb demand for meat in China and around the world is the use of edible insects as an alternative protein source. In 2013, FAO issued a major report highlighting edible insects and their potential impact on global food and feed security. Entomophagy—the practice of eating insects, especially by people—dates back a millennium and is currently practiced by over two billion people worldwide.[39] Edible insects present a viable alternative food source due to their low environmental footprint, high nutritional value, and economic benefits.

Insects are one of the most numerous and diverse group of animals on the planet, with more than 1 million known species.[40] As noted in Figure 1, researchers at the University of Wageningen in the Netherlands estimate that there are 2037 identified edible insect species, with the highest notable concentrations in China, Thailand, Mexico, and the Democratic Republic of the Congo.[41] The most commonly consumed insects include beetles (*Coleoptera*), caterpillars

(*Lepidoptera*), bees, wasps and ants (*Hymenoptera*), and grasshoppers, locusts and crickets (*Orthoptera*)—representing over 75% of insect protein sources.[42]

Edible insects are believed to have been an important source of nutrients throughout history. Tools made of bone found at early hominid sites in southern Africa suggest that hominids foraged for terminates—driving the bone tool into termite hills to force the termites emerge—as a food source for millions of years.[43] Entomophagy is referenced in the primary religious texts of the Christian and Islamic faiths (noting acceptance of eating insects, such as locust).[44] In ancient Europe, entomophagy appears in the writings of Aristotle of Greece, Diodorus of Sicily, and Pliny the Elder of Rome. In addition, the Italian entomologist and naturalist Ulysse Aldovandi, considered to be the founder of the modern-day study of insects, noted that insects were important food items in ancient Far Eastern civilizations, namely China, as far back as several centuries BCE.[45]

**Figure 1: Recorded Edible Insect Species, By Country**




*Source: Jongema (2017)*

Today, edible insects are considered an environmental alternative to traditional livestock sources for various reasons. An examination of five edible insect species indicated significantly lower greenhouse gas (GHG) emissions—carbon dioxide, ammonia, and methane—than conventional livestock.[46] Insects are generally believed to be more efficient at converting feed into protein over conventional livestock; crickets, for example, need 12 times less feed than cattle and half as much feed as pigs and chickens to produce the same amount of protein.[47] In addition, insect rearing is not necessarily a land constrained activity; feed is the major requirement for land use, unlike the need for pasture space in conventional livestock. [48] Finally, some insects can be fed on organic waste streams, such as the black soldier fly (*Hermetia illucens*)[49] although the efficiency of feed conversion and survival rate within different insect species has been shown to vary substantially based on the nutritional quality of the diet.[50]

Edible insects may also offer health and economic benefits to local populations. Insects have high energy and protein content, meet amino acid requirements for humans, are high in polyunsaturated and monounsaturated fats, and rich in minerals, such as copper, iron, magnesium, and zinc.[51] Insects have comparative nutritional value to other livestock protein sources, such as chicken, pork, and beef.[52] Insect farming can be a low-capital/low-tech investment that offers flexible income to communities across geographic areas (urban v. rural) and demographic (women, landless, etc.). Finally, certain insects provide valuable products to humans, including silk from silkworms and honey from bees—when produced on a microscale, these products can provide valuable commodities and food sources to local communities.[53]

### 1.5 Entomophagy and Sericulture in China

China has a rich history of entomophagy. The cocoons of a wild species of silkworm (*Theophila religiosae*) were found within ruins dating between 2,000-2,500 years BCE in Shanxi

Province, China. Each cocoon had a large hole on it, indicating that the silkworm pupae may have been consumed as a food source.[54] Ancient Chinese recorded texts, such as Zhou Li (Rites of Zhou), Tian Guan (Book of Celestial Officials), and Nei Ze (Book of Rites), include reference to edible insect species as traditional foods, describing methods of procurement and preparation.[55, 56] The Chinese also used insects as a form of traditional medicine dating back almost 3,000 years.[57] In Li Shizen's Compendium of Materia Medica—one of the largest and most comprehensive books on Chinese medicine during the Ming Dynasty (1364-1644) in China—Li notes that silkworms (*Bombyx batryticatus*) were traditionally dried and consumed to clear toxins.[58]

Silkworms play an important part in China's history with entomophagy due to their central role in sericulture. According to legend, silkworms are believed to have been domesticated around 2500 BCE in China after the then wife of the Emperor accidentally dropped a silkworm cocoon into a warm glass of water, causing the delicate threads to unwind. The secrets of sericulture were closely guarded for the next 3,000 years, inspiring the famous Silk Road that connected China to Europe and the rest of Asia.[59] Although the secrets of Chinese silk eventually reached other countries in Asia and Europe, today China remains a powerhouse, producing around 170,000 metric tons of raw silk annually that account for nearly 85 percent of the global market.[60]

Sericulture in China has traditionally been dominated by many small-scale farms, due to the unique process and skills required to rear silkworms and extract silk. Before the 1990s, the sericulture commodity chain in China was largely inefficient. Unorganized individual silkworm farmers had limited connections to markets to sell their cocoons and faced fluctuating market conditions. The late 1990s lead to the privatization of silk companies in China under the slogan of “agricultural industrialization” and the emergence of “dragon-head” enterprises in China—leading agribusiness enterprises supported by the local, regional, and national governments to contribute to rural development.[61]

The emergence of “dragon-head” enterprises, such as Xinyuan Company, led to the development of silkworm cocoon purchasing contract with local farmers, ensuring certain levels cash income to farmers and motiving continued growth of the sericulture sector. Contract farming—defined by the FAO as an agreement between farmers and processing and/or marking firms for the production and supply of an agreed upon quantity of an agricultural product, usually at a set price—has emerged as an increasingly important part of sericulture in China.[62] Although each “dragon-head” enterprise within the silk industry may develop their own unique contracts with local farmers (some companies, for example, provide technical support for new farmers), silkworm farmers in China have benefited from greater economic security.[63]

One of the main byproducts of the sericulture process is silkworm pupae. It is estimated that 4000 to 6500 silkworm cocoons are required to produce 1 kg of silk.[64] China’s market share of the silk industry produces an estimated 1,360,000 metric tons of fresh (340,000 metric tons dried) silkworm pupae byproduct. Silkworm pupae has traditionally been used as fertilizer, animal feed, medicine, and food material in China.[65] However, as the sericulture industry has becoming increasingly industrialized and centralized, silkworm pupae are increasingly considered as a waste product.[66]

### 1.6 Nutritional Value of Silkworms

To assess the viability of silkworm pupae as an alternative protein source for human consumption or feed for pigs, a greater understanding of their nutritional value is needed in comparison to other insects and livestock products. Rumpold and Schlüter compared the nutritional compositions—including the amino acid spectra, fatty acid composition, and mineral and vitamin content—of 236 edible insects derived from hundreds of studies. They concluded that although there was variation among insect species, many edible insects provide satisfactory protein, amino acid, and micronutrients for human nutritional needs.[67] Specifically, the nutritional value of the silkworm (*Bombyx mori*) compares favorably with averages across the most commonly consumed insects including beetles (*Coleoptera*), caterpillars (*Lepidoptera*), bees, wasps and ants (*Hymenoptera*), and grasshoppers, locusts and crickets (*Orthoptera*)—representing over 75% insect of protein sources.[68]

In comparison to traditional livestock commodities, such as beef, pork, and chicken, silkworm pupae are close in protein content and provide a denser nutrient food source. As Tables 3 and 4 demonstrate, silkworm pupae are comparable in protein and essential amino acids with traditional livestock commodities and outperform these same livestock commodities in terms of micronutrient content. Specifically, silkworm pupae have nearly seven times the concentration of iron, triple the concentration of calcium, and double the concentration of magnesium over traditional livestock sources.

**Table 3: Comparison in essential amino acids composition among insect fresh weight (silkworm pupae) and common animal food stuffs fresh weight**

| Component (g/100 g) | Pupae | Beef meat | Pork meat | Chicken meat | RDA[a] |
|---|---|---|---|---|---|
| Protein g% | 15.8 | 21.35 | 21.30 | 19.40 | 0.66 g/kg/d |
| Aspartic acid | 1.54 | 2.07 | 1.13 | 1.91 | 2.20 mg/kg/d |
| Threonine | 0.75 | 0.87 | 0.94 | 0.95 | 11 mg/kg/d |
| Serine | 0.82 | 0.86 | 0.90 | 0.88 | |
| Glutamic acid | 2.03 | 3.61 | 3.26 | 2.85 | |
| Proline | 1.02 | 0.89 | 0.85 | 0.73 | |
| Glycine | 0.78 | 1.08 | 1.02 | 0.90 | |
| Alanine | 0.97 | 1.32 | 1.25 | 1.15 | |
| Cystine | 0.08 | 0.23 | 0.29 | 0.25 | |
| Valine | 0.84 | 1.02 | 1.21 | 1.04 | 15 mg/kg/d |
| Methionine | 0.36 | 0.61 | 0.59 | 0\|62 | 10 mg/kg/d |
| Isoleucine | 0.69 | 0.92 | 1.14 | 0.98 | 15 mg/kg/d |
| Leucine | 1.04 | 1.82 | 1.74 | 1.64 | 21 mg/kg/d |
| Phenylalanine | 0.82 | 0.86 | 0.83 | 0.82 | 21 mg/kg/d |
| Histidine | 0.42 | 0.82 | 0.82 | 0.69 | 15 mg/kg/d |
| Lysine | 1.03 | 1.94 | 1.80 | 1.79 | 18 mg/kg/d |
| Arginine | 0.69 | 1.30 | 1.33 | 1.34 | |

[a] Recommended daily allowances for adults.

*Source: Simone Belluco et al. (2013)*

**Table 4: Comparison in minerals composition among insect fresh weight (silkworm pupae) and common animal foodstuffs fresh weight**

| Component (mg/100 g) | Pupae | Beef meat | Pork meat | Chicken meat | RDA[a] |
|---|---|---|---|---|---|
| Phosphorus | 175 | 191.50 | 160.00 | nd | 1000 mg |
| Iron | 7.0 | 1.67 | 0.80 | nd | 10 mg |
| Calcium | 24.0 | 6.50 | 8.00 | 8.00 | 1000 mg |
| Zinc | 2.10 | 3.41 | 1.60 | 1.26 | 10 mg |
| Copper | 0.45 | 0.05 | 0.13 | 0.06 | 1.2 mg |
| Magnesium | 54.0 | 19.25 | 17.0 | 26.00 | nd |
| Manganese | 0.69 | nd | nd | nd | 1 mg |

[a] Recommended daily allowances for adults.

*Source: Simone Belluco et al. (2013)*

These results are comparable to studies that have analyzed other silkworm breeds, such as the eri silkworm (*Samia cynthia*).[69] Overall, the nutrient content of silkworm pupae is consistent with recommendations outlined by the World Health Organization (WHO) and could theoretically serve as an alternative dietary supplement of protein and amino acids for human or animal consumption.[70]

**1.7 Moving Forward: Silkworms as a Protein Source in Feed and Food**

The unique role of silkworms in Chinese history and culture is evident in the resurgence of edible insects in China. In 2013, the Chinese Ministry of Health added silkworm pupae among its novel food sources, boosting scientific interest around the topic.[71] In addition, the Chinese Government has invested in research around the feasibility and use of insect protein, specifically silkworms, in space travel as part of their space program.[72] As of 2009, there were 178 common species of edible insects identified and named in China, from 96 genera, 53 families, and 11 orders.[73] Lou Zhi-Yi of the Shanghai Institute of Entomology compiled an extensive table of edible insects, including regional consumption patterns, preparation, and collection methods (Appendix 1).[74] The silkworm may offer an opportunity for China to merge traditional knowledge and modern science to meet the food and nutrition challenges of today and the projected demands of tomorrow.

## 2.0 Methodology

A series of hypothetical scenarios are evaluated to compare two means by which silkworm pupae byproduct from the sericulture industry could be reused as a protein replacement to offset GHG emissions from the livestock sector in China. Scenario A examines the hypothetical reuse of silkworm pupae as a partial protein replacement in the average Chinese diet for the three major animal protein sources: beef, pork, and chicken. Scenario B examines the hypothetical use of silkworm pupae as a partial protein replacement in pig feed for soybean meal (SBM). The results of the two scenarios are compared to assess the most efficient use of silkworm pupae byproduct from the sericulture industry to mitigate GHG emissions from the livestock sector in China.

Greenhouse gas emissions (Mt CO2-eq) is the comparative unit of measurement to assess the potential GHG emission mitigation impact for both scenarios, dependent on the percentage of silkworm pupae usability. The silkworm pupae usability rate is defined as the percentage of silkworm pupae from the sericulture industry in China that is viable for protein replacement for human consumption and/or pig feed. The usability rate for silkworm pupae is important to both scenarios as the quality of silkworm pupae that can be used in animal feed or for direct human consumption may vary considerably. This in turn has impact on the hypothetical GHG mitigation potential.

## 2.1 Assumptions

The hypothetical scenarios reviewed are built on a series of underlining assumptions, as outlined in the following section.

### 2.1.1 Silkworm Pupae Emissions

It is assumed that the GHG emission intensity for silkworm pupae is zero for both scenarios. This is because the silkworm pupae considered in this study are not reared for the primary purpose of protein replacement, but are reused as a byproduct of the sericulture industry in China. The major GHG emissions from rearing and processing of the silkworm pupae are already being considered in the GHG emissions from the sericulture industry in China. Due to limitations in data, neither scenarios include GHG emissions that might result in additional processing and transport of silkworm pupae for use as a protein replacement in human diets and pig feed.

### 2.1.2 Available Silkworm Pupae Byproduct from the Sericulture Industry in China

The total available silkworm pupae available to substitute in both scenarios is calculated based on raw silk production in metric tons (Mt). A ratio is used to estimate the average fresh weight—and equivalent dried weight—silkworm pupae produced for each metric ton of raw silk. This ratio—8:1 for fresh and 2:1 for dried silkworm pupae—is used to estimate the total silkworm pupae byproduct from the sericulture industry in China.[75] Analysis is presented for both fresh and dried weight silkworm pupae, yielding variances in potential emission reductions for both scenarios.

### 2.1.3 Silkworm Pupae Substitution Ratio

It is assumed in both scenarios that silkworm pupae can be substituted in an equal ratio (1:1) to the alternative protein sources assessed. Silkworm pupae have been noted to include essential amino acids, constituting them as a complete protein source, as outlined in the introduction section of this study. Although the protein concentration may vary by protein source (i.e., beef may have a higher concentration of protein over silkworm pupae), but for this study it is assumed that one metric ton of pork, beef, or chicken is equal in protein value to one metric ton of silkworm pupae for human consumption, as well as one metric ton of soybean meal (SBM) being equal in protein value to one metric ton of silkworm pupae for pig feed.

**2.2 Scenario A: Silkworm Pupae Protein Substitution for Human Consumption**

Scenario A examines the hypothetical reuse of silkworm pupae as a partial protein replacement in the average Chinese diet for the three major animal protein sources: beef, pork, and chicken. GHG emission intensities for beef, pork, and chicken are measured as GHG emissions (Mt CO2-eq) per metric ton (Mt) carcass weight (CW). The Global Livestock Environment Assessment Model (GLEAM) developed by FAO provides the framework for GHG emissions and emission intensities for the main livestock commodities examined. GLEAM utilizes life cycle assessment (LCA) to identify the main emission sources—methane, nitrous oxide, and carbon dioxide—across the supply chain of livestock commodities (Appendix 2).

Pork emission intensity is based on average emission intensities across three production systems (backyard, intermediate, and industrial), as data discerning the percentage of pigs raised in China in each production system was not found in the literature examined for this study. Beef emission intensity is averaged using dairy cattle that produce milk and meat at the end of their life, as well as specialized cattle just reared for meat. The grouping of dairy and specialized cattle likely represents a conservative ratio of emissions per unit of beef consumed in China, but this estimate is used to ensure consistency across emission reporting for all the major livestock sector product assessed. Chicken emission intensity includes chickens that lay eggs and produce meat at the end of their life, as well as broiler chickens that are just reared for meat. GHG emission intensities for beef, pork, and chicken are summarized in Table 5.

**Table 5: Emission Intensities by Protein Source**

| Protein Source | GHG Emissions (Mt CO2-eq/Mt CW) |
|---|---|
| Pork | 6.1 |
| Beef | 46.2 |
| Chicken | 5.4 |

*Source: Gerber et al. (2013)*

Chinese domestic consumption totals for beef, pork, and chicken are measured in metric tons (Mt) of carcass weight (CW) and based on 2017 data from the United States Department of Agriculture (USDA).[76] Estimates derived from GLEAM are used to calculate estimated Chinese national GHG emissions from consumption of beef, pork, and chicken by consumption weight. As previously noted in this study, the total available silkworm pupae available to substitute is calculated based on raw silk production in China. Chinese domestic production of raw silk is measured in metric tons (Mt) and based on 2015 data from the International Sericultural Commission.[77] As previously noted, the assumed emissions from silkworm pupae is zero.

**2.3 Scenario B: Silkworm Pupae Protein Substitution for Soybean Meal in Pig Feed**

Scenario B examines the hypothetical use of silkworm pupae as a partial protein replacement for soybean meal (SBM) in Chinese pig feed. The average composition of pig feed was assessed to determine the average percentage of SBM present. Industrial feed typically has three components: energy (grains such as corn, barley, or wheat), protein (soybean meal or fishmeal) and pre-mix (micro-nutrients and additives, such as antibiotics). The ratio of energy, protein, and pre-mix varies by production system.[78] Data discerning the percentage of pigs raised in China in each production system was not found in the literature examined for this study. An industry average inclusion rate of 30% SBM is used (i.e., per 1 metric ton of feed, 0.30 metric ton is soybean meal and the remaining 0.70 metric is energy and pre-mix).[79]

The estimated GHG emission for SBM is measured as GHG emissions (Mt CO2-eq) per metric ton (Mt) dry mass (DM) SBM. For this study, a SBM emission ratio of 3.17 Mt CO2-eq per Mt DM is applied. This estimate is based on the GLEAM assessment by FAO. To estimate total emissions from the use of SBM in China as a baseline for comparison, USDA data (March 2017) on soybean meal production and consumption in China was assessed.[80] As in Scenario A, Chinese domestic production of raw silk is measured in metric tons (Mt) and based on 2015 data from the International Sericultural Commission.[81] As previously noted, the assumed emissions from silkworm pupae is zero.

**3.0 Results and Discussion**

The results from both Scenario A and B provide a hypothetical snapshot of the potential GHG emission mitigation that could be possible with the use of silkworm pupae as a protein substitute in China. The direct replacement of animal protein for silkworm pupae protein in China, as outlined in Scenario A, yielded the highest possible GHG emission mitigation potential. Specifically, a focused replacement of beef protein for silkworm pupae protein in China would yield the highest estimated GHG emission mitigation potential. As expected, the possible GHG emission mitigation potential for Scenario B was significantly lower because emissions from soybean meal (SBM) production in China are a fraction of emissions for pork, beef, or chicken production.

Despite the low mitigation potential, there is a point at which substituting silkworm pupae protein for SBM protein in pig feed in Scenario B could offset more GHG emissions than a pure 1:1 animal protein to silkworm pupae protein replacement as outlined in Scenario A. This variability is due to different usability rates assessed across both scenarios, and the results are outlined below. However, Scenario A will continue to provide the highest mitigation potential unless much of silkworm pupae from the sericulture industry is unusable for human consumption (i.e., due to contamination or quality concerns), but still largely viable for animal consumption.

### 3.1 Scenario A: Silkworm Pupae Protein Substitution for Human Consumption Results

The results from Scenario A indicated that the best use of silkworm pupae protein substitution would be allocated towards a reduction in beef consumption in China. Using consumption data from the USDA and average GHG emissions data derived from GLEAM, estimates for the annual GHG emissions for consumption of each main animal protein and the estimated mitigation potential via silkworm pupae protein substitution are outlined in Table 6. Although beef represents a fraction of total meat consumption in China compared to pork, the total emissions from beef are slightly higher than that of pork. This is worth highlighting as although the impacts of the pork industry have been noted previously in this study, the GHG emission intensity for beef is significantly higher so that even a small percentage of beef consumption will have a major impact on GHG emissions.

**Table 6: Scenario A Results (100% Usability Rate)**

| SWP Type | Livestock Product | Chinese Consumption (Mt CW/yr) | Estimated Emissions (Mt CO2-eq/yr) | Avail. SWP Byproduct (Mt) | Max % SWP Sub by Livestock Product | Estimated Emission Mitigation (Mt CO2-eq/yr) |
|---|---|---|---|---|---|---|
| **Fresh** | Pork | 54,070,000 | 329,827,000 | 1,360,000 | 2.52% | 8,296,000 |
| | Beef | 7,673,000 | 354,492,600 | 1,360,000 | 17.72% | 62,832,000 |
| | Chicken | 12,715,000 | 68,661,000 | 1,360,000 | 10.70% | 7,344,000 |
| **Dried** | Pork | 54,070,000 | 329,827,000 | 340,000 | 0.63% | 2,074,000 |
| | Beef | 7,673,000 | 354,492,600 | 340,000 | 4.43% | 15,708,000 |
| | Chicken | 12,715,000 | 68,661,000 | 340,000 | 2.67% | 1,836,000 |

*Source: USDA (2017) and Gerber et al (2013); author's calculations*

As indicated in Table 7, Chinese consumption of pork, beef, and chicken make up a substantial percentage of global consumption. Despite Chinese pork having a larger share of global production and consumption (50%) compared to beef (14.5%), the emission intensities of beef production resulted in total higher emissions for beef compared to pork. Combined, Chinese consumption resulted in an estimated 0.75 GtCO2-eq a year of GHG emissions, or 11% of the estimated 7.1 GtCO2-eq a year from global livestock industry.

**Table 7: Chinese Livestock Consumption in 2016**

| Livestock Product | Chinese Consumption (Mt CW/yr) | % of Global Consumption |
|---|---|---|
| Pork | 54,070,000 | 50% |
| Beef | 7,673,000 | 14.5% |
| Chicken | 12,715,000 | 13% |

*Source: USDA (2017)*

Insert Chart—Baseline (BAU) v. Mitigation

**3.1.1 Beef**

The mitigation potential for substituting silkworm pupae for beef consumption in China is dependent on the form of the silkworm pupae (fresh or dried mass) and the usability rate. Based on the data, it is hypothetically possible for fresh silkworm pupae to replace an estimated 18% of beef consumed in China, assuming a 100% usability rate of silkworm pupae. This protein substitution would mitigate an estimated 62,832,000 Mt CO2-eq a year of GHG emissions. For comparison, this is equal to the average emissions from over 18 coal-fired power plants or 13.2 million cars driven in one year.[82] If dried silkworm pupae were used instead—assuming the same usability rate of 100%—it would be enough to replace an estimated 4.4% of total beef consumption in China and mitigate an estimated 15,708,000 Mt CO2-eq a year of GHG emissions.

**3.1.2 Pork**

The mitigation potential for substituting silkworm pupae for pork consumption in China is also dependent on the form of the silkworm pupae (fresh or dried mass) and the usability rate. Based on the model, it is hypothetically possible for fresh silkworm pupae to replace an estimated 3% of pork consumed in China, assuming a 100% usability rate of silkworm pupae. This protein substitution would mitigate an estimated 8,296,000 Mt CO2-eq a year of GHG emissions. For comparison, this is equal to the average emissions from over 2 coal-fired power plants or 1.75 million cars driven in one year.[83] If dried silkworm pupae were used instead, it would be enough to replace about 1% of total pork consumption in China—mitigating an estimated 2,074,000 Mt CO2-eq a year of GHG emissions.

**3.1.3 Chicken**

The mitigation potential for substituting silkworm pupae for chicken consumption in China is dependent on the form of the silkworm pupae (fresh or dried mass) and usability rate as seen with beef and pork. Based on the model, it is hypothetically possible for fresh weight silkworm pupae to replace an estimated 11% of chicken consumed in China, assuming a 100% usability rate of silkworm pupae. This protein substitution would mitigate an estimated 7,344,000 Mt CO2-eq a year of GHG emissions. For comparison, this is equal to the average emissions from two coal-fired power plants or 1.5 million cars driven in one year.[84] If dried silkworm pupae were used instead, it would be enough to replace about 3% of total chicken consumption in China—mitigating an estimated 1,836,000 Mt CO2-eq a year of GHG emissions.

**3.2 Scenario B: Silkworm Pupae Protein Substitution for Soybean Meal in Pig Feed Results**

The results of Scenario B indicated that a partial replacement of silkworm pupae protein for SBM in pig feed would result in a modest offset of potential GHG emissions, as outlined in Table 8. As indicated previously in this study, Brazil and Argentina are responsible for a large share of the imports of soybeans used to make SBM to China, relating back to land-change emissions from soybean production. To calculate emissions for soybean meal, an average of 3.17 Mt CO2-eq/Mt soybean meal was used, per the GLEAM model developed by the FAO.

**Table 8: Scenario B Results (100% Usability Rate)**

| SWP Type | Chinese SBM Production (Mt) | Chinese SBM Consumption (Mt) | SBM Emissions by Consumption (Mt CO2-eq/yr) | Max % SWP Sub | Avail. SWP Byproduct (Mt) | Emission Mitigation (Mt CO2-eq/yr) |
|---|---|---|---|---|---|---|
| **Fresh** | 68,508,000 | 66,638,000 | 211,242,460 | 2.0% | 1,360,000 | 4,311,200 |
| **Dried** | 68,508,000 | 66,638,000 | 211,242,460 | 0.51% | 340,000 | 1,077,800 |

*Source: USDA (2017) and Gerber et al (2013); author's calculations*

The mitigation potential for substituting silkworm pupae for soybean meal in pig feed in China is varied and depends on the state of the silkworm pupae (fresh v dried mass) and usability rate, as seen in Scenario A. It is hypothetically possible for fresh weight silkworm pupae to replace an estimated 2% of soybean meal used in China, assuming a 100% usability rate of silkworm pupa. This protein substitution would mitigate an estimated 4,311,200 Mt CO2-eq a year of GHG emissions. For comparison, this is equal to the average emissions from just over 1 coal-fired power plant or over 900,000 cars driven in one year.[85] If dried silkworm pupae were used instead, it would be enough to replace about 0.5% of total soybean meal used in China for pig feed—mitigating an estimated 1,077,800 Mt CO2-eq a year of GHG emissions.

### 3.3 Comparing Scenarios A and B

The results of both Scenario A and B indicate that the use of silkworm pupae protein as a partial replacement of beef, pork, or chicken would yield a higher possible mitigation potential for GHG emissions than the use of silkworm pupae protein as a replacement for SBM. At comparable usability rates, the mitigation potential of Scenario A far outweighs that of Scenario B with the use of either fresh and dried weight silkworm pupae. Tables 9 and 10 highlight the impacts on potential emission mitigation with variation in usability rates. For example, there may be several factors—such as health concerns, differences in quality of raising the silkworms, processing the cocoons and subsequent silkworm pupae—that may impact the usability of silkworm pupae form the sericulture industry in China. For example, it may be that only 50% of the silkworm pupae collected form the sericulture industry in China is fit for human consumption, at which point the potential emission mitigation would be halved.

**Table 9: Scenario B Results for Fresh SWP**

| Usability Rate | Estimated Emission Mitigation (Mt CO2-eq/yr) | | |
|---|---|---|---|
| | Pork | Beef | Chicken |
| 100% | 8,296,000 | 62,832,000 | 7,344,000 |
| 95% | 7,881,200 | 59,690,400 | 6,976,800 |
| 90% | 7,466,400 | 56,548,800 | 6,609,600 |
| 85% | 7,051,600 | 53,407,200 | 6,242,400 |
| 80% | 6,636,800 | 50,265,600 | 5,875,200 |
| 75% | 6,222,000 | 47,124,000 | 5,508,000 |
| 70% | 5,807,200 | 43,982,400 | 5,140,800 |
| 65% | 5,392,400 | 40,840,800 | 4,773,600 |
| 60% | 4,977,600 | 37,699,200 | 4,406,400 |
| 55% | 4,562,800 | 34,557,600 | 4,039,200 |
| | 4,148,000 | 31,416,000 | 3,672,000 |

*Source: Gerber et al (2013); author's calculations*

**Table 10: Scenario B Results for Dried SWP**

| Usability Rate | Estimated Emission Mitigation (Mt CO2-eq/yr) | | |
|---|---|---|---|
| | Pork | Beef | Chicken |
| 100% | 2,074,000 | 15,708,000 | 1,836,000 |
| 95% | 1,970,300 | 14,922,600 | 1,744,200 |
| 90% | 1,866,600 | 14,137,200 | 1,652,400 |
| 85% | 1,762,900 | 13,351,800 | 1,560,600 |
| 80% | 1,659,200 | 12,566,400 | 1,468,800 |
| 75% | 1,555,500 | 11,781,000 | 1,377,000 |
| 70% | 1,451,800 | 10,995,600 | 1,285,200 |
| 65% | 1,348,100 | 10,210,200 | 1,193,400 |
| 60% | 1,244,400 | 9,424,800 | 1,101,600 |
| 55% | 1,140,700 | 8,639,400 | 1,009,800 |
| 50% | 1,037,000 | 7,854,000 | 918,000 |

*Source: Gerber et al (2013); author's calculations*

However, there is a point at which the differences between the usability rates of Scenarios A and B vary enough to impact total emission mitigations in such a way as to make silkworm pupa protein used as feed replacement more sustainable than human protein replacement. Specifically, the estimated emission mitigation of Scenario B for using silkworm pupae as a protein replacement for SBM in pig feed is 4,311,200 Mt CO2-eq per year at a 100% usability rate. As outlined in Table 11, the point at which Scenario B—potential emission mitigation of is 4,311,200 Mt CO2-eq per year— becomes more sustainable than Scenario A vary by animal protein source.

For pork, the usability rate for equilibrium between Scenarios A and B is around 55% for Scenario A and 100% for Scenario B—below this usability rate in Scenario A, and Scenario B has a higher mitigation potential. For chicken, the usability rate for equilibrium between Scenarios A and B is around 50% for Scenario A and 100% for Scenario B—below this usability in Scenario A, and Scenario B has a higher mitigation potential. Finally, for beef, this drops considerably—even at 7% usability rate of silkworm pupae for beef protein replacement, it is still more "sustainable" from a GHG mitigation perspective than using silkworm pupae as a protein supplement for feed at 90% recovery rate/usability. The usability rate needs to dip to around 5% for beef substitution for Scenario A to be less sustainable than Scenario B.

**Table 11: Scenario A: Emission Mitigation by Usability Rates**

| Usability Rate | Estimated Emission Mitigation (Mt CO2-eq/yr) | | |
|---|---|---|---|
| | Pork | Beef | Chicken |
| 55% | 4,562,800 | 34,557,600 | 4,039,200 |
| 50% | 4,148,000 | 31,416,000 | 3,672,000 |
| 45% | 3,733,200 | 28,274,400 | 3,304,800 |
| 40% | 3,318,400 | 25,132,800 | 2,937,600 |
| 35% | 2,903,600 | 21,991,200 | 2,570,400 |
| 30% | 2,488,800 | 18,849,600 | 2,203,200 |
| 25% | 2,074,000 | 15,708,000 | 1,836,000 |
| 20% | 1,659,200 | 12,566,400 | 1,468,800 |
| 15% | 1,244,400 | 9,424,800 | 1,101,600 |
| 10% | 829,600 | 6,283,200 | 734,400 |
| 5% | 414,800 | 3,141,600 | 367,200 |

*Source: USDA (2017) and Gerber et al (2013); author's calculations*

### 4.0 Risk Factors and Recommendations

The hypothetical scenarios presented in this study indication indicate that silkworm pupae could provide a source alternative protein and GHG mitigation across the livestock sector in China. However, there are several risks factors that must be considered and assessed before these hypothetical scenarios are explored further and potentially implemented in China. Specifically, these risks include possible microbiological and chemical exposure, allergens, and exposure from processing silkworm pupae from the sericulture industry. For each of these risks, suggested recommendations are outlined that may mitigate the potential impacts.

### 4.1 Microbiological and Chemical Risks

There are two primary bacterial risks in insects used for feed and for food—those that derive from the insect lifecycle and those that are introduced during the farming and/or processing of the insect. Insects have a unique biota that may contain microbial bacteria that could be passed on to animals or humans if not treated properly and consumed. As insects are processed with the contents of their guts usually intact, frass (insect waste) and other substrate is present and could contaminate the insect over time if not properly processed. The Scientific Committee of the European Food Safety Authority noted that "pathogenic bacteria (such as *Salmonella*, *Campylobacter* and verotoxigenic *E. coli*) may be present in non-processed insects depending on the substrate used and the rearing conditions."[86] Thus proper processing is critical with farmed insects used in feed or as food for human consumption to mitigate risk.

Insects raised for feed and/or food may carry viruses, but this risk is likely less than that of bacteria. According to the Scientific Committee of the European Food Safety Authority, "most viruses in insects are specific at the family or species level and are therefore only pathogenic for invertebrates and not for humans or other vertebrates such as farm animals and birds."[87] See Appendix 3 for more details. A recent study highlighted the extensive research that has been conducted on silkworm to assess potential pathogens, silkworm specific diseases, and the inheritance of disease resistance through breeding.[88] However, there remains clear gaps to assess the specific pathogens that may impact silkworms in the pupae stage and the possible risks to animals and/or humans through consumption.

In addition to bacterial and viral risks, there is also the risk of parasitic and fungal infection. The Scientific Committee of the European Food Safety Authority notes that the general risk of parasite being passed through human consumption is limited in the literature to insects harvested in the wild. There are no documented cases of parasitic infection being passed through consumption from farmed insects, but further study on the parasite that may target silkworms is needed. Insects may also be carriers of fungi and yeasts with potential hazards to animals and humans. A report commissioned by the Scientific Committee of the Federal Agency for the Safety of the Food Chain (FASFC) noted that "yeasts and fungi were found in considerable amounts in fresh, freeze-dried as well as in frozen insects (*T. molitor* and *L. migratoria*)."[89]

Finally, insect used for feed and/or may contain hazardous chemicals. Examples of these risks include heavy metals, polybrominated diphenyl ethers, mycotoxins and plant toxins.[90] Insects may also contain elevated levels of trace elements, such as selenium, which may accumulate in the insect from the feeding substrate. Other chemicals are likely to be used during rearing of insects, such as biocides to clean facilities and equipment or antibiotics to treat certain diseases.[91]

### 4.2 Recommendations to Mitigate Microbiological and Chemical Risks

Overall, further studies on the potential impact of specific silkworm bacterial, viral, parasitic, chemical, and fungal exposure for animal and/or human consumption is required. Clear processing guidelines, including but not limited to storage and hygienic measures throughout the supply chain, for silkworm pupae as a byproduct of the sericulture industry may significantly decrease the potential for exposure to these outlined risks. Further data need to be collected and assessed before silkworm pupae from the sericulture industry is converted as an alternative protein source for pig feed and/or mass human consumption.

### 4.3 Allergen Risks

Although there are no recorded allergens for animal consumption of insects or silkworms, there are cases of human allergic reactions due to silkworm pupae consumption. As of 2008, there had been thirteen recorded cases of severe anaphylactic reaction caused by silkworm pupae consumption in China—one of which was a French national. It is believed that materials derived from the bodies of the silkworm may contain allergens, including silk, that can trigger reactions. Individuals with an existing crustacean shellfish allergy may have allergic reactions upon consuming insects, including silkworm pupae, due to "the cross-reactivity between homologous proteins found in the different species."[92] Anaphylactic shock can lead to death in the absence of treatment and thus these risks should be treated seriously to avoid potential harm for consumers.

**4.4 Recommendations to Mitigate Allergen Risks**

To mitigate the potential risks of allergic reaction from the consumption of silkworm pupae, further studies need to be conducted that explores the cause of these documented reactions. Specifically, one clear gap is the need for labelling of potential allergens on products that may contain silkworm or another insect parts. Labeling is currently absent in China, and this measure may provide the proper warning to consumers and decrease the risk of exposure to serious anaphylactic shock in some cases.

**4.5 Processing Risks**

As noted previously in this study, the sericulture industry in China is predominately structured around micro-farming of silkworms for the curation of silk. Individual farmer or collectives under contracts with larger, "dragon-head" enterprises, sell cocoons in bulk. It is theoretically possible, given the current structure, for these "dragon-head" enterprises to play a critical role in converting the current silkworm pupae waste stream into an alternative protein source. However, there remain key knowledge gaps in the current processing and handling of silkworm pupae byproduct, as well as the proposed additional processing that would be necessary to convert this byproduct to a viable alternative protein source.

The process of extracting the silk fibers from the cocoon usually involves heat. This process—either through boiling or baking—loosens the fibers on the silkworm cocoon and kills the silkworm pupae inside the cocoon. This process is critical because if the silkworm pupae are allowed to fully transform into a silk moth, it will puncture the cocoon by releasing a liquid that degrades the cocoon and damages any viable silk fibers that could be extracted. The exact process of extracting the silk is not cited clearly in literature examined for this study. Datta notes that the cocoons can be boiled in hot water alone or boiled in water and a chemical compound that helps to further "loosen" the silk fibers.[93] This latter process could expose the silkworm pupae to these potentially harmful chemicals, which could be passed on to animals and/or humans during consumption.

**4.6 Recommendations to Mitigate Processing Risks**

Overall, further study is required to understand fully the supply chain of silk processing in China. Once the silkworms reach the pivotal point of harvesting for raw silk, it is unknown if the silkworm pupae are killed and the silk treated before being sold to "dragon-head" enterprises for harvesting, or if those enterprises do this process themselves. This is an important distinction because the silkworms once killed will begin to decompose rapidly unless processed/preserved, exposing them to potential bacterial and other risks which may be passed to consumers, as outlined above. However, as previously mentioned, clear guidelines on handling silkworm pupae byproduct—in terms of hygiene, processing, and storage—would make a tremendous difference and help to mitigate not only processing risks, but also health risks as outlined above.

**5.0 Conclusion**

This study has outlined the potential environmental impact that silkworm pupae protein substitution could have in China to offset GHG emissions from the livestock sector. The most efficient use of the silkworm pupae byproduct from the sericulture industry would be directed towards partially replacing a percentage of beef consumed in China. Although this study does not quantify the additional potential impacts on the environment, such as water and land savings, it is clear that a reduction in livestock consumption in China would yield more environmental benefits than simply a reduction in GHG emissions. These factors should be further explored to strengthen the case and incentive for the use of silkworm pupae byproduct as an alternative source of protein.

Assuming the risks outlined above can be further assessed  and mitigated and further assessed, it is the recommendation that silkworm pupae byproduct be further explored as a possible protein supplement in China. If this concept proves to be viable, the methods can be outsourced to other countries, such as India, where sericulture is an important and growing industry. Overall, the silkworm may offer an opportunity for China to merge traditional knowledge and modern science to meet the food and nutrition challenges of today and the projected demands of tomorrow in a sustainable way.

## 6.0 Appendixes

### 6.1 Appendix 1: Food Insects in China

| Insect | Region | Preparation | Collection |
|---|---|---|---|
| Locusts (Acrididae) | Most of China | Dried in sun and made into porridge or cake; fried with viscera, head and limbs removed | Collected from the wild with graminale |
| Pupae of silkworm (*Bombyx mori*) | Jiangsu and Zhejiang | Deep-fried in oil, or the dry body stir-fried with chives | Obtained from silk reeling factories |
| Wasps (*Vespa spp.*) | Most of China | Parched or canned | Collected from nests in trees, tree caves, and under mud |
| Sphinx larvae (*Sphinx spp.*) | Shangdong, Henan, Hebei, Anhwei and Jiangsun | Parched after soaking in salty water and cooked with noodles | Collected from soybean fields |
| Termites (Isoptera) | Yunnan, Guangxi, Guangdong and Fujian | Parched | Collected from timbers and from nests under ground |
| Larvae of fly (Muscidae) | South Yangtse river area | Cleaned and made into 'Ba Zhen Cake' with rice powder | Culled from runnels near manure pits |
| Cordyceps (parasitic fungus on Hepialidae caterpillars) | Yunnan, Szechuan, Tibet | Stewed with chicken, used as tonic | Found under grass roots in high mountains |
| Litchi bug (*Tessaratoma papillosa*) | Guangxi, Guangdong, Fujian | Head, wings, legs and viscera are removed, body salted and wrapped into cabbage leaves, then instantly cooked in hot ash | Found on litchi and longan trees |
| True water beetle (Dytiscidae) | Guangxi and Guangdong | Soaked in salty water and dried. Legs and wings removed. | Collected from water fields, and pools |
| Mole cricket (Gryllotalpidae) | Guangxi and Guangdong | Limbs and viscera are removed | Collected from fertile arable lands |
| Belostoma (Belostomatidae) | Guangdong | Soaked in salty water and dried. Legs and wings removed. | Collected from water fields and pools |
| Bamboo weevil larvae (Curculionidae) | Guangxi and Szechuan | Imago: head, wings, legs and viscera removed, soaked into condiment and parched on ash. Larvae: stir-fried with condiment | Collected from bamboo forests |

| Insect | Region | Preparation | Collection |
| --- | --- | --- | --- |
| Larvae of chafer (Scarabaeidae) | All China | Head, legs and viscera are removed, then stir-fried with oil and salt | Collected from dry land and manure piles of poultry |
| Larvae of Ephemeridae | All China | boiled | Collected from streams and pools |
| Cricket (Gryllidae) | China | Chained with steel thread, baked with sauce and sugar. | Collected from caves near fields, from bean and vegetable fields, and under stones in grassfields. |
| Larvae of Cerambycidae | Szechuan, Hunan, and Northeast China | Eaten raw or parched | Collected from tree stems |
| Larvae of bag worm (Psychidae) | Jiangsu, Shangdong | Parched or made into marmalade and sauce | Collected from forests and fruit gardens |
| Larvae of pink bollworm | Jiangsu, Shangdong | Pressed for oil; or eaten parched | Found in cotton storages |
| Chafer (Scarabaeidae) | Jiangsu | Parched and ground into powder | Collected from forests and fruit garden |
| Blattaria | Guangdong | Cooked | Closet |

*Source: Lou Zhi-Yi (1997)*

## 6.2 Appendix 2: Sources of GHG Emissions Considered in GLEAM Assessment

**TABLE 1.** Sources of GHG emissions considered in this assessment

| Supply chain | Activity | GHG | Included | Excluded |
|---|---|---|---|---|
| UPSTREAM | Feed production | $N_2O$ | Direct and indirect $N_2O$ from:<br>• Application of synthetic N<br>• Application of manure<br>• Direct deposition of manure by grazing and scavenging animals<br>• Crop residue management | • $N_2O$ losses related to changes in C stocks<br>• Biomass burning<br>• Biological fixation<br>• Emissions from non-N fertilizers and lime |
| | | $CO_2$<br>$N_2O$<br>$CH_4$ | • Energy use in field operations<br>• Energy use in feed transport and processing<br>• Fertilizer manufacture<br>• Feed blending<br>• Production of non-crop feedstuff (fishmeal, lime and synthetic amino acids)<br>• $CH_4$ from flooded rice cultivation<br>• Land-use change related to soybean cultivation | • Changes in carbon stocks from land use under constant management practices |
| | Non-feed production | $CO_2$ | • Embedded energy related to manufacture of on-farm buildings and equipment | • Production of cleaning agents, antibiotics and pharmaceuticals |
| ANIMAL PRODUTION UNIT | Livestock production | $CH_4$ | • Enteric fermentation<br>• Manure management | |
| | | $N_2O$ | • Direct and indirect $N_2O$ from manure management | |
| | | $CO_2$ | • Direct on-farm energy use for livestock (e.g. cooling, ventilation and heating) | |
| DOWNSTREAM | Post farmgate | $CO_2$<br>$CH_4$<br>HFCs | • Transport of live animals and products to slaughter and processing plant<br>• Transport of processed products to retail point<br>• Refrigeration during transport and processing<br>• Primary processing of meat into carcasses or meat cuts and eggs<br>• Manufacture of packaging | • On-site waste water treatment<br>• Emissions from animal waste or avoided emissions from on-site energy generation from waste<br>• Emissions related to slaughter by-products (e.g. rendering material, offal, hides and skin)<br>• Retail and post-retail energy use<br>• Waste disposal at retail and post-retail stages[1] |

[1] Food losses are not included.
*Source:* Authors.

*Source: Gerber et al (2013)*

### 6.3 Appendix 3: Viruses Infecting Insects and Presence of Vertebrate Relatives

| | Genetic information | | | | | Vertebrate relatives | Comments |
|---|---|---|---|---|---|---|---|
| | dsDNA | ssDNA | ssRNA(-) | ssRNA(+) | dsRNA | | |
| **Poxviruses** | **x** | | | | | **x** | rare in caterpillars |
| Ascoviruses | x | | | | | | frequent in caterpillars |
| Asfarviruses | x | | | | | x | rare case |
| Baculoviruses | x | | | | | | common in caterpillars |
| Bracovirus | x | | | | | | common in wasps |
| Herpesviruses | x | | | | | | rare case |
| Ichnoviruses | x | | | | | | common in wasps |
| **Iridoviruses** | **x** | | | | | **x** | common in insects/ only in fish |
| **Parvoviruses** | | **x** | | | | **x** | in crickets |
| Bunyaviruses | | | x | | | x | arbovirus |
| Orthomyxoviruses | | | x | | | x | rare cases |
| Rhabdoviruses | | | x | | | x | mainly in aphids |
| **Dicistroviruses*** | | | | **x** | | **x** | in all insect species |
| Flaviviruses | | | | x | | x | arbovirus/ mosquito and tick |
| **Iflaviruses*** | | | | **x** | | **x** | in all insect species |
| Nodaviruses | | | | x | | x | only in fish |
| Tetraviruses | | | | x | | | rare in caterpillars |
| Togaviruses | | | | x | | x | arbovirus/ mosquito and tick |
| **Reoviruses** | | | | | **x** | **x** | unique genus in caterpillars |

Notes: Virus data from King et al., 2012; *picorna-like; bold/shaded: in species related to farmed insects.

*Source: ESFA Scientific Committee (2015)*

**7.0 Work Cited**

Bailey, Rob, Antony Froggatt, and Laura Wellesley. "Livestock – Climate Change's Forgotten Sector." London: Chatham House, 2014.

Belluco, Simone, Carmen Losasso, Michela Maggioletti, Cristiana C. Alonzi, Maurizio G. Paoletti, and Antonia Ricci. "Edible Insects in a Food Safety and Nutritional Perspective: A Critical Review." Comprehensive Reviews in Food Science and Food Safety 12, no. 3 (2013): 296-313.

Brown-Lima, Carrie, Melissa Cooney, and David Cleary. "An Overview of the Brazil-China Soybean Trade and Its Strategic Implications for Conservation." Arlington: The Nature Conservancy, 2010.

Chen, Fang, Jianwei Lu, Mingchu Zhang, Kaiyuan Wan, and Dongbi Liu. "Mulberry Nutrient Management for Silk Production in Hubei Province of China." Journal of Plant Nutrition and Soil Science 172, no. 2 (2009): 245-53.

d'Errico, F., L.R. Blackwell, and L.R. Berger. "Bone Tool Use in Termite Foraging by Early Hominids and Its Impact on Our Understanding of Early Hominid Behavior." South African Journal of Science 97, no. 3-4 (2001): 71-75.

Datta, R. K., and Mahesh Nanavaty. Global Silk Industry: A Complete Source Book. 1 ed. New Delhi: APH Publishing Corporation, 2012.

Dennis G. A. B. Ooninxc, Joost van Itterbeeck, Marcel J. W. Heetkamp, Henry van den Brand, Joop J. A. van Loon, Arnold van Huis. "An Exploration on Greenhouse Gas and Ammonia Production by Insect Species Suitable for Animal or Human Consumption." PLoS ONE 5, no. 12 (2010): 1-7.

Downs, M., P. Johnson, and M. Zeece. "Insects and Their Connection to Food Allergy." In Insects as Sustainable Food Ingredients, 255-72. Cambridge: Academic Press, 2016.

Economist. "Empire of the Pig." The Economist (2014). Published electronically December 17, 2014. http://www.economist.com/news/christmas-specials/21636507-chinas-insatiable-appetite-pork-symbol-countrys-rise-it-also.

EFSA Scientific Committee. "Scientific Opinion on a Risk Profile Related to Production and Consumption of Insects as Food and Feed." EFSA Journal 13, no. 10 (2015).

Environmental Protection Agency. "Overview of Greenhouse Gases." https://www3.epa.gov/climatechange/ghgemissions/gases.html.

Feng, Ying, Min Zhao, Zhao He, Zhiyong Chen, and Long Sun. "Research and Utilization of Medicinal Insects in China." Entomological Research 39, no. 5 (2009): 313-16.

Gerber, P.J., H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, and G. Tempio. "Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities." Rome: Food and Agriculture Organization of the United Nations (FAO), 2013.

Guo-Ping, Kang, and Guo Zi-Jie. "Overview of Silkworm Pathology in China." African Journal of Biotechnology 10, no. 79 (2011): 18046-56.

Han, Siqi. Environmental Impacts of China's Pork Industry, China Environment Forum. Washington, D.C.: The Wilson Center, 2014.

Hisano, Hui Ni; Shuki. "Development of Contract Farming in Chinese Sericulture and the Silk Industry." In The Political Economy of Agro-Food Markets in China, edited by Louis Augustin-Jean; Bjorn Alpermann. New York, NY: St. Martin's Press, 2014.

Huis, Arnold van, Joost Van Itterbeeck, Harmke Klunder, Esther Mertens, Afton Halloran,

Giulia Muir, and Paul Vantomme. "Edible Insects: Future Prospects for Food and Feed Security." Rome, Italy: Food and Agricultural Organization of the United Nations, 2013.
International Sericultural Commission. "Global Silk Industry Statistics." http://inserco.org/en/?q=statistics.
Jiang, Suwei, and Richard Ferguson. "China's Agricultural Challenges: Roads to Be Travelled." London: PricewaterhouseCoopers LLP, 2015.
Jongema, Yde. "List of Edible Insects of the World." Wageningen University, http://www.wur.nl/en/Expertise-Services/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm.
Li, Shizhen. "Compendium of Materia Medica: Bencao Gangmu." edited by Xiwen Luo. Beijing: Foreign Languages Press, 2003.
Lokeshwari, R. K., and T. Shantibala. "A Review on the Fascinating World of Insect Resources: Reason for Thoughts." Psyche 2010 (2010).
Longvah, T., K. Mangthya, and P. Ramulu. "Nutrient Composition and Protein Quality Evaluation of Eri Silkworm (Samia Ricinii) Prepupae and Pupae." Food Chemistry 128, no. 2 (2011): 400-03.
Lundy, Mark E., Michael P. Parrella, and Gotthard Kunze. "Crickets Are Not a Free Lunch: Protein Capture from Scalable Organic Side-Streams Via High-Density Populations of Acheta Domesticus." PLoS ONE 10, no. 4 (2015).
MacLeod, M., P. Gerber, A. Mottet, G. Tempio, A. Falcucci, C. Opio, T. Vellinga, B. Henderson, and H. Steinfeld. "Greenhouse Gas Emissions from Pig and Chicken Supply Chains: A Global Life Cycle Assessment." Rome, 2013.
Noroozi, B., S.H. Bahrami, and M. Arami. "Use of Silk Industry Waste – Silkworm Pupa: A Remediation of Environmental Pollution." In Survival and Sustainability: Environmental Concerns in the 21st Century. Berlin: Springer Berlin Heidelberg, 2011.
Patil, Sarvamangala R., S. Amena, A. Vikas, P. Rahul, K. Jagadeesh, and K. Praveen. "Utilization of Silkworm Litter and Pupal Waste-an Eco-Friendly Approach for Mass Production of Bacillus Thuringiensis." Bioresource Technology 131 (2013): 545-47.
Pultrone, Caterina, Carlos A. da Silva, and Andrew Shepherd. "Guiding Principles for Responsible Contract Farming Operations." Rome: United Nations Food and Agricultural Organization, 2012.
Rumpold, Birgit A., and Oliver K. Schlüter. "Nutritional Composition and Safety Aspects of Edible Insects." 802-23, 2013.
Schneider, Mindi, and Shefali Sharma. "China's Pork Miracle? Agribusiness and Development in China's Pork Industry." In Global Meat Complex: The China Series. Washington D.C.: Institute for Agriculture and Trade Policy.
Shao, Yongyu. "Current State of China's National New-Type Urbanization Construction and Deployment of New Reinforcement Measures." Shanghai: Mizuho Bank, 2016.
Sharma, Shefali. "The Need for Feed: China's Demand for Industrialized Meat and Its Impacts." In Global Meat Complex: The China Series. Minneapolis, 2014.
"Silkworm." In Encyclopedia of Entomology, edited by John L. Capinera. London, 2008.
United States Department of Agriculture. "Global Meat Consumption Generally Increases with Higher Incomes." https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=76868.
United States Department of Agriculture. "Oilseeds: World Markets and Trade." Washington, D.C., 2017.

United States Department of Agriculture. "Livestock and Poultry: World Markets and Trade." Washington, D.C., 2017.

United States Environmental Protection Agency. "Greenhouse Gas Equivalencies Calculator." https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.

United Nations Department of Economic and Social Affairs. "World Population Prospects: The 2015 Revision." New York: United Nations, 2015.

Wellesley, Laura, Catherine Happer, and Antony Froggatt. "Changing Climate, Changing Diets: Pathways to Lower Meat Consumption." London: Chatham House, 2015.

World Food Programme. "10 Facts About Nutrition in China." World Food Programme, http://www.wfp.org/stories/10-facts-about-nutrition-china.

Xiaoming Chen, Ying Feng, Zhiyong Chen. "Common Edible Insects and Their Utilization in China." Entomological Research 39 (2009): 299-303.

Yang, Yunan, Liman Tang, Ling Tong, and Hong Liu. "Silkworms Culture as a Source of Protein for Humans in Space." Advances in Space Research 43, no. 8 (2009): 1236-42.

Zhi-Yi, Luo. "Insects as Food in China." Ecology of Food and Nutrition 36, no. 2-4 (1997): 201-07.

Zhou, Jun, and Dingxian Han. "Proximate, Amino Acid and Mineral Composition of Pupae of the Silkworm Antheraea Pernyi in China." Journal of Food Composition and Analysis 19, no. 8 (2006): 850-53.

Zhou, Zhangyue, Weiming Tian, Hongbo Liu, and Lijuan Cao. "Food Consumption Trends in China." Queensland: Australian Agriculture, Fisheries and Forestry Department, 2012.

**8.0 Endnotes**

[1] World Food Programme, "10 Facts About Nutrition in China," World Food Programme, http://www.wfp.org/stories/10-facts-about-nutrition-china.
[2] Laura Wellesley, Catherine Happer, and Antony Froggatt, "Changing Climate, Changing Diets: Pathways to Lower Meat Consumption," (London: Chatham House, 2015).
[3] Rob Bailey, Antony Froggatt, and Laura Wellesley, "Livestock – Climate Change's Forgotten Sector," (London: Chatham House, 2014).
[4] United Nations Department of Economic and Social Affairs, "World Population Prospects: The 2015 Revision," (New York: United Nations, 2015).
[5] Bailey, Froggatt, and Wellesley.
[6] Wellesley, Happer, and Froggatt.
[7] Bailey, Froggatt, and Wellesley.
[8] World Food Programme.
[9] Arnold van Huis et al., "Edible Insects: Future Prospects for Food and Feed Security," (Rome, Italy: Food and Agricultral Organization of the United Nations, 2013).
[10] Luo Zhi-Yi, "Insects as Food in China," *Ecology of Food and Nutrition* 36, no. 2-4 (1997).
[11] International Sericultural Commission, "Global Silk Industry Statistics," http://inserco.org/en/?q=statistics.
[12] Wellesley, Happer, and Froggatt.
[13] P.J. Gerber et al., "Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities," (Rome: Food and Agriculture Organizaton of the United Nations (FAO), 2013).
[14] Ibid.
[15] Enviromental Protection Agency, "Overview of Greenhouse Gases," https://www3.epa.gov/climatechange/ghgemissions/gases.html.
[16] Gerber et al.
[17] Ibid.
[18] Ibid.
[19] Bailey, Froggatt, and Wellesley.
[20] United Nations Department of Economic and Social Affairs.
[21] Wellesley, Happer, and Froggatt.
[22] United States Department of Agriculture, "Global Meat Consumption Generally Increases with Higher Incomes," http://www.ers.usda.gov/data-products/chart-gallery/detail.aspx?chartId=39393.
[23] Bailey, Froggatt, and Wellesley.
[24] Mindi Schneider and Shefali Sharma, "China's Pork Miracle? Agribusiness and Development in China's Pork Industry," in *Global Meat Complex: The China Series* (Washington D.C.: Institute for Agriculture and Trade Policy).
[25] Ibid.
[26] Wellesley, Happer, and Froggatt.
[27] Schneider and Sharma.
[28] Ibid.

[29] Zhangyue Zhou et al., "Food Consumption Trends in China," (Queensland: Australian Agriculture, Fisheries and Forestry Department, 2012).
[30] Yongyu Shao, "Current State of China's National New-Type Urbanization Construction and Deployment of New Reinforcement Measures," (Shanghai: Mizuho Bank, 2016).
[31] Suwei Jiang and Richard Ferguson, "China's Agricultural Challenges: Roads to Be Travelled," (London: PricewaterhouseCoopers LLP, 2015).
[32] Schneider and Sharma.
[33] Ibid.
[34] The Economist, "Empire of the Pig," *The Economist* (2014), http://www.economist.com/news/christmas-specials/21636507-chinas-insatiable-appetite-pork-symbol-countrys-rise-it-also.
[35] Carrie Brown-Lima, Melissa Cooney, and David Cleary, "An Overview of the Brazil-China Soybean Trade and Its Strategic Implications for Conservation," (Arlington: The Nature Conservancy, 2010).
[36] Ibid.
[37] Schneider and Sharma.
[38] Siqi Han, *Environmental Impacts of China's Pork Industry*, *China Environment Forum* (Washington, D.C.: The Wilson Center, 2014).
[39] Huis et al.
[40] Ibid.
[41] Yde Jongema, "List of Edible Insects of the World," Wageningen University http://www.wur.nl/en/Expertise-Services/Chair-groups/Plant-Sciences/Laboratory-of-Entomology/Edible-insects/Worldwide-species-list.htm.
[42] Huis et al.
[43] F. d'Errico, L.R. Blackwell, and L.R. Berger, "Bone Tool Use in Termite Foraging by Early Hominids and Its Impact on Our Understanding of Early Hominid Behaviour," *South African Journal of Science* 97, no. 3-4 (2001).
[44] Huis et al.
[45] Ibid.
[46] Joost van Itterbeeck Dennis G. A. B. Ooninxc, Marcel J. W. Heetkamp, Henry van den Brand, Joop J. A. van Loon, Arnold van Huis, "An Exploration on Greenhouse Gas and Ammonia Production by Insect Species Suitable for Animal or Human Consumption," *PLoS ONE* 5, no. 12 (2010).
[47] Ibid.
[48] Huis et al.
[49] Dennis G. A. B. Ooninxc.
[50] Mark E. Lundy, Michael P. Parrella, and Gotthard Kunze, "Crickets Are Not a Free Lunch: Protein Capture from Scalable Organic Side-Streams Via High-Density Populations of Acheta Domesticus," ibid.10, no. 4 (2015).
[51] Birgit A. Rumpold and Oliver K. Schlüter, "Nutritional Composition and Safety Aspects of Edible Insects," (2013).
[52] Huis et al.
[53] Ibid.
[54] "Silkworm," in *Encyclopedia of Entomology*, ed. John L. Capinera (London2008).
[55] Ying Feng Xiaoming Chen, Zhiyong Chen, "Common Edible Insects and Their Utilization in China," *Enthmological Research* 39 (2009).

[56] Zhi-Yi.
[57] Ying Feng et al., "Research and Utilization of Medicinal Insects in China," *Entomological Research* 39, no. 5 (2009).
[58] Shizhen Li, "Compendium of Materia Medica: Bencao Gangmu," ed. Xiwen Luo (Beijing: Foriegn Languages Press, 2003).
[59] R. K. Datta and Mahesh Nanavaty, *Global Silk Industry: A Complete Source Book*, 1 ed. (New Delhi: APH Publishing Corporation, 2012).
[60] Commission.
[61] Hui Ni; Shuki Hisano, "Development of Contract Farming in Chinese Sericulture and the Silk Industry," in *The Political Economy of Agro-Food Markets in China*, ed. Louis Augustin-Jean; Bjorn Alpermann (New York, NY: St. Martin's Press, 2014).
[62] Caterina Pultrone, Carlos A. da Silva, and Andrew Shepherd, "Guiding Principles for Responsible Contract Farming Operations," (Rome: United Nations Food and Agricultural Organization, 2012).
[63] Hisano.
[64] Fang Chen et al., "Mulberry Nutrient Management for Silk Production in Hubei Province of China," *Journal of Plant Nutrition and Soil Science* 172, no. 2 (2009).
[65] R. K. Lokeshwari and T. Shantibala, "A Review on the Fascinating World of Insect Resources: Reason for Thoughts," *Psyche* 2010 (2010).
[66] B. Noroozi, S.H. Bahrami, and M. Arami, "Use of Silk Industry Waste – Silkworm Pupa: A Remediation of Environmental Pollution," in *Survival and Sustainability: Environmental Concerns in the 21st Century* (Berlin: Springer Berlin Heidelberg, 2011).
[67] Rumpold and Schlüter.
[68] Huis et al.
[69] Jun Zhou and Dingxian Han, "Proximate, Amino Acid and Mineral Composition of Pupae of the Silkworm Antheraea Pernyi in China," *Journal of Food Composition and Analysis* 19, no. 8 (2006).
[70] T. Longvah, K. Mangthya, and P. Ramulu, "Nutrient Composition and Protein Quality Evaluation of Eri Silkworm (Samia Ricinii) Prepupae and Pupae," *Food Chemistry* 128, no. 2 (2011).
[71] Simone Belluco et al., "Edible Insects in a Food Safety and Nutritional Perspective: A Critical Review," *Comprehensive Reviews in Food Science and Food Safety* 12, no. 3 (2013).
[72] Yunan Yang et al., "Silkworms Culture as a Source of Protein for Humans in Space," *Advances in Space Research* 43, no. 8 (2009).
[73] Xiaoming Chen.
[74] Zhi-Yi.
[75] Sarvamangala R. Patil et al., "Utilization of Silkworm Litter and Pupal Waste-an Eco-Friendly Approach for Mass Production of Bacillus Thuringiensis," *Bioresource Technology* 131 (2013).
[76] United States Department of Agriculture, "Livestock and Poultry: World Markets and Trade," (Washington, D.C. 2017).
[77] Commission.
[78] Shefali Sharma, "The Need for Feed: China's Demand for Industrialized Meat and Its Impacts," in *Global Meat Complex: The China Series* (Minneapolis2014).
[79] M. MacLeod et al., "Greenhouse Gas Emissions from Pig and Chicken Supply Chains: A Global Life Cycle Assessment," (Rome2013).

---

[80] United States Department of Agriculture, "Oilseeds: World Markets and Trade," (Washington, D.C. 2017).
[81] Commission.
[82] United States Environmental Protection Agency, "Greenhouse Gas Equivalencies Calculator," https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator.
[83] Ibid.
[84] Ibid.
[85] Ibid.
[86] EFSA Scientific Committee, "Scientific Opinion on a Risk Profile Related to Production and Consumption of Insects as Food and Feed," *EFSA Journal* 13, no. 10 (2015).
[87] Ibid.
[88] Kang Guo-Ping and Guo Zi-Jie, "Overview of Silkworm Pathology in China," *African Journal of Biotechnology* 10, no. 79 (2011).
[89] http://www.afsca.be/scientificcommittee/opinions/2014/_documents/Advice14-2014_ENG_DOSSIER2014-04.pdf
[90] Committee.
[91] Ibid.
[92] M. Downs, P. Johnson, and M. Zeece, "Insects and Their Connection to Food Allergy," in *Insects as Sustainable Food Ingredients* (Cambridge: Academic Press 2016).
[93] Datta and Nanavaty.