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Can we farm aquatic insects for human food or livestock feed?

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EDITORIAL

Abstract

Six of the 12 living orders of aquatic insects contain species engaged in entomophagy, but few are being harvested effectively, leading to overexploitation and local extinction. Existing practices range from including insects (e.g. dipterans) in the core diets of many indigenous peoples to consumption of selected insects as novelty food (e.g. caddisflies). Comparison of nutritional worth of aquatic insects to the human diet and to domestic animal feed are examined. Questions are raised as to whether natural populations of aquatic insects can yield sufficient biomass to be of practicable and sustained use, whether some species can be brought into high-yield cultivation, and what are the requirements and limitations involved in achieving this?

1. Background

More than 2,100 insect species are recorded to be consumed, chiefly in the tropics and subtropics. The orders with most species are the following in descending sequence: Coleoptera, Lepidoptera (caterpillars), Hymenoptera, Orthoptera, Heteroptera, Odonata, Isoptera, Diptera and others (Jongema, 2017). Insects are also increasingly being used as 'aquafeed' – see recent reviews by Lock *et al.* (2018) and Hua *et al.* (2019). Some terrestrial insect food species have advanced to the stage where their yields are very high and sustainable – see the recent rearing successes, on an industrial scale, using mealworms, crickets, houseflies and black soldier flies. Given these advancements in terrestrial insects, the purpose of this article is to explore the potential of aquatic insects in farming for human food and livestock feed.

2. Aquatic insects

Of the 30 orders of true insects, 12 are aquatic, or semi-aquatic, in either some or all life stages (egg, larva/nymph, pupa, adult). Of these, six contain species known to be eaten by humans, with an estimated 253 named species thought to be edible (Macadam and Stockan, 2017). These range from those (e.g. dipterans) forming the dietary cores of certain indigenous peoples to those such as caddisfly larvae, consumed as 'trendy' snacks (POGOGI, 2012; Polhemus and Polhemus, 2008) by a wealthy few in modern Western society.

Aquatic insects are a hugely diverse group, with around 76,000 species adapted to a wide range of habitats – from cold, freshwater springs, permanent ponds and lakes to large rivers, intermittent streams and phytotelmata – although they are very rare in the oceans (Williams and Feltmate, 2017). Insect orders contain species that are aquatic only in some life stages (e.g. mayflies, stoneflies, dragonflies, caddisflies, and megalopterans), whereas others contain both aquatic and terrestrial species (e.g. beetles, true bugs, neuropterans, orthopterans, and dipterans). Aquatic species live on various forms of decaying organic matter, associated bacteria and hyphomycete fungi. Algae are also grazed, and many species are predators, particularly those in the Odonata (e.g. dragonflies and damselflies), Heteroptera (pond-skaters, giant water bugs and water scorpions), and Coleoptera (diving beetles) (Merritt and Wallace, 2009). Aquatic insects respond to a variety of environmental conditions and are increasingly used as indicators of water quality (Hershey and Lamberti, 2001). Their use as human food and livestock feed is another application recently proposed (Williams and Williams, 2017), but while knowledge of terrestrial insect entomophagy is proceeding apace, the same is not true for aquatic insects.

3. Aquatic insects having the greatest harvesting potential

Six of the 12 orders of aquatic insects are likely to yield candidate species.

Ephemeroptera

There are over 3,000 known species of mayfly, the nymphs of which live in a wide range of freshwaters, especially running waters. Their candidacy lies in the ability of some species (e.g. *Hexagenia limbata*) to emerge from very large rivers in staggering numbers – enough to stop traffic at bridges over the Mississippi River. Although emergence is seasonal, the adults could be harvested and stored in bulk. The possibility of laboratory rearing such species has been trialled, including at elevated water temperatures, to speed up their life cycle. There has been some success (Fremling, 1973; Vancsa *et al.*, 2014/15; Waltz and Burian, 2008). In Malawi, adult *Caenis kungu* are collected and eaten as dried cakes, and on the shores of Lake Victoria mayflies of the genus *Povilla* are dried and made into 'insect flour' for meal preparation (Bergeron *et al.*, 1988). The crude protein content of dried mayflies in China has been reported to be 66% (Chen *et al.*, 2010).

Odonata

The almost 6,000 species of dragonfly and damselfly are found from the polar tree-line to the tropics, although the greatest diversity occurs in the latter. In China, nymphs of six to seven species are eaten regularly, especially *Crocothemis servilia*, *Gomphus cuneatus* and *Lestes praemorsa* (Feng *et al.*, 2001). In the Neotropics there is a preference for species of the family Aeschnidae. In Laos, the local peoples target individual adult *Anax guttatus* and capture them as a welcome addition to their diet (Pemberton, 1995). The crude protein content of nymphs varies between 40 and 65% (Chen *et al.*, 2010).

Trials have successfully reared the lentic species *Ischnura ramburii* in modest densities (>1,200), using fruit-flies as prey, but yields have yet to be financially viable (Locklin *et al.*, 2012).

Heteroptera

This order, 'true bugs', with its 3,800 species is perhaps the best-known and most extensively eaten group of aquatic insects. Not only are their nymphs and adults eaten, but also, in Mexico, their eggs (known as 'ahuahutle') – which, in the case of corixids (water boatmen) command a high price (Ramos-Elorduy, 2006; Van Itterbeeck and Van Huis, 2012). Giant water bugs (Belostomatidae) are eaten globally, but in many parts of Asia they are a prised delicacy (Durst and Hanboonsong, 2015; Tao and Li, 2018). In particular, *Lethocerus indicus* which grows up to 12 cm in length, is commonly eaten in southeast Asia. They can be caught at lights, to which they are attracted (DeFoliart, 2009; Hanboonsong, 2010), however artificial lights constitute a critical factor in the local extinction of the insect (Yoon *et al.*, 2010). The Rajamangala University of Technology Isan in Thailand seems to have developed a rearing method (Hanboonsong *et al.*, 2013). In other areas conservation techniques are proposed (Wang and Chen, 2018). There is potential for raising lentic species in tanks, with *Lethocerus deyrolli* responding to farming in Japan (Inoda, 2017; Inoda and Kamimura, 2004). Unfortunately, the highly cannibalistic nature of *Lethocerus* poses additional problems in designing farming protocols (Hanboonsong *et al.*, 2013). The water-scorpion, *Laccotrephes maculatus* (Nepidae) is eaten by the indigenous peoples of Manipur, India (Shantibala *et al.*, 2014) and, in Thailand, school children are encouraged to raise insects, including *L. indicus*, to promote nutrition (Yhoung-aree, 2010). Many of the insects consumed are gathered in the rainy season (May-July) when their pond and wetland habitats are abundant in the landscape (Williams, 2006). Edible heteropterans particularly attracted to these temporary waterbodies include naucorids (creeping water bugs), notonectids (back-swimmers), and gerrids (water striders) (Jongema, 2017). There has been some success in raising multiple generations of some of these smaller bugs in the laboratory, provided that they are supplied with suitable live food, for example as in the case of *Notonecta hoffmanni* (Hirooka *et al.*, 2016; McPherson, 1966). It should be possible to scale-up some of these methods for greater yield.

Coleoptera

There are more than 400,000 species of beetle, with roughly 5,000 considered to be aquatic. The latter are found in almost all freshwater habitats. Although key to the proper functioning of their respective ecosystems, lotic species are likely not good candidates for mass harvesting, with the possible exception of riffle beetles (Elmidae) (Ramos-Elorduy *et al.*, 2009). However, lentic dwellers, such as gyrinids and dytiscids, often occur naturally at high densities and might be more suitable. Globally, around 78 species are considered to be edible (Ramos-Elorduy *et al.*, 2009). Mexico leads with 36 species eaten, followed by China

(Pemberton, 1995), and Japan (POGOGI, 2012). Certain genera are favoured world-wide, with 22 species within the dytiscid genus *Cybister* recorded as eaten (Jongema, 2017). *Cybister tripunctatus* is well known for its high fat content and antioxidant properties (Shantibala *et al.*, 2014). In local markets in Guangdong, China, some highly sought after species are now being hatched in purpose-built nurseries (Inoda and Kamimura, 2004; Yhoung-aree, 2010). Parallel, mass rearing of mosquito larvae can provide a steady supply of prey.

Diptera

There are greater than 120,000 known species of true (two-winged) flies with many yet to be described. Of particular interest are four large aquatic families: Tipulidae (craneflies), Culicidae (mosquitoes), Chironomidae (non-biting midges), and Simuliidae (blackflies). The adults are typically terrestrial, with the pupae and larvae living in water (Williams and Feltmate, 2017). Populations can be vast in certain habitats where they have been studied largely from a human health perspective (vectors of disease, etc.). Far less studied has been their potential to provide humans with a high-quality food resource. The following are brief examples of these possibilities:

- Tipulidae. Craneflies are abundant in shallow waters where they are important in the break-down of riparian leaves. The larvae and adults are eaten by a wide variety of birds, fishes, amphibians and reptiles (Byers and Gelhaus, 2008), and their high diversity (over 15,000 species) should yield some that are suited to farming – perhaps in leaf-filled, polythene-lined pools. Many species are of a decent size (1-2 cm) for harvesting, but suitable methods would need to be developed.
- Culicidae. Several of the 3,500 or so of these biting flies have been studied because of the role in their transmission of diseases to humans. However, their global distribution, rapid development, and occurrence at very high densities make them prime candidates for entomophagy in several ways. For example, mass emergences of adult culicids, such as those that take place on the Arctic Tundra (Culler *et al.*, 2015), but which are not yet harvested. In contrast, emerging adults of the culicid sister group, the Chaoboridae, are actively and sustainably collected on the shores of Lake Victoria by local Luo villagers (Ayieko and Oriaro, 2008). At other sites, mass rearing and harvesting of culicids should be possible through scaled-up methods already proven in the laboratory (e.g. Das *et al.*, 2007; Vladimirova, 1966). Additionally, harvested larvae can provide food directly (dried) or provide live prey for cultures of dytiscid beetles and giant water bugs (see above; Chandra *et al.*, 2008).
- Chironomidae. Non-biting midges often occur at very high densities and have a global distribution. Around 5,000 species have been formally described, although in total the species count may exceed 20,000. They are mostly small, but the larvae of some (e.g. species of *Chironomus* – 'bloodworms') can exceed 1 cm. In the laboratory, the latter can be grown to adult size in as little as 20-22 days. Such cultures would seem to be good candidates for up-scaling to bulk production, particularly as they can be fed on farm manure and waste lagoon effluent on which, over 5 months, the larval yield was 51 kg, wet weight (Bouguenec and Giani, 1992). Further, Shaw and Mark (1980) reported that on a 13.5 ha farm in Hong Kong, chicken manure was successfully used to rear chironomids which were then used to feed fishes – the larval yield being 25 g/m^2 per week. The intervening 40 years do not appear to have produced further examples, although (Bektas and Guler, 2019) have reported the addition of aquatic insects to the feed rations of poultry.
- Simuliidae. Blackflies have been studied extensively due to their blood-sucking behaviour which spreads several human diseases, such as onchocerciasis (river blindness). Worldwide, there are around 1,900 species and, while the adults are terrestrial, the larvae and pupae are confined to rivers and streams where they attach themselves to solid surfaces and feed by filtering food particles from the passing water. Where conditions are favourable, the larvae can reach very high densities (120 per cm^2 of rock surface (Malmqvist, 1994) and emerging adults can form dense clouds. Clearly, both life history stages have high potential to be harvested for human food, as the larvae can be easily swept into a net and the adults are attracted by lights. Larvae also rapidly colonise flat, artificial substrates placed in areas of fast current. There are few recorded instances of such harvesting, apart from that of larvae being eaten by certain tribes in northern Thailand (Leksawasdi, 2010). There has been some success in rearing *Simulium damnosum* in the laboratory, in 1967 (Raybould, 1967), but nothing of significance since.

Trichoptera

There are of the order of 7,000 known species of caddisfly, all but a few confined to freshwater lotic and lentic habitats, where under favourable conditions they can reach very high densities. For example, where there are fast currents laden with fine particulate organics, larvae of the net-spinning families (e.g. Hydropsychidae) can occur at densities exceeding 1000 larvae per m^2. Synchronous emergence of adults from large rivers have resulted in 'shad-fly' plagues – made more troublesome by their attraction to lights in riparian suburbs, as is seen annually in the St. Lawrence and Niagara Rivers of Canada (Resh and Rosenberg, 2015). However, as with similar mass emergences, the biomass harvesting opportunities have been ignored – even if the insects might be collected, dried, and shipped to developing nations, rather than for 'home' consumption. There are some rare examples of entomophagy in caddisflies, most notably in Japan where larvae are boiled, sautéed in soya sauce and sugar, and sold as the delicacy 'Zaza-Mushi' (POGOGI, 2012). There are also anecdotal records of caddisflies being eaten in Mexico, and southern Asia (Deutsch and Murakhver, 2012).

4. Nutrition

Compared with terrestrial insects, there is very little information available on the nutritional value of aquatic insects. What is known is that the latter, in general, tend to be excellent sources of protein – for example, in mayflies it makes up 66.3% of their body weight, in odonates it is 40-65%, in heteropterans 42-73%, and beetles 23-66% (Chen *et al.*, 2010; Shantibala *et al.*, 2014). Insects are high in mineral content (e.g. iron and zinc), B-vitamins, and essential amino-acids (Bergeron *et al.*, 1988; Okedi, 1992). However, they tend to be low in carbohydrates. Eating insects in combination with another source of carbohydrate (such as rice, millet or cassava) could help towards creating a more balanced diet. Newly emerged adult females may have greater fat content in readiness for egg laying; there may be other seasonal variations and changes associated with life-history. Much more basic, quantitative research needs to be done on this aspect of nutrition (but see Bell *et al.*, 1994 and Ayieko *et al.*, 2010b).

5. Harvesting versus culturing

Interestingly, aquatic insects already contribute to the diets of some indigenous peoples, through harvesting of natural populations at times dictated by species availabilities. Knowledge of habitats and life cycles is fundamental for this, and likely has been drawn into local folklore and tradition. However, based on this same information there is the potential for culturing edible species, using the simplest of materials – such as creating shallow artificial ponds for attracting migrating adult water-beetles, or raising odonates, or placing flat tiles (or pieces of 'astro-turf') in rivers and streams for colonisation by net-spinning caddisflies or blackflies.

A form of cultivation, akin to mussel farming, has been practiced, historically, in Mexico to gather the eggs of aquatic heteropterans (Van Itterbeeck and Van Huis, 2012). Unfortunately, while there are published methods describing the mass rearing of insects in closed systems, there are relatively few that involve aquatic species (Cohen, 2018; Inoda and Kamimura, 2004). Future emphasis needs to be put on designing such rearing protocols – so that the bulk production success achieved with, crickets, mealworms and flies can be duplicated for aquatic insects. Cross-fertilisation of mass rearing ideas among taxa can be productive (Benedict *et al.*, 2009; Keiper and Foote, 1996; Mason and Lewis, 1970; Yokoyama *et al.*, 2009).

6. Conclusions

Of the 30 extant orders of insect, 12 are aquatic or semi-aquatic. Of the latter, six are deemed to be already used as food for humans and/or their livestock. However, these usages are, at present, very small. Table 1 summarises both these existing and possible future uses, and gives examples of potential harvesting protocols.

Of these six orders, there are few containing species that are being harvested effectively. Of those that are (e.g. beetles and heteropterans), their management is largely at

Table 1. Summary of the existing and potential use of aquatic insects as food and feed, together with possible protocols for harvesting.

Order/Family	Existing	Potential	Harvesting protocol
Ephemeroptera	low	could be higher	netting mass emergences of adults; possible breeding of lentics in tanks and lotics in reversed-funnel systems
Odonata	medium	could be higher	individually, via sap on sticks; possible breeding of lentics in tanks
Hemiptera	med/high	could be higher	netting and attracted to lights; up-scaling of lab protocols
Coleoptera	med/high	could be higher	wild collection of adults; some captive breeding
Diptera			
Tipulidae	none	could be viable	netting adults; creation of shallow, leaf-litter-filled pools for larvae
Culicidae	none	could be viable	netting of adults where dense
Chaoboridae	medium	viable	existing netting of adults where they occur on lake shorelines
Chironomidae	low	very high	wild collection where densities are high; up-scaling of lab-breeding protocols; waste lagoon rearing; route biomass through carp or *Tilapia* to improve aesthetics; use as animal feed for pigs, poultry, cattle
Simuliidae	very low	could be viable	collection of adults at lights; wild collecting of larvae on flat surfaces in fast water
Trichoptera	low	could be higher	wild-caught for specialist market; same as for simuliids; possibility of rearing lentic species in tanks/ponds

a 'hunter-gatherer' stage. Sustainability has hardly entered the equation and, therefore, an increasing number of species have become rare, for example the dytiscid beetle *C. tripunctatus* and the belostomatid *L. indicus*. Groups that currently have no or very little engagement with entomophagy are the craneflies (tipulids), biting midges (culicids), and blackflies (simuliids), but all of these have the potential to be higher, giving suitable improvements in rearing technology. Groups currently eaten by people, albeit at a low level, are the mayflies, caddisflies, and non-biting midges (chironomids) which again, with improved methodologies, have considerably higher potential. The latter applies also to those groups with a current medium engagement with entomophagy, namely the odonates, heteropterans, beetles, and chaoborids (phantom midges). A number of these are, however, facing local extinction if harvesting methods are not broadened to include population-sustainment. Other factors are also taking their toll, such as pollution, use of insecticides, and climate change (Ayieko *et al.*, 2010a; Ramos-Elorduy, 2006).

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