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Review

The ecological, economic and public health impacts of nuisance chironomids and their potential as aquatic invaders

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Abstract

This review examines the ecological, economical, and public health significance of chironomids and provides examples of chironomid invasions via international shipping and the subsequent local and regional impacts. Dispersal and adaptation mechanisms as facilitators of chironomid invasions are presented, and control methods are discussed. Impacts ranged from increased nuisance occurrences to agricultural disruption. Anthropogenic activities including pollution-related decimation of aquatic benthic communities might allow introduction of invasive chironomids. Chironomids can inhabit many environments, including eutrophic lakes and wastewater treatment areas, and may accumulate contaminants in high concentrations. Health concerns include the association of chironomid egg masses with *Vibrio cholerae*, roles of chironomids as vectors for avian botulism, and effects of chironomid chemicals as human allergens. Therefore, the presence of new chironomid species in an environment may present threats to public health and local ecosystems.

Key words: *Chironomidae*, swarms, disease-vector, agricultural pest, nuisance, allergen

Introduction

Chironomids are important organisms to consider from an invasive species perspective. Many studies focus on the ecological roles of chironomids (Oliver 1971; Armitage et al. 1995), associations with microorganisms (Halpern et al. 2004; Halpern et al. 2006; Halpern et al. 2007; Raz et al. 2010; Senderovich and Halpern 2012), and their use as indicator species (Wilson and McGill 1977; Ruse and Wilson 1994), but very few focus on the potential impacts of introductions of non-native chironomids into new environments. Chironomids exemplify the characteristics of invasive species (Demoor 1992). They have the ability to reproduce quickly and in large numbers, are highly diverse (Armitage et al. 1995), compete with other benthic organisms for food, are capable of thriving in low resource and otherwise undesirable locations, and can be transported long-range via human assisted means that make up for their lack of natural widespread movement (Brodin and Andersson 2009; Hughes et al. 2010; Evenhuis and Eldredge 2013; Gruszka et al. 2013). Chironomids can be tolerant to extreme environmental changes. Larvae of certain species are able to undergo complete desiccation and be revived under more amenable conditions (Hilton 1952). They can exist in temporary aquatic environments and adapt by digging deeper into sediment to find their preferred conditions (Frouz et al. 2003). Their resilient and rapid colonizing capabilities make them highly suitable for successful invasion of new territories. Indeed, previous instances of successful chironomid invasions (Jacobsen and Perry 2007) confirm the invasive potential of this adaptable group of organisms.

Chironomids have become a problem in urban and residential areas associated with polluted, warm, and/or eutrophic waters, because of their ability to adapt to harsh or unnatural environments (Clement et al. 1977; Tabaru et al. 1987; Langton et al. 1988; Hirabayashi and Okino 1998; Broza 2000; Broza et al. 2003; Frouz et al. 2003; Lods-Crozet and Castella 2009). In this paper, a review of the life cycle and negative impacts of chironomids introduces the means and effects an invasion could have on an ecosystem, causing new problems or amplifying existing ones. "Globally, nearly 100 of the 4,000 known chironomid species are documented as pestiferous" (Ali 1996). Chironomids are indeed of interest in invasive species biology due to their impact as nuisances, ecological disrupters, public health risks, and economic pests. This literature review examines that perspective and whether chironomids are a group of organisms that we should be concerned about as invasive pests.

Ecology and biology background

Life cycle

Chironomids start as eggs in a gelatinous matrix that is protective and often colonized by various bacteria. For most chironomid species, the subsequent life stages consist of four larval instars that develop in the water. Most chironomids are aquatic, however, the larvae of a few midge species, such as *Limnophyes minimus* Meigen, 1818, *Pseudosmittia longicrus* Kieffer, 1921, and *Smittia pratorum* Goetghebuer, 1927, can exist terrestrially in habitats such as soil and vegetation (Delettre 2000). The larvae of several species that are commonly referred to as "bloodworms" have a bright red color because they possess hemoglobin near the surface of the exterior larval casing. The hemoglobin molecules are conserved in the transition from larva to adult (Armitage et al. 1995).

The larval stage is followed by the pupal stage, which can be free-swimming or sedentary, also in the water. The pupae swim to the surface and emerge as adults to begin their terrestrial and aerial phases of life where they often create nuisance swarms when mating occurs.

For many chironomid species, the adult phase of life is short and therefore, synchronized emergence is an effective means for assuring that adult males encounter adult females leading to higher reproductive success. Since the larval stages sometimes occur in very high density, these synchronized emergences can create dense swarms of flying insects. In addition, seasonality of emergence can vary among species, and some species have multiple generations per season (Armitage et al. 1995). As a result, swarms of chironomids can occur several times per year.

Aquatic food web and trophic interactions

Chironomid larvae have a variable diet depending on the species. For example, some Tanypodinae midges consume various benthic invertebrates and *Chironomus attenuates* Walker, 1848 ingests oligochaetes (Loden 1974). Species of *Orthocladiinae* and *Tanytarsini* are prevalent colonizers and consumers of leaf litter in streams (Grubbs et al. 1995). Other species eat algae, plant matter or debris, and the large nuisance species *Chironomus plumosus* Linnaeus, 1758 employs a filter-feeding system (Oliver 1971).

Chironomids play an important role in the food web and in the transfer of toxic metals to fish that feed on them. Chironomid larvae are bioaccumulators of mercury, which is then present in adults in high concentrations (Chetelat et al. 2008). Accumulation of chromium and lead by chironomids was linked to the reactive and recoverable amount present in the sediment (Desrosiers et al. 2008). Other metals accumulated by chironomids include cadmium, copper, arsenic, iron, nickel and manganese (Desrosiers et al. 2008). A geological survey of the flora and fauna of Walnut Lake in West Bloomfield, MI, USA reported that fish diets consisted primarily of chironomid larvae (Hankinson et al. 1908). Fish that include high proportions of chironomid biomass in their diet include important commercial varieties such as Salmonidae, Coregonidae, and *Tilapia* species (Armitage et al. 1995).

The larvae of the chironomid *Cardiocladius oliffi* Freeman, 1956 is capable of feeding on *Simulium squamosum* Enderlein, 1921, an African dipteran fly associated with onchoceriasis (Boakye et al. 2009). Certain chironomid larvae are parasites of catfish, sponges, mayfly nymphs, and mollusks. Specifically, the parasitic *Baeoctenus bicolor* Saether, 1976 feeds on gill tissue of unionid bivalve mollusks (Gordon et al. 1978). As reviewed by Armitage et al. (1995), *Cryptochironomus spp.* are associated with parasitism in gastropods such as *Lymnea*, *Radix* and *Physa*. *Symbiocladius* spp. are ectoparasites of mayflies, attaching to the wing-buds and thus disrupting the normal developmental processes of the host. Non-indigenous chironomid introductions therefore have the potential to change ecosystems. Conceivably, native organisms may not have evolved the defenses needed to persist in the presence of the parasitic alien chironomids. Chironomids' trophic positions in the aquatic food web and environmental disruption may exacerbate the effects of an invasion event.

Ecosystem roles

Chironomids have a significant role in ecosystems, as they are often the most prevalent freshwater invertebrates in their environment. They influence the energy flow of aquatic systems by representing a large percentage of the biomass found in lower trophic levels. Distributions of species in the benthic community are affected by environmental parameters including pollution, industrialization, urbanization, and eutrophication. Chironomids are particularly resilient in their ability to adapt to harsh environmental conditions, for example, in flooded soils that eventually dry out, rain pools, and moss patches that are only temporarily aquatic (Frouz et al. 2003).

Chironomids are capable of having significant effects on other forms of life in their environment, including plants and other organisms. Larvae of *Cricotopus lebetis* Sublette, 1964 are known to damage hydrilla plants by nestling in submerged stems and burrowing further throughout their development (Cuda et al. 2002). Although hydrilla is considered an invasive aquatic weed, this example suggests that chironomid larvae have the potential to damage other plants, such as rice crops (Clement et al. 1977; Marcum 1998; Stevens et al. 2006), triggering as yet unpredictable effects on natural ecosystems. Interestingly, a negative correlation of Eurasian milfoil, an aquatic invasive plant species, with midge presence suggests a potential biological control against milfoil infestation (Johnson and Mulla 1983).

Biogeography and limitations on dispersion

Chironomids are rapid and opportunistic colonizers of aquatic environments. For example, in Switzerland, chironomids quickly colonized shallow ponds created in an attempt to retard the terrestrialization of surrounding wetlands (Lods-Crozet and Castella 2009). In England, when a relief channel was constructed in the River Thames, a series of lakes were created and quickly colonized by chironomids (Ruse 2002). The man-made Volta Lake in Ghana was rapidly colonized by *Chironomus, Nilodorum,* and *Dicrotendipes* and made up eighty percent of the total invertebrate population in the initial stages of the lake, and constituted sixty-eight percent of the total invertebrate community as the lake matured (Petr 1971).

Chironomid distributions are limited by environmental factors, including the sediment content and the quality and salinity of the water (Armitage et al. 1995). For example, the non-native splash zone midge, *Telmatogeton japonicus* is known to thrive in waters of high salinity, but its tolerance to freshwater is unknown (Raunio et al. 2009). Because the usual habitat of *T. japonicus* is salt water, its invasion of coastal sea areas (Raunio et al. 2009) was at least somewhat predictable, but its potential to invade adjacent freshwater areas is likely be limited.

Chironomid distribution is also limited by their natural methods of dispersal. *Halocladius* is known to spread short distances by aerial routes within a range of one hundred to two hundred meters (Neumann 1976). The oviposition flight is up to eight hundred and fifty meters for *Chironomus imicola* Kieffer, 1913 (McLachlan 1983) and up to one thousand meters for *Chironomus anthracinus* Zetterstedt, 1860 (Tokeshi and Reinhardt 1996). Without human and animal assistance, long-range movement of chironomids between and within biogeographical regions would be nearly impossible. However, natural limitations to long distance movement may be bypassed by being transported by airplane or boat. Moreover, as waters undergo eutrophication and more man-made aquatic structures are constructed, chironomids may find more areas subject to their invasion worldwide.

Some reviews regarding the worldwide biogeographic distribution of chironomids are available (Brundin 1966, Ashe et al. 1987); however, a recent comprehensive review of chironomid worldwide biogeography is not available (Armitage et al. 1995). Determining natural distributions of chironomids is difficult because the lives of identifiable adults is brief and the identification of larval forms is difficult due to the lack of species level classification keys. Issues such as a constantly changing environmental landscape and the presence of morphologically similar species make tracking current biogeographic data very difficult for chironomids (Armitage et al. 1995). However, the recent development of molecular bar-coding for larval forms (Carew et al. 2011) may enable greater understanding of chironomid biogeography.

Stress tolerance and use as bio-indicators

Chironomids often serve as indicators of water and sediment quality (Wilson and McGill 1977; Ruse and Wilson 1994). The taxa of chironomids in an environment can also indicate the type of pollutants present, as certain chironomid species may be especially resistant to specific types of pollutants. For example, *Cricotopus* and *Tanytarsus* species were present in sewage-related locations, *Procladius* and *Dicrotendipes* were associated with areas rich in agricultural run-off, and *Chironomus* was correlated with alkaline waters and organic pollutants (Rae 1989). *Chironomus* *decorus* Johannsen, 1905 and *Glyptotendipes paripes* Edwards, 1929 larval densities were positively correlated with the density of algae in the environment and *Chironomus crassicaudatus* Malloch, 1915 was associated with the presence of cyanobacteria (Ali et al. 2002). Such tolerance allows them to potentially outcompete native benthic species in stressed aquatic ecosystems.

Impacts of chironomids

The negative impacts of chironomids described in this section are used to illustrate how alien chironomid species could negatively affect the habitat and ecology of invaded areas. While native chironomid populations also cause many of the problems described here, an invader with aggressive reproductive strategies could exacerbate such impacts. The economic and general nuisance issues are the most concrete examples of problems for humans in nearby chironomid-rich environments. Previous studies of the ecological and public health implications of chironomids warrant additional concern regarding the impacts of new introductions of chironomids. Invaders could cause these negative impacts themselves and potentially amplify the negative impacts of native populations.

Nuisance pests

As summarized in Table 1, mass chironomid emergences have enormous nuisance potential. The most common complaints about chironomids are that large numbers of flying insects die in high concentrations, which affects the cleanliness of the area, including cars and buildings. Dead chironomids increase slip and fall risks and health hazards that include respiratory allergens and breeding or transport of pathogenic bacteria (Hirabayashi and Okino 1998). Swarming chironomids can damage property, cause a persistent smell akin to rotting fish, get inside homes through screen doors, and fly into pharmaceutical or food products in areas associated with these industries (Tabaru et al. 1987). For many species, swarms occur in the evenings, are attracted to light, and can dangerously or economically impact human evening activities. For example, swarms of *C. plumosus* interfered with an evening baseball game of an American League playoff in Cleveland, Ohio USA (Withers 2007). Effects of swarming chironomids on automobile transportation include clogging radiators and air conditioning units, obscuring windshields and headlights, and creating slippery road conditions.

Swarms occurring in tourist areas, which are often located near water bodies that may be suitable for chironomid reproduction, can deter tourists, causing millions of dollars in lost revenues (Ali 1996). One lakefront business is cited as spending fifty-thousand dollars annually to control the swarms and clean up after them (Ali 1996). As many as ten thousand chironomids have been caught by a single light trap near Lake Suwa, and more than thirty percent of tourists surveyed responded that they "could not stand anymore" the emergences of nuisance chironomids under such conditions (Hirabayashi and Okino 1998). Common nuisance associations occurred in urban and eutrophic natural water bodies as well as in man-made aquatic infrastructure, such as wastewater treatment areas, drinking water treatment facilities, water spreading basins, fish farms, rice paddies, and sewage ditches. Effects range from general nuisance to public health and safety concerns and local economic impacts. Table 1 summarizes some specific examples of nuisance chironomids.

Public health

Vectors for disease organisms

Although chironomids do not bite and spread disease, such as malaria or West Nile virus, like their relatives the mosquito, they nevertheless can have significant impacts on public health. Chironomids can be vectors for the spread of pathogenic species of bacteria. Because chironomids often colonize drinking water and wastewater treatment facilities, the threat of contamination from bacterial organisms such as *Salmonella* or *Vibrio cholerae* Pacini, 1854 is plausible.

Association of chironomid egg masses with *V. cholerae* and various other bacterial pathogens has been described by Halpern et al. (2007). *V. cholerae* was found mostly inside chironomid eggs and was observed to be responsible for their degradation. The breakdown of the chironomid eggs by the *V. cholerae* hemagglutinin protease provides nutrients for other bacteria, including pathogens such as *Aeromonas veronii* Hickman-Brenner et al. 1988, *Aeromonas caviae* (ex Eddy 1962) Popoff 1984, and *Aeromonas hydrophila* Schubert 1964, that occur in the exterior egg matrix (Halpern et al. 2007). *V. cholerae* populations associated with chironomids increase in direct proportion to water temperature, with 35 different *V. cholera* serotypes detected (Halpern et al. 2004).

Table 1. Pestiferous Chironomid occurrences.

Specific species or general population	Area of concern	Environmental characteristics	Nuisance effects	Reference
Glyptotendipes paripes and *Chironomus crassicaudatus*	Lake Monroe-Sanford, FL, USA	Eutrophication of natural body of water	High larval density (6000 larvae/square meter) leading to massive swarms and economic impact (3-4 million US dollars spent to control and clean up), decreased tourism	Ali and Baggs 1982
Tokunagayusurika akamusi Tokunaga, 1938 and *Chironomus plumosus* and the general population	Lake Suwa, Japan and Japan in general	Eutrophication of natural bodies of water, alteration in pollution levels, change from brackish to freshwater, algal blooms, increased vegetation	Massive emergences from bodies of water mostly in the summer months. Severe economic, safety and nuisance effects at residences, resorts, businesses and streets. Increased complaints and decreased tourism	Tabaru et al. 1987; Sasa 1987; Iwakuma 1992
Chironomus salinarius and general population	Italy	Salt-water lakes	Massive emergences during peak months, safety concerns at Marco Polo airport in Venice, as dead midges are known to accumulate on runways	Ali and Majori 1984; Armitage et al. 1995
Chironomus sp. and general population	Ibirtie watershed, Brazil	Urbanization and eutrophication	Massive nuisance emergences	Moreno and Callisto 2006
General population	Bedok reservoir, Singapore	Possible elimination of small chironomid feeding fish by the presence invasive fish species, urbanization	Massive nuisance emergences, local economic impacts, health concerns (allergy)	Lin and Quek 2011
General population	Israel	Man-made aquatic infrastructure-wastewater stabilization ponds, drinking water treatment facilities	Massive nuisance emergences ("Billions emerging each day")	Broza 2000
General population	Any location using water spreading basins	Man-made aquatic infrastructure-water spreading basins	Spread of chironomids from one aquatic environment to another	Bay et al. 1966
Cricotopus subletteorum Spies, 1998	Southern California, USA	Natural bodies of water in proximity to urban areas	Massive nuisance emergences, unpredictable and frequent	Spies 1998
Chironomus plumosus	Cleveland, Ohio,USA	Natural bodies of water in urban areas	Massive nuisance emergence, interfered with baseball playoffs game	Withers 2007
Chironomus calligraphus	Georgia,USA	Man-made aquatic infrastructure, wastewater treatment facilities	Massive nuisance emergences- thrives in diverse habitat	Gray et al. 2012
Paratanytarsus grimmii Schneider, 1885, *Tanytarsus* spp., *Micropsectra* spp., *Chironmus* spp., *Polypedilum* spp., *Paratanytarsus* spp., *Cricotopus* spp.	Germany, England, Cyprus, Japan (wide range)	Man-made aquatic infrastructure, drinking water treatment systems-larval colonization of granular activated carbon absorbers and the slow sand filter beds	Contamination of drinking water; spread of larvae or eggs to aquariums through tap water	Langton et al. 1988; Olsen et al. 2009; Peters et al. 2003; Hirabayashi et al. 2004; Learner 2000; Alexander et al. 1997; Duggan 2010
Limnophyes minimus and *Metriocnemus eurynotus* Holmgren, 1883	Sewage areas	Sewage associated locations	Massive nuisance emergences	Learner 2000
General population	Switzerland	Man-made shallow ponds created to retard the terrestrialization of wetlands	Rapid and opportunistic colonization of a new environment	Lods-Crozet and Castella 2009
General population	England	Man-made relief channel in the River Thames leading to the creation of a series of lakes	Rapid and opportunistic colonization of a new environment	Ruse 2002
Chironomus spp., *Nilodorum* spp., and *Dicrotendipes* spp.	Ghana	Man-made lake- Volta lake	Rapid and opportunistic colonization of a new environment	Petr 1971
General population	England	Man-made relief channel in the River Thames leading to the creation of a series of lakes	Rapid and opportunistic colonization of a new environment	Ruse 2002

While most strains are not the O1 and O139 strains that cause lethal human disease, other *V. cholerae* strains can also cause illness. Among humans, volunteers who ingested non-O1 strains of *V. cholerae* experienced symptoms similar to the classical pathogenic responses, but of smaller duration and severity than caused by O1 or O139 infections (Cheasty 1999). *Aeromonas sanarellii* and *Aeromonas taiwanensis* were both identified in chironomid egg masses in the same area where they were isolated from the feces of patients with diarrhea (Beaz-Hidalgo et al. 2012). *Aeromonas aquariorum*, another dangerous bacterial species known to cause diarrheal sickness, is also associated with chironomid egg masses (Figueras et al. 2011). Chironomids that grew in *Salmonella*-contaminated areas produced culture positive *Salmonella* that carried over to the adult stage (Moore et al. 2003). In addition to *V. cholerae*, *Aeromonas*, and *Salmonella* as potentially pathogenic types, the egg masses are also associated with bacteria that are resistant to metals and pollutants, which may convey protection to chironomid larvae in contaminated waters (Senderovich and Halpern 2012).

Waterfowl interactions with chironomids may possibly be a link in the spread of *V. cholerae* (Halpern et al. 2008) and other pathogens. Chironomid larvae are part of the waterfowl diet and can survive gut passage, supporting the possible spread of cholera mediated by chironomids (Green and Sanchez 2006). Non-O1 strains were isolated from fish, such as tilapia, that are known to eat chironomid larvae and are themselves part of the waterfowl diet (Halpern et al. 2008). A connection between chironomid larvae as vectors for the transfer of botulinum toxin to birds has also been suggested. Birds can pick up the toxin directly from the water or secondarily as a consequence of eating invertebrates, such as chironomids (Sonne et al. 2012). Significant levels of the type E botulinum toxin have been measured in chironomid larvae (Perez-Fuentetaja et al. 2011).

Allergy associations

The role of chironomid antigens in human allergy is supported by several studies. Thirty percent of asthmatic patients in a study had a positive IgE-mediated hypersensitive reaction to extracted chironomid antigens (Sasa 1987). Chironomid hemoglobins are the likely causative agent of environmental allergies associated with nuisance swarms (Cranston et al. 1983). Strong allergic reactions were elicited via skin tests using chironomid hemoglobins (Baur et al. 1982). In a Spanish clinical case study involving patients who presented with allergy symptoms (conjunctivitis, rhinitis, bronchial asthma, and/or urticaria) to fish food that contained chironomids as an ingredient, skin prick tests with chironomid extracts produced positive reactions in four out of five patients (Aldunate 1999). In another study, a fifty-four year-old man developed IgE-dependant nephrotic syndrome due to the inhalation of ground chironomid larvae in the preparation of fish food; the respiratory allergen was identified as hemoglobin, Chi t 1, of *Chironomus thummi* Kieffer, 1911 (Moneret Vautrin and Bertheau 2005). Thus, large swarms of nuisance chironomids pose a public health threat to those suffering from allergies, as inhalation is sufficient to trigger serious reactions.

Agricultural pests

Chironomids pose a threat to agriculture, as the larvae of some species are capable of colonizing vegetation in newly flooded rice paddies. The rice economy of Asia, Europe and North America is negatively affected by the rapid colonization of pestiferous chironomid species. Larvae of *Chironomus* species have been observed to harm the roots of rice plants, diminishing the ability of new crops to take hold in Australia (Stevens et al. 2006). In the USA, destruction of rice fields by chironomids has been reported in northern California (Marcum 1998). The most commonly observed species in California rice paddies were *Paratanytarsus* sp., *Tanytarsus* sp., *Cladotanytarsus* sp., *Paralauterbornellia* sp., *Procladius* sp., *Cricotopus sylvestris* Fabricius, 1794 and *Cricotopus bicinctus* Meigen, 1818 (Clement et al. 1977). Larvae of these species were most likely transferred to the rice fields via adult midge females from nearby aquatic environments and were observed to damage the rice plants by feeding on the seeds themselves as well as on the growing seedlings (Clement et al. 1977). Some species of *Orthocladinae* damage crops such as horseradish, and lotus leaves reportedly are consumed by *Stenochironomus nelumbus* Tokunaga, 1935 (Tabaru et al. 1987).

In addition to threatening agricultural plants, chironomids can also colonize fish culture ponds, posing a nuisance to the workers in this industry and possible contamination of the fish or other seafood products associated with the infested area. Chironomids are also nuisances at eel ponds. When eel food was switched to raw fish, it encouraged the mass breeding of pest species such as *Polypedilum nubifer, Cricotopus bicinctus,* and *Chironomus* sp. (Tabaru et al. 1987). The monitoring and control of midges in these situations is important to consider, as some species are known agricultural pests that could be transferred to non-native environments.

Table 2. Examples of invasions of non-native chironomids.

Species Name	Origin	Invasion Location	Invasion Method	Impacts	Reference
Polypedilum nubifer Skuse, 1889	Afrotropical, Palearctic, Oriental and Australasian regions	Florida, USA, Missouri,USA	Unknown	General nuisance, colonization of aquatic infrastructure, agricultural impacts	Jacobsen and Perry 2007; Li et al. 2011; Stevens et al. 2006; Wallace et al. 2009
Chironomus calligraphus Goeldi, 1905	Neotropical	Coastal Georgia,USA	Unknown	Colonization of aquatic infrastructure (wastewater treatment lake), economic impacts	Gray et al. 2012
Chironomus columbiensis Wulker, Sublette, Morath & Martini, 1989	South and Central America	Florida,USA	Unknown	Colonization of temporary, man-made aquatic environments	Hribar et al. 2008
Telmatogeton japonicas Tokunaga, 1933	Japan, Hawaii	Germany, Denmark, Sweden, Poland, Belgium, Great Britain, Madeira, Azores, New York, Florida, Canada, Iceland	International shipping, ballast water	Not reported	Brodin and Andersson 2009; Jensen 2010; Raunio et al. 2009
Kiefferulus longilobus Kieffer, 1916	Australia, Thailand	Hawaii	Airplane stowaways	Not reported	Evenhuis and Eldredge 2013; Cranston et al. 1990; Cranston 2007
Cricotopus bicinctus Meigen, 1818	Continental United States	Hawaii	Unknown	Agricultural impacts- rice pest	Englund and Arakaki 2004; Boesel 1985
Eretmoptera murphyi Schaeffer, 1914	South Georgia (South Atlantic Ocean)	Antarctica	Soil transplant experiments, imported construction vehicles	Increased nutrient cycling compared to sparse native fauna and introduction of fungal commensals	Hughes and Worland 2010; Hughes et al. 2013
Limnophyes minimus Meigen, 1818	Palearctic region	Marion Island (sub-Antarctic Indian Ocean islands)	Unknown	10 fold increase in nutrient cycling	Hanel and Chown 1998
Thalassomya frauenfeldi Schiner, 1856	Unknown	Turkey	Unknown	Not reported	Tasdemir 2012; Saether and Spies 2011

Interspecific chironomid competition

Chironomus plumosus is known to negatively affect native species of chironomids. When *C. plumosus* was experimentally added to a system with the typical invertebrate population of a lake in Poland, the populations of the midges *Tanytarsus gregarius* Kieffer, 1909 and *Cladotanytarsus mancus* Walker, 1856, both primarily utilizing a plant diet, were reduced [Kajak et al. (1968) as cited in Armitage et al. (1995)]. In Japan, *Spaniotoma akamusi* Tokunaga, 1938 larvae share a habitat with *C. plumosus* but may avoid interspecific competition by emerging at different times and by burrowing deeper into sediments than *C. plumosus* (Yamagishi and Fukuhara 1971). Competition between species is a realistic means by which a non-native could replace or interfere with a native chironomid species.

Chironomid invasions

Instances of new infestations of chironomids are known and established. Some chironomids may also facilitate the introduction of other invasive species (Coulter et al. 2011; Jackson et al. 2012) and can result in changes to existing aquatic habitats. Table 2 summarizes known invasions of new habitats by non-native chironomids, along with documented impacts where their effects have been studied. An invasive chironomid can cause problems that exceed the extent of those caused by the native populations. The addition of new species could exacerbate environmental, economic, nuisance and public health issues.

Although some species mentioned in Table 2 do not have reported effects, their status as non-native in addition to their potential impacts, are of interest. In general, many of the Chironomidae family have the properties of invasive organisms, including high fecundity, aggressive colonization, ecological impacts, negative impacts on human health, environmental damage, reduction of biodiversity, multiple means of dispersal, and negative economic effects (Demoor 1992; NISC 2006; Litchman 2010). The known negative impacts of chironomids imply that non-native species are capable of causing such damage; however, further research is needed in many cases to determine if particular chironomid invasions have harmful effects.

Invasion examples

The first documented evidence of *Polypedilum nubifer* in Florida occurred in October 2002 in the Florida Everglades (Jacobsen and Perry 2007). This species reaches nuisance numbers in Asia (Li et al. 2011) and Australia (Stevens et al. 2006), and thus is a concern in new habitats. *P. nubifer* is a common inhabitant of warm eutrophic waters and causes many problems in areas such as drainage channels, water treatment ponds, and rice fields. *P. nubifer* larvae recently have been identified in Missouri (Wallace et al. 2009). Other species of the genus *Polypedilum*, such as *P. halterale* Coquillett, 1901 and *P. digitifer* Townes, 1945, are also noted as nuisance species (Boesel 1985). *P. nubifer* has been reported to cause heavy losses to the rice economy in China (Li et al. 2011). The wild rice industry is an important natural resource and economic feature around the Laurentian Great Lakes (Drewes and Silbernagel 2012) and could be negatively impacted by a further range extension of *P. nubifer* and other chironomid rice crop pests.

Another example of an invasion by a non-native chironomid is the unintentional introduction of *Eretmoptera murphyi* to the South Orkney Islands, Antarctica. *E. murphyi* reportedly was introduced into Antarctica with soil samples and imported construction vehicles; however, other explanations have been suggested because it was not discovered until the 1980s (Hughes et al. 2010; Hughes and Worland 2010). *E. murphyi* has been reported to reach densities as high as 400,000 individuals m^{-2} on Signy Island (Hughes and Worland 2010). *E.murphyi* is a detritivorous midge, and its presence is thought to have greatly increased nutrient cycling in invaded areas (Hughes et al. 2013). A range of fungal species were found in the gut of the invasive midge *E. murphyi* (Bridge and Denton 2007). Although these species of fungi are only associated with the gut of arthropods, this indicates the potential of chironomid larvae to harbor more dangerous strains, as over 90 different species of fungi are associated with chironomid digestive systems (Siri et al. 2008). When a chironomid invades a new environment, it represents the invasion not only of an insect, but also of all of the parasites and commensals associated with it (Bridge and Denton 2007).

Limnophyes minimus Meigen, 1818 has invaded new habitats, including Marion Island, a sub-Antarctic island in the Indian Ocean (Hanel and Chown 1998). *L. minimus* is estimated to have increased nutrient cycling at least ten-fold more than the native species that mediated that ecological function. Chironomid invasions of Antarctic, sub-Antarctic, and comparable invasions in Arctic regions are expected to become more common as global warming enables growth of midge populations in these regions. Correspondingly, temperate areas, such as the Great Lakes may experience successful introductions of sub-tropical species.

The first report of *Chironomus calligraphus* Goeldi, 1905 in the state of Georgia appeared in 2012 (Gray et al. 2012). *C. calligraphus* occurred at nuisance densities in a wastewater treatment lake of a pulp plant in coastal Georgia, causing substantial economic impact. Since *C. calligraphus* is described as having a predominantly Neotropical distribution, this infestation represents an invasion by a non-endemic species. A study of the site revealed that larvae were primarily associated with leaf sheaths and root masses of cattails in the lake, which led to a successful pest management system involving the removal of all cattails plus the application of larvicide. Also of the genus *Chironomus*, *C. columbiensis* displays a penchant for colonization of man-made and temporary aquatic environments, which can lead to economic and nuisance effects in introduced regions (Hribar et al. 2008).

The rice pest *Cricotopus bicinctus* has been recorded as an introduced species to Hawaii (Englund and Arakaki 2004). While currently considered common in Ohio, *C. bicinctus* was formerly found in very low numbers in that Great Lakes state. *C. bicinctus* is a known pest that causes agricultural disruption in rice fields (Clement et al. 1977) and yields nuisance populations in areas associated with aquaculture, such as eel ponds (Tabaru et al. 1987).

Telmatogeton japonicus, a marine splash midge, was transported to Europe from the Pacific region probably via shipping, as they are known to attach to ship hulls and possibly in ballast tanks (Brodin and Andersson 2009). The ability of *T. japonicus* to be moved via shipping in the east Atlantic Ocean and south Baltic Sea suggests that *T. japonicus* could also be introduced into other suitable aquatic environments, such as the Great Lakes; however, the tolerance of this splash zone chironomid to freshwater is unknown.

New invasion or cryptic species?

Identification of chironomids is difficult and presents problems for determining presence of non-native species. It is possible that newly discovered species are in fact cryptic species that do not represent an invasion. For example, *Thalassomya frauenfeldi* was observed in Turkey (Tasdemir 2012) and may represent a new introduction, as reference biogeographical data indicates it as "doubtful" in Turkey, but could also represent a previously un-described endemic species (Saether and Spies 2011). Additionally problematic is that many habitats have not been adequately surveyed for chironomids, or identifications have not been made to the species-level.

Invasion routes

Because their life cycle comprises benthic, pelagic, aerial, and terrestrial phases, chironomids have multiple means by which they can be introduced and spread. Among the invasion methods are natural and human-mediated transport. Unlike many other aquatic invasive species, chironomids can disperse by aerial routes (Delettre and Morvan 2000). In Iowa fishponds, the spread of native chironomids to nearby bodies of water took about two weeks from initial filling of a source pond (Kaatz et al. 2010). Passive dispersal by wind can take adults much further (Armitage et al. 1995).

Chironomids travel still further by hitchhiking on other organisms, such as birds, as suggested by Darwin when referring to the transport of lower freshwater animals by waterfowl (Darwin 1859). Soil containing chironomid larvae has been shown to adhere to the feathers and feet of birds as they flew from place to place (Frisch et al. 2007). Bird feces is another route, as live *Chironomus salinarius* Kieffer, 1915 were detected in the feces of black-tailed godwits in Spain (Green and Sanchez 2006).

Chironomid mobility is also mediated by turtles. The marine chironomids, *Pontomyia* sp. and *Clunio* sp., have been found among the epibiota on Hawksbill sea turtles in Puerto Rico (Scharer and Epler 2007). Most reports of this genus have been from the Indo-Pacific and according to Scharar and Epler (2007) only a few reports previously from Florida and Belize. Whether this represents a new introduction or not, the observation on sea turtles certainly represents a means for non-native chironomid expansion once introduced to new environments. Freshwater turtles may also mediate chironomid dispersal since *Chironomus inquinatus* Correia, Trivinho-Strixino and Michailova, 2006 larvae were reported as epibionts on the side-necked turtle, *Phrynops geoffroanus* Schweigger, 1812 in Brazil (Marques et al. 2008). These natural dispersal mechanisms of chironomids are important considerations for their further dispersal within an ecosystem or region once invasion has occurred.

Man-made forms of long distance transport also mediate chironomid movement to foreign environments. The spread of *K. longilobus* to Hawaii has been speculated to have occurred as adult stowaways on airplanes (Evenhuis and Eldredge 2013). The invasive chironomid, *E. murphyi,* was detected in non-Antarctic soil samples taken from construction vehicles imported from the Falkland Islands and South Georgia in the South Atlantic Ocean (Hughes et al. 2010). As with many other aquatic invaders, ballast tanks can be a vehicle for introduction of chironomids. At a Polish shipyard in the south Baltic Sea, the ballast tank sediments of ships from various European ports were found to harbor many organisms including chironomid larvae (Gruszka et al., 2013). Attachment to ships' hulls, as in the marine splash midge, *T. japonicas* (Brodin and Andersson 2009), is another means of international shipborne transport.

The sale of aquarium fish food and fish bait represents another path by which chironomids may be introduced into new environments. First, they may be sold directly under the label of "bloodworms" as live fish food. Seaweed packaging accompanying the sale of bait worms is another vector for the transfer of chironomids, as chironomid larvae have been found adhering to such plant material (Haska et al. 2012). Such anthropogenic dispersal mechanisms are important considerations for developing methods of preventing invasions of non-native chironomids over long distances (e.g., intercontinental).

Discussion of invasion trends

Table 2 reveals the common effects of the introduction of non-natives. Six of the nine examples of non-native chironomids have documented impacts in their introduced regions. With four of six cases represented, the most common effects were related to the colonization and disruption of man-made aquatic infrastructure and agriculture (*P. nubifer, C. calligraphus, C. columbiensis,* and *C. bicinctus*), which can lead to economic loss and increased nuisance presence in populated areas. Two of six cases (both in Antarctica) show impacts on nutrient cycling in isolated ecosystems (*E. murphyi* and *L. minimus*). As mentioned and demonstrated by *E. murphyi*, introduction of commensals is also a concern in a chironomid invasion. The remaining 3 of 9 cases do not have studied or reported impacts (*T. japonicas, K. longibilus* and *T. frauenfeldi)*, but are of interest due to their means of spread and introduction, and in the case of *T. frauenfeldi*, to illustrate the uncertainty between detection of invasive species and clarification of their status as cryptic endemic species.

Considering means of transport, three of the nine cases in Table 2 were assisted by man-made forms of transport, as evidenced by *T. japonicas*, *K. longibilus,* and *E. murphyi* (ships, airplanes, motor vehicles and ships, respectively). Of the cases that do not have a reported method of introduction, similar forms of transport very likely played a role to overcome the barriers to invasion. Once a non-native reaches a new environment, the novel methods of short range spread mediated by other organisms, such as birds and turtles, as well as the natural dispersal methods of wind and flight may facilitate invasion. Table 2 also illustrates frequent features of invaded ecosystems. Of the nine cases, eight involved transfer of a non-native to a coastal region (*P. nubifer, C. calligraphus, C. columbiensis, T. japonicas, K. longibilus, C. bicinctus, E. murphyi, and L. minimus*). The exception to this is *T. frauenfeldi*, which has been suggested to be a non-native, but is not established as such due to the possibility that it represents a cryptic species previously un-described in Turkey. Of the seven coastal cases, four were invasions of isolated environments (Hawaiian and Antarctic islands), suggesting that ecosystems removed from the distribution of most chironomid species are highly vulnerable. Because most chironomid species have a cosmopolitan distribution (Coffman 1978), newly formed aquatic habitats within a region of established chironomid presence are also of concern. For example, in an area where a nuisance chironomid is known to occur, a new drainage canal or aquaculture venture constructed in a populated area several miles away from a source lake may enable a native to become a nuisance invader within its own region.

Potential magnification of negative impacts

Recent trends in invasive ecology support the idea that native species in stressed environments may not be well suited for rapid and dramatic environmental change. When rapid environmental changes occur, organisms that can adapt to the harsh, unnatural, or unfamiliar conditions have a significant survival advantage. In polluted areas or areas otherwise inaccessible to other benthic organisms, such as wastewater ponds, sewage systems, temporary aquatic environments and man-made aquatic infrastructure, chironomids have an advantage. Their resistance to pollutants, numerous mechanisms of spread, ability of the larvae of some species to inhabit low-oxygen environments, and often high fecundity allow them to thrive in stressed or opportunistic conditions where other organisms are less successful.

If an invasive non-native chironomid can coexist with native populations this could potentially amplify the presentation of documented negative impacts. If the invaders were able to adapt to the conditions of the new environment without displacing the local natives, for example by reproducing at a different time than the native species, then negative impacts might be seen at times when they were previously not occurring.

Chironomids are often the dominant benthic invertebrate. Invading chironomids could provide an abundant food source for other invasive organisms precipitating an "invasional meltdown" scenario (Simberloff and Von Holle 1999). Native chironomids potentially enhanced the establishment of the invasive round goby by providing a superior food source (Coulter et al. 2011). Chironomids were seen as prominent food sources for invasive carp and crayfish in studies done at Lake Naivasha, Kenya (Jackson et al. 2012). By impacting biomass at lower trophic levels, invading chironomids can potentially impact ecosystems from a bottom-up approach. Invading chironomids could facilitate invasion of another non-native species, which are predatory to the invading chironomids.

In places with newly constructed aquatic infrastructure, creation of new residential areas close to aquatic environments, or recent eutrophication, introduced chironomids may become pests. The more aggressive, resilient and disruptive the invader, the more magnified the negative impacts can be. Therefore, mitigation or prevention of chironomid infestations is of increasing importance.

Control of chironomids

The control of midge populations has been attempted where chironomid emergences cause nuisance swarms, health hazards, or agricultural damage. While chemical insecticides are among the most frequently used methods, bio-control and physical methods, such as light and sound, have also been employed.

Management of chironomids (mainly *Chironomus* spp., *Procladius* spp., and *Tanytarsus* spp.) at man-made recreational lakes was investigated using various insecticides, including the commercial product Abate® and fenthion (Mulla et al. 1971). Among known invasive species (see Table 1), *Polypedilum nubifer* control has been attempted in Australia with pyriproxyfen (S-31183) (Trayler et al. 1994) and biological agents, i.e. nymphal odonates (Arena and Calver 1996). Control of the common rice pest *Chironomus tepperi* Skuse, 1889 was attempted using several insecticides including trichlorfon, which proved to be the most effective (Stevens and Warren 1992). Treatment of Tanytarsini midges in slow sand filter beds was effective with permethrin treatment (Peters et al. 2003). Other methods of control include Cat-Floc LS®, a coagulant, hydrogen peroxide, a water-purifying agent (Alexander et al. 1997), and shock chloramination (Broza et al. 1998).

Bacillus thuringiensis var. *israelensis* (Bti), a known midge pathogen (Kondo et al. 1995), has been tested with moderate success for control of chironomids in wastewater stabilization ponds (Craggs et al. 2005). In rice fields, Bti reduced populations of *C. tepperi*; whereas, the same treatment had no effect on Tanypodinae chironomids (Stevens et al. 2013).

While the commercial products described above appear to be successful control agents, research nevertheless continues on alternative methods that may not have as many effects on non-target organisms. *Chironomus transvaalensis* Kieffer, 1923 is attracted to highly polarized light as compared to non-polarized light, behavior that may be useful for controlling the organisms (Lerner et al. 2008). Because most aquatic insects are attracted to polarized light, non-target collections would be expected. Acoustic traps, using sounds of frequency three hundred to three hundred and ninety Hz, were effective at capturing newly emerged adults of *C. plumosus* (Hirabayashi and Nakamoto 2001). The nuisance, health, and agricultural impacts of chironomids provide sufficient motivation to make considerable investments in controlling or reducing the densities of chironomids in many locations.

Conclusions

The reviewed literature establishes that chironomids are important in ecosystem health and invasion biology, and that they have important implications for public health and economics. Because chironomids are key organisms in aquatic ecosystems, any invasive chironomid species presents potential problems. Moreover, their bacterial and allergy associations, nuisance predilections, agricultural disruptions, bioaccumulation and contaminant transfer, parasitic associations, ability to thrive in a vast array of aquatic habitats, and previous history of biological invasions makes them important organisms to consider in preventing future nuisance introductions. Accidental introductions via ballast water, waterfowl, and other vectors are real possibilities and may have negative impacts on rice farming, tourist venues, and aquatic ecosystems. A better understanding of these diverse and abundant organisms could be beneficial to humans and the environment.

Despite all the information presented throughout this review, uncertainty nevertheless still remains as to the harm that chironomids may cause when they invade an aquatic ecosystem. This review is not intended to state that all non-native chironomids create negative impacts upon introduction, but is intended to raise important questions about potential effects of invasion and raise awareness about the negative effects of chironomid presence in human environments and ecological systems.

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