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History of Freshwater Invasions in Illinois: Learning from the Past to Inform the Future

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HISTORY OF FRESHWATER INVASIONS IN ILLINOIS:
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TO INFORM THE FUTURE

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ABSTRACT

Globalization has increased worldwide species invasions at an accelerating rate over the last century, with freshwater ecosystems particularly highly impacted. In North America, Illinois straddles the Laurentian Great Lakes and Mississippi watersheds. Many aquatic non-native species have breached this divide by traveling through rivers and canals in Illinois. Preventing future species movement is an important regional and continental priority. The goal of this thesis was to assemble a comprehensive database of occurrences of aquatic non-native species through the invasion sequence, and assess historical, temporal, and geographic trends of species in Illinois. I assembled a comprehensive database of known occurrences of aquatic non-native species (n=99) in Illinois inland waters. I determined their vector, location, current stage in the invasion sequence (introduction or establishment), and ecological impacts. The arrival of non-native species has accelerated since 1873, and the rate of species establishment has increased linearly. The Great Lakes Basin was the main source of established species into Illinois. Established species that are not native to North America (n=43) were delivered to the continent historically through deliberate releases (e.g., fish stocking), and unintentional releases (e.g., solid ballast of ships). Over the last two and a half decades, unintentional release (e.g., shipping) was dominant. Sixty of the 99 introduced species established reproducing populations. Eighteen established species had high or very high ecological impacts. Assessing ecological impacts by surveying invasive species experts that have the education and experience with these species in the field is a novel type of impact assessment and is a quick way to assess impacts of numerous species. Spatially, established species were more likely to be recorded, and first recorded, along the invasion corridor in Illinois (counties that contain the waterways that comprise the aquatic link between Lake Michigan and Mississippi River). Established species are spreading into and through the invasion corridor faster than they can be transported via recreational boating activities. Ten established species were recorded in more than 50% of Illinois counties while six established species were only found in one county. I recommend a multi-vector management and policy approach, increasing early detection efforts along the invasion corridor, broad sampling of counties with low number of records, and increasing efforts to control and slow the spread of established species in Illinois that cause the highest ecological impacts. Because rivers and canals in Illinois act as conduits of aquatic invasive species between the Great Lakes and Mississippi River Basins, it should be a management focus for North America. Only with cooperation at regional, national, and international scales, can we properly address the increasing introduction, establishment, spread, and potential impacts of non-native species.

CHAPTER I

INTRODUCTION

Non-native Species

The introduction and spread of invasive species has increased worldwide, especially in freshwater ecosystems (Mills et al. 1993; Ricciardi 2006; Keller, Zu Ermgassen, and Aldridge 2009). Non-native species have been transported beyond their native range and introduced to a new region usually by human activity either deliberately or unintentionally (Kolar and Lodge 2001). In the United States, species are generally considered non-native if they were introduced by humans after European colonization and do not have any evolutionary history in the new region (Ricciardi 2006).

Established species are non-native species with a reproducing population outside their native range (Kolar and Lodge 2001; Keller, Zu Ermgassen, and Aldridge 2009). Once non-native species are established, eradication is nearly impossible (Carpenter, Stanley, and Vander Zanden 2011; Vander Zanden et al. 2010). Therefore, it is essential to understand how non-native species establish and spread in new regions, and then to apply appropriate management techniques so that their impact can be minimized if they become invasive (Lodge et al. 2006).

Three definitions of *invasive species* have been proposed, each corresponding to different aspects of the impacts that these species can have. In the management definition, invasive species are non-native species that have established reproducing populations that cause harm or have the potential to cause harm to other native biota, humans, or the economy (US President 1999). The second definition is focused on ecology, and holds that invasive species are simply those non-native species that have established a reproducing population beyond their native range (Ricciardi 2006). The third definition holds that an invasive species is a non-native species that spreads from its introduction point and becomes abundant (Kolar and Lodge 2001). For the purposes of this thesis, invasive species are those non-native species that are established with a reproducing population outside their native range and have spread from their introduction point and caused harm, or have the potential to cause harm to other native biota, humans, or the economy.

Not all non-native species become invasive as defined for this thesis. To do this they must move through all steps of the invasion sequence To become invasive, a non-native species must be transported, released, and then become established. Finally, a species must spread and cause harm.(Figure 1; Kolar and Lodge 2001). In the first of these steps, the species must be moved through a transport vector. A species that enters the transport pathway does not necessarily have a chance to move outside its native range and become non-native. This is because different vectors have different levels of organism survival en route. For example, unintentional vectors like ballast water may have low survivorship, while intentional vectors like the aquarium trade are likely to have high survivorship. In the second step, the species has survived transport to a new region. Once in this new region the species could fail to be released, or move onto the third step where it is released into the new region. Once released in the new region, these species are *introduced* non-native species. Introduced species may not persist due to environmental conditions and interactions with other organisms in the new ecosystem, including native and non-native species. The fourth step is passed if the introduced non-native species establishes reproducing populations in the non-native region, at which point it is referred to as *established*. The fifth and final step is reached if the non-native species spreads widely and causes impacts (i.e., becomes an *invasive species*; Kolar and Lodge 2001). In general, a small fraction of non-native species become invasive (Williamson and Fitter 1996), although any species that enters the invasion sequence could potentially move completely through the entire sequence.

Potential non-native aquatic species are transported to new regions through many vectors of transportation and commerce (step 2 in Figure 1). Unintentional vectors of transportation, which are byproducts of human activity, include shipping activities through ballast water and hull fouling (Holeck et al. 2004; Grigorovich et al. 2003), recreational boating and fishing gear, and through the aquarium trade (Keller and Lodge 2009; Mills et al. 1993). Deliberate vectors, which are when humans knowingly release non-native species into the environment, include transport of sport fish to stock lakes outside their native range, aquaculture, through live food and bait trades, and through the watergarden trade (Ricciardi, 2006). With globalization, the number of transport

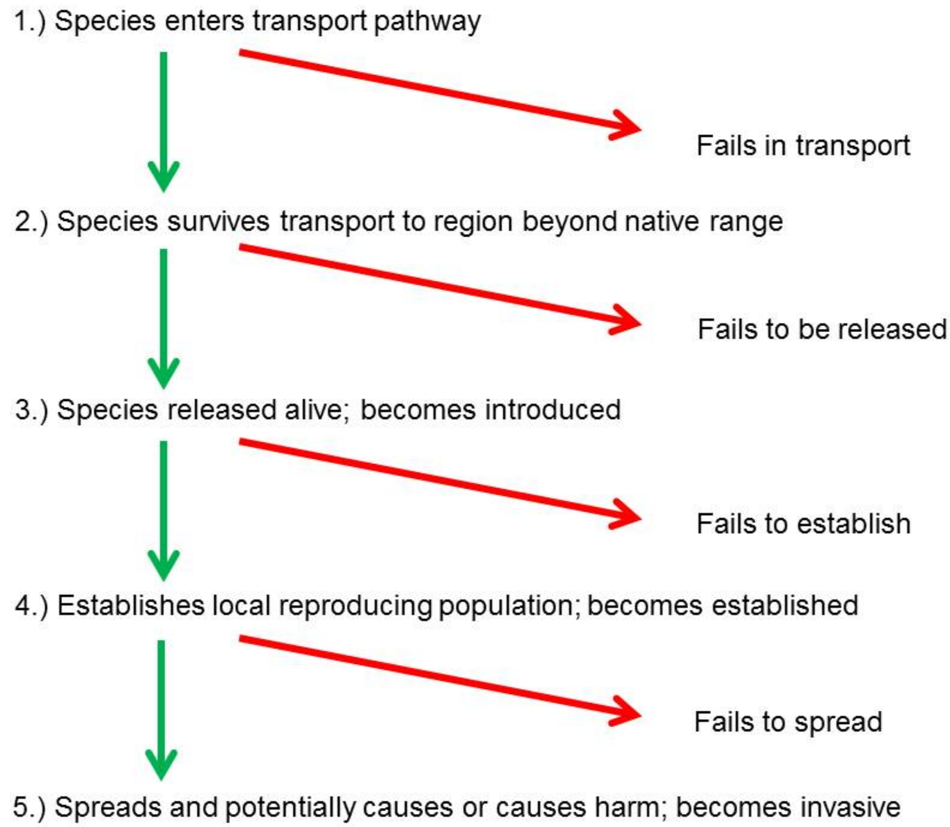

Figure 1. Steps in the invasion sequence. Green arrows indicate successful movement of a species through the pathway while red arrows indicate failure of a species to move onto the next step. Adapted from Kolar and Lodge, 2001.

vectors, release events, and the number of introduced non-native species has increased in the Great Lakes Basin (Ricciardi 2006).

Invasive species can negatively affect ecosystems and human activities. They can decrease native biodiversity by outcompeting native species for resources, through predation, and/or through altering patterns of disturbance (Mills et al. 1993; Sax et al. 2007). For example, predatory lionfishes (*Pterois volitans* and *P. miles*), most likely were transported and released through the aquarium trade to the western Atlantic Ocean (Whitfield et al. 2002). These species have established and quickly spread throughout the western North Atlantic Ocean, Caribbean, and Gulf of Mexico (Schofield 2010). Large impacts have been documented, including decreased recruitment of native fishes due to predation by lionfishes(Albins and Hixon 2008), and a substantial decline in the biomass of the lionfishes' prey fishes (Green et al. 2012).

Invasive species cause about $120 billion each year in the United States in environmental damages (Pimentel, Zuniga, and Morrison 2005). One example of a particularly damaging species is the zebra mussel (*Dreissena polymorpha*). The zebra mussel was transported from Eurasia via ballast water in ships and was first introduced to Lake St. Clair (Mills et al. 1993). Zebra mussels have established and spread from the Great Lakes Basin across North America, causing tens of millions of dollars in damage to industry in the US, while also decreasing native unionid mussels richness and abundance (Drake and Bossenbroek 2004; Bossenbroek et al. 2007). Zebra mussels clog water intake and outtake pipes of factories and water treatment plants (Mills et al. 1993).Treatment plants and factories must remove pipes and experiment with control efforts which range in their effectiveness and cost (Leung et al. 2002). Invasive species also affect the aesthetics of water bodies. For example, Eurasian watermilfoil (*Myriophyllum spicatum*) creates dense canopies in water bodies that limit opportunities for fishing and swimming (Jerde et al. 2010).

Freshwater ecosystems and invasions in Illinois, including the Great Lakes

The state of Illinois has a high diversity of freshwater ecosystems (Figure 2). The northeast of the state borders Lake Michigan, which is connected to the rest of the Laurentian Great Lakes and the Atlantic Ocean via the St. Lawrence River. There are several small rivers that flow into Lake Michigan from Illinois, but most of the state is in the Mississippi River Basin. The Chicago Area Waterways System (CAWS) connects Lake Michigan to the Des Plaines River, which flows into the Illinois River, and into the Mississippi River (which comprises the western border of the state). The Wabash and Ohio Rivers comprise the southeastern border and also flow into the Mississippi River. Lakes in Illinois are man-made, such as Lake Shelbyville and Carlyle reservoirs along the Kaskaskia River, and natural (e.g Horseshoe Lake in St. Louis near the Mississippi River). Illinois also contains wetlands, with almost half of Illinois's wetlands located in the southern third of the state (Suloway and Hubbell 1994).

Figure 2. Major rivers and lakes of Illinois (Mapsof.net, 2012).

Most freshwater ecosystems in Illinois have been extensively altered by humans, including the creation of reservoirs and the loss of wetlands. Many lakes act as reservoirs for to regulate drought and flood conditions. Historically, 23% of Illinois surface area was composed of wetlands, however, currently only 3.5% of Illinois is covered by wetlands (McCauley and Jenkins 2005; Suloway and Hubbell 1994).

Perhaps the greatest alteration to aquatic ecosystems in the region by humans was the creation of the Chicago Sanitary and Ship Canal (CSSC) which was completed in 1900 and connects the Mississippi and Lake Michigan water systems through the Des Plaines and Illinois Rivers (Jerde et al. 2010). This permitted the flow of the Chicago and Calumet Rivers to be connected and reversed, allowing for transport of waste and storm water away from Chicago and facilitating shipping. This canal facilitates the movement of invasive species because it is a permanent aquatic connection between the Mississippi River and Great Lakes Basins (Horner, Sparks, and Charlebois 1999). One imminent invasion that may occur through the CSSC is the movement of silver carp *(Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*), collectively known as Asian carp, through the Mississippi and Illinois Rivers into Lake Michigan. Some evidence suggests that these species are either already in Lake Michigan or will arrive soon, (Jerde et al. 2010; Jerde et al. 2011).

The Great Lakes Basin is a highly invaded system with 182 established non-native species (Ricciardi 2006). Non-native species came with increasing human populations in the Great Lakes Basin (Mills et al. 1993). For example, power plants have created favorable warmer localized habitats in which warm water species can survive cold winter temperatures in the Great Lakes (Mills et al. 1993). Human vectors now connect the Great Lakes to freshwater ecosystems throughout the world via planes, automobiles, and ships, which frequently travel from all major global coastal regions to the Great Lakes (Keller et al. 2011). The opening of the St. Lawrence Seaway in 1959 (a canal and lock system that connects Lake Ontario to Montreal, Canada), has enhanced movement of goods and non-native species throughout the Great Lakes via ships (Ricciardi 2006) This increasing globalization and movement of goods provides an opportunity for growth in biological invasions (Mack et al. 2000; Hulme 2009).

The areas of Illinois in the Mississippi River Basin are also highly invaded. Round goby (*Neogobius melanstomus*) has expanded its range through the Illinois Waterway and into the Illinois River (Irons, McClelland, and Pegg 2006). Other widespread, non-native fish species include white perch (*Morone Americana*), bighead carp (*Hypophthalmichthys nobilis*), silver carp (*H. molitrix*), common carp (*Cyprinus carpio*), and goldfish (*Carassius auratus*; Irons et al. 2006; Sparks 2010). In addition to fish, Illinois has non-native mollusks (e.g., zebra mussels [*Dreissena polymorpha*], and Asian clam [*Corbicula fluminea*]), crustaceans (e.g., rusty crayfish [*Orconectes rusticus*]), and many non-native aquatic plants (e.g., purple loosestrife [*Lythrum salicaria*], curly pondweed [*Potamogeton crispus*], and Eurasian watermilfoil [***Myriophyllum spicatum***]).

Thesis Project

The initial goal of this thesis project was to create a comprehensive database of non-native aquatic species occurrences in Illinois, because Illinois's records were in scattered datasets that existed in various places and files across Illinois. These datasets typically are regional in scope or taxonomy. Policy-makers and managers often rely on these scattered and incomplete datasets to establish targets for reducing arrival and spread of invasive species (Keller, Zu Ermgassen, and Aldridge 2009; Fuentes et al. 2013). If the historical data are not complete and organized, it hinders the ability of managers and policy-makers to effectively manage limited budgets. Therefore, a comprehensive database is needed to inform policy-makers and managers in the state, and improve effectiveness of strategies to control invasive species in Illinois.

I assembled a database of aquatic non-native species and present my analysis of the data here. In chapter II, I describe species trends through time and at each step in the invasion sequence. In chapter III I describe species historically, temporally, and spatially by county. Both of these chapter results are discussed in in the context of management and policy on aquatic non-native species.

The goal of Chapter II was to assess aquatic non-native species in each step of the invasion sequence (introduced, established, and invasive) in Illinois. This is needed because different management actions are required depending on which step each species is found. I determined the establishment status of each introduced aquatic non-native species. Because the ecological impacts of few established species have been studied in Illinois, and established species are observed regularly in the field by educated ecologists, I conducted a survey of Illinois invasive species experts to determine the average level of ecological impacts caused by each established species. For each stage in the invasion sequence, I examined vectors or time periods that have been particularly important. I also determined which species and the number of species that spread into Illinois via the Great Lakes and the Mississippi River.

The goal of chapter III was to assess historical, temporal, and geographic trends in the arrival and spread of aquatic invaders in Illinois. I determined which areas were most important as points of introduction for new species, and which contained the greatest numbers of established aquatic non-native species. Next, I determined the most likely vectors for each species to Illinois to infer which modes of human transport have been most important. Finally, I gathered statewide data at the county scale to test the importance of some human and environmental factors that are strongly associated with species introduction and spread . My ultimate goal was to provide information useful to prevent and reduce the overall impacts from non-native species.

CHAPTER II

STRADDLING THE DIVIDE: INVASIVE AQUATIC SPECIES IN ILLINOIS AND MOVEMENT BETWEEN THE GREAT LAKES AND MISSISSIPPI BASINS

Introduction

Rates of introduction and spread of non-native species continue to increase worldwide, with freshwater ecosystems highly impacted (e.g., Ricciardi 2006; Keller et al. 2009). Human actions have connected aquatic ecosystems directly (e.g. canals; Mills et al. 1993) and indirectly (e.g. international shipping and aquarium trades; Ricciardi 2006; Keller et al. 2011), allowing for unprecedented movement and introduction of non-native species across natural barriers. Many of these species become established and a portion have large ecological and economic impacts.

To become invasive, non-native species must be transported, introduced beyond captivity, establish reproducing population(s), spread, and cause harm (Kolar and Lodge 2001). Although many studies have determined the suite of non-native species that have been introduced to a region, and the subset of those that have become established, few studies have quantitatively assessed which established species have become invasive. This is partly due to the difficulty in defining *invasive*. For example, some authors believe this designation should be reserved strictly to describe ecological impacts, while others believe it should be used for species that negatively impact the economy or human health (Colautti and MacIsaac 2004). In reality, negative impacts from non-native species occur as a gradation from low to high, and the single term *invasive* does not capture these differences. Despite this, it is important for managers and policy-makers to know the number and type of species that are or may become invasive in their region. Under any definition of invasive these species are those which control is most likely to be required. Information about realized or likely impacts of invasive species can be used to prioritize prevention and control strategies and to assess which vectors have imported the greatest number of harmful species.

Understanding the introduction, establishment, and impacts of aquatic non-native species in the US state of Illinois is particularly important because it contains part of the boundary between the Laurentian Great Lakes and Mississippi River Basins and the canals which connect the two basins (Figure 3). These basins are among the most economically important in North America, and invasive species threaten many of the ecosystem services that they provide. The largest connection between these basins is Illinois' Chicago Sanitary and Ship Canal (CSSC), which opened in 1900 to facilitate navigation between the basins and disposal of sewage. This is the only connection between the two basins in which a continuous aquatic habitat is maintained throughout the year even at low flow conditions (US Army Corps of Engineers 2013). This connection has allowed species to move between basins (Horner, Sparks, and Charlebois 1999), including the zebra mussel (*Dreissena polymorpha*), which spread from the Great Lakes to the Mississippi, and subsequently as far as California (US Geological Survey, 2012-2014). Currently, the role of the CSSC for species range expansion has been highlighted by the potential for bighead (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*; these species are often collectively referred to as Asian carp) to enter the Great Lakes at Lake Michigan.

Species can be introduced to Illinois either through direct introduction (e.g., releases by aquarists and escape from watergardens) or through spread from neighboring states and waterbodies. Spread from outside Illinois may occur as species naturally move through connected waterbodies, such as the Mississippi River or Lake Michigan, or when species are transported overland from other states (e.g. on recreational boats). The CSSC connection of the Great Lakes and Mississippi River Basins within Illinois means that invasions which occur in and spread through the state can have important consequences for much of North America. Thus, a better understanding of the range of species that are established and invasive, and the vectors that have transported them, could inform management and policy with continent-wide implications.

Because of the need for baseline information by scientists, managers, and policy-makers, I assessed aquatic non-native species in each step of the invasion sequence (introduced, established, and invasive) in Illinois. I assembled a database of all aquatic non-native species recorded in the state, including establishment. I conducted an innovative survey of Illinois invasive species experts to measure the ecological impacts caused by each established species because these experts have the education and experience with these species in the field. For each stage in the invasion sequence, I examined the vectors and time periods responsible for Illinois species invasion.

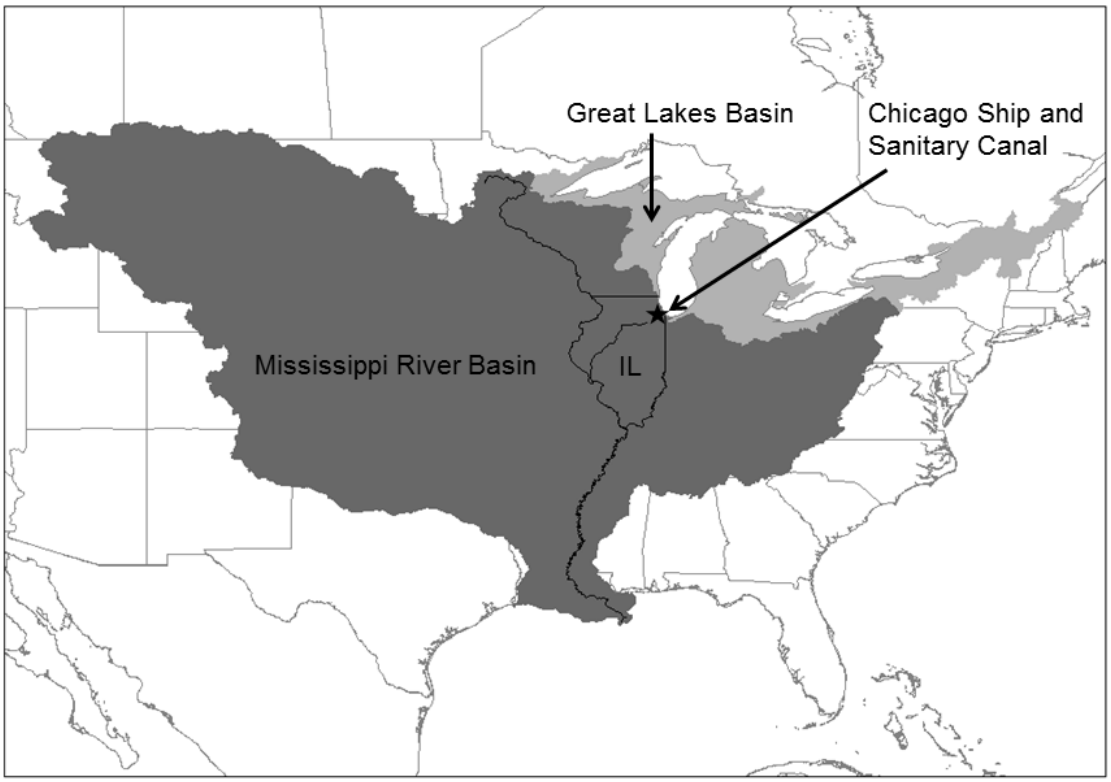

Figure 3. The most likely direction from which established species arrived in Illinois (IL). Twenty-eight species were established in the Great Lakes Basin, but not the Mississippi River Basin, prior to their discovery in Illinois. Six species were established in the Mississippi Basin prior to discovery in Illinois, and 20 species have an unknown source.

Methods

Database Development

I defined Illinois to include all inland waters of the state, including those parts of the rivers (Mississippi, Ohio, and Wabash) that form its border. Illinois also includes a portion of Lake Michigan. This was not included in my database because its boundaries are not ecological and is more appropriately considered part of the larger Great Lakes ecosystem.

From personal and institutional databases, published literature, and direct contact with experts, I compiled a list of records for aquatic species documented in Illinois that are not native to any part of the state (see Table 4 in appendix). Species were classified as introduced if they were recorded at least once beyond direct human cultivation, and established if at least one population was reproducing. I searched all available sources.

For aquatic plants, I used the USDA PLANTS definition of *obligate wetland*, which is that the species occurs (under natural conditions) in wetlands with a 99% probability (USDA NRCS 2012). Parts of Illinois fall into four USDA wetland regions, and any plant species defined as obligate wetland within one or more of those regions was included (Lichvar 2012). The only exception to this was common reed (*Phragmites australis*), which is classified as a facultative wetland species but was included because of its large impacts on wetlands (Meyerson et al. 2000; Chambers, Meyerson, and Saltonstall 1999).

For some plant species I found conflicting reports of whether they are native to Illinois. In these cases I assessed the data used by different sources (e.g., USDA PLANTS database [USDA NRCS 2013], BONAP [Kartesz 2013], Swink and Wilhelm [1994]) to make my decision, and then confirmed that decision with local experts and recent literature (e.g. Stuckey and Salamon 1987; Saltonstall 2002; Stevens and Hoag 2006; Saltonstall 2013; Ciotir et al. 2013).

For each species, I recorded the location and date of sampling, status of the population (i.e., established vs. not established), and the researcher identity. When location data were not given as latitude and longitude coordinates I used descriptions of sampling sites to estimate coordinates. When this was not possible, the record's location was designated at the county level. Duplicate records were removed when species, date, location, and researcher identity were identical.

Analysis of Introduction and Establishment Records

Average annual rate of new species discovery was calculated for each 10 year period between 1873 (the year of first discovery of a non-native species) and 2012. Linear regression on this time series was used to determine if rate of discovery has changed over time.

For species not native to any part of North America, I determined the most likely vector that delivered them to the continent. Following Ricciardi (2006), these vectors were shipping (including ballast water, solid ballast, and hull fouling), deliberate release through production or stocking efforts, unintentional release (including ornamental and aquaculture escape, and bait bucket release), aquarium release, or unknown. Species that are hybrids between non-native and native North American species were excluded from the vector analysis because their geographic origin is uncertain.

Illinois is at the junction of the Great Lakes and Mississippi River Basins (Figure 3), and non-native species have entered Illinois through each. I determined the relative importance of the basins by searching for records of each Illinois established species in them. I assessed a species as entering Illinois through the Great Lakes if it was discovered there, and not in the Mississippi River Basin, prior to its discovery in Illinois. The reverse rule was used to assess a species as entering through the Mississippi River Basin. Resources for this analysis were Ricciardi (2006), US Geological Survey Nonindigenous Aquatic Species factsheets (2012-2014; USGS NAS), Mills et al. 1993, Les and Mehrhoff 1999, Grigorovich et al. 2008, and Sheen et al. 2009.

Impacts of Established Species

To become invasive, an established species must cause environmental or economic harm (Kolar and Lodge 2002). I searched for written reports of impacts for established species in Illinois but found that few species have been studied. Despite this, established species are observed regularly in the field by trained ecologists. To leverage the observations and experience of these experts I adapted a survey previously used by Howeth et al. (*in prep*). I identified Illinois experts, invited them to participate, and asked them to score species on a four point scale of ecological impacts. Impact categories were: (1) None to Low: *Non-native species has little to no discernible impact on existing biota*; (2) Moderate: *Non-native species causes discernible decline in the abundance of existing biota* *in most locations;* (3) High: *Non-native species causes discernible decline in the abundance of existing biota and becomes a dominant component of the food web*; and (4) Very High: *Non-native species causes discernible decline in the abundance of existing biota, with local extirpation of species likely. Food webs are highly altered and ecosystem-level consequences apparent*. Experts could also check 'Unknown' if they were unfamiliar with the impacts of a species. Twenty-six surveys were distributed and all were returned. The list of respondents is in the appendix (Table 7). Scores for each species were averaged for analysis, and based on the survey scoring system I defined the following impact ranges: average score ≥3.5 = *Very High*; 2.5–3.49 = *High*; 1.5-2.49 = *Moderate*; <1.5 = *Low*.

Results

Sampling Records

Data for aquatic non-native species were collected from 12 sources within and outside of Illinois (Table 4 in appendix). The US Geological Survey's Nuisance Aquatic Species program provided almost half of the established species records (49.4%), followed by the Illinois Natural History Survey (17.0%), and the Illinois Department of Natural Resources (13.8%). Records of species *absence* were infrequently encountered and were not used for analysis.

The annual number of records of established species has increased since the 1870's, with a particular jump during the 1990s and a peak in 2000 (Figure 11 in appendix). When the number of records of established species per year is plotted against the number of established species discovered in each year a logarithmic curve is seen (Figure 4). This curve is increasingly horizontal at the right hand end of the graph, indicating that most species have been discovered or that no new species are arriving. Recent years have included those with the greatest number of records (Figure 4). The same pattern is evident for records of only fishes or vascular plants.

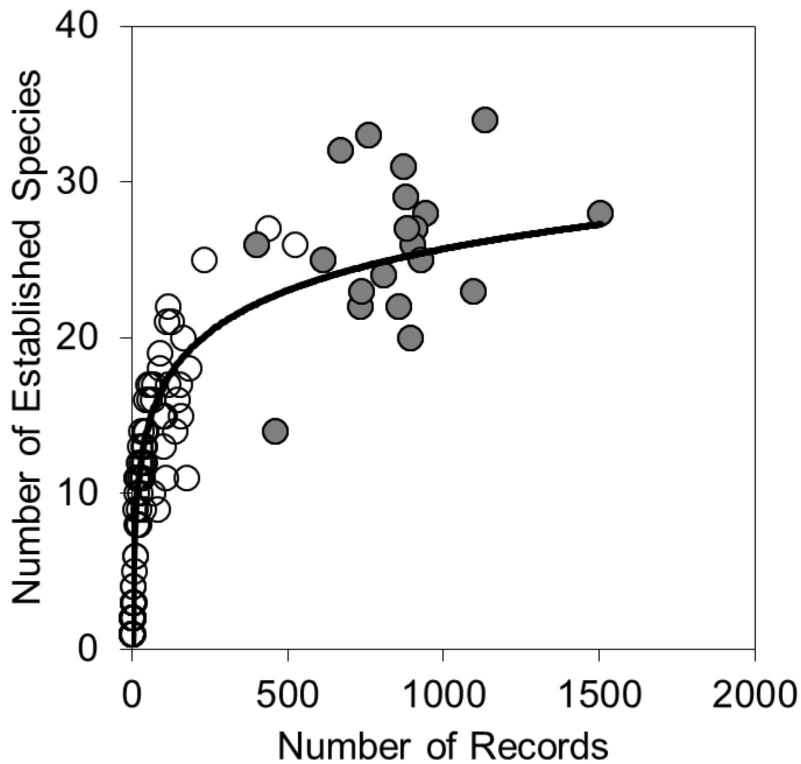

Figure 4. Number of established species and number of records by year within Illinois inland waters between 1873 and 2012. Line fitted by logarithmic regression: $y = 4.52\ln(x) - 1.5882$ ($r^2 = 0.91$). Shaded circles are the most recent 20 years of sampling records.

Records of Introduced Species

A total of 99 aquatic non-native species were recorded from Illinois waters, represented by 22,283 records (Tables 5 and 6 in appendix). Thirty-nine species (268 total records) have failed to establish (Table 6), with the earliest of these being American shad (*Alosa sapidissima*), first sampled in 1873. Species that failed to establish have generally been sampled infrequently, are intentionally stocked, or are from climatically different regions. For example, red-bellied pacu *(Piaractus brachypomus)*, a tropical fish popular in the aquarium trade, was recorded on four occasions over 15 years but has failed to become established (Table 6).

The cumulative number of introduced species increased at an accelerating rate from 1873 through 2012 (Figure 5; linear regression, n=14 decades, r^2 = 0.601, p= 0.001). A second-order polynomial ($y=0.004x^2-13.79+12,795$, $r^2=0.989$) better fits the introduced species data than a linear line ($r^2=0.946$; Figure 5a). Average rate of discovery over the full period was 0.71 species per year or one new species every 17 months. Over the last 30 years, the rate was 1.33 species per year or one new species every nine months.

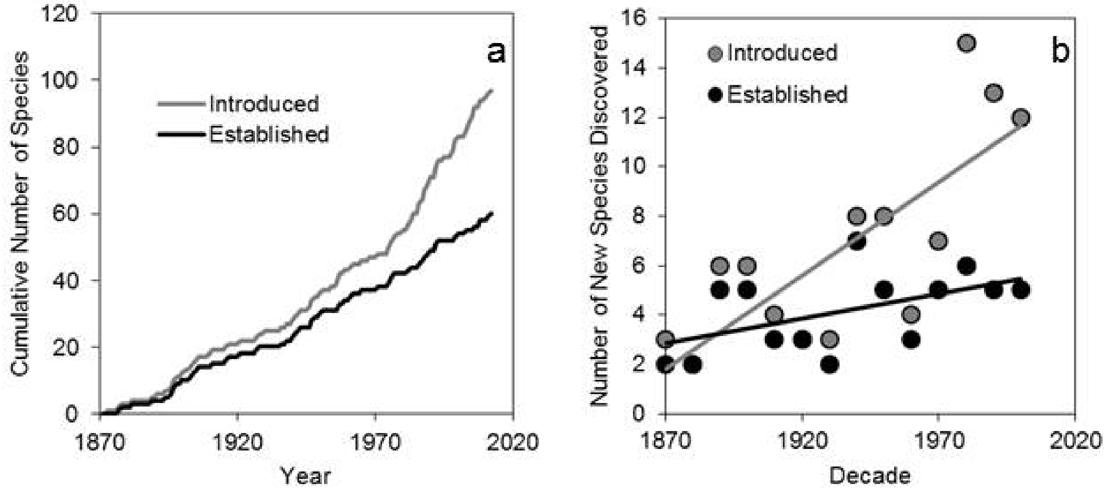

Figure 5. (a) Cumulative number of introduced (gray line) and established (black line) species in Illinois inland waters between 1873 and 2012. The introduced line is fitted by a second-order polynomial ($y=0.004x^2-13.79+12{,}795$, $r^2=0.989$). The established trendline is linear ($y=0.429x-806.37$, $r^2=0.991$). (b) Number of new introduced (gray points) and established (black points) species discovered in each decade. Line fitted by linear regression for introduced ($y = 0.076x - 140.43$, $r^2=0.601$, $p=0.001$), and established ($y=0.0202x - 34.982$, $r^2=0.276$, $p=0.054$) species.

Established species

Sixty non-native species have become established in Illinois, represented by 22,015 records. Forty-three of these species are non-native to North America. The earliest recorded establisher was watercress (*Nasturtium officinale*) in 1877. Since then, species from five phyla have become established (Table 1).

A linear regression of decade with number of established species discovered in each decade showed a positive trend (Figure 5; $n=14$, $r^2 = 0.276$, $p=0.054$). In addition, the trendline of year with cumulative number of established species is linear (Figure 5a; $y=0.429x-806.37$, $r^2=0.991$). The rate of discovery of new established species (from 1873 through 2012) was 0.43 per year, equivalent to one new species every 28 months. Over the last 30 years, the rate was 0.57 species per year or one new species every 21.2 months.

Established species that are not native to North America (n=43) were delivered to the continent through a range of vectors (Figure 6a). Before 1990, deliberate releases (e.g., fish stocking), and unintentional releases (e.g., movement of vascular plants through the solid ballast of ships) were most important (Figures 6b and c). More recently (1990 onwards), unintentional release and shipping were the dominant vectors, with shipping transporting species from three different phyla (Figures 6b and c). The highest number of established fishes was discovered between 1960 and 1989; three of these as a result of deliberate release through stocking (Figure 6b and c).

Twenty-eight species established in the Great Lakes Basin, but not the Mississippi River Basin, prior to their discovery in Illinois (Figure 3). Six species established in the Mississippi Basin prior to discovery in Illinois, and 20 species had an unknown source.

Table 1. Number of records and established species in Illinois inland waters between 1873 and 2012.

Phylum or Division	**Number of Records**	**Number of Species**
Crustaceans	266	4
Fishes	14,404	16
Hydroid	1	1
Mollusks (bivalves and gastropods)	2,218	6
Vascular plants	5,126	33
Total	**22,015**	**60**

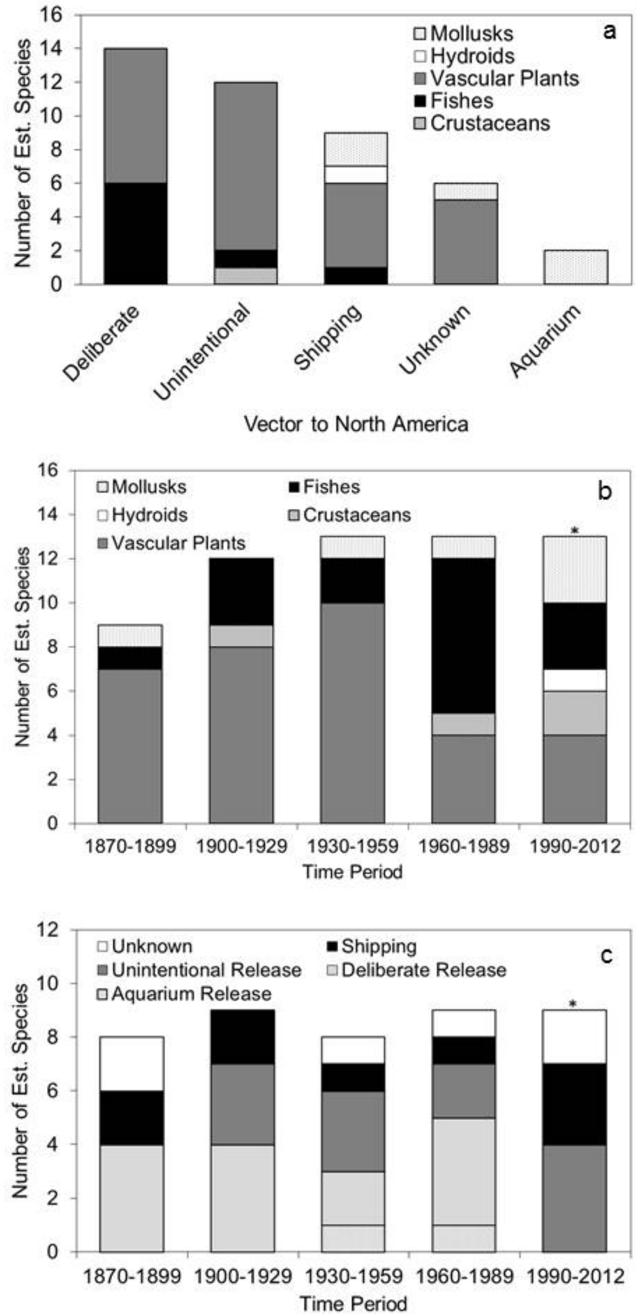

Figure 6. Number of species non-native to North America and initial vector to North American freshwaters. (a) Initial vectors of established species in inland Illinois waters non-native to North American freshwaters from 1870-2012. (b) Number of established species in inland Illinois waters discovered by 30 year time periods from 1870-2012. (c) Vectors of established species in Illinois inland waters non-native to North American freshwaters discovered by 30 year time period from 1870- 2012. The * indicates bar spans 22 years.

Ecological Impacts of Established Species

Two established species (the plant *Crypsis schoenoides* and the hydroid *Cordylophora caspia*) were not assessed for invasiveness because I was unable to find experts familiar with them. All other species received two or more expert rankings. The maximum was 13 for curly pondweed (*Potamogeton crispus*) and purple loosestrife (*Lythrum salicaria*).

Established species were ranked as having a range of ecological impacts from low to very high (Figure 7). Six plant species and one mollusk species (11.67%) received an average impact rank of *Very High* (i.e., ≥3.5) while eleven species (18.33%; plants, fish, mollusks, and crustaceans) were ranked as having *High* impacts (Table 2). Twenty species (33.33%; plants, fishes, and crustaceans) were ranked as having *Moderate* impacts, and the remaining twenty species (33.33%; plants, fishes, and mollusks) were ranked as having *Low* impacts (Table 5 in appendix).

For species non-native to the US, average impact was not significantly related to the vector that delivered the species to North America (ANOVA, $p=0.932$). There was also no significant relationship between year of first discovery in Illinois and average impact when the 58 assessed established species were considered (Linear regression, $r^2=0.048$, $p=0.099$), or when vascular plants ($r^2=0.044$, $p=0.247$) or fishes ($r^2=0.002$, $p=0.871$) were analyzed separately. Average impact increased with total number of records for vascular plant species only (linear regression, $r^2=0.265$, $p=0.003$). When analyzed for fishes ($r^2=0.231$, $p=0.060$), or all species combined ($r^2=0.056$, $p=0.073$), there were not significant relationships. Average impact increased with the number of Illinois counties in which the species was sampled when all species were considered (n = 58, r^2=0.180, p=0.001), as well as when only vascular plants (n=32, r^2=0.245, p=0.004) or fishes (n=16, r^2=0.479, p=0.003) were included.

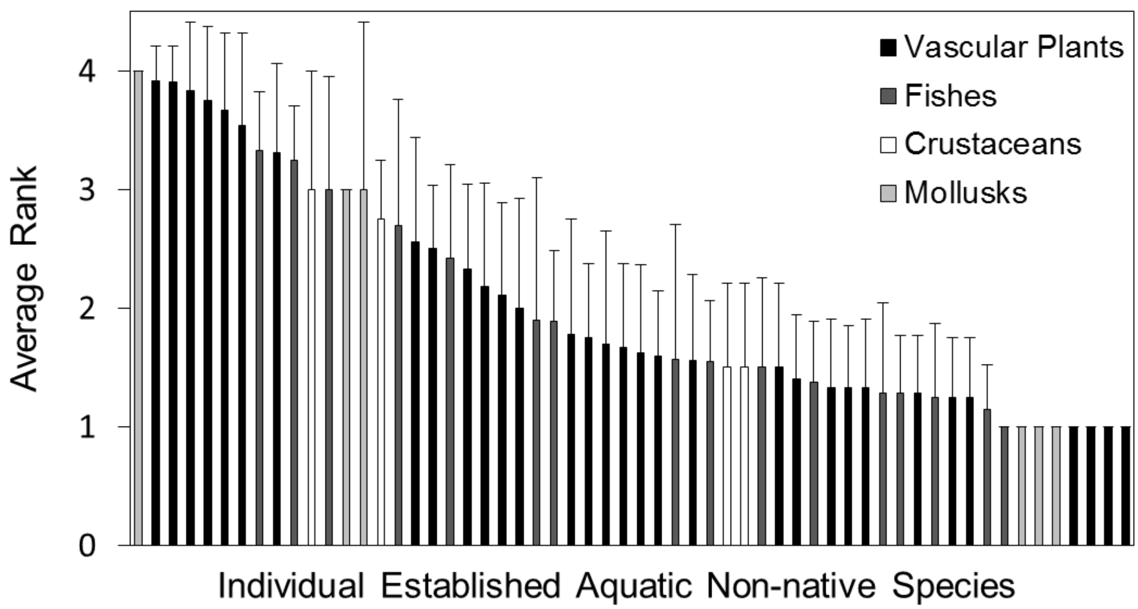

Figure 7. Average rank of each individual established species. Experts ranked ecological impacts of established species from one (none to low) to four (very high). Error bars indicate one standard deviation.

Table 2. The 18 established species with an average ecological impact rating of ≥ 2.5.

Group	**Scientific Name**	**Common Name**	**Average Rank**
Mollusks	*Dreissena polymorpha*	Zebra Mussel	4
Vascular Plants	*Phalaris arundinacea*	Reed Canarygrass	3.92
Vascular Plants	*Typha x glauca*	Hybrid Cattail	3.91
Vascular Plants	*Phragmites australis*	Common Reed	3.83
Vascular Plants	*Typha angustifolia*	Narrowleaf Cattail	3.75
Vascular Plants	*Myriophyllum spicatum*	Eurasian Watermilfoil	3.67
Vascular Plants	*Lythrum salicaria*	Purple Loosestrife	3.54
Fishes	*Hypophthalmichthys molitrix*	Silver Carp	3.33
Vascular Plants	*Potamogeton crispus*	Curly Pondweed	3.31
Fishes	*Hypophthalmichthys nobilis*	Bighead Carp	3.25
Crustaceans	*Daphnia lumholtzi*	Water Flea	3
Fishes	*Cyprinus carpio*	Common Carp	3
Mollusks	*Cipangopaludina chinensis malleata*	Chinese Mystery Snail	3
Mollusks	*Bithynia tentaculata*	Mud Bithynia, Faucet Snail	3
Crustaceans	*Orconectes rusticus*	Rusty Crayfish	2.75
Fishes	*Neogobius melanostomus*	Round Goby	2.7
Vascular Plants	*Egeria densa*	Brazilian Waterweed	2.56
Vascular Plants	*Butomus umbellatus*	Flowering Rush	2.5

Discussion

Illinois waters' are highly invaded with 99 introduced aquatic non-native species, sixty of which are now established. Eighteen (30%) of these established species were assessed by experts as having *High* or *Very High* ecological impacts. The rate of new species arrival increased, and many of these species have been successfully moving through the invasion sequence. The number of introduced species increased at an accelerating rate since 1873, and the rate of species establishment has increased linearly. This indicates that Illinois waters' are becoming more invaded through time because discovery rate is a proxy for invasion rate (Ricciardi 2006). This pattern is similar to observations in other ecosystems, including the Great Lakes (Ricciardi 2006) and Great Britain (Keller et al 2009). Average rate of invasion for established species in Illinois (0.43 species/year) is less than the Great Lakes Basin invasion rate (1.1 species/year; Ricciardi 2006), but Illinois also contains far less aquatic habitat per km^2 of surface water than the larger and more diverse Great Lakes Basin.

A main innovation of my work is the explicit consideration of the different levels of ecological impact caused by established species. This innovation was conducted by surveying invasive species experts that have the education and experience with these species in the field. Along with most other freshwater ecosystems, the large number of established species and the relatively low number studied have created a dearth of knowledge about their range of impacts. One response to this was to assess species as *invasive* only if there were suitable records of ecological or economic impacts (Hansen et al. 2013; Kolar and Lodge 2001). While this approach is useful for some questions, my results show that reducing invasiveness to a binary (i.e., Yes/No) variable loses a lot of information. Indeed, the plot of average impacts generated from my survey (see Figure 7) shows that there is no break where a threshold could readily be applied. Instead, established species have impacts that range continuously from low to very high.

My results indicate that 30% of established species caused high or very high ecological impacts. This is higher than previous estimates, including the 'tens rule.' This rule states that about 10% of established species will become invasive (Williamson and Fitter 1996).

For Illinois, the average impact of established species increases with the distribution of the species (measured by the number of counties where the species was recorded). This is logical, given that higher impact ratings from the survey are likely to be given for species that are more widespread, and because it increases the chance that the experts who responded to the survey have encountered the species. This is consistent with definitions of invasive species, in which these species spread throughout an area (e.g. Illinois), and cause harm to the ecological community (Kolar and Lodge 2001).

As the number of records increased for established plants, average impact also increased. This could be an artifact of sampling in which plant species with low ecological impact are categorized as low priority, and thus less sampling effort is focused on these species (Hansen et al. 2013). Six plants were ranked as causing very high ecological impacts, more than for fish species. Time since first discovery and vector type were not associated with level of impact. Therefore, those species that were discovered in the early 20th century do not have higher impacts than species discovered more recently.

The Great Lakes Basin is a main source of established species into Illinois (Figure 3). Recently (1990-2012), three species from three different phyla were introduced to the Great Lakes through shipping have spread into Illinois. This is consistent with previous results showing that the Great Lakes is a starting point for new invasions across the region (Rothlisberger and Lodge 2013; Vander Zanden and Olden 2008). Before 1990, deliberate release (e.g. fish stocking) of established species into Illinois was a dominant vector, however, this vector has not introduced new species since 1973. Unintentional release continues to be a dominant vector. Other factors besides source of arrival and type of vector contribute to establishment and spread of each non-native species, including: initial propagule pressure (Simberloff 2009), life history, environmental suitability (e.g., Gallardo and Aldridge 2013), and lag times at any step in the invasion sequence (Crooks 2005).

Given available data, I used the number of records as a proxy for sampling effort. The increase in occurrence records during the latter part of the 20th century is presumably a combination of increased number and population size of non-native species, and sampling effort. Ascertaining sampling effort is further complicated because the occurrence records include results of both organized institutional sampling using established methods (e.g., transects and calculations of catch per unit effort), and opportunistic sampling (e.g., reports from the public that are later confirmed by experts). For the latter, increased public knowledge of invasive species issues may increase reporting rates. Finally, the transition from records kept exclusively on paper to those kept electronically may contribute to the increase in data that were available.

My data may represent an underestimate of the true number of introduced and established species in Illinois. Lag time at any step in the invasion sequence, including introduction, establishment, spread, subsequent detection, and management efforts (Crooks 2005), can contribute to such underestimates. The number of introduced species is expected to be higher than my records suggest because many introduced species are likely to not persist long enough to be recorded (Ricciardi 2006; Taylor and Hebert 1993). My records of established species are likely to be more accurate because these species are sampled multiple times over longer time periods. However, several groups of species (algae, coelenterates, and crustaceans) were infrequently recorded in Illinois. This may be a true representation that these groups are not widely established, but this may also be because these species can be more difficult to collect and identify (e.g. vascular plants are easier [Crall et al. 2006]).

Other confounding factors include assigning vectors and direction of arrival of non-native species to Illinois. In some cases it was difficult to ascertain vectors or direction of arrival because the information does not exist in the literature for each established species in Illinois. Many of the species may have combinations of multiple invasions without documentation and could represent independent releases within Illinois.

Compiling this database was necessary. No individual database contributed more than half of the species records. If USGS NAS was the sole source of records, the analysis would be incomplete, and would not fully inform scientists, managers, and policy-makers.

Policy Implications

Shipping and other unintentional vectors (e.g. contaminated imports and ornamental and aquaculture escape) are the most important vectors of aquatic non-native species to North America that become established in Illinois. Increased efforts to prevent introductions from these vectors would likely be the most effective way to reduce the problems from future invasive species in the state. This illustrates that Illinois has little direct power to affect control of the vectors that introduce many of its non-native species. For example, most ships that deliver new species to the Great Lakes do not pass through Illinois waters, and may discharge ballast elsewhere. Likewise, once aquarium and watergarden species are allowed into the US, it is difficult to prevent their spread across the nation through trade, especially with internet purchases (Keller and Lodge 2007). For Illinois to avoid future invasions, a more coordinated regional and federal response will be required.

Although federal and regional collaborations may be most effective, there is still much that can be done in Illinois, and many efforts are underway. For example, the new *Be a Hero, Transport Zero* campaign (2014) aims to educate the public about the risks from species introduction and spread. Likewise, Illinois recently added 27 species of aquatic plants to the list of non-native species that are banned from sale in the state. This is encouraging because Indiana, a neighboring state, recently banned sale of the same set of species. Overall, Illinois has many challenges for managing the arrival of new aquatic non-native species, and many of these cannot be addressed unilaterally. The state has made progress with recent efforts to reduce vectors over which it controls.

Despite recent advances, efforts to prevent invasions across the Midwest have little evidence of success. Many states in the region have focused on outreach and educational campaigns to inform non-native species consumers to refrain from releasing their pets, bait, or food into the environment. These campaigns have also been aimed at boaters to educate them how to stop spreading aquatic non-native species by properly cleaning and drying their boats before moving between waterbodies. My results show an accelerating increase in the number of aquatic invaders and continued unintentional releases, which suggest a need for additional or alternate strategies to effectively combat invaders. These alternate strategies should include prioritizing and addressing unintentional releases (especially shipping) that would ideally include an increased role for regional and national efforts.

Management activities are underfunded for invasive species (Vander Zanden and Olden 2008), and managers cannot address all established species. Therefore, managers can use records and lists of species at each step of the invasion sequence to inform their decisions (e.g. my results assessing non-native species through the invasion sequence). Because the ecological impacts of several aquatic plant species were ranked as *very high*, I recommend increasing efforts to control and slow the spread of these species. I also recommend investigating organisms with *high* ecological impacts in Illinois. Because many of these species may cause large ecological impacts across North America, managers from other regions should assess the invasion status of these species in their region and act accordingly.

The Midwest has many established species. When comparing US Geological Survey Nonindigenous Aquatic Species factsheets (2012-2014) for animal species established outside of the Great Lakes and non-native to the entire US state, Illinois (n=27) contains more established animal species than all surrounding states (Iowa [n=13], Missouri [n=20], Kentucky [n=21], and Indiana [n=23]), except Wisconsin (n=29). Although the surrounding states have many established aquatic animal species, their invaders don't have a main perennial connection between large basins and thus, are less likely to move from one basin to another. Illinois is in the unique position where the CSSC directly connects the Great Lakes and Mississippi River Basins and species can be transported across the state from one side to the other. Because invasive species threaten biodiversity and the ecosystem services that each basin offers (Cambray 2003; Mack et al. 2000) and Illinois acts as a conduit of invasive species between the Great Lakes and Mississippi River Basins, Illinois is a key player in management and regulation of non-native species between these two large ecologically and economically important basins.

It is important that a national and regional level policy for non-native species is enacted because non-native species do not adhere to political boundaries (Bossenbroek et al. 2007; Peters and Lodge 2009; Cambray 2003) and the effectiveness of any given state's policy can be undermined by those of its neighbors (Peters and Lodge 2009; Rothlisberger and Lodge 2013). Illinois has enacted a diverse range of policies with the goal to control the introduction, establishment, and spread of non-native species. For example, the injurious species list (2002) denotes species that cannot be possessed, bought, sold, transported, or released. The list currently includes aquatic non-native species such as: rusty crayfish, zebra mussels, silver and bighead carp, round goby, curly pondweed, and brittle waternymph. My results indicate that this goal has not been achieved because these species have continued to arrive, establish, and spread to new locations. Current US federal regulations have not reached their goals for decreasing the introduction, establishment, and spread of non-native species. For example, the Lacey Act (1900), which bans importation and interstate commerce in declared injurious species, covers a very small number of species, and those species have often only been listed after they were already established and causing harm (Fowler et al. 2007). Strong national programs and laws, where potential invasive species are evaluated and assessed for risk before being permitted into the country, will probably be necessary for effective management of invasive species in the US. My results indicate that such approaches will be necessary to protect Illinois from future invasions.

CHAPTER III

SPATIAL TRENDS IN THE ARRIVAL AND SPREAD OF AQUATIC INVADERS IN ILLINOIS

Introduction

Increasing globalization has increased worldwide species invasions at an accelerating rate over the last century (Hulme 2009; Mack et al. 2000). Freshwater ecosystems have been strongly impacted, due to high rates of species transport and this transport overcoming the ecological isolation of freshwaters (Mills et al. 1993; Strayer and Findlay 2010; Strayer 2010). Because the damages from aquatic invasive species can be large, it is important to understand the factors that make an introduced species likely to become established, spread, and cause impacts (Kolar and Lodge 2001).

Increased rates of aquatic non-native species introduction and spread are facilitated by human vectors. Some of the most important vectors include shipping, the aquarium and watergarden trades, canals, and stocking of species for sport (Ricciardi 2006). These vectors have proven effective both for long-distance spread (e.g., between continents) and localized spread (e.g., sport fish movement to new lakes within a region). Accidental transport of aquatic species on recreational boats is also a strong vector for spread, particularly in landscapes where waterbodies are relatively close to each other and organisms are unlikely to desiccate en-route (Anderson et al. 2014).

The potential for non-native species to disperse naturally has been enhanced by human modifications to many waterways. In particular, the construction of canals that connect previously isolated waterbodies has allowed many species to increase their range (Rahel 2007; Mills et al. 1993; Gallardo 2014). For example, the canals that connect the Rhine River in Western Europe to the Danube River in Eastern Europe have allowed many invasive species, including zebra mussel (*Dreissena polymorpha*) to spread across that continent (Bij de Vaate et al. 2002).

The US state of Illinois has been strongly impacted by aquatic invasive species. Illinois lies at the junction of the Laurentian Great Lakes and Mississippi River Basins. The connection between these basins occurs in Illinois at the Chicago Ship and Sanitary Canal, completed in 1900. This is the only connection between the two basins in which a continuous aquatic habitat is maintained throughout the year even at low flow conditions (US Army Corps of Engineers 2013). Thus, species can arrive in Illinois through spread from either of these basins (Horner, Sparks, and Charlebois 1999), which are themselves highly invaded, or through direct releases into the state. Once established, invasive species in Illinois have the potential to spread across much of North America.

To understand and manage the threat of non-native species, policy-makers and managers often rely on historical data to establish targets for reducing arrival and spread of future invasive species (Keller, Zu Ermgassen, and Aldridge 2009; Fuentes et al. 2013). Understanding previous trends in vectors, species spread rates and routes, and the regions where new species are most likely to be introduced, can inform efforts to prevent the arrival of new invaders, rapidly identify those that become established, and slow the spread of existing invaders. For example, if certain regions of the state have historically been more likely to be the first to receive new invaders, these regions may be good candidates for increased management efforts to prevent new arrivals, and increased sampling efforts so that new species are rapidly identified.

The goal of this chapter is to assess geographic trends in the arrival and spread of aquatic non-native species in Illinois. I gathered a database of occurrences of non-native species in the state. This allowed me to determine which areas were most important as the initial points of introduction for new species, and which contained the greatest numbers of established species. Next, I determined the most likely vectors for each species to Illinois. Finally, I gathered statewide data at the county scale to test the importance of some human and environmental factors that were shown in other systems to be strongly associated with species introduction and spread. My ultimate goal is to provide information that can be useful for reducing the overall impacts from established aquatic non-native species.

Methods

Database of Non-native Aquatic Species Records

Introduced species were defined as those that are not native to any part of Illinois but have been recorded beyond cultivation in the state. Established species are the subset of introduced species that have at least one population reproducing within Illinois. When there was doubt about whether or not a recorded species was native to Illinois, I referenced literature (e.g. Stuckey and Salamon 1987; Saltonstall 2002; Stevens and Hoag 2006; Saltonstall 2013; Ciotir et al. 2013) and contacted local experts to arrive at a consensus opinion.

Species considered aquatic were animals that live a majority of their lives in freshwater, and plants defined as *obligate wetland* vascular plants by the United States Department of Agriculture (USDA NRCS 2012). A single plant species not meeting this requirement, common reed (*Phragmites australis*; considered by the USDA to be a facultative wetland plant) was included because of its high association with wetlands, and its large impacts in these ecosystems (Meyerson et al. 2000, Chambers et al. 1999).

I searched for records of aquatic, non-native species within Illinois, including the portion of the rivers that border Illinois. Lake Michigan was not included because Illinois's boundaries in Lake Michigan are arbitrary, records are scarce for offshore sampling, and because the small portion of Lake Michigan over which Illinois has some control is most appropriately treated as part of the Great Lakes ecosystem. Records were collected from institutional databases, published literature, and through direct communication with aquatic invasive species experts (see Chapter II for full details).

Data included in each record were species identity, location and date of sampling, establishment status of the population, and collector identity. For most records, location was available as latitude and longitude. When this wasn't the case, I determined latitude and longitude from descriptions of the sampling site. If this wasn't possible, records were entered at the county level. All records were compiled into a Microsoft Access database and imported into ArcGIS 10.1 ©ESRI (Redlands, California, USA).

Vector(s) to Illinois

I determined the most likely vector(s) that moved each established species into Illinois. Many species can be moved by multiple vectors (e.g., non-native plants can be spread through the watergarden trade or as contaminants on recreational boats). In cases where the responsible vector could not be determined I recorded all potential vectors. Once this was completed for all species, I also determined the total number of times each vector was mentioned across all species. Vectors were assigned to categories as follows: shipping (including ballast water, solid ballast, and hull fouling), deliberate release (through cultivation or stocking), unintentional release (including ornamental and aquaculture escape, and bait bucket release), recreational boating, thoroughfare (including canals, railways, and highways), transport on birds, natural dispersal (i.e., unaided by direct human vectors), and unknown. Hybrids between non-native and native North American species were excluded from vector analysis because it is not possible to determine where the hybridization occurred (i.e., before or after the non-native species reached Illinois). Sources were Mills et al. 1993; Callaghan 1998; Les and Mehrhoff 1999; Saltonstall 2002; Delisle et al. 2003; Grigorovich et al. 2008; Sheen et al. 2009; U.S. Geological Survey 2012-2014; Efloras 2008; Global Invasive Species Database 2010, 2013; Missouri

Botanical Garden 2013; Indiana Department of Natural Resources 2005; Minnesota Department of Natural Resources 2014; and NatureGate 2014.

Locations of First Record

From the records described above, I determined how many times each of the 102 Illinois counties was the location of the first record of an established species. In several cases more than one county had records of a new species during the same calendar year. When this occurred, I divided the species by the number of counties in which it was discovered in that first year. For example, in the first year of discovery, common carp (*Cyprinus carpio*), was found in both Cook and Mason counties, and its record was split evenly (i.e., 0.5 for each county).

Illinois includes the most significant aquatic link between the Great Lakes and Mississippi River Basins. I hypothesized that counties containing the waterways that make up this link would be more highly invaded because species can spread via natural dispersal through this likely *invasion corridor*. Additionally, I anticipated that counties bordering those directly on the invasion corridor would be more invaded because transport distances are relatively short and may facilitate increased spread rates. To test these hypotheses, I created a categorical variable to distinguish between the 43 *primary* counties that border or include the invasion corridor (i.e., Lake Michigan, the Chicago Area Waterways System [CAWS], the portion of the Des Plaines River that connects the CAWS to the Illinois River, and the Illinois, Mississippi, and Ohio rivers), the 29 *secondary* counties that border primary counties but not the invasion corridor, and the remaining 30 *tertiary* counties. I used a Kruskal-Wallis one-way analysis of variance test and the Dwass-Steel-Chritchlow-Fligner Test for all pairwise comparisons to determine whether the number of times established species are first recorded in each county is different across primary, secondary, and tertiary counties.

Drivers of Number of Established Species per County

Other studies found that human population size (Keller, Zu Ermgassen, and Aldridge 2009; Pysek et al. 2010), and the number of people visiting waterbodies (Drake and Mandrak 2014; Leung, Bossenbroek, and Lodge 2006) can be positively related to the number and/or spread of established species in a given region. To investigate these relationships I gathered data on the human population of each Illinois county from the 2010 US census (US Census Bureau, 2010), the number of boat registrations submitted in each county between April 1st 2013 and March 31st 2014 (Illinois Department of Natural Resources [IDNR] records) and the number of fishing licenses sold to people who gave their addresses in each county between April 1st 2013 and March 31st 2014 (IDNR records). The former of these may be an indication of the strength of some vectors such as the number of people purchasing non-native species for their watergardens. The latter two of these are included as correlates of the number of people engaged in activities that bring them into contact with surface water. They are also indicative of the angling and boating vectors that are well known to spread non-native species. All variables were log-transformed to meet assumptions for analysis.

Initial analyses showed that human population, number of registered boats, and number of registered anglers by county were all highly correlated to each other (Pearson correlation coefficients from 0.951– 0.978, all p-values <0.001). I chose to use only the number of registered boats for further analysis. This was chosen because I felt that it is most strongly related to activities that could introduce more types of non-native species and spread those already established.

To account for different amounts of habitat in each county I set the response variable for the following analyses as the total number of established non-native species per km^2 of surface water in each county. Because fishes and plants have different vectors of natural and anthropogenic spread, I also tested the relationship between the predictor variables and the number of fishes and plants (per km^2 of surface water) for each county. Surface water area was calculated from the National Hydrology Dataset (2013) and included all waterbodies classified as permanent rivers, streams, lakes, ponds, reservoirs, and marshes (i.e., intermittent waterbodies were excluded).

I used ANOVA and Tukey's post-hoc test to determine whether the number of established species per km^2 of surface water is different across primary, secondary, and tertiary counties. Next, I regressed the number of boat registrations per county against the number of established species. To test whether the effect of boats depends on the distance of a county from the invasion corridor, I repeated the boating regression separately for primary, secondary, and tertiary counties.

Results

Record Analysis by County

I found records for 99 aquatic, non-native species introduced to Illinois. Thirty-nine of the species failed to establish and 31 of these were recorded in fewer than four counties, with 22 recorded from just one county (Table 9 in appendix). The remaining sixty species are established. The greatest number of individual records of established non-native species occurred in Mason County (n=3,619; Figure 8). Carroll, Tazewell, and Cass Counties had the second, third, and fourth highest number of records, respectively. Cook, Alexander, Lake, and Whiteside counties also had relatively high numbers of records. Forty-five counties had fewer than 66 records for established species.

The counties with the highest numbers of established species were all in the northeast of the state (Figure 9), including Cook (n=43), Will (n=34), DuPage (n=32), Grundy (n=32), and Lake (n=31) counties. In addition to other northeast counties, seven counties along the Illinois River and four counties along the Mississippi River had between 19 and 25 species (see Figure 9). Twelve counties had fewer than eight recorded established species, and 47 counties have fewer than 13 established species.

Many of the established species have spread widely throughout Illinois (Table 8). Common carp (*Cyprinus carpio*) was recorded from every county, followed by Asian clam (*Corbicula fluminea*; n=94 counties), marshpepper knotweed (*Polygonum hydropiper*; n=71), reed canarygrass (*Phalaris arundinacea*; n=71), common reed (*Phragmites australis*; n=68), creeping yellowcress (*Rorippa sylvestris*; n=65), narrowleaf cattail (*Typha angustifolia*; n=65), sweet flag (*Acorus calamus*; n=58), brittle waternymph (*Najas minor*; n=54), and curly pondweed (*Potamogeton crispus*; n=52). Twenty species were found in more than 34 counties.

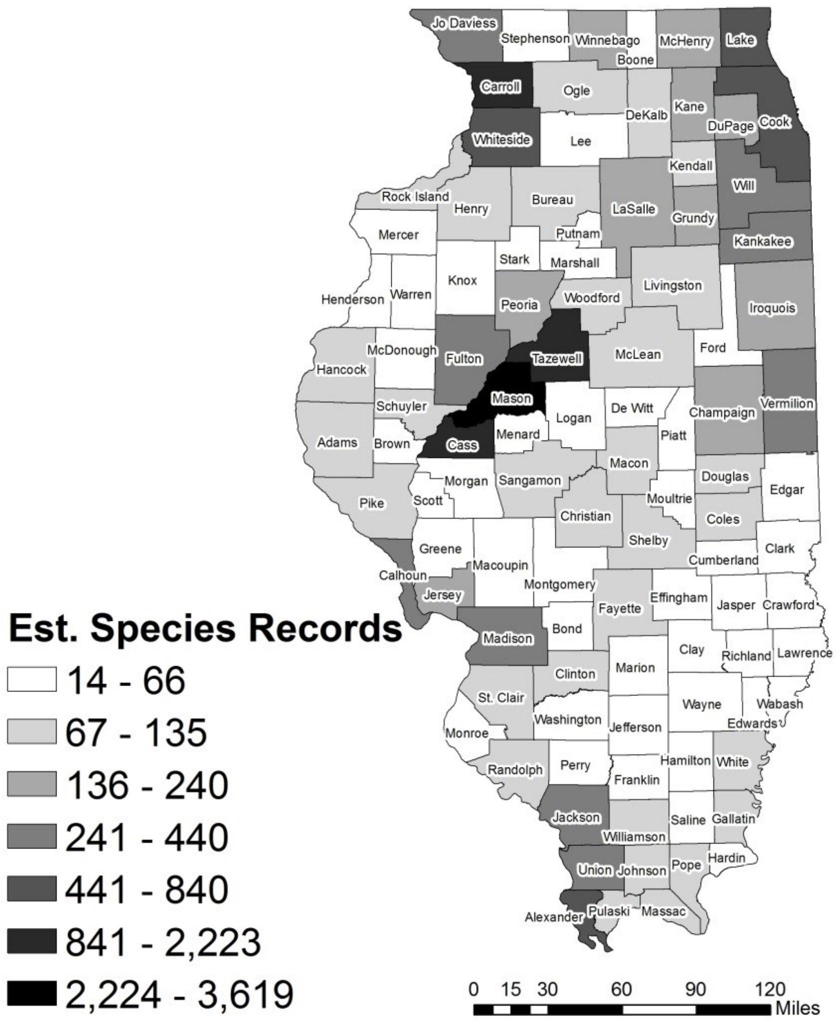

Figure 8. Number of records of established aquatic non-native species in each Illinois county.

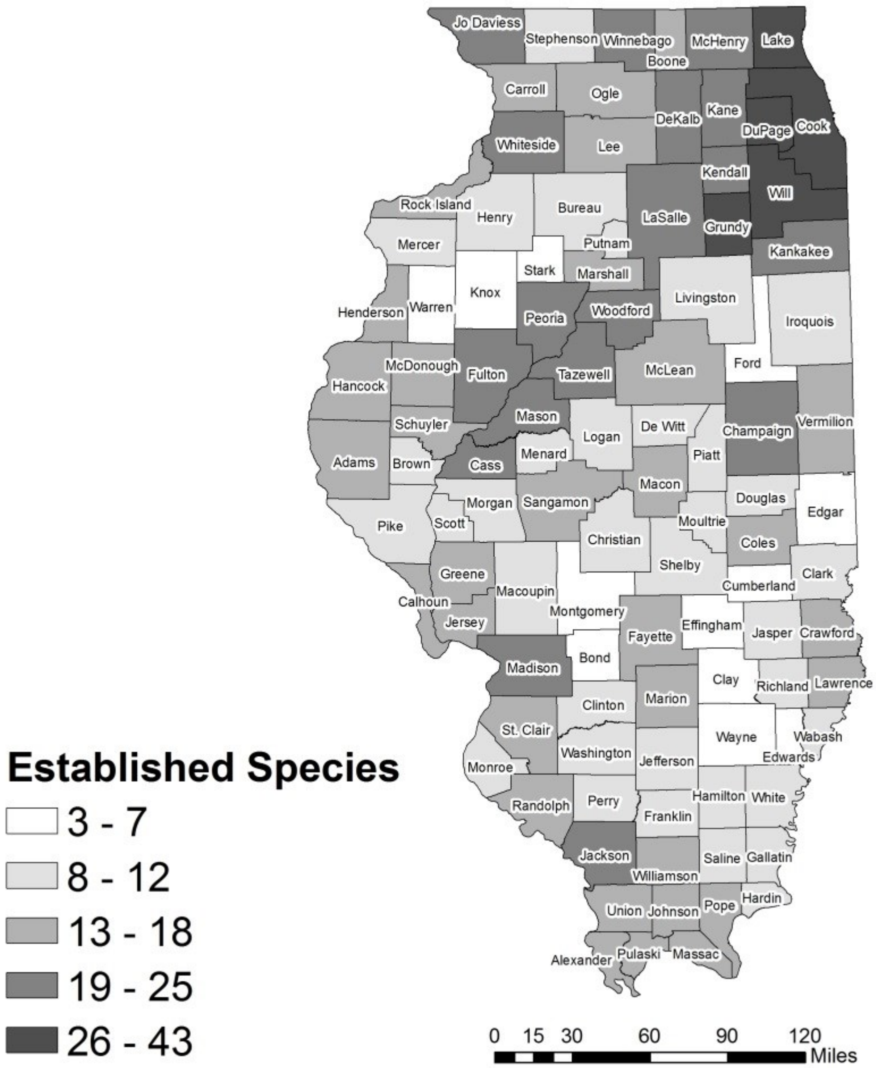

Figure 9. Number of established aquatic non-native species by county.

Vector(s) to Illinois

Two or more vectors were cited for 27 established species (i.e. 45%). For the 18 species with just one vector listed, the most prevalent vector was unintentional release (n=7). Vectors for nine species were unknown. The vectors mentioned most often were: deliberate release (n=20), unintentional release (n=19), natural dispersal (n=15), unknown (n=9), recreational boating (n=7), thoroughfares (n=5), shipping (n=5), and transport on birds (n=4).

Locations of First Record

First record for established species occurred in 28 counties (Figure 10), with Cook County having the greatest number (n=17.33). Seventy-seven percent of first species records occurred along the invasion corridor, and these primary counties had significantly more first species records than secondary or tertiary counties (Kruskal-Wallis Test $p=0.035$, Dwass-Steel-Critchlow-Fligner Test primary vs. secondary $p<0.001$, primary vs. tertiary $p<0.001$, secondary vs. tertiary $p=0.886$). The average number of first species records was 1.07 for primary (averaged across all counties in this category), 0.34 for secondary, and 0.13 for tertiary counties.

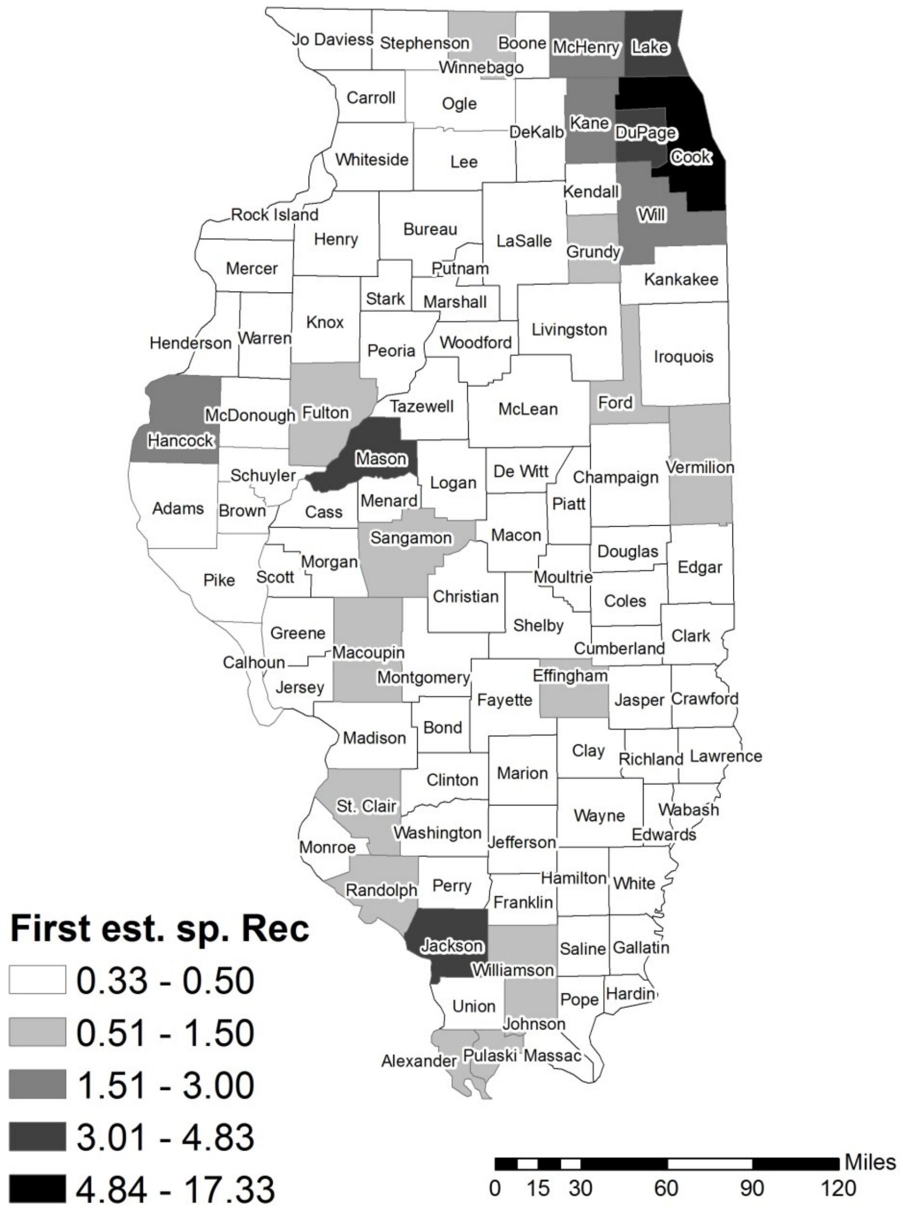

Figure 10. County location of each first established species record. In several cases, more than one county had records of a new species during the same calendar year. When this occurred, I divided the species by the number of counties in which it was discovered in that first year.

Drivers of Number of Established Species

The average number of established species per km^2 of surface water for counties in each invasion corridor category is shown in Table 3. Primary counties contained significantly more total established species than tertiary counties (ANOVA $p<0.001$, Tukey's post-hoc test primary vs. secondary $p=0.062$, primary vs. tertiary $p<0.001$, secondary vs. tertiary $p=0.134$). When only plants were included, primary counties contained significantly more established plant species than either secondary or tertiary counties (ANOVA $p<0.001$, Tukey's post-hoc test primary vs. secondary $p=0.015$, primary vs. tertiary $p<0.001$, secondary vs. tertiary $p=0.139$). In contrast, no significant differences were found when only fishes were included (ANOVA $p=0.270$).

No relationship was found between the number of boats registered in each county and the total number of established species per km^2 of surface water (linear regression, $p=0.172$). The same was true when only plants were considered ($p=0.550$). When only fishes were considered, the regression was significant but the relationship was negative ($p=0.009$, $r^2=0.067$).

I repeated these regressions separately for primary, secondary, and tertiary counties. For primary and tertiary counties I found no significant relationships between number of registered boats and total number of established species, number of plants, or number of fishes, per km^2 of surface water. For secondary counties there was no significant relationship for either total number of established species or plants, but there was a significant relationship between the number of established fishes per county (linear regression; p=0.035, r^2=0.155).

Table 3. The average number of established species per km^2 of surface water for counties in each invasion corridor category. Primary counties (n=43) are counties that border or include the invasion corridor (i.e., Lake Michigan, the Chicago Area Waterways System [CAWS], the portion of the Des Plaines River that connects the CAWS to the Illinois River, and the Illinois, Mississippi, and Ohio rivers). Secondary counties (n=29) border primary counties but not the invasion corridor. Tertiary counties (n=30) are the remaining counties. Numbers in parentheses are one standard deviation. The * indicates a significant (p<0.05) Tukey's post-hoc test between primary counties and the indicated county category.

Category	**Total Established Species**	**Established Plant Species**	**Established Fish Species**
Primary Counties	18 (7.8)	9.1 (5.2)	6.1 (2.7)
Secondary Counties	12.1 (6.1)	7.5* (4.8)	3 (1.5)
Tertiary Counties	11.1* (4.5)	7.1* (3.5)	2.5 (1.5)
ANOVA	p<0.001	p<0.001	p=0.270

Discussion

The invasion corridor that runs through Illinois and connects the Great Lakes to the Mississippi River was important for both the initial discovery and the subsequent establishment of aquatic, non-native species in Illinois. My results show that primary counties were the sites of significantly more first records of introduced and later established species than other counties. Although this is not definitive evidence that this is where the species were first introduced in the state, it is the best proxy available. An alternative explanation for the high number of first records along the invasion corridor would be that these have also been the sites of more intensive sampling, thus leading to a higher probability of finding new species. My results on number of records (Figure 8) make this alternative unlikely. Carroll, Tazewell and Cass counties are three of the four counties in Illinois that have the largest numbers of non-native species records, but none of them have been a site of first record. I conclude that the initial introduction of non-native species to Illinois occurs disproportionately along the invasion corridor. This is probably driven in large part by natural spread of species into the state from either Lake Michigan or the Mississippi River.

As for all established species records, the number of established species was higher in primary than tertiary counties. The average number of established species decreased with distance from the invasion corridor (Table 3). The same is true when plants or fish were considered alone. I suggest two explanations. First, the aquatic connections between the Great Lakes and Mississippi River Basins provide opportunities for species to disperse naturally, or to spread via boats (e.g., mollusks on boats). Second, the invasion corridor is a large riverine/canal system offering habitats that may not be found elsewhere in the state. It is possible that many of the established species are unable to persist elsewhere.

Recreational boat movement is a vector for the spread of non-native species, but in contrast to some previous studies (Johnson, Ricciardi, and Carlton 2001; Johnson, Bossenbroek, and Kraft 2006; Kelly et al. 2012; Minchin et al. 2006) number of registered boats was not associated with the number of established species in Illinois counties. This was true both when I examined all counties. Together with finding more established species along the invasion corridor, this indicates that the dispersal of established species through the invasion corridor may be greater than the overland spread of non-native species among waterbodies. Also, many boats are launched in locations outside the county in which they are registered, and thus, established species distributions and boat movement, rather than boat registrations, may be correlated. Other factors that could be important to the spread of species at the county level, which I did not test, are environmental variables and native species densities (Stohlgren et al. 2006; Jarnevich et al. 2006).

Many species have multiple vectors to Illinois that include natural dispersal and human associated vectors (e.g., recreational boating, unintentional release, and deliberate release). At a continental scale, the invasion corridor running through Illinois offers particularly strong opportunities for non-native species to expand their range through natural dispersal. Many other states contain a boundary between the Great Lakes and Mississippi River Basins, but none have an aquatic corridor connecting these basins as large as the CAWS in Illinois. Also, these aquatic connections are intermittent and connect during infrequent high flood events; thus, most have a low chance of transferring harmful species between the basins (US Army Corps of Engineers 2013). Harmful species like the zebra mussel (*Dreissena polymorpha;* Horner et al. 1999) and round goby (*Neogobius melanostomus*; Irons et al. 2006) have spread from the Great Lakes to the Mississippi through Illinois' invasion corridor, and there is concern about the potential for bighead (*Hypopthalmichthys nobilis*) and silver carp (*H. molitrix*) to spread from the Mississippi into Lake Michigan (Jerde et al. 2013). Indeed, the invasion corridor may make spread through Illinois more likely to occur via natural dispersal than in most other states, and a probable vector for some species for which I could find no vector information, and as an additional mode of spread for species that are elsewhere spread more often through human vectors.

Although few species established in Illinois are described as being moved by recreational boating and angling, these vectors are known to be strong across many regions because boaters and anglers move boats and equipment between basins (Bossenbroek et al. 2007; Johnson, Ricciardi, and Carlton 2001) and many fail to clean their equipment (Anderson et al. 2014). In Europe, for example, fishing and leisure activities account for 19% of introductions (Gallardo and Aldridge 2013). Closer to Illinois, several studies have found that patterns in boat ownership and movement can explain the spread of several non-native species (Muirhead and MacIsaac 2011; Leung, Bossenbroek, and Lodge 2006; Bossenbroek et al. 2007). This indicates that there is potential for recreational boating and angling to spread more species into secondary and tertiary counties. Unintentional and deliberate release are among primary vectors for the region (Grigorovich et al. 2003; Ricciardi 2006), and are also widespread as vectors into Illinois.

The dataset presented here is a compilation of results from a variety of sampling techniques. A standardized sampling protocol would facilitate sharing of data and communication between agencies and database information networks (Simpson et al. 2009). Agencies also constrain sampling spatially. For example, the US Geological Survey's Long Term Resource Monitoring Program (USGS LTRMP) has several fixed sites where they sample regularly for organisms and environmental parameters along the Mississippi and Illinois Rivers that have each generated thousands of records. USGS LTRMP has a fixed site at the county with the highest number of records, Mason. Thus, Figure 8 best reflects the distribution of sampling effort by county. Those counties with more records have a higher sampling effort and likely a more complete knowledge of species composition than counties with very low number of recorded occurrences.

Policy Implications

My work demonstrates that counties along the invasion corridor were the likely entry points for many established aquatic non-native species. Without changes in management and policy these counties are likely to continue to be sites of first introduction. Because many species likely entered the invasion corridor from either the Great Lakes or the Mississippi River, efforts to prevent movement along the full length of the invasion corridor could protect each of these ecosystems from future invasions. To address these concerns, starting in 1996, the government funded and set up a series of three electric barriers (which became operational in 2002, 2006, and 2011, respectively) near the junction of the Great Lakes and Mississippi River (Patel et al. 2010; US Army Corps of Engineers Chicago District 2014). This technology is aimed at preventing the spread of bighead and silver carp into the Great Lakes. It will not stop the movement of aquatic invasive species that are unaffected by electric fields (e.g., plants). More recently, the US Army Corps of Engineers published the Great Lakes and Mississippi River Interbasin Study (2014) that contains a range of management approaches to address the risk from species dispersal along the Illinois invasion corridor. These range from no new action from the federal government, to full ecological separation between the Great Lakes and Mississippi River Basins. My results, combined with others who have measured the number and taxonomic diversity of established species that could move through the invasion corridor in the future (Jerde et al. 2010), suggest that the invasion corridor will remain important for aquatic invasions across North America.

My data indicate different levels of sampling effort among Illinois counties. A caveat of these data is that negative results (i.e., area was sampled and non-native species were not found) were not available. Despite this, the variation among counties stretches over two orders of magnitude and indicates that there are real differences in sampling effort. This leads to two recommendations, the adoption of which could help in efforts to detect non-native species. First, sampling effort should be more evenly distributed across counties to ensure that managers have a better indication of the distribution of all non-native species. Second, collecting formal records of negative sampling results would help determine whether species are not present, or whether sampling effort is too low.

My results support continued sampling throughout the invasion corridor, especially near the junction of the Chicago River (where the invasion corridor meets the Great Lakes) and the junction of the Illinois and Mississippi Rivers. Sampling at these locations would provide early warning of new species entering Illinois. Although non-native species can rarely be controlled or eradicated, early detection would allow for consideration of control efforts which are generally more efficient and cost-effective than simply allowing a species to spread (Simberloff et al. 2013). It would also give early warning for preparations to deal with the new invasive species.

As well as natural spread, I found that non-native species have likely entered Illinois through human vectors, including unintentional (i.e. ornamental and aquaculture escape, and bait bucket release) and intentional releases (i.e. through cultivation or stocking), and recreational boating and angling. A new campaign with the slogan *Be a Hero, Transport Zero* (2014) was launched as part of outreach efforts to educate the public about how to prevent species spread. This program will hopefully prove successful at preventing new introductions, and limit the spread of species established in Illinois but with limited ranges (e.g., six species have so far been found in just one county each). At the other end of the spectrum, ten established species (eight plants, one fish, and one mollusk) have been recorded in >50% of Illinois counties (Table 8 in appendix). While efforts to slow the spread of these species may be useful, in most regions adaptation to ecological and economic costs is the only option (Lodge et al. 2006).

For new introductions, the continuing risk from human vectors is illustrated by the number of species that were recorded in Illinois but are not yet established

(Table 9 in appendix). Many of these may be climatically limited, but at least some have been sampled multiple times and may in the future become established. For example, common water hyacinth (*Eichhornia crassipes*) is invasive in many southeastern US states (USDA, NRCS, 2014) and is among the IUCN's list of 100 of the world's worst invasive species (Kulhanek, Ricciardi, and Leung 2011; Lowe et al. 2000). This species, and similar introduced species, should be a high priority for monitoring, management, and regulation.

Species currently found in a small number of counties, and not in major connected waterbodies, may be candidates for eradication (e.g. parrot feather watermilfoil [*Myriophyllum aquaticum*] and sacred lotus [*Nelumbo nucifera*]). My data will allow managers to determine which species are locally established and to weigh the many factors (including cost of action/inaction, reinvasion likelihood, species traits, degree of spread within and type of each county's waterbodies, and availability of effective herbicides and pesticides) that must be considered before decisive action (Vander Zanden et al. 2010).

CHAPTER IV

CONCLUSION

The increase in arrival, establishment, and spread of aquatic, non-native species worldwide is an ecological and economic concern. Important locations to focus response efforts include highly connected regions, such as Illinois, where non-native species cross between the Great Lakes and Mississippi River both naturally and with human aid. In this project, a comprehensive database of aquatic non-native species occurrences in Illinois was compiled and analyzed. Chapter II quantified which non-native species are found at each step in the invasion sequence, and the increasing rate of arrival of aquatic non-native species in Illinois. Most species moved from the Great Lakes Basin into Illinois, and recently the dominant vector was unintentional release, including shipping (steps 2 and 3 in Figure 1). Ninety-nine aquatic non-native species are introduced (step 3), while 60 have established (step 4), and 18 have high or very high ecological impacts (step 5). Assessing ecological impacts by surveying trained ecologists that have experience with these species in the field is a novel type of impact assessment and a quick way to assess impacts of numerous species. Chapter III's results indicate that many factors have played a part in creating the current geographic distribution of non-native species across Illinois. Among these are the many initial and enduring introductions along the invasion corridor, and the vectors of dispersal especially through the invasion corridor.

This gives an important basis for the ongoing sampling and management efforts by managers and policy makers in Illinois. Using a multi-vector management approach, increased early detection efforts along the invasion corridor, and a broad sampling of counties with a low number of records, could help to better inform managers in prioritizing regulation, prevention, and control, and recommended management options at each step of the invasion sequence (Khuroo, Reshi, Rashid, Dar, & Khan, 2008; Lodge et al., 2006). I hope other states, regions, and countries will use this as a model to analyze the status of their aquatic non-native species at each step in the invasion sequence, and collaborate on the regional, national, or international scale. Integrating data collection and policy/ management from the bottom-up, and top-down, will also contribute to further inform decisions of managers and policy-makers to prevent and slow introduction, establishment, and spread of non-native species throughout the state of Illinois, between the Great Lakes and Mississippi River Basins, and ultimately, across North America.

APPENDIX A

SUPPLEMENTAL TABLES AND FIGURES

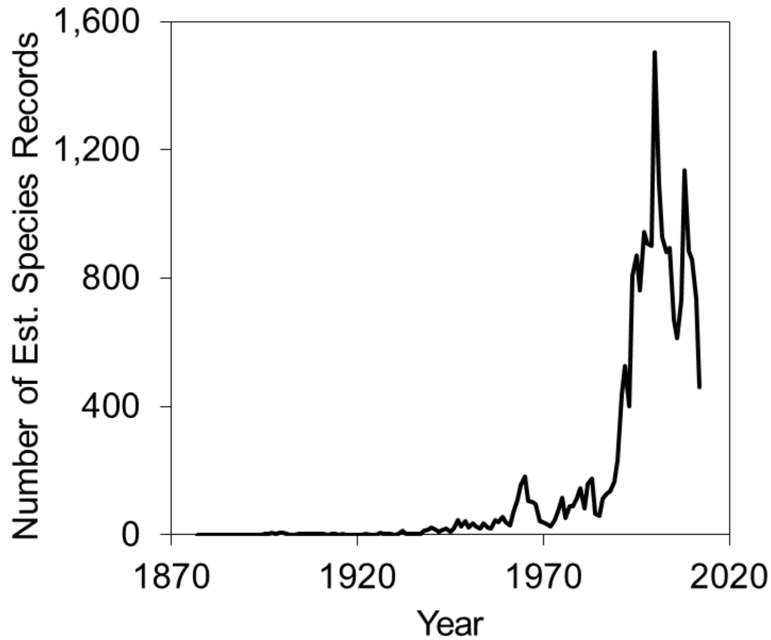

Figure 11. Number of established aquatic non-native species records within Illinois inland waters between 1873 and 2012.

Table 4. Sources and number of established aquatic non-native species records in inland waters of Illinois.

Source	Number of Records
US Geological Survey's Nuisance Aquatic Species Program	10,878
Illinois Natural History Survey	3,748
Illinois Department of Natural Resources	3,030
US Geological Survey's Long Term Resource Monitoring Program	2,328
Illinois State Museum	530
Illinois Environmental Protection Agency	418
Early Detection & Distribution Mapping System	408
Field Museum of Natural History	264
Morton Arboretum	242
US Department of Agriculture's Animal and Plant Health Inspection Service	157
Bell Museum of Natural History	7

Table 5. The 60 established aquatic non-native species found within Illinois inland waters. Categories include: Group, scientific name, common name, year of first discovery (year disc), number of records (# records), number of Illinois counties each species is present (# Co), vector, vector source, and average (avg) ecological impact rank. Vectors are Shipping-Hull Fouling (S(HF)), Shipping-Ballast Water (S(BW)), Shipping- Solid Ballast (S(SB)), Bait Release (BR), Aquarium Release (AQ), Deliberate Release (R(D)), Canals (C), Unintentional Release (R(U)), Unknown (U), or Not Applicable (N/A; e.g. because species is a hybrid).

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vector	Vector Source	Avg Rank
Crustaceans	*Apocorophium lacustre*	A Scud	2003	6	5	S(HF)	Grigorovich et al 2008	1.5
Crustaceans	*Daphnia lumholtzi*	Water Flea	1992	28	16	R(U)	USGS NAS	3
Crustaceans	*Eurytemora affinis*	A Calanoid Copepod	1976	1	1	S(BW)	Ricciardi 2006, USGS NAS	1.5
Crustaceans	*Orconectes rusticus*	Rusty Crayfish	1906	231	23	BR	USGS NAS	2.75
Fishes	*Ameiurus catus*	White Catfish	1965	12	11	R(D)	USGS NAS	1.29
Fishes	*Carassius auratus*	Goldfish	1917	643	43	R(D)	USGS NAS	1.55
Fishes	*Ctenopharyngodon idella*	Grass Carp	1971	975	48	R(D)	USGS NAS	2.42
Fishes	*Cyprinus carpio*	Common Carp	1894	9873	102	R(D)	USGS NAS	3
Fishes	*Cyprinus carpio x Carassius auratus*	Common Carp X Goldfish	1959	419	40	N/A	N/A	1.9

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vector	Vector Source	Avg Rank
Fishes	*Gasterosteus aculeatus*	Threespine Stickleback	1988	27	3	U	USGS NAS	1
Fishes	*Hypophthalmichthys molitrix*	Silver Carp	1983	1221	48	R(D)	USGS NAS	3.33
Fishes	*Hypophthalmichthys nobilis*	Bighead Carp	1986	690	47	R(D)	USGS NAS	3.25
Fishes	*Misgurnus anguillicaudatus*	Oriental Weatherfish	1987	29	2	R(U)	Ricciardi 2006, USGS NAS	1.14
Fishes	*Morone americana*	White Perch	1990	280	16	C	Ricciardi 2006, USGS NAS	1.89
Fishes	*Morone americana x Morone mississippiensis*	White Perch X Yellow Bass	2000	6	1	N/A	N/A	1.29
Fishes	*Morone saxatilis*	Striped Bass	1977	71	22	R(D)	USGS NAS	1.25
Fishes	*Neogobius melanostomus*	Round Goby	1993	80	7	S(BW)	Ricciardi 2006, USGS NAS	2.7
Fishes	*Oncorhynchus mykiss*	Rainbow Trout	1950	35	13	R(D)	Ricciardi 2006, USGS NAS	1.38

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vector	Vector Source	Avg Rank
Fishes	*Osmerus mordax*	Rainbow Smelt	1936	19	12	R(D)	USGS NAS	1.57
Fishes	*Salmo trutta*	Brown Trout	1928	24	11	R(D)	USGS NAS	1.5
Hydroids	*Cordylophora caspia*	Freshwater Hydroid	1999	1	1	S(BW)	USGS NAS	N/A
Mollusks	*Bithynia tentaculata*	Mud Bithynia, Faucet Snail	1889	1	1	S(SB)	USGS NAS	3
Mollusks	*Cipangopaludina chinensis malleata*	Chinese Mystery Snail	1938	88	18	AQ	USGS NAS	3
Mollusks	*Corbicula fluminea*	Asian Clam	1962	1543	94	AQ	USGS NAS	1
Mollusks	*Corbicula largillierti*	None	2008	5	3	U	N/A	1
Mollusks	*Dreissena polymorpha*	Zebra Mussel	1989	578	45	S(BW)	USGS NAS	4
Mollusks	*Eupera cubensis*	Mottled Fingernailclam	2006	3	3	S(HF)	Sheen et al 2009	1
Vascular Plants	*Acorus calamus*	Calamus, Sweet Flag	1904	110	58	R(D)	eFloras (2008)	1.63

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vector	Vector Source	Avg Rank
Vascular Plants	*Alopecurus geniculatus*	Water Foxtail	1927	9	6	R(D)	Ricciardi 2006	1
Vascular Plants	*Butomus umbellatus*	Flowering Rush	1957	23	5	R(U)	Les and Mehrhoff 1999	2.5
Vascular Plants	*Crypsis schoenoides*	Swamp Pricklegrass	1947	16	7	U	N/A	N/A
Vascular Plants	*Egeria densa*	Brazilian Waterweed	1992	28	16	R(U)	Les and Mehrhoff 1999	2.56
Vascular Plants	*Iris pseudacorus*	Paleyellow Iris	1942	45	20	R(D)	Ramey 2001	1.75
Vascular Plants	*Juncus compressus*	Roundfruit Rush	1982	23	3	R(U)	Mills et al 1993	1.25
Vascular Plants	*Lycopus europaeus*	Gypsywort	1976	9	4	S(SB)	Mills et al 1993	1.33
Vascular Plants	*Lysimachia punctata*	Large Yellow Loostrife	1947	2	2	R(U)	Missouri Botanical Garden 2013	1.6
Vascular Plants	*Lythrum hyssopifolium*	Hyssop Loosestrife	2011	2	1	U	N/A	1

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vecto r	Vector Source	Avg Rank
Vascular Plants	*Lythrum salicaria*	Purple Loosestrife	1903	185	42	S(SB)	Mills et al 1993	3.54
Vascular Plants	*Marsilea quadrifolia*	European Waterclover	1941	20	6	R(D)	Les and Mehrhoff 1999	1.56
Vascular Plants	*Mentha aquatica*	Water Mint	1896	57	35	R(D)	NatureGate	1.4
Vascular Plants	*Mentha x gracilis*	Gingermint	1897	52	28	N/A	N/A	1
Vascular Plants	*Mentha x piperita*	Peppermint	1943	13	11	N/A	N/A	1.33
Vascular Plants	*Mentha x villosa*	Spearmint x Apple Mint	1951	3	3	N/A	N/A	1.5
Vascular Plants	*Myosotis scorpioides*	True Forget-Me-Not	1897	49	15	R(D)	Ricciardi 2006	1.7
Vascular Plants	*Myriophyllum aquaticum*	Parrot Feather Watermilfoil	2008	2	1	R(U)	Les and Mehrhoff 1999	1.78
Vascular Plants	*Myriophyllum spicatum*	Eurasian Watermilfoil	1916	1465	38	R(U)	Les and Mehrhoff 1999	3.67

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vector	Vector Source	Avg Rank
Vascular Plants	*Najas minor*	Brittle Waternymph	1961	517	54	R(D)	Mills et al 1993	2.33
Vascular Plants	*Nasturtium officinale*	Watercress	1877	167	38	R(D)	Mills et al 1993	2.18
Vascular Plants	*Nelumbo nucifera*	Sacred Lotus	2012	2	2	R(U)	eFloras (2008)	2.11
Vascular Plants	*Nymphoides peltata*	Yellow Floatingheart	1948	10	5	R(U)	Mills et al 1993	2
Vascular Plants	*Phalaris arundinacea*	Reed Canarygrass	1900	225	68	R(D)	Jakubowski et al. 2012	3.92
Vascular Plants	*Phragmites australis*	Common Reed	1921	268	66	S(SB)	Burk 1877	3.83
Vascular Plants	*Polygonum hydropiper*	Marshpepper Knotweed	1882	149	71	U	N/A	1.67
Vascular Plants	*Potamogeton crispus*	Curly Pondweed	1911	1131	52	R(U)	Les and Mehrhoff 1999	3.31
Vascular Plants	*Puccinellia distans*	Weeping Alkaligrass	1957	42	16	S(SB)	Mills et al 1993	1.25

Continued

Table 5. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co	Vecto r	Vector Source	Avg Rank
Vascular Plants	*Rorippa sylvestris*	Creeping Yellowcress	1878	213	65	S(SB)	Mills et al 1993	1.29
Vascular Plants	*Salix caprea*	Goat Willow	1905	22	5	R(U)	Missouri Botanical Garden 2013	1
Vascular Plants	*Schoenoplectus mucronatus*	Bog Bullrush	1975	14	4	U	N/A	1.33
Vascular Plants	*Typha angustifolia*	Narrowleaf Cattail	1898	242	65	U	N/A	3.75
Vascular Plants	*Typha x glauca*	Hybrid Cattail	1940	11	9	N/A	N/A	3.91

Table 6. The 39 aquatic non-native species discovered but not established in inland waters of Illinois. Categories include: group, scientific name, common name, year of discovery (year disc), number of records (# records), and number of Illinois counties each species is present (# Co).

Group	Scientific Name	Common Name	Year Disc	# Records	# Co
Coelenterates	*Craspedacusta sowerbyi*	Freshwater Jellyfish	1993	15	10
Crustaceans	*Argulus japonicus*	Parasitic Copepod	1980	1	1
Crustaceans	*Procambarus clarkii*	Red Swamp Crayfish	2010	1	1
Fishes	*Alosa pseudoharengus*	Alewife	1956	13	3
Fishes	*Alosa sapidissima*	American Shad	1873	2	2
Fishes	*Carassius carassius*	Crucian Carp	1910	1	1
Fishes	*Channa argus*	Northern Snakehead	no date	1	1
Fishes	*Colossoma or Piaractus sp.*	Unidentified Pacu	2004	1	1
Fishes	*Herichthys cyanoguttatum*	Rio Grande Cichlid	1984	3	1
Fishes	*Melanotaenia nigrans*	Black-Banded Rainbowfish	1930	1	1
Fishes	*Menidia beryllina*	Inland Silverside	1978	27	11
Fishes	*Morone chrysops x Morone saxatilis*	Wiper	1982	62	33
Fishes	*Mugil cephalus*	Flathead Mullet	1995	2	1
Fishes	*Mylopharyngodon piceus*	Black Carp	2003	14	5

Continued

Table 6. *Continued*

Group	Scientific Name	Common Name	Year Disc	# Records	# Co
Fishes	*Oncorhynchus kisutch*	Coho Salmon	1990	12	2
Fishes	*Oncorhynchus tshawytscha*	Chinook Salmon	1988	14	3
Fishes	*Oreochromis mossambicus*	Mozambique Tilapia	1986	1	1
Fishes	*Oreochromis niloticus*	Nile Tilapia	1999	13	1
Fishes	*Petromyzon marinus*	Sea Lamprey	1957	1	1
Fishes	*Piaractus brachypomus*	Pirapatinga, Red-Bellied Pacu	1992	4	4
Fishes	*Poecilia latipinna*	Sailfin Molly	1998	2	1
Fishes	*Poecilia reticulata*	Guppy	1968	1	1
Fishes	*Pterygoplichthys disjunctivus x Pterygoplichthys pardalis*	Vermiculated Sailfin Catfish X Amazon Sailfin Catfish	2004	1	1
Fishes	*Salmo salar*	Atlantic Salmon	1986	1	1
Fishes	*Sander x Sander canadensis x vitreus*	Sauger X Walleye Hybrid (Saugeye)	2006	1	1
Fishes	*Scardinius erythrophthalmus*	Rudd	1988	22	9
Fishes	*Tinca tinca*	Tench	1891	3	3

Continued

Table 6. *Continued*

Group	**Scientific Name**	**Common Name**	**Year Disc**	**# Records**	**# Co**
Mollusks	*Dreissena rostriformis bugensis*	Quagga Mussel	2005	2	2
Mollusks	*Radix auricularia*	European Ear Snail	1901	3	1
Mollusks	*Rangia cuneata*	Common Rangia or Wedge Clam	1989	2	2
Reptiles	*Alligator mississippiensis*	American Alligator	2005	4	3
Vascular Plants	*Alisma plantago-aquatica*	European Water Plantain	1998	1	1
Vascular Plants	*Alternanthera philoxeroides*	Alligatorweed	no date	1	1
Vascular Plants	*Cardamine flexuosa*	Woodland Bittercress	1946	7	4
Vascular Plants	*Eichhornia crassipes*	Common Water Hyacinth	1975	21	8
Vascular Plants	*Glyceria maxima*	Reed Mannagrass	2006	2	1
Vascular Plants	*Macrothelypteris torresiana*	Swordfern	1999	1	1
Vascular Plants	*Mentha x verticillata*	Water Mint x Wild Mint	1984	2	2
Vascular Plants	*Oryza sativa*	Rice	1954	1	1

Table 7. Respondents (and affiliations) to ecological impacts of established aquatic non-native species survey.

Name	Affiliation
Catherine A. McGlynn	Northeast Illinois Invasive Plant Partnership
Chris Bickers	Illinois Department of Natural Resources
Chris Evans	Illinois Department of Natural Resources
Christopher A. Taylor	Illinois Natural History Survey
David M. Ketzner	University of Illinois, Illinois Natural History Survey
Debbie Maurer	Lake County Forest Preserves
Eric Ulaszek	Illinois Natural History Survey
Gordon C. Tucker	Eastern Illinois University
Greg Spyreas	Illinois Natural History Survey
Gregg Zink	Integrated Lakes Management Inc.
James E. Garvey	Southern Illinois University
James Ellis	Illinois Natural History Survey
Jeffrey A. Stein	Illinois Natural History Survey
Jeremy Tiemann	Illinois Natural History Survey
Karla Gage	River to River Cooperative Weed Management Area
Kevin Irons	Illinois Department of Natural Resources
Kevin S. Cummings	Illinois Natural History Survey
Les Frankland	Illinois Department of Natural Resources
Paul B. Marcum	Illinois Natural History Survey
Philip Willink	Shedd Aquarium
Robert Kirschner	Chicago Botanic Garden
Sergiusz Czesny	University of Illinois, Illinois Natural History Survey
Stephen Pescitelli	Illinois Department of Natural Resources
Steven Butler	Illinois Natural History Survey
Trent Thomas	Illinois Department of Natural Resources
William Perry	Illinois State University

Table 8. Established aquatic non-native species found in each county.

County	Acorus calamus	Alopecurus geniculatus	Ameiurus catus	Apocorophium lacustre	Bithynia tentaculata	Butomus umbellatus	Carassius auratus	C. chinensis malleata	Corbicula fluminea	Corbicula largillierti	Cordylophora caspia	Crypsis schoenoides	Ctenopharyngodon idella	Cyprinus carpio	C. carpio x C. auratus	Daphnia lumholtzi	Dreissena polymorpha	Egeria densa	Eupera cubensis	Eurytemora affinis	Gasterosteus aculeatus	Hypophthalmichthys molitrix	Hypophthalmichthys nobilis	Iris pseudacorus	Juncus compressus	Lycopus europaeus	Lysimachia punctata	Lythrum hyssopifolia	Lythrum salicaria	Marsilea quadrifolia
Adams	X						X		X					X	X		X					X	X							
Alexander	X						X		X				X	X			X					X	X							
Bond									X					X																
Boone	X							X						X																
Brown	X						X		X				X	X			X					X	X							
Bureau							X		X				X	X	X		X													
Calhoun	X			X			X		X				X	X	X		X					X	X							
Carroll	X					X			X					X			X												X	
Cass	X						X		X				X	X	X	X	X					X	X	X						
Champaign	X							X	X					X										X						X
Christian									X					X		X						X							X	
Clark									X				X	X								X	X						X	
Clay									X					X																
Clinton			X						X				X	X	X	X						X	X							
Coles	X								X				X	X	X							X		X						X
Cook	X	X			X	X	X	X	X			X	X	X	X	X	X		X		X		X	X	X				X	
Crawford	X								X				X	X								X	X						X	
Cumberland	X								X					X															X	
De Witt									X					X		X						X								
DeKalb	X						X		X					X	X														X	
Douglas									X					X	X														X	
DuPage		X				X	X	X	X			X		X	X		X	X	X					X	X	X	X		X	
Edgar	X								X					X																
Edwards									X					X				X												
Effingham									X					X																
Fayette	X		X				X		X					X															X	
Ford									X					X																
Franklin							X		X				X	X		X		X				X	X						X	
Fulton	X	X	X				X		X				X	X	X		X					X	X						X	
Gallatin									X					X			X	X				X	X							
Greene	X								X				X	X	X		X						X							
Grundy			X	X			X		X			X	X	X	X	X	X			X		X	X						X	
Hamilton	X								X					X				X				X							X	
Hancock	X	X					X		X					X	X		X					X	X						X	

Continued

Table 8. *Extended*

County	Mentha aquatica	Mentha x gracilis	Mentha x piperita	Mentha x villosa	Misgurnus anguillicaudatus	Morone americana	Morone saxatilis	Morone americana x M. mississippiensis	Myosotis scorpioides	Myriophyllum aquaticum	Myriophyllum spicatum	Najas minor	Nasturtium officinale	Nelumbo nucifera	Neogobius melanostomus	Nymphoides peltata	Oncorhynchus mykiss	Orconectes rusticus	Osmerus mordax	Phalaris arundinacea	Phragmites australis	Polygonum hydropiper	Potamogeton crispus	Puccinellia distans	Rorippa sylvestris	Salix caprea	Salmo trutta	Schoenoplectus mucronatus	Typha angustifolia	Typha x glauca
Adams	X	X									X		X							X		X	X		X					
Alexander						X	X					X							X	X		X			X			X		
Bond																				X		X								
Boone			X								X		X					X		X	X	X	X	X	X		X		X	
Brown		X																							X				X	
Bureau																				X	X	X			X					
Calhoun	X					X														X		X	X		X					
Carroll									X		X	X	X					X		X		X	X		X		X		X	
Cass	X	X				X	X				X				X					X	X	X	X		X				X	
Champaign	X	X	X								X	X	X							X	X	X	X		X	X			X	
Christian		X					X													X	X	X			X				X	
Clark											X	X				X				X		X			X					
Clay																						X								
Clinton												X										X								
Coles	X	X										X								X	X		X						X	
Cook	X	X	X	X	X	X			X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	
Crawford												X	X								X	X			X				X	
Cumberland												X									X		X							
De Witt											X	X						X		X		X								
DeKalb	X	X							X		X		X					X		X	X	X	X	X	X				X	
Douglas	X											X								X	X									
DuPage	X	X	X						X		X	X	X					X		X	X	X	X	X	X	X			X	
Edgar	X										X	X										X								
Edwards																							X							
Effingham				X								X									X	X								
Fayette	X		X									X	X							X	X	X							X	
Ford												X								X	X		X		X					
Franklin							X					X									X									
Fulton	X					X					X		X						X	X	X	X	X		X				X	
Gallatin												X									X				X				X	X
Greene												X	X									X	X		X				X	
Grundy	X	X				X	X				X		X				X	X	X	X	X	X	X	X	X		X		X	X
Hamilton												X									X								X	
Hancock	X	X									X									X	X		X		X				X	

Continued

Table 8. *Continued*

County	Acorus calamus	Alopecurus geniculatus	Ameiurus catus	Apocorophium lacustre	Bithynia tentaculata	Butomus umbellatus	Carassius auratus	C. chinensis malleata	Corbicula fluminea	Corbicula largillierti	Cordylophora caspia	Crypsis schoenoides	Ctenopharyngodon idella	Cyprinus carpio	C. carpio x C. auratus	Daphnia lumholtzi	Dreissena polymorpha	Egeria densa	Eupera cubensis	Eurytemora affinis	Gasterosteus aculeatus	Hypophthalmichthys molitrix	Hypophthalmichthys nobilis	Iris pseudacorus	Juncus compressus	Lycopus europaeus	Lysimachia punctata	Lythrum hyssopifolia	Lythrum salicaria	Marsilea quadrifolia
Hardin									X	X			X	X			X	X				X								
Henderson							X		X					X	X		X						X							
Henry														X	X															
Iroquois							X		X					X	X								X							
Jackson	X						X		X				X	X		X						X	X	X					X	X
Jasper	X								X				X	X		X														
Jefferson	X						X		X					X				X					X							
Jersey									X				X	X	X	X	X					X	X							
Jo Daviess						X	X		X				X	X	X		X												X	
Johnson									X				X	X		X		X				X							X	
Kane	X						X	X	X					X	X		X							X		X			X	
Kankakee							X	X	X					X	X		X						X	X					X	
Kendall	X						X	X	X			X		X	X									X		X			X	
Knox									X				X	X																
Lake	X						X	X	X					X	X		X	X			X			X	X				X	
LaSalle	X						X		X	X			X	X	X		X					X	X	X						
Lawrence	X						X		X					X								X	X							
Lee							X							X	X															
Livingston	X								X					X																
Logan									X				X	X															X	
Macon	X								X					X		X						X	X	X					X	
Macoupin	X								X					X																
Madison	X		X				X		X				X	X			X					X	X						X	X
Marion	X								X				X	X								X	X	X						
Marshall							X		X					X		X	X					X							X	
Mason	X			X			X		X		X		X	X	X	X	X					X	X							
Massac	X								X				X	X			X	X				X								
McDonough	X													X	X									X						X
McHenry	X	X						X	X					X			X							X		X		X	X	
McLean	X							X	X					X																
Menard	X								X				X	X								X	X							
Mercer			X				X		X					X	X							X								
Monroe									X			X	X	X								X	X							
Montgomery	X								X					X																

Continued

Table 8. *Extended*

County	Mentha aquatica	Mentha x gracilis	Mentha x piperita	Mentha x villosa	Misgurnus anguillicaudatus	Morone americana	Morone saxatilis	Morone americana x M. mississippiensis	Myosotis scorpioides	Myriophyllum aquaticum	Myriophyllum spicatum	Najas minor	Nasturtium officinale	Nelumbo nucifera	Neogobius melanostomus	Nymphoides peltata	Oncorhynchus mykiss	Orconectes rusticus	Osmerus mordax	Phalaris arundinacea	Phragmites australis	Polygonum hydropiper	Potamogeton crispus	Puccinellia distans	Rorippa sylvestris	Salix caprea	Salmo trutta	Schoenoplectus mucronatus	Typha angustifolia	Typha x glauca
Hardin	X											X										X			X					
Henderson	X					X						X									X	X			X				X	
Henry											X		X							X	X		X		X					X
Iroquois												X								X	X	X		X	X				X	
Jackson	X	X					X				X	X	X						X	X	X		X		X	X			X	
Jasper																					X							X		X
Jefferson												X									X	X							X	
Jersey						X														X		X	X		X				X	
Jo Daviess	X	X									X	X	X				X	X		X	X	X	X		X					
Johnson	X									X	X	X									X	X	X						X	
Kane	X		X						X		X		X				X	X		X	X	X	X	X	X		X		X	
Kankakee		X				X			X				X					X		X	X	X	X	X	X				X	X
Kendall	X	X	X						X		X		X					X		X	X	X	X	X	X				X	
Knox											X										X		X						X	
Lake	X	X							X		X	X	X				X	X	X	X	X	X	X	X	X	X	X		X	X
LaSalle			X				X		X						X			X			X	X		X	X		X		X	
Lawrence	X						X					X	X								X	X	X		X				X	
Lee									X		X		X				X	X		X	X	X	X	X					X	
Livingston																		X		X	X	X			X				X	
Logan																				X	X	X			X				X	
Macon	X	X														X				X	X	X			X				X	
Macoupin							X				X	X										X	X						X	
Madison						X						X							X	X	X		X		X				X	
Marion							X					X									X	X	X					X	X	
Marshall													X							X	X	X			X				X	
Mason						X	X	X					X		X					X	X	X			X			X	X	
Massac												X								X	X	X	X		X				X	
McDonough									X			X								X	X	X	X		X				X	
McHenry	X	X							X		X		X				X	X		X	X	X	X	X	X		X		X	
McLean											X	X						X		X	X	X	X	X					X	
Menard																						X			X				X	
Mercer							X													X			X		X					
Monroe																			X	X		X								
Montgomery																X				X	X									

Continued

Table 8. *Continued*

County	Acorus calamus	Alopecurus geniculatus	Ameiurus catus	Apocorophium lacustre	Bithynia tentaculata	Butomus umbellatus	Carassius auratus	C. chinensis malleata	Corbicula fluminea	Corbicula largillierti	Cordylophora caspia	Crypsis schoenoides	Ctenopharyngodon idella	Cyprinus carpio	C. carpio x C. auratus	Daphnia lumholtzi	Dreissena polymorpha	Egeria densa	Eupera cubensis	Eurytemora affinis	Gasterosteus aculeatus	Hypophthalmichthys molitrix	Hypophthalmichthys nobilis	Iris pseudacorus	Juncus compressus	Lycopus europaeus	Lysimachia punctata	Lythrum hyssopifolia	Lythrum salicaria	Marsilea quadrifolia
Morgan	X						X		X					X															X	
Moultrie	X								X					X									X						X	
Ogle							X							X			X							X					X	
Peoria	X		X	X			X	X	X				X	X	X		X					X	X						X	
Perry									X				X	X								X								
Piatt								X	X					X										X						
Pike				X					X				X	X			X					X	X							
Pope	X								X				X	X			X	X				X	X						X	
Pulaski	X								X	X			X	X	X		X	X				X	X							
Putnam							X		X				X	X			X					X								
Randolph	X						X		X				X	X			X					X	X							
Richland	X								X				X	X															X	
Rock Island							X		X				X	X	X		X						X						X	
Saline									X					X				X												
Sangamon	X								X				X	X		X							X	X			X		X	
Schuyler	X						X		X					X	X		X					X	X							
Scott	X								X				X	X	X		X					X							X	
Shelby	X								X					X		X														
St. Clair	X						X		X			X	X	X	X							X	X							
Stark														X																
Stephenson							X							X	X															
Tazewell	X		X				X		X				X	X	X		X					X	X							
Union	X		X						X				X	X			X					X	X							
Vermilion	X							X	X					X								X							X	X
Wabash									X				X	X			X						X							
Warren														X	X															
Washington			X						X				X	X								X	X							
Wayne								X	X					X				X												
White								X	X				X	X			X	X					X							
Whiteside	X		X				X	X	X				X	X	X		X												X	
Will	X	X				X	X	X	X			X		X	X		X		X		X	X	X	X					X	
Williamson	X								X					X				X				X	X						X	
Winnebago	X						X		X					X	X		X						X						X	
Woodford								X	X				X	X			X							X					X	
TOTAL	**58**	**6**	**11**	**5**	**1**	**5**	**43**	**18**	**94**	**3**	**1**	**7**	**48**	**102**	**40**	**16**	**45**	**16**	**3**	**1**	**3**	**48**	**47**	**20**	**3**	**4**	**2**	**1**	**42**	**6**

Continued

Table 8. *Extended*

County	Mentha aquatica	Mentha x gracilis	Mentha x piperita	Mentha x villosa	Misgurnus anguillicaudatus	Morone americana	Morone saxatilis	Morone americana x M. mississippiensis	Myosotis scorpioides	Myriophyllum aquaticum	Myriophyllum spicatum	Najas minor	Nasturtium officinale	Nelumbo nucifera	Neogobius melanostomus	Nymphoides peltata	Oncorhynchus mykiss	Orconectes rusticus	Osmerus mordax	Phalaris arundinacea	Phragmites australis	Polygonum hydropiper	Potamogeton crispus	Puccinellia distans	Rorippa sylvestris	Salix caprea	Salmo trutta	Schoenoplectus mucronatus	Typha angustifolia	Typha x glauca
Morgan		X									X									X					X				X	
Moultrie													X			X				X		X								
Ogle	X	X											X					X		X	X	X			X				X	
Peoria	X					X					X	X	X		X					X	X		X	X	X				X	
Perry											X	X									X	X								
Piatt		X							X				X							X			X							
Pike													X							X					X					
Pope							X				X	X													X				X	X
Pulaski	X											X								X	X		X		X					
Putnam		X											X												X					
Randolph						X	X					X							X				X							
Richland												X								X		X			X				X	
Rock Island																	X					X	X		X				X	
Saline							X					X									X	X							X	
Sangamon	X	X									X	X								X		X	X						X	
Schuyler				X																X		X			X				X	
Scott																				X	X								X	
Shelby			X									X	X							X	X	X	X						X	
St. Clair	X	X										X								X	X	X							X	
Stark																				X		X								
Stephenson											X							X		X	X						X			
Tazewell	X					X	X				X	X	X		X		X	X	X		X	X	X		X				X	
Union	X		X									X	X							X		X			X				X	
Vermilion	X										X	X	X	X						X	X	X	X		X				X	
Wabash	X											X										X			X					
Warren																				X	X									
Washington												X								X			X						X	
Wayne							X					X													X					
White							X														X				X					X
Whiteside		X					X				X	X	X				X	X	X	X		X	X		X		X			
Will		X			X	X			X		X	X	X		X		X	X		X	X	X	X	X	X				X	X
Williamson							X				X	X					X				X	X	X						X	
Winnebago		X					X		X		X		X			X	X	X		X	X	X	X		X		X		X	
Woodford	X	X	X			X	X						X						X	X	X	X	X		X				X	
TOTAL	**35**	**28**	**11**	**3**	**2**	**16**	**22**	**1**	**15**	**1**	**38**	**54**	**38**	**2**	**7**	**5**	**13**	**23**	**12**	**68**	**66**	**71**	**52**	**16**	**65**	**5**	**11**	**4**	**65**	**9**

Table 9. Introduced but not established aquatic non-native species found in each county.

County	Alisma plantago-aquatica	Alligator mississippiensis	Alosa pseudoharengus	Alosa sapidissima	Alternanthera philoxeroides	Argulus japonicus	Carassius carassius	Cardamine flexuosa	Channa argus	Colossoma or Piaractus sp.	Craspedacusta sowerbyi	Dreissena rostriformis bugensis	Eichhornia crassipes	Glyceria maxima	Herichthys cyanoguttatum	Macrothelypteris torresiana	Melanotaenia nigrans	Menidia beryllina	Mentha x verticillata	Morone chrysops X M. saxatilis
Adams																				
Alexander					X															
Bond																				
Boone																				
Brown																				X
Bureau																				
Calhoun																				
Carroll																				
Cass																				X
Champaign								X					X							
Christian																				
Clark																		X		
Clay																				
Clinton																				X
Coles																				X
Cook		X	X	X			X	X	X		X								X	X
Crawford																		X		
Cumberland																				
De Witt																				X
DeKalb																				X
Douglas																				
DuPage										X			X						X	
Edgar																				
Edwards																				
Effingham																				X
Fayette																				
Ford																				
Franklin																		X		X
Fulton											X	X								X
Gallatin											X									
Greene																				
Grundy			X																	X
Hamilton																				
Hancock																				

Continued

Table 9. *Extended*

County	Mugil cephalus	Mylopharyngodon piceus	Oncorhynchus kisutch	Oncorhynchus tshawytscha	Oreochromis mossambicus	Oreochromis niloticus	Oryza sativa	Petromyzon marinus	Piaractus brachypomus	Poecilia latipinna	Poecilia reticulata	Procambarus clarkii	Pterygoplichthys disjunctivus X P. pardalis	Radix auricularia	Rangia cuneata	Salmo salar	Sander canadensis X S. vitreus	Scardinius erythrophthalmus	Tinca tinca
Adams																			
Alexander		X													X				
Bond																			
Boone																			
Brown																			
Bureau																			
Calhoun		X																	
Carroll																		X	
Cass																			
Champaign											X								
Christian																			
Clark																			X
Clay																			
Clinton																		X	
Coles																			
Cook			X	X		X							X	X				X	X
Crawford																			
Cumberland																			
De Witt																			
DeKalb																		X	
Douglas																			
DuPage								X				X							
Edgar																			
Edwards																			
Effingham																			
Fayette																			X
Ford																			
Franklin																			
Fulton																			
Gallatin																			
Greene																			
Grundy																		X	
Hamilton																			
Hancock																			

Continued

Table 9. *Continued*

County	Alisma plantago-aquatica	Alligator mississippiensis	Alosa pseudoharengus	Alosa sapidissima	Alternanthera philoxeroides	Argulus japonicus	Carassius carassius	Cardamine flexuosa	Channa argus	Colossoma or Piaractus sp.	Craspedacusta sowerbyi	Dreissena rostriformis bugensis	Eichhornia crassipes	Glyceria maxima	Herichthys cyanoguttatum	Macrothelypteris torresiana	Melanotaenia nigrans	Menidia beryllina	Mentha x verticillata	Morone chrysops X M. saxatilis
Hardin											X	X	X							
Henderson																				
Henry																				
Iroquois																				
Jackson											X							X		X
Jasper																				
Jefferson																				X
Jersey	X																			
Jo Daviess																				
Johnson											X		X			X				
Kane																				
Kankakee											X									
Kendall								X					X							
Knox																				
Lake		X	X					X					X	X						
LaSalle																				X
Lawrence																				
Lee																				
Livingston																				
Logan																				X
Macon																				X
Macoupin																				X
Madison																				X
Marion																				X
Marshall																				
Mason																				X
Massac													X							
McDonough																				X
McHenry																				
McLean																				X
Menard																				X
Mercer																				
Monroe																				
Montgomery																				X

Continued

Table 9. *Extended*

County	Mugil cephalus	Mylopharyngodon piceus	Oncorhynchus kisutch	Oncorhynchus tshawytscha	Oreochromis mossambicus	Oreochromis niloticus	Oryza sativa	Petromyzon marinus	Piaractus brachypomus	Poecilia latipinna	Poecilia reticulata	Procambarus clarkii	Pterygoplichthys disjunctivus X P. pardalis	Radix auricularia	Rangia cuneata	Salmo salar	Sander canadensis X S. vitreus	Scardinius erythrophthalmus	Tinca tinca
Hardin																			
Henderson																			
Henry																			
Iroquois																			
Jackson									X										
Jasper																			
Jefferson																			
Jersey	X																		
Jo Daviess																			
Johnson																			
Kane									X										
Kankakee																			
Kendall																		X	
Knox																			
Lake			X	X					X	X								X	
LaSalle																		X	
Lawrence																			
Lee																			
Livingston																			
Logan																			
Macon																			
Macoupin																			
Madison		X																	
Marion																			
Marshall																			
Mason																			
Massac																			
McDonough																			
McHenry																			
McLean																			
Menard																			
Mercer																			
Monroe		X																	
Montgomery																			

Continued

Table 9. *Continued*

County	Alisma plantago-aquatica	Alligator mississippiensis	Alosa pseudoharengus	Alosa sapidissima	Alternanthera philoxeroides	Argulus japonicus	Carassius carassius	Cardamine flexuosa	Channa argus	Colossoma or Piaractus sp.	Craspedacusta sowerbyi	Dreissena rostriformis bugensis	Eichhornia crassipes	Glyceria maxima	Herichthys cyanoguttatum	Macrothelypteris torresiana	Melanotaenia nigrans	Menidia beryllina	Mentha x verticillata	Morone chrysops X M. saxatilis
Morgan																				X
Moultrie																				
Ogle																				
Peoria											X									
Perry																				
Piatt																				
Pike																				X
Pope																				X
Pulaski																				
Putnam																				
Randolph																	X	X		X
Richland																				
Rock Island																				
Saline																				
Sangamon																				X
Schuyler																				
Scott																				
Shelby																				
St. Clair																		X		X
Stark																				
Stephenson																				
Tazewell															X					X
Union																		X		
Vermilion																				
Wabash																		X		
Warren																				
Washington																				
Wayne																				
White																		X		
Whiteside																				
Will		X									X		X					X		X
Williamson						X					X							X		X
Winnebago				X																
Woodford																				
TOTAL	**1**	**3**	**3**	**2**	**1**	**1**	**1**	**4**	**1**	**1**	**10**	**2**	**8**	**1**	**1**	**1**	**1**	**11**	**2**	**33**

Continued

Table 9. *Extended*

County	Mugil cephalus	Mylopharyngodon piceus	Oncorhynchus kisutch	Oncorhynchus tshawytscha	Oreochromis mossambicus	Oreochromis niloticus	Oryza sativa	Petromyzon marinus	Piaractus brachypomus	Poecilia latipinna	Poecilia reticulata	Procambarus clarkii	Pterygoplichthys disjunctivus X P. pardalis	Radix auricularia	Rangia cuneata	Salmo salar	Sander canadensis X S. vitreus	Scardinius erythrophthalmus	Tinca tinca
Morgan																			
Moultrie																			
Ogle																			
Peoria				X															
Perry																			
Piatt					X														
Pike																			
Pope																			
Pulaski																			
Putnam																			
Randolph		X													X	X			
Richland																			
Rock Island																			
Saline																			
Sangamon																			
Schuyler																			
Scott																			
Shelby																			
St. Clair																			
Stark																			
Stephenson																			
Tazewell																			
Union							X												
Vermilion																			
Wabash																			
Warren																			
Washington																			
Wayne																	X		
White																			
Whiteside																			
Will																		X	
Williamson									X										
Winnebago																			
Woodford																			
TOTAL	**1**	**5**	**2**	**3**	**1**	**1**	**1**	**1**	**4**	**1**	**1**	**1**	**1**	**1**	**2**	**1**	**1**	**9**	**3**

REFERENCE LIST

Albins, Ma, and Ma Hixon. 2008. "Invasive Indo-Pacific Lionfish Pterois Volitans Reduce Recruitment of Atlantic Coral-Reef Fishes." *Marine Ecology Progress Series* 367 (September 11): 233–238. doi:10.3354/meps07620. http://www.int-res.com/abstracts/meps/v367/p233-238/.

Anderson, Lucy G, Piran C L White, Paul D Stebbing, Grant D Stentiford, and Alison M Dunn. 2014. "Biosecurity and Vector Behaviour: Evaluating the Potential Threat Posed by Anglers and Canoeists as Pathways for the Spread of Invasive Non-Native Species and Pathogens." *PloS One* 9 (4) (January): e92788. doi:10.1371/journal.pone.0092788.

Be a Hero, Transport Zero, 2014. "Aquatic invasive species, Be a Hero, Transport Zero." Illinois-Indiana Sea Grant, Urbana, IL, 60801. Accessed September 26, 2014. http://www.iisgcp.org/ais/transportzero.html

Bij de Vaate, A, K Jazdzewski, H A M Ketelaars, S Gollasch, and G Van der Velde. 2002. "Geographical Patterns in Range Extension of Ponto-Caspian Macroinvertebrate Species in Europe." *Canadian Journal of Fisheries and Aquatic Sciences* 59 (7) (July): 1159–1174. doi:10.1139/f02-098.

Burk, Isaac. *1877*. "List of Plants Recently Collected on Ships' Ballast in the Neighborhood of *Philadelphia*." *Proc*eedings of the *Academy of Natural Sciences of Philadelphia 29*: *105*-*109*.

Bossenbroek, Jonathan M, Ladd E Johnson, Brett Peters, and David M Lodge. 2007. "Forecasting the Expansion of Zebra Mussels in the United States." *Conservation Biology* 21 (3) (June): 800–810. doi:10.1111/j.1523-1739.2006.00614.x.

Callaghan, D A. 1998. "Lythrum Hyssopifolium L." *Journal of Ecology* 86: 1065–1072. doi:10.1046/j.1365-2745.1998.00320.x.

Cambray, JA. 2003. "Impact on Indigenous Species Biodiversity Caused by the Globalisation of Alien Recreational Freshwater Fisheries." *Hydrobiologia* 500 (1-3) (June): 217–230. doi:10.1023/A:1024648719995.

Carpenter, Stephen R., Emily H. Stanley, and M. Jake Vander Zanden. 2011. "State of the World's Freshwater Ecosystems: Physical, Chemical, and

Biological Changes.” *Annual Review of Environment and Resources* 36 (1) (November 21): 75–99. doi:10.1146/annurev-environ-021810-094524. http://www.annualreviews.org/doi/abs/10.1146/annurev-environ-021810-094524.

Chambers, Randolph M., Laura A Meyerson, and Kristin Saltonstall. 1999. “Expansion of Phragmites Australis into Tidal Wetlands of North America.” *Aquatic Botany* 64: 261–273.

Ciotir, Claudia, Heather Kirk, Jeffrey R. Row, and Joanna R. Freeland. 2013. “Intercontinental Dispersal of Typha Angustifolia and T. Latifolia between Europe and North America Has Implications for Typha Invasions.” *Biological Invasions* 15 (6) (November 29): 1377–1390. doi:10.1007/s10530-012-0377-8.

Colautti, Robert I., and Hugh J. MacIsaac. 2004. “A Neutral Terminology to Define ‘invasive’ Species.” *Diversity and Distributions* 10 (2) (February 24): 135–141. doi:10.1111/j.1366-9516.2004.00061.x.

Crall, Alycia W, Laura A Meyerson, Thomas J Stohlgren, Catherine S Jarnevich, Gregory J Newman, and Jim Graham. 2006. “Show Me the Numbers : What Data Currently Exist for Non-Native Species in the USA ?” *Frontiers in Ecology and the Environment* 4 (8): 414–418.

Crooks, Jeffrey A. 2005. “Lag Times and Exotic Species: The Ecology and Management of Biological Invasions in Slow-Motion.” *Ecoscience* 12 (3): 316–329.

Delisle, Fanny, Claude Lavoie, Martin Jean, Daniel Lachance, Fanny Delislet, and Centre De. 2003. “Reconstructing the Spread of Invasive Plants: Taking into Account Biases Associated with Herbarium Specimens.” *Journal of Biogeography* 30 (7): 1033–1042.

Drake, D Andrew R, and Nicholas E Mandrak. 2014. “Bycatch, Bait, Anglers, and Roads: Quantifying Vector Activity and Propagule Introduction Risk across Lake Ecosystems.” *Ecological Applications : A Publication of the Ecological Society of America* 24 (4) (June): 877–94.

Drake, Jm, and Jm Bossenbroek. 2004. “The Potential Distribution of Zebra Mussels in the United States.” *Bioscience* 54 (10): 931–941. http://apps.isiknowledge.com/full_record.do?product=WOS&search_mode=GeneralSearch&qid=54&SID=1EA3IFaiBPNCG9gg2lc&page=1&doc=1.

eFloras. 2008. Missouri Botanical Garden, St. Louis, MO & Harvard University Herbaria, Cambridge, MA. Accessed September 26 2013. http://www.efloras.org.

Fowler, Andrea J, David M Lodge, and Jennifer F Hsia. 2007. “Failure of the Lacey Act to Prevent US Ecosystems against Animal Invasions.” *Frontiers in Ecology and the Environment* 5 (7): 353–359.

Fuentes, Nicol, Aníbal Pauchard, Paulina Sánchez, Jocelyn Esquivel, and Alicia Marticorena. 2013. “A New Comprehensive Database of Alien Plant Species in Chile Based on Herbarium Records.” *Biological Invasions* 15 (4) (September 13): 847–858. doi:10.1007/s10530-012-0334-6.

Gallardo, Belinda. 2014. “Europe’s Top 10 Invasive Species: Relative Importance of Climatic, Habitat and Socio-Economic Factors.” *Ethology Ecology & Evolution* 26 (2-3) (April 24): 130–151. doi:10.1080/03949370.2014.896417.

Gallardo, Belinda, and David C Aldridge. 2013a. “Priority Setting for Invasive Species Management: Risk Assessment of Ponto-Caspian Invasive Species into Great Britain.” *Ecological Applications* 23 (2): 352–364.

Gallardo, Belinda, and David C. Aldridge. 2013b. “The ‘Dirty Dozen’: Socio-Economic Factors Amplify the Invasion Potential of 12 High-Risk Aquatic Invasive Species in Great Britain and Ireland.” Edited by Chris Frid. *Journal of Applied Ecology* 50 (3) (June 30): 757–766. doi:10.1111/1365-2664.12079.

Global Invasive Species Database. 2010. “Phalaris arundinacea (grass).” IUCN Species Survival Commission, Invasive Species Specialist Group. Accessed July 7, 2014. http://www.issg.org/database/species/ecology.asp?si=394

———. 2013. “Najas minor (aquatic plant).” IUCN Species Survival Commission, Invasive Species Specialist Group. Accessed July 7, 2014. http://www.issg.org/database/species/ecology.asp?si=1560&fr=1&sts=&lang=EN

Green, Stephanie J, John L Akins, Aleksandra Maljković, and Isabelle M Côté. 2012. “Invasive Lionfish Drive Atlantic Coral Reef Fish Declines.” *PloS One* 7 (3) (January): e32596. doi:10.1371/journal.pone.0032596.

Grigorovich, Igor A, Robert I Colautti, Edward L Mills, Kristen Holeck, Albert G Ballert, and Hugh J MacIssac. 2003. “Ballast-Mediated Animal Introductions in the Laurentian Great Lakes: Retrospective and Prospective Analyses.” *Canadian Journal of Fisheries and Aquatic Sciences* 60: 740–756.

Grigorovich, Igor A., Ted R. Angradi, Erich B. Emery, and Matthew S. Wooten. 2008. “Invasion of the Upper Mississippi River System by Saltwater Amphipods.” *Fundamental and Applied Limnology* 173 (1): 67–77.

Hansen, Gretchen J a, M Jake Vander Zanden, Michael J Blum, Murray K Clayton, Ernie F Hain, Jennifer Hauxwell, Marit Izzo, et al. 2013. “Commonly Rare and Rarely Common: Comparing Population Abundance of Invasive and Native Aquatic Species.” *PloS One* 8 (10) (January): 1–8. doi:10.1371/journal.pone.0077415.

Holeck, Kristen T, Edward L Mills, Hugh J Macisaac, R Margaret, Robert I Colautti, and Anthony Ricciardi. 2004. “Bridging Troubled Waters : Biological Invasions , Transoceanic Shipping , and the Laurentian Great Lakes” 54 (10): 919–929.

Horner, Rodney, Richard Sparks, and Pat Charlebois. 1999. “Illinois State Comprehensive Management Plan for Aquatic Nuisance Species.”

Howeth, Jennifer G, Crysta A Gantz, Paul L. Angermeier, Emmanual A. Frimpong, Michael Hoff, Reuben P Keller, Nicholas E. Mandrak, et al. “Predicting Invaders from Trade: Climate Match, Trophic Guild, and Fecundity Influence Invasion Success of Non-Native Freshwater Fishes.” *In Review*.

Hulme, Philip E. 2009. “Trade, Transport and Trouble: Managing Invasive Species Pathways in an Era of Globalization.” *Journal of Applied Ecology* 46 (1) (February): 10–18. doi:10.1111/j.1365-2664.2008.01600.x.

Indiana Department of Natural Resources. 2005. “Aquatic Invasive Species Chinese Mystery Snail.” Indiana Department of Natural Resources, Indianapolis, IN 46204. Accessed July 7, 2014. http://www.in.gov/dnr/files/CHINESE_MYSTERY_SNAIL.pdf

Injurious species, *17 Ill. Adm. Code 805*. 2002. Fish and Aquatic Life Code 515 ILCS 5.

Irons, Kevin S, Michael A McClelland, and Mark A Pegg. 2006. “The University of Notre Dame Expansion of Round Goby in the Illinois Waterway.” *American Midland Naturalist* 156 (1): 198–200.

Jakubowski, Andrew R., Michael D. Casler, and Randall D. Jackson. 2012. “Genetic Evidence Suggests a Widespread Distribution of Native North American Populations of Reed Canarygrass.” *Biological Invasions* 15 (2) (August 4): 261–268. doi:10.1007/s10530-012-0300-3.

Jarnevich, C S, T J Stohlgren, D Barnett, and J Kartesz. 2006. "Filling in the Gaps: Modelling Native Species Richness and Invasions Using Spatially Incomplete Data." *Diversity and Distributions* 12 (5) (September): 511–520. doi:10.1111/j.1366-9516.2006.00278.x.

Jerde, Christopher L, Matthew A Barnes, Andrew R Mahon, W Lindsay Chadderton, and David M Lodge. 2010. "Aquatic Invasive Species Risk Assessment for the Chicago Sanitary and Ship Canal."

Jerde, Christopher L, W Lindsay Chadderton, Andrew R Mahon, Mark A Renshaw, Joel Corush, Michelle L Budny, Sagar Mysorekar, and David M Lodge. 2013. "Detection of Asian Carp DNA as Part of a Great Lakes Basin-Wide Surveillance Program." *Canadian Journal of Fisheries and Aquatic Sciences* 70 (4): 522–526.

Jerde, Christopher L., Andrew R. Mahon, W. Lindsay Chadderton, and David M. Lodge. 2011. "'Sight-Unseen' Detection of Rare Aquatic Species Using Environmental DNA." *Conservation Letters* 00 (April 4): 1–8. doi:10.1111/j.1755-263X.2010.00158.x. http://doi.wiley.com/10.1111/j.1755-263X.2010.00158.x.

Johnson, Ladd E, Anthony Ricciardi, and James T Carlton. 2001. "Overland Dispersal of Aquatic Invasive Species: A Risk Assessment of Transient Recreational Boating." *Ecological Applications* 11 (6): 1789–1799.

Johnson, Ladd E., Jonathan M. Bossenbroek, and Clifford E. Kraft. 2006. "Patterns and Pathways in the Post-Establishment Spread of Non-Indigenous Aquatic Species: The Slowing Invasion of North American Inland Lakes by the Zebra Mussel." *Biological Invasions* 8 (3) (April): 475–489. doi:10.1007/s10530-005-6412-2.

Kartesz, John T. 2013. "The Biota of North America Program (BONAP). North American Plant Atlas." Biota of North America Program, Chapel Hill, NC. Accessed 2012-2013. http://www.bonap.org/napa.html

Keller, Reuben P, Philine S E Zu Ermgassen, and David C Aldridge. 2009. "Vectors and Timing of Freshwater Invasions in Great Britain." *Conservation Biology* 23 (6) (December): 1526–1534. doi:10.1111/j.1523-1739.2009.01249.x.

Keller, Reuben P., John M. Drake, Mark B. Drew, and David M. Lodge. 2011. "Linking Environmental Conditions and Ship Movements to Estimate Invasive Species Transport across the Global Shipping Network." *Diversity* *and Distributions* 17 (1) (January 26): 93–102. doi:10.1111/j.1472-4642.2010.00696.x.

Keller, Reuben P., and David M Lodge. 2007. “Species Invasions from Commerce in Live Aquatic Organisms : Problems and Possible Solutions.” *BioScience* 57 (5): 428–436.

Keller, Reuben P., and David M. Lodge. 2009. “Invasive Species.” In *Encyclopedia of Inland Waters*, edited by Gene E. Likens, 3:92–99. Oxford: Elsevier.

Kelly, Noreen E., Kristina Wantola, Erika Weisz, and Norman D. Yan. 2012. “Recreational Boats as a Vector of Secondary Spread for Aquatic Invasive Species and Native Crustacean Zooplankton.” *Biological Invasions* 15 (3) (August 10): 509–519. doi:10.1007/s10530-012-0303-0.

Khuroo, Anzar a., Zafar Reshi, Irfan Rashid, G. H. Dar, and Zafar S. Khan. 2008. “Operational Characterization of Alien Invasive Flora and Its Management Implications.” *Biodiversity and Conservation* 17 (13) (July 16): 3181–3194. doi:10.1007/s10531-008-9419-z. http://link.springer.com/10.1007/s10531-008-9419-z.

Kolar, Cynthia S, and David M Lodge. 2001. “Progress in Invasion Biology: Predicting Invaders.” *Trends in Ecology and Evolution* 16 (4): 199–204.

Kulhanek, Stefanie A, Anthony Ricciardi, and Brian Leung. 2011. “Is Invasion History a Useful Tool for Predicting the Impacts of the World’s Worst Aquatic Invasive Species?” *Ecological Applications* 21 (1): 189–202.

Lacey Act of 1900, *US Code 16*, §§ 3371-3378 et seq. 1900. *An act to enlarge the powers of the Department of Agriculture, prohibit the transportation by interstate commerce of game killed in violation of local laws, and for other purposes*. United States Statutes at Large 31: Chapter 553, 187-89.

Les, Donald H, and Leslie J Mehrhoff. 1999. “Introduction of Nonindigenous Aquatic Vascular Plants in Southern New England : A Historical Perspective.” *Biologica* (1): 281–300.

Leung, Brian, Jonathan M. Bossenbroek, and David M. Lodge. 2006. “Boats, Pathways, and Aquatic Biological Invasions: Estimating Dispersal Potential with Gravity Models.” *Biological Invasions* 8 (2) (March): 241–254. doi:10.1007/s10530-004-5573-8.

Leung, Brian, David M Lodge, David Finnoff, Jason F Shogren, Mark a Lewis, and Gary Lamberti. 2002. “An Ounce of Prevention or a Pound of Cure: Bioeconomic Risk Analysis of Invasive Species.” *Proceedings. Biological Sciences / The Royal Society* 269 (1508) (December 7): 2407–13. doi:10.1098/rspb.2002.2179.

Lichvar, Robert W. 2012. “The National Wetland Plant List”. Hanover, NH. http://www.poa.usace.army.mil/portals/34/docs/regulatory/nationalwetlandplantlistoct12.pdf.

Lodge, David M., Susan Williams, Hugh J. MacIssac, Hayes Keith R., Brian Leung, Sarah Reichard, Richard N. Mack, et al. 2006. “Biological Invasions: Recommendations for U.S. Policy and Management.” *Ecological Applications* 16 (6): 2035–2054.

Lowe, S, M Browne, S Boudjelas, and M De Porter. 2000. “100 of the World’s Worst Invasive Alien Species; a Selection from the Global Invasive Species Database.”

Mapsof.net. 2012. “Illinois Rivers and Lakes.” Mapsof.net. Accessed January 27, 2012. http://mapsof.net/map/illinois-rivers-and-lakes.

Mack, Richard N., Daniel Simberloff, W M Lonsdale, Harry Evans, Michael Clout, and Fakhri A. Bazzaz. 2000. “Biotic Invasions: Causes, Epidemiology, Global Consequences, and Control.” *Ecological Applications* 10 (3): 689–710.

McCauley, Lisa A, and David G Jenkins. 2005. “GIS-Based Estimates of Former and Current Depressional Wetlands in an Agricultural Landscape.” *Ecological Applications* 15 (4): 1199–1208.

Meyerson, Laura A, Kristin Saltonstall, L. Windham, E. Kiviat, and S. Findlay. 2000. “A Comparison of Phragmites Australis in Freshwater and Brackish Marsh Environments in North America.” *Wetlands Ecology and Management* 8: 89–103.

Mills, Edward L, Joseph H Leach, James T Carlton, and Carol L Secor. 1993. “Exotic Species in the Great Lakes: A History of Biotic Crises and Anthropogenic Introductions.” *Journal of Great Lakes Research* 19 (1): 1–54.

Minchin, D, O Floerl, D Savini, and A Occhipinti-Ambrogi. 2006. “Small Craft and the Spread of Exotic Species.” In *The Ecology of Transportation: Managing Mobility for the Environment*, 99–118.

Minnesota Department of Natural Resources. 2014. "Faucet Snail (Bithynia tentaculata)." Minnesota Department of Natural Resources St. Paul, MN 55155- 4046, USA. Accessed July 7, 2014. http://www.dnr.state.mn.us/invasives/aquaticanimals/faucet_snail/index.html

Missouri Botanical Garden. 2013. "Lysimachia punctata." Missouri Botanical Garden, St. Louis, MO. Accessed September 26 2013. http://www.missouribotanicalgarden.org/

———. 2013. "Salix caprea." Missouri Botanical Garden, St. Louis, MO. Accessed September 26 2013. http://www.missouribotanicalgarden.org/

Muirhead, Jim R., and Hugh J. MacIsaac. 2011. "Evaluation of Stochastic Gravity Model Selection for Use in Estimating Non-Indigenous Species Dispersal and Establishment." *Biological Invasions* 13 (11) (August 17): 2445–2458. doi:10.1007/s10530-011-0070-3.

National Hydrology Dataset 1:24,000. 2007. "Geospatial Data Gateway." United States Department of Agriculture Natural Resources Conservation Service. Accessed June 12, 2013. http://datagateway.nrcs.usda.gov

NatureGate Ltd. 2014. "Water mint." NatureGate Ltd., Helsinki, Finland. Accessed March 4, 2014. http://www.luontoportti.com/suomi/en/

Patel, Anjali G, Katherine Glassner-Shwayder, and Tim Eder. 2010. "Halting the Invasion: Maintaining the Health of the Great Lakes and Mississippi River Basins by Preventing Further Exchange of Aquatic Invasive Species." *Environmental Practice* 12 (4): 342–356. doi:10.10170S1466046610000499.

Peters, Jody A., and David M. Lodge. 2009. "Invasive Species Policy at the Regional Level: A Multiple Weak Links Problem." *Fisheries* 34 (8): 373–381.

Pimentel, David, Rodolfo Zuniga, and Doug Morrison. 2005. "Update on the Environmental and Economic Costs Associated with Alien-Invasive Species in the United States." *Ecological Economics* 52 (3) (February): 273–288. doi:10.1016/j.ecolecon.2004.10.002.

Pysek, Petr, Vojtech Jarosík, Philip E Hulme, Ingolf Kühn, Jan Wild, Margarita Arianoutsou, Sven Bacher, et al. 2010. "Disentangling the Role of Environmental and Human Pressures on Biological Invasions across Europe." *Proceedings of the National Academy of Sciences of the United States of America* 107 (27) (July 6): 12157–12162. doi:10.1073/pnas.1002314107.

Rahel, Frank J. 2007. “Biogeographic Barriers, Connectivity and Homogenization of Freshwater Faunas: It’s a Small World after All.” *Freshwater Biology* 52 (4) (April): 696–710. doi:10.1111/j.1365-2427.2006.01708.x.

Ramey, Victor. 2001. “Yellow flag, *Iris pseudacorus*.” University of Florida, IFAS, Center for Aquatic and Invasive Plants, Gainsville, FL 32653. Accessed February 25, 2014. http://plants.ifas.ufl.edu/node/205

Ricciardi, Anthony. 2006. “Patterns of Invasion in the Laurentian Great Lakes in Relation to Changes in Vector Activity.” *Diversity and Distributions* 12 (4) (July): 425–433. doi:10.1111/j.1366-9516.2006.00262.x.

Rothlisberger, John D, and David M Lodge. 2013. “The Laurentian Great Lakes as a Beachhead and a Gathering Place for Biological Invasions.” *Aquatic Invasions* 8 (4) (October): 361-374.

Saltonstall, Kristin. 2002. “Cryptic Invasion by a Non-Native Genotype of the Common Reed, Phragmites Australis, into North America.” *Proceedings of the National Academy of Sciences of the United States of America* 99 (4): 2445–2449.

———. 2003. “Genetic Variation among North American Populations of Phragmites Australis: Implications for Management.” *Estuaries* 26 (2B): 444–451.

Sax, Dov F, John J Stachowicz, James H Brown, John F Bruno, Michael N Dawson, Steven D Gaines, Richard K Grosberg, et al. 2007. “Ecological and Evolutionary Insights from Species Invasions.” *Trends in Ecology & Evolution* 22 (9) (September): 465–71. doi:10.1016/j.tree.2007.06.009.

Schofield, Pamela. 2010. “Update on Geographic Spread of Invasive Lionfishes (Pterois Volitans [Linnaeus, 1758] and P. Miles [Bennett, 1828]) in the Western North Atlantic Ocean, Caribbean Sea and Gulf of Mexico.” *Aquatic Invasions* 5 (Supplement 1): S117–S122. doi:10.3391/ai.2010.5.S1.024.

Sheen, Martin E., Kevin S. Cummings, Thomas Minarik Jr., and Jennifer Wasik. 2009. “The Discovery of the Nonindigenous, Mottled Fingernail Clam, Eupera Cubensis (Prime, 1865) (Bivalvia: Sphaeriidae) in the Chicago Sanitary and Ship Canal (Illinois River Drainage), Cook County, Illinois.” *Journal of Great Lakes Research* 35 (4): 627–629.

Simberloff, Daniel. 2009. “The Role of Propagule Pressure in Biological Invasions.” *Annual Review of Ecology, Evolution, and Systematics* 40: 81–102. doi:10.1146/annurev.ecolsys.110308.120304.

Simberloff, Daniel, Jean-Louis Martin, Piero Genovesi, Virginie Maris, David A Wardle, James Aronson, Franck Courchamp, et al. 2013. "Impacts of Biological Invasions: What's What and the Way Forward." *Trends in Ecology & Evolution* 28 (1) (January): 58–66. doi:10.1016/j.tree.2012.07.013.

Simpson, Annie, Catherine Jarnevich, John Madsen, Randy Westbrooks, Christine Fournier, Les Mehrhoff, Michael Browne, Jim Graham, and Elizabeth Sellers. 2009. "Invasive Species Information Networks: Collaboration at Multiple Scales for Prevention, Early Detection, and Rapid Response to Invasive Alien Species." *Biodiveristy* 10 (2&3): 5–13.

Sparks, Richard E. 2010. "Forty Years of Science and Management on the Upper Mississippi River: An Analysis of the Past and a View of the Future." *Hydrobiologia* 640 (1) (January 6): 3–15. doi:10.1007/s10750-009-0069-2.

Stevens, Michelle, and Chris Hoag. 2006. "USDA NRCS plants guide: narrowleaf cattail: *Typha angustifolia*." United States Department of Agriculture Natural Resources Conservation Service. Accessed September 19, 2013. http://plants.usda.gov/plantguide/pdf/cs_tyan.pdf

Stohlgren, Thomas J., David Barnett, Curtis Flather, Pam Fuller, Bruce Peterjohn, John Kartesz, and Lawrence L. Master. 2006. "Species Richness and Patterns of Invasion in Plants, Birds, and Fishes in the United States." *Biological Invasions* 8 (3) (April): 427–447. doi:10.1007/s10530-005-6422-0.

Strayer, David L. 2010. "Alien Species in Fresh Waters: Ecological Effects , Interactions with Other Stressors , and Prospects for the Future." *Freshwater Biology* 55: 152–174. doi:10.1111/j.1365-2427.2009.02380.x.

Strayer, David L., and Stuart E. G. Findlay. 2010. "Ecology of Freshwater Shore Zones." *Aquatic Sciences* 72 (2) (February 9): 127–163. doi:10.1007/s00027-010-0128-9.

Stuckey, Ronald. L., and Douglas P. Salamon. 1987. "*Typha angustifolia* in North America: a Foreigner Masquerading as a Native." *Ohio Journal of Science*. 87(2):4-4.

Suloway, L., and M. Hubbell. 1994. "Wetland resources of Illinois: an analysis and atlas." Illinois Natural History Survey, Special Publication 15, Champaign, Illinois.

Swink, F., and G. S. Wilhelm. 1994. *Plants of the Chicago Region*. 4th ed.Indianapolis, IN. Indiana Academy of Science.

Taylor, Derek J, and Paul D N Hebert. 1993. “Cryptic Intercontinental Hybridization in Daphnia (Crustacea) : The Ghost of Introductions Past.” *Proceedings of the Royal Society B Biological Sciences* 254 (1340): 163–168.

USDA, NRCS. 2012. “The PLANTS Database.” United States Department of Agriculture Natural Resources Conservation Service National Plant Data Team, Greensboro, NC 27401-4901 USA. Accessed December 3, 2012. http://plants.usda.gov

———. 2013. “The PLANTS Database.” United States Department of Agriculture Natural Resources Conservation Service National Plant Data Team, Greensboro, NC 27401-4901 USA. Accessed September 17 2013. http://plants.usda.gov

US Army Corps of Engineers Chicago District. 2014. Electric barriers. U.S. Army Corps of Engineers. Accessed September 25, 2014. http://www.lrc.usace.army.mil/Missions/CivilWorksProjects/ANSPortal/Barrier.aspx

US Army Corps of Engineers. 2013. “Focus Area 2 Aquatic Pathways Assessment Summary Report.”

———. 2014. “The GLMRIS Report, Great Lakes and Mississippi River Interbasin Study.” http://glmris.anl.gov/documents/docs/glmrisreport/GLMRIS_Report.pdf.

US Census Bureau. 2010; “American Fact Finder, 2010 Census.” Department of Commerce, United States Census Bureau. Accessed December 10, 2013. http://factfinder2.census.gov.

US Geological Survey. 2012-2014. “Nonindigenous Aquatic Species.” NonIndigenous Aquatic Species Program, Gainesville, FL. Accessed 2012- 2014. http://nas.er.usgs.gov/.

US President. 1999. “Presidential Documents, Executive Order 13112, Invasive Species.” *Federal Registrar* 64 (25): 6183–6186.

Vander Zanden, M Jake, and Julian D Olden. 2008. “A Management Framework for Preventing the Secondary Spread of Aquatic Invasive Species.” *Canadian Journal of Fisheries and Aquatic Sciences* 65: 1512–1522. doi:10.1139/F08-099.

Vander Zanden, M. Jake, Gretchen J.A. Hansen, Scott N. Higgins, and Matthew S. Kornis. 2010. “A Pound of Prevention, plus a Pound of Cure: Early Detection and Eradication of Invasive Species in the Laurentian Great Lakes.” *Journal of Great Lakes Research* 36 (1): 199–205.

Whitfield, Paula E, Todd Gardner, Stephen Vives, Matthew R Gilligan, Walter R Courtenay Jr., G Caleton Ray, and Jonathan A Hare. 2002. “Biological Invasion of the Indo-Pacific Lionfish Pterois Volitans along the Atlantic Coast of North America.” *Marine Ecology Progress Series* 235: 289–297.

Williamson, Mark, and Alastair Fitter. 1996. “The Varying Success of Invaders.” *Ecology* 77 (6): 1661–1666.

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