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Exploiting a pest insect species *Sphenarium purpurascens* for human consumption: ecological, social, and economic repercussions

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RESEARCH ARTICLE

Abstract

Insect species, especially those considered to be pests, can be exploited for human consumption. One of the most devastating pest insect species in central Mexico is the grasshopper *Sphenarium purpurascens*. Here we develop a sustainable exploitation strategy that produces a considerable biomass of *S. purpurascens* while minimising the damage they cause to agricultural fields by changing the chemical control methods to a mechanical method. In this model the biomass-per-stage of grasshoppers that can be extracted annually using the mechanical method was calculated and their potential abundance was estimated using Maxent. With a calculated population density of 10-55 individuals of *S. purpurascens* per m^2 over approximately 1,050,000 ha of the agroecosystems in Mexico, the estimated biomass of this insect averaged 350,000 tons per year (generating a gross income of US$ 3.5×10^8 million). Unlike chemical control methods, mechanical control has no toxic effects on human populations or other species inside or outside of the agroecosystems. Promoting a change from chemical to mechanical control methods of pest species could greatly impact on the health of millions of people globally and on the environment, reducing carbon dioxide and methane emissions, land clearing and the use of pesticides while obtaining economic profit.

Keywords: grasshopper, human diet, sustainable model, Mexico, Maxent, protein

1. Introduction

Insects have been part of the diet of some cultures for thousands of years (Bodenheimer, 1951; Yen, 2009). The estimated number of insect species consumed in the world varies, between 1,000 (Cerritos, 2011; De Foliart, 1995; Morris, 2008) and 2,000 species (Jongema, 2014) and several of them are considered as pest species. Many insect species have been exploited in agroecosystems in informal ways. For example, in America, no governmental or private programs for the exploitation of insect species exist at present (Cerritos, 2009). However, in Thailand a program to harvest the Bombay locust for human consumption is already underway (Hanboonsong, 2010). More than 20 Orthoptera species which cause great damage to crops in Latin America and Africa are used for human consumption (Cerritos, 2011). In Mexico, the grasshopper *Sphenarium purpurascens* is one of the most devastating species for corn, bean, pumpkin, and alfalfa crops in central and southern parts of the country (Cerritos, 2002). This species has been exploited for human consumption since prehispanic times, being the most widely consumed in the country and one of the most important worldwide (Cerritos, 2011; De Sahagún, 2006). Many prehispanic cultures did not consider grasshoppers to be a harmful species for crops. On the contrary, grasshoppers were regarded as a valuable nutritional resource.

Many edible insect species have been shown to have high nutritional value (Bodenheimer, 1951; De Foliart, 1992; Oonincx and De Boer, 2012; Ramos-Elorduy, 1987, 1997). In fact, the amount and quality of protein contained in individuals of these species is of a higher dietary value than any type of conventional cattle meat (Cerritos, 2011). In addition, these proteins are highly digestible and the richness of vitamins and minerals make insects excellent candidates for exploitation as a component of human diet (Ramos-Elorduy *et al.*, 1982). For example, *S. purpurascens* has an approximate 50% weight/protein ratio in dry weight, regardless of its developmental stage (Cerritos, 2011). From an environmental point of view, it seems that the production of insect biomass for human consumption is more profitable when compared to conventional cattle. Conventional cattle needs to consume, on average, ten times more matter than insects do in order to produce the same biomass (Begon *et al.*, 2006) and the differences in land required and carbon dioxide (CO_2) and methane (CH_4) production are of the same order of magnitude (Oonincx and De Boer, 2012; Oonincx *et al.*, 2010).

Each year orthopteran pests cause enormous damage to agriculture worldwide, leading to significant economic losses and, more importantly, decreasing the production of basic food sources for humans (Hewitt and Onsager, 1983; National Grasshopper Management Board, 1995; Pfadt and Hardy, 1987; http://www.fao.org/newsroom). The Food and Agriculture Organization of the United Nations (FAO) has calculated that in Africa approximately US$ 2.5 billion and hundreds of thousands of tons of basic grains are lost every year due to *Schistocerca gregaria* only (http://www.fao.org/newsroom). Approximately US$ 400 million is invested in measures to control this locust species. Currently, Orthoptera are mainly controlled with insecticides (Lomer *et al.*, 1999; Steedman, 1990). However, the results are often unsatisfactory and in many cases there are reports of re-emergence with higher population densities (Dempster, 1975; Georghiou, 1990). Previous research has proposed that mechanical control methods, such as hand-picking or using nets or other tools capable of selectively capturing unwanted insects, could be a better method of decreasing population sizes in agroecosystems (Lockwood, 1998; Van Huis, 1996). Such methods would have the additional benefits that: (1) extracted insects could potentially be used for human consumption or for feeding cattle; (2) they do not induce resistance to insecticides; (3) they do not contaminate soil, water and human populations; and (4) they do not have negatives consequences for non-target species (Cerritos and Cano-Santana, 2008). Mechanical extraction is a sustainable way of conserving not only native pest species but also other insect species that can benefit agroecosystems, such as pollinators and predators of pest species.

There are more than 350 species of grasshoppers and locusts which periodically invade agrosystems worldwide (Cerritos, 2011). Some of them are locally endemic but others have continental or even global distributions (Cerritos, 2009). When land-use changes increase resource availability, local, native insect populations can increase significantly and be considered 'native plagues' (Speight *et al.*, 1999). Additionally, non-native plague species may migrate into the area and in some cases change the interactions between native species (Speight *et al.*, 1999). Management for native plagues usually aims to control the population to some acceptable level, whereas plagues of non-native species may be targeted for total removal.

Insect biomass extraction in Asia, several Southern African countries, and Latin America tends to occur informally and currently no formal exploitation programs exist for edible insect species in agroecosystems, regardless of whether the exploited species are plague species or rare species. However, there are examples of the use of mechanical control to extract insect biomass for human consumption. For example, in Thailand and Korea several species of locusts are extracted mechanically avoiding the use of insecticides in crops (De Foliart, 1997; Pemberton, 1994). Additionally, Akpalu *et al.* (2009) proposed a sustainable exploitation model for the overexploited African mopane worm, *Imbrasia belina*, although this program has not yet been implemented. Finally, in the Puebla-Tlaxcala Valley in Mexico mechanical control of *S. purpurascens* produces hundreds of tons of food per year for human consumption, though it remains to be calculated how much biomass could be extracted from the whole country if mechanical control was applied everywhere.

In this study a conceptual model for a sustainable exploitation plan for insect pests is presented. This model combines the abundance of pest insects at different life cycle stages with their current and potential biomass per area translated into edible protein biomass. Then the economic, social (human health) and ecological repercussions of applying such an exploitation plan are analysed. *S. purpurascens* is used as a case study to present the model. This model focuses on pest species that damage agroecosystems and could be easily adapted for any other insect species anywhere in the world.

2. Materials and methods

The conceptual model has three main components. The first step is to determine the biomass of the species at each life-stage accounting for growth and mortality rates (Box A in Figure 1), which can then be translated into an amount of protein. This is then combined with species' distribution models to provide the potential biomass in an area (Box B in Figure 1). Finally, combining the biomass by stage (taking into consideration the growth and mortality rates) with the biomass by area, the amount of insects that can be extracted from an area can be estimated.

Therefore, this model can provide a metric for sustainable insect protein production per area per season (Box C in

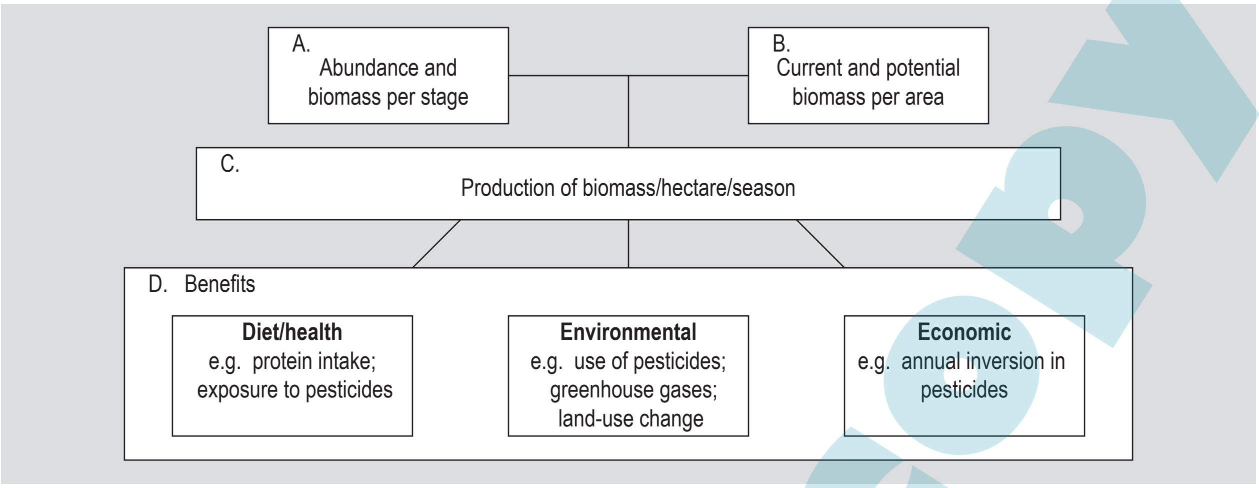

Figure 1. Sustainable exploitation model of an insect pest in agroecosystems and the ecological, economic, and human health benefits.

Figure 1). Using insects as a food source has many benefits (Box D in Figure 1). For example, eating insects is likely to help reduce some of the current global malnourishment problems, as protein sources would be more accessible for more people in terms of quantity and price. Moreover soil, water and air contamination through pesticides could be reduced and additionally money could be saved through reduced expenditure on chemical pesticides in agroecosystems. This would have a positive benefit on the final crop price, again making it more accessible to more people.

In the following sections we explain in detail each component of the conceptual model, using *S. purpurascens* as an example. Also, the methods used to elucidate the potential benefits of implementing this model in this case are presented.

Study case: *Sphenarium purpurascens* in Mexico

Abundance and biomass per stage

S. purpurascens is a hemimetabolous insect with seven developmental stages: an egg stage, five nymph stages, and an adult stage (Cano-Santana, 1994). The female lays eggs on the ground in small clusters called oothecae. Eggs hatch at the beginning of the rainy season and each nymphal stage lasts between 18 and 25 days, while the adult stage may live up to 30 days (Serrano-Limón and Ramos-Elorduy, 1990). The population size of this species does not vary strongly from season to season, and the main source of population regulation in agroecosystems is human control (Cerritos, 2002).

To determine the accumulated biomass per stage, 50 individuals in each of the different nymphal stages and in the adult stage were weighed. The density of eggs per area was obtained from existing data, which suggested that the number of eggs/m^2 may be between 500 and 5,000 and the density of reproductive grasshoppers/m^2 between 5 and 50 depending on the locality (Cerritos and Cano-Santana, 2008). The average number of eggs that each female lays was taken from the literature (Serrano-Limón and Ramos-Elorduy, 1990). According to the literature, these insects follow a type III demographic relationship, in which the highest mortality rate is in the first stages (Begon *et al.*, 2006). Therefore, the only factor regulating the population sizes of this plague species is the control method, which in this case should be mechanical extraction.

The biomass amount of this insect was calculated by averaging the weight of individuals in all the life cycle phases, with the average density of grasshoppers in each location by life cycle phases. To give more support to the biomass analysis, a small scale experiment simulating a systematic extraction of individuals of this species on a large scale was carried out. Five hundred eggs/m^2 were placed in a closed system within a farmed alfalfa field in the Puebla-Tlaxcala Valley, which is representative of the natural conditions for the grasshopper populations. The number of eggs used was chosen to represent the mean density in an agroecosystem where this species is considered a pest (Cerritos and Cano-Santana, 2008). Mesh was placed around the area to control the input and output of grasshopper individuals and others animal species. Once the experiment was assembled, a life table was produced considering the following three different scenarios of extraction: (1) higher extraction rate in juvenile stages than in the adult stage; (2) same amount of extraction in the juvenile and adult stages; and (3) higher extraction rate in the adult stage than in the juvenile stages, with three replicates per scenario. In the first scenario between 10 and 175 individuals per stage were extracted, with the highest number from the first juvenile stage, and the smallest number from the adult stage. In the second scenario approximately 60 individuals per stage were extracted. Finally, in the third scenario between 15 and 75 individuals were extracted with the highest number taken from the adult stage and the smallest number from the first juvenile stage. Between 310 and 360 individuals were extracted in total in each scenario. The mortality rate was determined by subtracting the number of extracted individuals from the total number of initial individuals. To compensate for mortality due to other causes we increased the total extraction by 10%. Using data from the secretaries of agriculture together with the minimum scale experiment the biomass values for each stage were added up to determine the total biomass extracted number in the complete life cycle. The total biomass extracted by stage was calculated by multiplying the average weight of each individual by the total number of extracted individuals.

Current and potential projections of biomass

Current infestation reports based on fieldwork conducted by the phytosanitary ministries in states currently affected by plagues of this species were obtained. These data were collected in at least five sites per state (50 sites in total from eight different states) and consist of the abundance and distribution of *S. purpurascens* as well as temperature, humidity, altitude, geographic coordinates, and land-use. The average abundance in the field was compared with the data obtained from the simulation of extraction per square meter.

To evaluate the potential distribution of *S. purpurascens* in Mexico Maxent was used. Maxent is a program that models species distributions using presence-only records (Phillips *et al.*, 2006; Phillips and Dudík, 2008) and environmental variables that are relevant to the habitat suitability of the species. To train the model we used the geographic coordinates from 50 records of *S. purpurascens*, eight environmental variables from WorldClim (Hijmans *et al.*, 2005): annual mean temperature; temperature seasonality; mean temperature of the warmest quarter; mean temperature of the coldest quarter; annual precipitation; precipitation seasonality; precipitation of the wettest quarter; precipitation of the driest quarter; soil layer (INIFAP/CONABIO, 1995); and land-use (Instituto Nacional de Estadística y Geografía, 2005). To calculate the potential distribution the model was transformed into a binary map, using the value of the maximum training sensitivity plus specificity as the threshold. Once we generated the potential map and the distribution of the species in hectares, we developed a demographic model to simulate a partial extraction of the *S. purpurascens* population.

Benefit analyses

We would expect three main benefits to arise from obtaining protein for human consumption from mechanical control of plague insect populations: (1) reduced emissions of greenhouse gases; (2) reduced net costs of control; and (3) reduced human health impacts from pesticide use. We discuss each of these benefits in turn in the following sections.

One of the potential environmental benefits of consumption of plague species such as grasshoppers is the reduction of greenhouse gases, especially when the emissions are compared with those generated by cattle. We estimated the emissions per hectare of the two main greenhouse gases (CO_2 and CH_4) due to vegetal biomass consumption by cattle (*Bos taurus* L.) and by grasshoppers (*S. purpurascens*). The cows weighed 651±53 kg and were fed with freshly ground corn (*Zea mays* L.). We estimated the accumulated animal biomass as 30% of the cows' weight. We then calculated an average consumption of 39 mg/day/grasshopper of grass biomass expressed in dry matter (Gurrola-Reyes *et al.*, 2009), with a grasshopper population density of 22 individuals/m^2 (Cano-Santana, 1994). Here we only compare the efficiency of biomass accumulation between this insect with the efficiency for cattle. Other types of conventional protein of animal source could be used, such as pork or chicken, and the biomass production rate of these animals would be somewhere between cattle and *S. purpurascens* (Cerritos, 2011). The equivalent emissions of CO_2were estimated based on the carbon contained in the dry matter of the food and the carrying capacity in a hectare. The cows' CH_4 emissions were estimated using methods previously reported (González-Ávalos and Ruiz-Suárez, 2007). This CH_4 emission calculation depends on the enteric and anaerobic fermentation of bovine manure due to environmental conditions. This calculation was not performed for grasshoppers as there are no studies showing methanogenic bacteria in this organism. Finally we estimated the amount of vegetal, insect, and conventional cattle biomass that could be obtained per area per season in the agroecosystems of Mexico. Approximately 50% of the dry weight of *S. purpurascens* is protein. We estimated the number of people in Mexico who could obtain their daily source of protein from *S. purpurascens* for a period of one year by multiplying half of the expected obtained biomass in dry weight (total value multiplied by 0.5) per year, and dividing this figure by the average intake of protein that a person needs daily (25 g) (Serrano-Limón and Ramos-Elorduy, 1990).

The economic impact of changing the control methods for this grasshopper species was also estimated. The annual inversion cost of chemical agents was calculated by multiplying the total number of infested hectares by the numbers of litres used annually per hectare (2 litres of malathion for *S. purpurascens* in Mexico). It was also evaluated the economic benefit of mechanical extraction of *S. purpurascens* in the whole country. The total number of tons that could be extracted was multiplied by the current average cost per kilogram in central Mexico. Currently the cost per kilogram, once the grasshoppers have been prepared for human consumption, is equivalent to five U.S. dollars (Cerritos and Cano-Santana, 2008).

The human health impact of changing the method of grasshopper population control in Mexico was evaluated using data from different health ministries on the number of people directly affected, both physiologically (intoxications) and genetically (mutagenesis), by the use of pesticides in agriculture.

3. Results

Biomass

The average weight of each individual ranges from 0.044 g in the first juvenile stage to 0.454 g at adulthood (Figure 2A). The average weight at each stage shows a geometric relationship of biomass accumulation (Figure 2B). Therefore the average biomass of *S. purpurascens* which could be extracted per hectare in one year is 300 kg. However, depending on the level of extraction, this value could vary between 200 and 500 kg (Figure 2C). If we extract a higher number of individuals in the initial juvenile stages rather than in the last juvenile stages and adulthood there would be less accumulated biomass (Figure 2C). The projections indicate that even if only 5 females were left per square meter this would be enough to obtain 250 individuals in the next generation and therefore have the same extraction levels in the following year (Figure 2A). If extraction of the grasshoppers started in April/May (first juvenile stages of *S. purpurascens*) and continued up to October/November (adults), the regulation of biomass extraction would be sustainable and protein production could continue all year round. One of the most important advantages of grasshoppers over conventional cattle is the speed at which they reach maturity. Cattle require significantly longer than a year to be ready for human consumption.

Distribution

Instead of being considered a plague, an abundant insect species could be thought of as mini-cattle with more benefits than conventional cattle. To calculate the total biomass that could be obtained across Mexico, a map of the current and potential distributions of the species was created. Currently, *S. purpurascens* is found in all states in the centre of the country (Estado de México, Tlaxcala, Puebla, Hidalgo, Queretaro, Morelos, Guanajuato, Jalisco, and Michoacán)

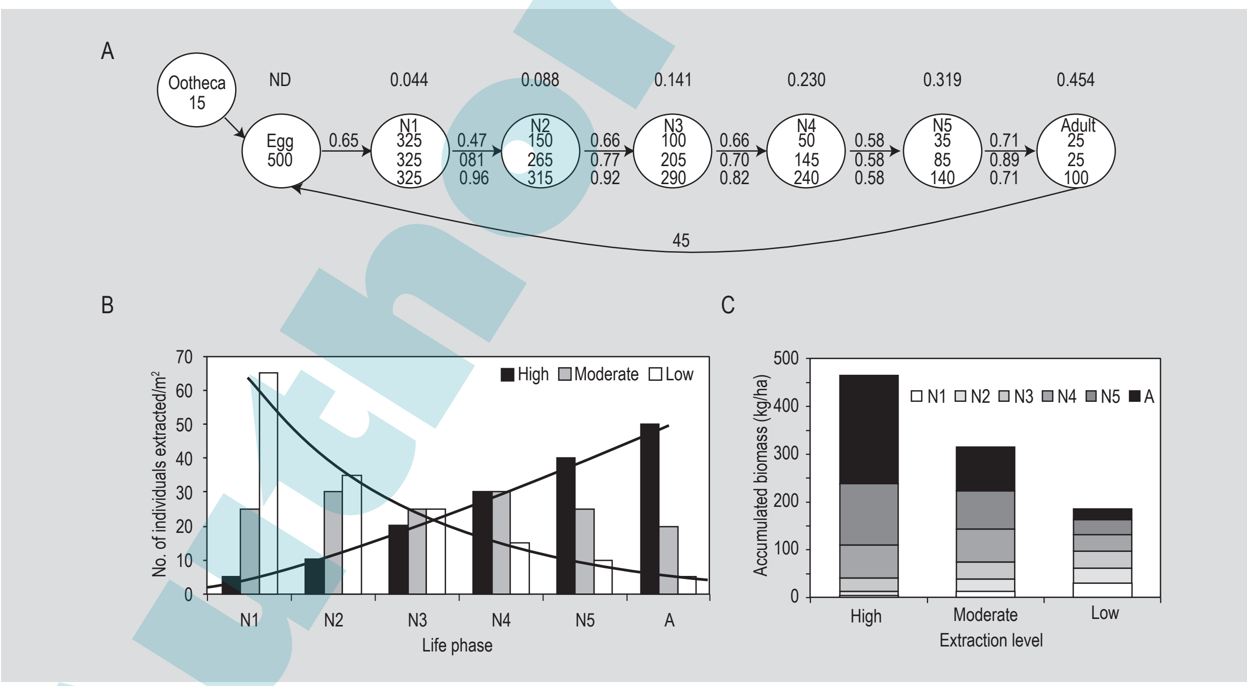

Figure 2. Extraction model for *Sphenarium purpurascens* which takes into consideration the biomass obtained in different life-history stages. (A) Diagrammatic life table showing the survival under three extraction levels (probability of an individual to survive to the next stage and the mean number of insects surviving is given around the arrow respectively within the circles) and the mean weight per gram (numbers on top) in each stage. (B) Amount of individuals extracted/m^2 from three scenarios of extraction. (C) Accumulated biomass per hectare in each stage for the three levels of extraction. N1, N2, etc.= first, second, etc. nymphal stage; A = adult; ND = not determined.

and some southern and south-western states (Guerrero and Oaxaca), with densities of 10 to 55 individuals per square meter across 1,050,000 hectares of agroecosystem (Figure 3). This abundance was calculated by using the level of chemical control in each region and environmental factors such as altitude, humidity, temperature, and land use. Field studies indicate that *S. purpurascens* is found in temperate sub-humid and dry climates, with temperatures oscillating between 5 and 25 °C and at altitudes between 600 and 2,500 meters above sea level.

However the predicted number of hectares occupied by this grasshopper species is an underestimate because the native populations found in xeric shrub to pine-oak mixed woodlands in the central region of the country were not considered in this study. It is probable that this species is currently distributed across more than 2,000,0000 ha of Mexican territory. The potential distribution model showed that about 10,125,700 ha of current crop lands could potentially harbour this species (dark areas in Figure 3).The distribution models estimate that agricultural lands in the north of the country (Zacatecas, San Luis Potosi, Durango) and in southern Chiapas near the border with Guatemala have suitable environmental conditions for this species. Similarly, it is likely that *S. purpurascens* could establish in other countries near Mexico (e.g. Guatemala, Belize, and El Salvador). Although this species cannot fly, it can populate new areas quickly (Castellanos, 2001). Moreover, there are records of phylogenetically similar species in several Central American and Caribbean countries (Kevan, 1977).

The potentially available biomass varies with exploitation intensity. For example, if the level of exploitation is intense during the first juvenile stages, a minimum of 200,000 tons of biomass could be extracted throughout the country; however, if the extraction intensity is higher in the mature nymphal stages and/or adulthood, up to 500,000 tons could be obtained (Figure 4A). Furthermore, the amount of grasshoppers that can be extracted considering its potential distribution can increase by an order of magnitude (Figure 4B).

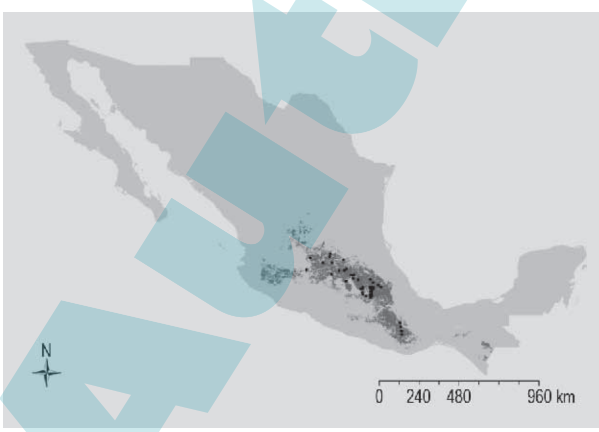

Figure 3. Current (black squares) and potential (dark grey) distribution of *Sphenarium purpurascens* in Mexico.

At present, only a few hundred tons of grasshoppers are extracted annually in two regions of Mexico, and only a small quantity of this biomass is used for human consumption as this species is usually chemically controlled with thousands of litres of pesticides, especially malathion. This is the case for the Puebla-Tlaxcala valley, the region where the species is currently most exploited. Less than 200 tons are extracted annually from that region, and chemicals are the main method of control (Cerritos and Cano-Santana, 2008). In the Valley of Puebla-Tlaxacala this insecticide is commonly applied to combat this grasshopper's species. Unfortunately, malathion is not specific for grasshoppers or other pest species so once applied it affects other insects that are actually beneficial to crops.

4. Discussion

These results show that plague insects have a large capacity to be exploited as food sources for human populations. A single species, *S. purpurascens*, in Mexico could potentially generate approximately 350,000 tons of protein annually in a sustainable way while avoiding considerable damage to agroecosystems. Below, the potential social, economic, and ecological repercussions of these practices are discussed.

Insects should be part of the human diet, not only because of their abundance but also because of the amount of nutrients that they contain. The demand for animal protein between

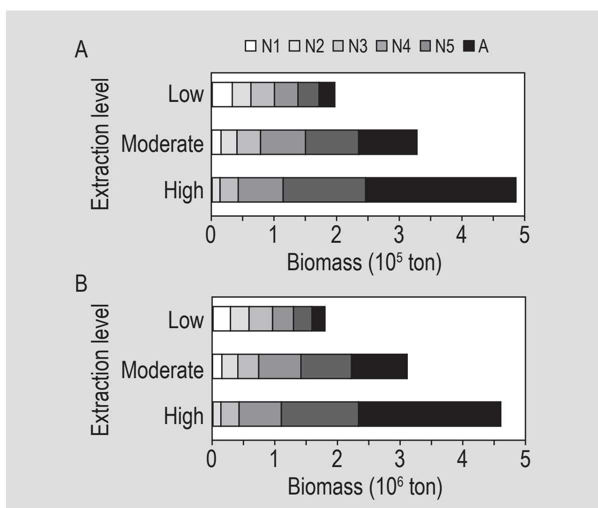

Figure 4. Obtained biomass by taking in consideration (A) the current and (B) the potential distribution in each stage for the three scenarios of extraction. These analyses indicate that between 200,000-500,000 and 2-6 million tons could be generated annually for the current and potential distributions, respectively. N1, N2, etc.= first, second, etc. nymphal stage; A = adult.

now and the year 2050 is projected to increase between 70-80% (Pelletier and Tyedmers, 2010). An annual extraction of 350,000 tons of grasshoppers for human consumption in Mexico could potentially provide 9 million people with their recommended daily protein intake for a year (25 g) (Figure 5). Insects, especially Orthoptera, contain an amount of protein that in some cases comes close to 50% of their dry weight (Ramos-Elorduy *et al.*, 1982). In Mexico diets are low in protein(Gomez *et al.*, 1997; Unicef-México, 2010), and child malnutrition is therefore high. More than a million infants suffer from severe malnutrition, which affects not only their weight but also has irreversible repercussions, such as reduced height and cognitive function (Gomez *et al.*, 1997; Unicef-México, 2010). Malnutrition is more severe in other Latin American countries and it is even worse in many regions of Africa (FAO, 2009). Indeed, it is in Africa that the most devastating Orthoptera species can be found due to their densities and their distributions. There, *Locusta migratoria* and *Schistocerca gregaria* could be important sources of protein.

The pesticides applied to control plague species in agriculture cause serious problems to both human populations and other species inside and outside agroecosystems. These methods are known to have negative effects on human health, causing anything from mild contamination to grave mutagenic effects that not only affect the individual but also their progeny (Giri *et al.*, 2002; Liu and Pleil, 2002; Waliszewski *et al.*, 1998). In Mexico, 50,000 cases of intoxication by agricultural insecticides are reported each year (Bahena, 2008). However, annual estimates of the real figure are twice as high (Figure 4). The most important advantage of mechanical control methods is the absence of toxic effects on human populations. Moreover, this alternative method may have additional economic benefits. It is calculated that to fumigate 1,000,000 ha of crops infested with Orthoptera species in Mexico 2 million litres of malathion are needed annually, which costs approximately US$ 10 million. However, if the same biomass was extracted by the mechanical method, we would obtain a gross amount of approximately US$ 350 million. Furthermore, changing the chemical control method to the mechanical method would not affect non-target species, create resistance to the control method, nor contaminate the water or soil. Even though these negative effects are not quantified in this study, it has been previously shown that the chemical method has serious detrimental consequences in regions where it is intensively applied (Fashing *et al.*, 2010; He and Zhu, 2004; Hoekstra, 1998; Lahr, 1998; MacCuaig, 2008; Stewart, 1998; Yang *et al.*, 2008).

Changing strategies to combat plague species could also have worldwide repercussions, especially if we consider the land requirements and CO_2 emissions when producing 350,000 tons of insect biomass instead of 350,000 tons of conventional cattle. Globally, one of the main environmental problems is the large amount of natural ecosystems that have been and are being cleared for farming and grazing

Topic	350,000 ton/year
Environmental	Needed (ha): cattle 7.2×10^6; grasshoppers 1.05×10^6 Produced (ton): CO_2: cattle 5.4×10^8, grasshoppers 1.04×10^7; CH_4: cattle 7.2×10^6, grasshoppers ND
Nutrimental	Average amount of protein needed: One day 25 g/person; One year 9 kg/person Number of people that could be fed by this biomass: 9.7×10^6 person
Economical	Mechanical control ↑: Sale: US$ 1/kg; Yield: US$ 3.5×10^8 Chemical control ↓: Pesticide cost: 2 l/ha, US$ 10/ha; 2×10^6 l, US$ 1×10^7
Health	Mechanical control: Contamination 0; Mutagenesis 0 Chemical control: Contamination 5×10^4 cases; Mutagenesis undefined
Agroecosystem	1 ha/year: 0.07 ton biomass, 0.7 ton manure; 1.5 ton of seed, 1.5 ton food for cattle; 0.250 ton biomass

Figure 5. Economic, ecological, and human health repercussions of exploiting *Sphenarium purpurascens* for human consumption. Based on the average number of tons of *S. purpurascens* that could be obtained (350,000 ton/year), the impact projections are performed for five different areas: environment, nutrition, human health, economy, and agriculture. ND = not determined.

activities to fulfil the consumption requirements of an increasing population (Foley *et al.*, 2011). Mexico is not the exception, with many naturally forested areas cleared for these human activities (Calderon-Aguilera *et al.*, 2011; Galicia and Garcıa-Romero, 2007; Martınez *et al.*, 2009; Masera *et al.*, 1995). This study shows that it is possible to produce the same biomass for human consumption in a smaller area. Due to the high metabolic efficiency of insects, with little energy lost both in maintenance and excretion, 80% of the consumed matter is assimilated in biomass. Conventional cattle, conversely, use a large amount of the energy they consume to maintain the individual and most of consumed matter is not assimilated but excreted. Thus, in conventional cattle, less than 10% of the consumed matter is assimilated as biomass. As a consequence of this metabolic difference, in order to generate 350,000 tons of biomass about one million hectares are needed for *S. purpurascens*, compared to 7.2 million hectares for conventional cattle. Furthermore, conventional cattle produce 500 million tons of CO_2 emissions per year, whereas *S. purpurascens* generates about 10 million tons. Another factor to consider is the extremely high CH_4 emissions of conventional cattle. In order to produce 350,000 tons of biomass per year it has been calculated that almost 50,000 tons of CH_4 are generated. Grasshoppers do not host methanogenic bacteria therefore they do not produce any CH_4.

An ideal scenario in agroecosystems, not only in Mexico but globally, would be a systematic use of all agricultural subproducts. For example, the most cultivated plant worldwide, corn, can be used for human and animal consumption: the biomass of plants that is not used for human consumption can be used to feed conventional cattle and even a population of insects such as *S. purpurascens* could be maintained without causing substantial corn production losses (Cerritos *et al.*, 2012). The results of this study show that, on average, one hectare could sustain the production of 1.5 tons of corn and 0.250 tons of insects, which is the area of land required to produce a single cow. Bedoya (2006) showed that alfalfa crops can also support grasshopper populations while still producing. This system could be entirely sustainable, maintain soil fertility if cattle manure is used (Figure 5), and be highly productive in terms of nutrients that could be used by humans.

Some factors that can have an impact on this new form of insect pest exploitation in agroecosystems require further investigation. For example, a more detailed assessment of the performance and costs of mechanical control methods is needed. While it has been shown that this method has been effective in reducing the population size of *S. purpurascens* in the Puebla-Tlaxcala Valley, further evaluation in other regions would be required. The acceptability of this 'new' food source by the human population has to be appraised. Mexico is a country with a long tradition of using these insects as a source of protein; however, they are still not considered part of the basic Mexican diet. Consolidating new food sources in society depends upon the efforts of the scientific community, companies committed to sustainable development and the government sector. One approach to introduce this new food could be to propose adding it as a supplement to primary consumer products. Although there is no formal recognition by government, in villages of the Puebla-Tlaxcala valley economically profitable harvesting of this species for human consumption has occurred for more than 30 years. This evidence suggests that, at least on a small-scale, an industry based on harvesting this species for human consumption can be maintained sustainably.

5. Conclusions

Based on the biomass of S. *purpurascens* that could be generated in one year in Mexico, it can be assumed that insects are excellent candidates to form part of the diet of any human population. Worldwide, the most abundant and devastating plague species belong to the Orthoptera order. If we change the control strategy from a chemical method to a mechanical one, it will not only improve the productiveness of agroecosystems but also produce additional biomass from insects (with more protein than conventional cattle). Combining the cultivation of plants with farming native insect species is a strategy based on prehispanic practices that could improve health, economic, and environmental conditions of modern societies.

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