Insects as a piece of the puzzle to mitigate global problems: an opportunity for ecologists

Chelse M. Prather\textsuperscript{a,\ast}, Angela N. Laws\textsuperscript{b}

\textsuperscript{a}Department of Biology, 300 College Park, University of Dayton, Dayton, OH, 45469-2320, United States
\textsuperscript{b}Department of Biology and Biochemistry, University of Houston, Houston, TX, United States

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Abstract

Although scientists have studied and touted the importance of insects to many ecosystem services for decades, insects and insect science are often poorly perceived by the public and by policy makers. Because insects do have important influences on many ecosystem services, they have even greater potential to be used to solve some anthropogenically-caused current global problems. We give several examples where insects are currently being used, or are being considered for future use, as a part of the solution to a global problem, including their potential roles as a part of the solution to sustainable fuel and food systems, deforestation and other environmental degradation, and global inequities. Ecologists have an important role to play in assessing how many of the proposed uses of insects will alter ecological processes and ecosystem services, or how their use may be effectively implemented.

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Introduction

Despite the large body of literature showing that many species of insects positively affect humans by providing or enhancing ecosystem services (Prather et al. 2013; Macadam & Stockan 2015; Pelini, Maran, Chen, Kaseman, & Crowther 2015), insects and insect science have a pervasive perception problem with members of the public and legislative entities (Lockwood 2013). Many people view insects negatively, often fearing and avoiding them (Kellert 1993), especially those they associate with diseases (Prokop & Fančovičová 2010). Assuch, people care little about insect extinctions, and the potential consequences of these extinctions (Wilson 1987; Kellert 1993). A general lack of awareness exists about how abundant and diverse insects are; children consistently underestimate the relative biomass (Snaddon, Turner, & Foster 2008) as well as the diversity of insects (Snaddon & Turner 2007).

People often lack positive experiences with insects, as well as fear and avoid them, which hampers insect conservation efforts (Lockwood 2013), and their use for other purposes (Looy, Dunkel, & Wood 2014). As a consequence, most funding of research on insects is related to how to control insect pests or insect disease vectors (Cheesman & Key 2007). Potentially even more troubling is that policy makers sometimes point to funding for basic science involving insects as wasteful spending. In the United States, insect research has long made the annual list of government wasteful spending created by some members of Congress. For example, on the
The Millennium Ecosystem Assessment identified four categories of ecosystem services: supporting, provisioning, regulating, and cultural services (WRI 2003, Scholzwalter & Tscharntke, this issue). Many studies focus on plants (Quijas, Schmid, & Belverna 2010; Isbell et al. 2011) and vertebrates (Terborgh et al. 2001; Estes et al. 2011) as critical providers of ecosystem services, but recent reviews have highlighted how important invertebrates generally (Lavelle et al., 2006; Prather et al. 2013) and insects in particular are to ecosystem services, having effects on services from all four categories (Losey & Vaughan 2006; Isacs et al. 2009; Nichols et al. 2008; Schowalter 2013).

Supporting services are those that are necessary for the maintenance of all other ecosystem services, and include basic ecosystem functions like primary production, nutrient cycling, and decomposition. As major herbivores, detritivores, and predators in many ecosystems, insects can have obvious and critical effects on supporting services (Weisser & Siemann 2004). Provisioning services are the material goods derived from ecosystems. Insects are not only often goods themselves (e.g., as food for domesticated species or humans) and produce goods (e.g., silk and honey, but influence the production of other goods (e.g., timber and food). Regulating services, such as erosion control, regulate ecosystem processes and maintain ecosystem structure. Insects play an essential role in the regulation of food web stability as they reach high relative biomass in most ecosystems on Earth and span many trophic levels. They also aid in the regulation of other important services, such as water filtration in streams, rivers, and lakes. Cultural services are the nonmaterial benefits obtained from ecosystems, such as educational opportunities or artistic inspiration. Cultural importance of insects (reviewed in Leather 2015) often manifests itself in ways driven by human aversion to insects; for instance, common phrases inspired by insects (e.g., “buzz off”) are often used pejoratively (Haslam 2006; Steuter & Wills 2009; Steuter 2010). Insects can be of great cultural importance with countless examples of their inspiration in music and art (e.g., in rock and roll: Coelho 2000; Prather et al. 2013), and insects have also been used with positive success in the treatment of children with mental disorders (Jun et al. 2016).

Although insects play a significant, if underappreciated, role in providing many ecosystem services, it is of extreme importance that many of the services that insects either directly provide or indirectly influence play a role in the mitigation of many global challenges that society faces (Table 1). Here, we demonstrate that not only are insect-influenced ecosystem services important to sustain, but that insects and insect science can be part of the toolkit for mitigating the effects of global change (Fig. 1). We were easily able to find examples of how insect-provided or influenced ecosystem services may be used as part of the solution to each of the anthropogenic global problems faced by humanity recently outlined by the United Nations Environmental Programme (UNEP 2016; Table 1), and the potential solutions that insects help to provide are derived from their effects on every category of ecosystem services. We describe three exemplary case studies of how insects and insect science may be used as a piece of the puzzle in helping to solve some of humanity’s major problems. We also describe the necessary role of ecologists in answering questions about the efficacy and environmental impact of using insects as part of the solution to global problems.

Sustainability of fuels

The need for sustainable, renewable, cleaner fuel sources has been a critical problem for decades (Hirsch, Bezdek, & Wendling 2006; Murray & King 2012), and apart of the solution to this problem may be the use of biofuels and biodiesels (Youngs & Somerville 2014). Renewable biofuels are fuels that are produced from materials derived from recently living dead plants or animals, or fuels extracted from waste from other processes. The materials used to make biofuels contain carbon that has been recently fixed, whereas buried fossil fuels contain carbon that has been fixed millennia ago and since stored underground. Thus, using biofuels recycles carbon instead of removing it from long-term storage and adding it back to the atmosphere as a greenhouse gas. The utility of biofuels as a sustainable renewable energy remains controversial (Tilman et al. 2009), but for our purposes, we leave this controversy aside, assuming they may play an important role in switching to more sustainable, renewable, cleaner fuel sources.

Some steps in the processes of producing biofuels (Fig. 2) and biodiesels are currently not very efficient or are rather energetically and economically costly. After CO₂ is fixed by plants and converted to biomass (Step 1), it is harvested (Step 2). After the biofuel materials are harvested, they are pre-processed (Step 3): the starting materials, such as plant biomass, are comminuted and exposed to chemical or physical treatments that remove chemical barriers to lignocellulolytic material (i.e., dry plant matter composed of carbohydrates, cellulose and hemicellulose, and the aromatic polymer, lignin) to enhance the efficiency of cellulose digestion. This step increases the ability of cellulose-specific
Table 1. Ecosystem services provided by insects and the societal problem these services address. Ecosystem Services marked with (*) are discussed in more detail in the text.

<table>
<thead>
<tr>
<th>Global challenge addressed</th>
<th>Example</th>
<th>Ecosystem service</th>
<th>Service category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food Stability</strong></td>
<td>● Insects are key pollinators for 75% of all crop plants (Klein et al., 2007)</td>
<td>Pollination</td>
<td>Supporting services</td>
</tr>
<tr>
<td></td>
<td>● Insects may be readily available for harvest and consumption when other protein sources are not</td>
<td>*Food-entomophagy</td>
<td>Provisioning services</td>
</tr>
<tr>
<td></td>
<td>● Insects may be used as a source material of biodiesel or their guts and symbions used to enhance the efficiency of current biofuel production</td>
<td>*Fuel-biofuels; Climate regulation</td>
<td>Provisioning &amp; regulating services</td>
</tr>
<tr>
<td><strong>Climate change mitigation</strong></td>
<td>● Insects used as food produce fewer greenhouse gases than many current sources of protein</td>
<td>*Food-entomophagy; Climate regulation</td>
<td>Provisioning &amp; regulating services</td>
</tr>
<tr>
<td></td>
<td>● Insects may be reared or collected for consumption and sale by otherwise disenfranchised groups for supplemental income</td>
<td>*Food-entomophagy</td>
<td>Provisioning services</td>
</tr>
<tr>
<td></td>
<td>● Women in Costa Rica rear butterflies for jewelry. Proceeds support a local insect zoo (<a href="https://www.facebook.com/insectopiamuseum/home">https://www.facebook.com/insectopiamuseum/home</a>)</td>
<td>Insect fashion</td>
<td>Provisioning &amp; cultural services</td>
</tr>
<tr>
<td></td>
<td>● Endangered butterflies have more efficiently been reared by women prisoners than in some zoo breeding programs, passing on critical technical skills to otherwise disenfranchised groups</td>
<td>Food web stability</td>
<td>Regulating Services</td>
</tr>
<tr>
<td></td>
<td>● Ecotourism to see insects may allow economic opportunity to poor sectors of society</td>
<td>*Ecotourism</td>
<td>Cultural services</td>
</tr>
<tr>
<td><strong>Global inequities</strong></td>
<td>● Insects are an important food source for higher trophic levels. Insectivorous birds (aerial foragers in North America) are declining more rapidly and ranges are shrinking more than for perching birds that feed mainly on seeds as insect populations decline (Nebel, Mills, McCracken, &amp; Taylor 2010)</td>
<td>Food web stability</td>
<td>Regulating services</td>
</tr>
<tr>
<td><strong>Declining biodiversity</strong></td>
<td>● Insects can be used as biocontrol agents for invasive species (Hajek 2004) or as biocontrol for disease vectors (Samish &amp; Rehacek 1999)</td>
<td>Biocontrol</td>
<td>Regulating services</td>
</tr>
<tr>
<td><strong>Clean water</strong></td>
<td>● Insects as indicators of stream quality (Macadam &amp; Stockan 2015)</td>
<td>Fresh water quality</td>
<td>Regulating services</td>
</tr>
<tr>
<td><strong>Disease regulation, invasive species</strong></td>
<td>● Ecotourism centered around insect displays (e.g. fireflies) and migrations (e.g. butterflies) can provide economic opportunity to local people, while providing incentives to protect sensitive habitat used by focal insects (Vidal et al. 2013)</td>
<td>Ecotourism</td>
<td>Cultural services</td>
</tr>
<tr>
<td><strong>Land use change, habitat loss, economic opportunity.</strong></td>
<td>● Insects collecting kits for children, iNaturalist and other apps that encourage citizen science</td>
<td>Recreation via citizen science</td>
<td>Cultural services</td>
</tr>
<tr>
<td><strong>Loss of connection to nature</strong></td>
<td>● Feeding edible insects organic waste streams limits these materials ability to pollute the environment</td>
<td>*Food-entomophagy</td>
<td>Provisioning services</td>
</tr>
</tbody>
</table>
enzymes to extract sugars from cellulose and facilitates microbial fermentation at downstream phases of production (Sun & Scharf 2010). Processing biomass to, ideally, contain pure cellulose is currently done through thermochemical means and is not very efficient. Step 4 of this process is using enzymes to break down the pre-processed cellulose to sugars, but the enzymes that are currently used in this process are not very efficient. Additionally, the conditions under which these reactions currently take place do not seem to promote optimal reaction efficiency. In Step 5 of this process, microbial communities convert the sugars into fuel through fermentation. The microbial communities that carry out this fermentation are again not efficient and the conditions in which these microbes are kept are not optimal for these reactions. Recently, insect scientists have been determining if and how insects may help to reduce some of the efficiency problems that the production of these fuels currently have.

The rationale for this is simple: folivorous and xylophagous insects are essentially tiny bioreactors that convert lignocellulolytic material to fuel for themselves. Thus, their digestive systems should contain the tools and conditions that can be used to streamline and optimize the process of converting lignocellulolytic materials to biofuel (reviewed in Sun & Scharf 2010; Manzano-Agugliaro 2012). To increase the efficiency of the pre-processing phase (Step 3), wood-digesting termites (e.g., Coptotermes formosanus and Reticulitermes flavipes) have been used as model lignocellulolytic organisms to identify the chemical conditions (e.g., oxygen profiles) under which lignin degradation occurs (Ke et al. 2010). Additionally, candidate enzymes have been identified from these species’ transcriptomes and their symbiotic gut fauna (e.g., protozoans: Scharf & Boucias 2010; Scharf et al. 2011; Sethi, Slack, Kovaleva, Buchman, & Scharf 2013), which more efficiently disrupt lignin to provide more access to cellulose to produce bioethanol at the pre-
processing phase than current thermochemical methods do. To increase the efficiency of the degradation of cellulose into sugars (Step 4), scientists are identifying the genes, enzymes, and environmental conditions used to degrade cellulose in lignocellulolytic insects’ guts (e.g., termites: Zhang et al. 2010; wood-feeding beetles: Geib, Tien, & Hoover 2010). Particularly interesting is that the metagenomics of pest species, like Asian long-horned beetles (Anoplophora glabripennis) that have devastated deciduous forests as invasive pests on several continents, have revealed promising lignin-degrading genes and cellulases that could be used both at the pre-processing phase and the cellulose degradation phase (Scully et al. 2013). Additionally, to increase the efficiency of the fermentation of sugars produced from cellulose into biofuels (Step 5), scientists have investigated the symbiotic microbial communities of lignocellulolytic insects that carry out the fermentation of simple sugars into biofuels as well as the genes of these symbionts (Huang, Zhang, Marshall, & Jackson 2010), and the optimal conditions under which fermentation occurs within these organisms (Cook & Doran-Peterson 2010).

Insects may also aid biodiesel production—in this case, insect bodies themselves may actually be used as feedstocks, the raw materials for biodiesel production. Currently, one of the major challenges with biodiesel production is procuring raw material that is both high in oil content and economically feasible (Koonin 2006). The plant oils that are currently a major source of feedstock for biodiesel production (e.g., soy, palm, and sunflower oils) are relatively expensive, have low concentrations of oil and also do not accumulate fat very quickly; thus, the yield of fuel per unit of material used is not very high. Certain larval stages of insects accumulate fat very quickly (e.g., black soldier fly larvae: Hermetia illucens; mopane worms: Gonomimbrasia belina; African weevil larva: Rhyynchophorus phoenicis; Liet al. 2011). As a consequence, scientists have been investigating the potential to use insect fat as a source of biodiesel, especially because insects can be fed organic wastes, which aids in the solution to other global problems, such as waste and pollution removal (Li, Zheng, Hou, Yang, & Yu 2011). Several species have undergone feasibility studies to determine the efficiency of biodiesel production from oils extracted from insects: yellow meal-worm beetles (Tenebrio molitor L.) fed organic vegetable waste (Zheng et al. 2013); domestic house fly larva (Musca domestica) fed swine manure (Yang, Li, Gao, Zheng, & Liu 2014); and black soldier fly larva fed lignocellulolytic materials. All of these studies concluded that these species, fed organic waste, showed great promise in increasing the efficiency and reducing the cost of biodiesel production. These studies were all conducted on a small-scale in the laboratory; no large-scale production of biodiesel from insect oils has taken place as yet.

Thus far, ecologists have been interested in how the large-scale production of plant-based biofuels may affect ecological systems, and how insect communities may be affected by and affect this production (Landis & Welting 2010). Although these are undoubtedly important questions, ecologists have an important role to play in answering questions that are relevant to the efficient production of biodiesel as well as how this type of biofuel production may affect ecological systems. Questions like the following may be particularly important:

- Which insect species are most feasible for large-scale rearing and processing for biodiesel? For example, which species can most cost-effectively be reared that have the highest fat content?
- What type of diet yields insects that are highest in lipid-rich material for efficient biodiesel production? Are organic waste streams a viable and cost-effective source of food?
- What environmental conditions are most suitable for rearing target species, and how might these conditions be achieved to rear insects at a large scale for biodiesel production?
- How would an increase in the rearing of insects for the production of biofuel affect other ecosystem services? What might an insect farm that affects other ecological processes as little as possible look like?
- How might the chemicals needed to extract lipid from insect bodies at a large scale affect other ecosystem services?

It is currently unclear to what extent insects and their genes, enzymes or microbiomes may be used in these processes in the future: the science behind insect use in the production of biofuel and biodiesel is currently in its infancy, but if any of these technologies are to become a reality, ecologists must be engaged in researching relevant questions. Using insects to increase the efficiency of biofuels would aid in the solution to multiple global anthropogenic challenges (Fig. 3): not only the efficient and economic production of sustainable fuels, but also mitigation of greenhouse gases through the recycling of recently fixed CO₂, the mitigation of environmental
degradation that occurs with fossil fuel extraction and refinement, and potentially a reduction in global conflicts through the reduced reliance on geopolitically unstable parts of the world for fossil fuel production.

**Sustainability of food systems**

Another major problem that humanity faces is the creation of sustainable, nutritious, economically viable food systems, including sustainable protein sources. The current major sources of protein globally (livestock: goats, sheep, and cattle; poultry: chicken and turkeys) pose some challenges in their production, nutritional quality, and their effects on socioeconomic systems. First, the rearing of animals used as major protein sources globally requires a tremendous amount of land. In fact, in 1700 only 3% of ice-free land globally was covered by rangelands; in 2000, rangelands covered 26% of ice-free lands on Earth (Ellis, Klein Goldewijk, Siebert, Lightman, & Ramankutty 2010). Additionally, major staple proteins are substantial contributors to greenhouse gas emissions. Livestock account for 18% of global greenhouse gas (GHG) emissions, including large amounts of methane and nitrous oxide, which are particularly potent GHGs (Steinfeld, Gerber, Wassenaar, Castel, & de Haan 2006), and the relative contribution of livestock to GHG production is predicted to increase in the future (Fiala 2008). Because of all these animals are endotherms, their ability to convert feed into usable biomass is rather inefficient. For instance, the production of 1 kg of high-quality meat requires 6 kg of plant feed (Pimentel & Pimentel 2003). Additionally, humans actually consume only about 7–8% of the calories from feed given to livestock with beef being the least efficient (humans ultimately only consume 3% of calories consumed by cattle; Shepon, Eshel, Noor, & Milo 2016). Nutritional, staple proteins are rather low in the ”good”, unsaturated fats, and high in “bad” saturated fats that cause humans’ many health problems. Correspondingly, high red meat intake is associated with many non-communicable diseases, including heart disease and certain cancers. Staple meats also contain relatively low amounts of certain micronutrients and vitamins (e.g., zinc), and almost no fiber (Van Huis, Dicke, & Van Loon 2015). Even given these problems with the current staples of protein, the FAO predicts that the global demand for meat will increase by 102% by 2050 (FAO 2006). Subsidizing these staple proteins with proteins originating from insects (i.e., entomophagy) may help to alleviate many of the challenges currently arising from our current protein sources (Van Huis et al. 2013, 2015).

First, entomophagy does not necessarily require intensive land conversion for the rearing of insects, as do our current major sources of protein (Oonincx & De Boer 2012; Van Huis et al. 2013). For instance, it is estimated that to produce similar quantities of meat that result from 1 ha of mealworm farming would require 2–3.5 ha for chicken and 10 ha for pork or beef, respectively. Additionally, the insect species targeted as potentially important protein sources would emit fewer greenhouse gases and require less energy and water when farmed compared to main staple sources of protein (Oonincx & De Boer 2012; Van Huis et al. 2013). Only a few insect species produce methane, and these are not species targeted for human consumption. Furthermore, if insects could be reared using organic waste streams as feed, their production would also further mitigate the emissions of greenhouse gases (Oonincx & De Boer 2012; Van Huis et al. 2013). Because they are ecotermic, insects are much more efficient at turning feed into biomass. Crickets, for example, need twelve times less feed than cattle, four times less feed than sheep, and half as much feed as pigs and broiler chickens to produce the same amount of protein (Van Huis et al. 2013). Not only can a greater percentage of the insect body be eaten...
and digested (e.g., 80–90% of insect bodies can be digested, depending on the species and preparation of insect; Kinyuru, Kenji, Njoroge, & Ayieko 2010), but the food conversion efficiency for insects is also very high.

Although the nutritional quality of insects varies widely, differing greatly among species and developmental stage within a species (Van Huis et al. 2013), it may, in some respects, be better than our current sources of protein. In general, insects are relatively nutritious: the caloric content of insects is similar to that of other meat on a fresh weight basis (Sirimungkararat, Saksirirat, Nopparat & Natongkham 2010). Insects have relatively balanced nutrient profiles and high amounts of certain minerals (Zielinska et al. 2015), including levels of iron, zinc, and calcium that rival or are higher than staple proteins (Bukkens 2005; Zielinska et al. 2015). The high levels of iron and zinc in insects are particularly important because anemia (iron deficiency) is the widest-spread nutritional disorder, and zinc deficiency is another significant global health problem (Van Huis et al. 2013). Additionally, insects tend to have greater concentrations of “good” fats (mono- and polyunsaturated fats, including omega-3 and omega-6 fatty acids) and lower levels of “bad” fats (saturated fats) than do other staple proteins (Zielinska et al. 2015). In laboratory studies, these insect fats also helped to promote the growth of skin fibroblasts, which are important in recovery of tissue after injury (Zielinska et al. 2015).

Lastly, entomophagy may also help empower groups that are disenfranchised in many places, such as women and children, providing alternative sources of income to the poorest sectors of society in developing countries (Van Huis et al. 2013). In places where entomophagy is already commonplace, members of these groups (for instance, women) do a disproportionate amount of the insect collection and the processing of insects (Kozanayi & Frost 2002). People with low incomes do not need to own land to collect insects in public lands. Additionally, insect production and transportation to market often requires little technology, allowing entry for many poor or mistreated sectors of society (Van Huis et al. 2013). Selling insects as food can supplement incomes and can actually provide greater incomes than many other jobs available to those sectors of society that may not have viable alternatives.

Although there are many indications that the rearing of edible insects for food will be more “environmentally friendly” than our current sources of protein, ecologists could play an important role in understanding the ways in which insect farming may indeed be conducted sustainably. At a recent meeting of the International Congress of Entomology (2016, Orlando, FL, USA), several symposia were dedicated to the science behind entomophagy, and included scientists as well as farmers, non-profit organizers, and people from industry. Several major themes emerged during these different symposia that highlight questions desperately needing to be answered by insect scientists, including ecologists, from the perspective of those in the entomophagy industry:

- Which insect species are most feasible for farming on a large scale, processing, and eating? For example, which species are most easily reared? Most nutritious? Most energy efficient?
- What environmental conditions are most suitable for rearing different species of insects, and how might these conditions be achieved on a large-scale?
- Could wild-caught harvesting of particular pest species be a viable source of edible insects when outbreaks occur?
- How can insect waste (i.e., frass) be disposed of or otherwise used?
- What science-based recommendations might guide inevitable and necessary regulations of this industry?

From a scientific and conservation perspective, many additional crucial questions also arise:

- For insects that are wild-caught or raised at local scales, could population sampling, estimates, and modeling by ecologists help to set limits to sustain populations? For instance, some evidence suggests that the Mopane worm, an important edible insect in South Africa, is currently being unsustainably overharvested. Bioeconomic models have had mixed success in determining if a restrictive collection period may aid in more sustainably harvesting these larvae (Akpalu, Muchaponda, & Zikhali 2009). Perhaps ecological methods used in other systems to determine sustainable harvest levels may be used to mitigate the decrease or extinction of culturally important species that are currently treated as “open access resources” (Sileshi & Kenis 2010).
- How would an increase in the rearing of insects affect other ecosystem services? What might an insect farm that affects other ecological processes as little as possible look like?
- What chemicals are required on large insect farms as well as during insect processing and how will these affect habitats and organisms local to insect farms? For instance, although the presence of unsaturated fatty acids is beneficial to human nutrition, these fats are rapidly oxidized by microbes, thus lowering the shelf-life of insect food products (Van Huis et al., 2013). What types of chemicals might be used as preservatives in insect-based foods, and what environmental effects might these have? We have seen other preservatives, such as bisphenol A (BPA), have deleterious environmental effects.

For many of the reasons outlined above, there have been major efforts to promote the use of insects as a protein source, spurred in large part by the Food and Agriculture Organization of the United Nations report promoting insects as an important future food source (Van Huis et al. 2013). Since then, many non-profit NGOs with the sole purpose of promoting insects as food have been developed, and a boom in start-ups that either farm potential species of insects, process these insects, or use processed insects in food has arisen.
In many Western countries, the normalization of entomophagy faces an uphill battle: people are not accustomed to eating insects, the legal constructs of doing so are still fuzzy, and there is not much infrastructure or market currently available to promote insects as food. Because of the large benefits that switching even a fraction of protein intake to insects has for helping to remedy multi-faceted global anthropogenic problems, research related to entomophagy is a high priority, including ecological research related to this industry.

**Habitat degradation/land use change/deforestation**

Habitat loss and habitat fragmentation are two leading causes of biodiversity loss (Pimm & Raven 2000; Wilcove & Master 2005). Deforestation has led to the loss of approximately one third of the world’s forests, and forests remaining are highly fragmented (Haddad et al. 2015), which is additionally concerning because deforestation contributes to global climate change by decreasing plant biomass available to fix and sequester CO₂ (IPCC 2007). Current efforts to mitigate climate change include significant efforts to curb deforestation (IPCC 2007), but halting deforestation requires local communities to find alternative sources of income, particularly those that promote the protection of intact ecosystems. Sustainable ecotourism is one way that communities could benefit economically from healthy, intact forests (Hoefle 2016).

In Tlaxcala state, Mexico, old growth forests support dense populations of synchronous fireflies. Local communities, such as those in Piedra Canteada, have built an ecotourism industry around these fireflies that has allowed them to shift their economy away from logging. In the 1990s, the community in Piedra Canteada developed a cooperative, which is made up of 42 local families, to promote camping and generate ecotourism revenues from visitors from nearby Mexico City to their forest. In 2011, they had the idea to center their ecotourism efforts on the intense firefly displays, which can be seen from June through August. While some logging still takes place, wood production has declined 60–70%. The cooperative has preserved 630ha of forest, and are planning to plant trees in previously logged areas. The cooperative is now careful about the use of herbicides and insecticides to protect the firefly populations. The tourism during the three months that fireflies display generates more income than a year’s worth of logging, and is creating new jobs. Surrounding areas are following suit, with firefly tours of their own (Associated Press 2016).

Similar conservation efforts have sprung up around ecotourism centered on fireflies in Malaysia (Nallakumar 2003; Bhuiyan, Siwar, & Ismail 2016) and Thailand (Cohen 2009), as well as migrating monarch butterfly (Danaus plexippus) populations in Mexico. The Monarch Butterfly Biosphere Reserve was created by the Mexican government in 1986 to protect forest habitat used by the butterflies during their migration (Lopez-Hoffman, Varady, Flessa, & Balvanera 2010; Vidal, Lopez-Garcia, & Rendon-Salinas 2013). Long term studies show that this reserve, in combination with efforts to provide alternate incomes to local communities that protect the forests, have led to declines in large-scale illegal logging in the area (Vidal et al. 2013). These examples show how ecotourism surrounding insects can generate income for local communities while reducing deforestation and incentivizing sustainable management of local habitats.

An important vein of research in ecology in the past several decades has been the role of tourism and ecotourism in affecting ecological processes. If local insect displays and migrations continue to become an important basis for ecotourism in some areas, ecologists undoubtedly have an important role in understanding the effects of ecotourism on local economies and ecosystems. For instance, the benefits of ecotourism can be little if the attraction, e.g., insect display, is threatened by land use changes. This situation is playing out with another community that has benefited from ecotourism to see a synchronous firefly (Pteroptyx tener) in mangroves of Malaysia. Mangrove display trees have been destroyed by intensive land use changes, and recently no new display trees were found (Jusoh & Hashim 2012), threatening this ecotourism industry and the economic and ecological benefits that it could provide.

Ecologists may be instrumental in answering questions about insect species that are the basis for ecotourism (hereafter called focal species), and the ecosystems they inhabit:

- Are the populations of focal species stable?
- What are the habitat requirements of focal insect species, and how are those habitat requirements being affected (positively or negatively) by human activities or changing climate?
- What are the conservation needs of focal insects? How much land is required to keep focal species’ populations stable?
- How can the conservation needs of focal insects and ecosystems be met in a way that also provides for local socioeconomic stability?
- What new focal species could help local economies benefit from ecotourism? Before these types of new industries are established, can ecotourism occur in such a way to limit other environmental impacts?

**Opportunities for ecologists**

Scientists that study insects have been touting the positive effects that insects can have on humans for decades (Wilson 1987). Still, insects and insect scientists have a pervasive perception problem. We have provided examples of how insects are being used or could be used as part of the solution to many current global anthropogenic problems: food and fuel security, global inequities, the mitigation of global climate...
change, and deforestation and other activities that degrade the environment. The implications of all of the potential uses of insects in solving global problems are great for the science of ecology as we have described. Because we do have so many examples of the multitude of ways in which insects may be used to mitigate some of humanity’s major problems, we suggest that ecologists take advantage of these realities to battle the perception problems that insects and insect science currently face. We suggest that ecologists that study insects consider reframing their research questions to reflect that basic insect science can be crucial in dealing with some of these major issues. For instance, both of the authors are currently involved in a study that is examining how the diversity of orthopteran species affects how grasslands function. A typical “elevator pitch” for this research may be: “We study the role that orthopteran diversity may play in affecting the functioning of grasslands. This research is of critical importance given that grazing grasslands are often managed by spraying broad spectrum pesticides that kill all insects, but we have evidence showing that grasshopper diversity may promote ‘healthy’ grassland systems.” A more persuasive and positive pitch may highlight the crucial role of insects and our science: “We do basic science to understand how insects may be used to solve some of humanity’s global problems. Currently, a quarter of Earth’s surface is covered by rangelands, where grasshoppers are heavily managed with pesticides that kill indiscriminately. However, our research shows that a more diverse grasshopper community promotes a healthy rangeland, and thus could be beneficial to the management of grazing systems that are in turn crucial for society.” Too often scientists are hesitant to oversell the broader implications of their work. If, however, funding for insect conservation and basic insect ecology depends on public and policymakers’ opinion, we argue this type of rhetoric is timely and critical.

Conclusion

We have no illusions that all global problems will be solved using insects. But the potential for insects and insect science to contribute to the mitigation of these and other global problems is limitless and will be defined by creative insect scientists and others. We have given many examples in which insects are already being used to solve problems, or areas in which insects show great potential to solve problems. We implore ecologists to be part of these solutions by both understanding and communicating that their research is a part of these solutions, and to become engaged in basic and applied ecology that answers interesting and essential questions related to the implementation of insects being used to solve humanity’s current problems.

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