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Modelling spread and assessing movement of Grass Carp, *Ctenopharyngodon idella*, in the Great Lakes basin

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

Grass Carp (*Ctenopharyngodon idella*), a species of Asian carp, was first introduced to North America in 1963 for aquatic macrophyte control. It has since escaped from impoundments where it was stocked and entered rivers of the central United States and has continued making its way up the Mississippi River basin towards the Great Lakes. Diploid (i.e., fertile) and triploid (i.e., functionally sterile) Grass Carp continue to be used for various purposes (e.g., biological control, polyculture) with varied regulations across states and provinces. Currently, Grass Carp is in close proximity to the Great Lakes basin with increasing occurrences in the Great Lakes basin itself including within the Grand River, Ontario, and there is recent evidence of recruitment within the U.S. waters of western Lake Erie. Management agencies need to understand the risk that Grass Carp poses to the Great Lakes. Ecological risk assessment evaluates the probability of introduction (i.e., arrival, survival, establishment and spread) and the potential ecological consequences of a species (Mandrak et al. 2012). Predicting and assessing the potential spread within and between lakes by natural dispersal is a critical step in understanding and preventing the spread of Grass Carp if it was to arrive and establish in the Great Lakes basin. Most existing research on Grass Carp movement has been undertaken in aquaculture ponds and river systems, which are quite different from large lakes. As such, a modelling approach, using information available up to 2014, was applied to address the likelihood of Grass Carp spread within the Great Lakes basin. An area-restricted individual-based model was used to predict spread rates and regions likely to attract Grass Carp when released from two of the most likely invasion sites: Chicago Area Waterway System, Lake Michigan; and, Maumee River, Lake Erie. Model results indicate that at slow and fast movement rates, Grass Carp is expected to reach another basin from the one in which it was introduced within 5–10 years. Further assessment of the likelihood of spread of Grass Carp within the Great Lakes basin was accomplished by examining the potential pathways (i.e., lock and canal systems) that Grass Carp may use to spread between the Great Lakes. Two *in situ* experiments assessed the likelihood of spread by direct natural dispersal through canals and locks between lakes Erie and Ontario, and between lakes Huron and Superior. Tagged fishes moved between lakes Erie and Ontario (7 out of 179) and between lakes Superior and Huron (8 out of 152) by moving through the locks and canals between these lakes; however, few tagged individuals managed movement of this extent. Together, these results demonstrate that Grass Carp is likely to spread into all of the Great Lakes if it arrives and establishes, but spread to Lake Superior, if it occurs, will likely take much longer.

La modélisation de la propagation et l'évaluation des déplacements de la carpe de roseau, *Ctenopharyngodon idella*, dans le bassin des Grands Lacs

RÉSUMÉ

La carpe de roseau (*Ctenopharyngodon idella*), une espèce de carpe asiatique, a d'abord été introduit en Amérique du Nord en 1963 pour le contrôle de la macrophyte aquatique. Depuis, des individus ont franchi les barrières des bassins de retenue et ont remonté les rivières du centre des États-Unis, du bassin du Mississippi jusqu'aux Grands Lacs. Les carpes de roseau diploïdes (c.-à-d. fertiles) et triploïdes (c.-à-d. biologiquement stériles) continuent à être utilisées à diverses fins (p. ex., contrôle biologique, polyculture) avec des réglementations qui varient entre les États et les provinces. À l'heure actuelle, les carpes de roseau sont proches du bassin des Grands Lacs et leur présence est croissante dans le bassin des Grands Lacs même, y compris dans la rivière Grand, en Ontario, et il y a des preuves récentes de recrutement dans les eaux américaines de l'ouest du lac Érié. Les organismes de gestion doivent comprendre le risque que pose la carpe de roseau pour les Grands Lacs. Une évaluation des risques écologiques a été menée pour évaluer la probabilité d'introduction (c.-à-d. l'arrivée, la survie, l'établissement et la prolifération) et les conséquences écologiques potentielles d'une espèce (Mandrak et coll. 2012). La prévision et l'évaluation de la propagation potentielle dans et entre les lacs par la dispersion naturelle sont une étape cruciale pour comprendre et prévenir la propagation de la carpe de roseau, si cela se produit, et son établissement dans le bassin des Grands Lacs. La plupart des recherches existantes sur les déplacements de la carpe de roseau ont été entreprises dans des étangs aquacoles et des réseaux hydrographiques, qui sont très différents des vastes étendues d'eau. Par conséquent, une approche de modélisation, utilisant les données disponibles jusqu'en 2014, a été appliquée pour répondre à la probabilité de la propagation de la carpe de roseau dans le bassin des Grands Lacs. Un modèle de zone d'accès restreint fondé sur l'individu a été utilisé pour prévoir les taux de propagation et les régions susceptibles d'attirer la carpe de roseau lorsqu'elle est rejetée à partir de deux sites d'envahissement les plus probables : le Chicago Area Waterway System (lac Michigan), et la rivière Maumee (lac Érié). Les résultats du modèle indiquent qu'à des taux de déplacement lent et rapide, la carpe de roseau devrait atteindre un autre bassin que celui où elle a été introduit au cours des cinq à dix prochaines années. Une évaluation plus approfondie de la probabilité de la propagation de la carpe de roseau dans le bassin des Grands Lacs a été réalisée en examinant les voies d'accès potentielles (p. ex., écluses, systèmes de canaux) que la carpe de roseau peut utiliser pour se propager entre les Grands Lacs. Deux expériences *in situ* ont évalué la probabilité de propagation par dispersion naturelle par les canaux et les écluses entre les lacs Érié et Ontario, et entre les lacs Huron et Supérieur. Les poissons marqués ont été transférés entre les lacs Érié et Ontario (7 sur 179) et entre les lacs Supérieur et Huron (8 sur 152) en passant par les écluses et les canaux entre ces lacs; toutefois, peu d'individus marqués sont parvenus à effectuer de tels déplacements. Ensemble, ces résultats démontrent que la carpe de roseau est susceptible de se propager dans l'ensemble des Grands Lacs si elle parvient à les atteindre et s'y établir, mais la propagation au lac Supérieur, si cela se produit, prendra probablement beaucoup plus de temps.

GENERAL INTRODUCTION

Grass Carp (*Ctenopharyngodon idella*), one of the four species of Asian carps, is a sub-tropical to temperate species native to the large rivers of eastern Asia. Grass Carp was originally brought to North America in 1963 and, by the late 1970s, had escaped from contained areas. Grass Carp (both diploid and triploid) continue to be widely used for vegetation control and polyculture throughout many of the U.S. states, although regulations vary by state. Grass Carp is currently established throughout the Mississippi River basin of the United States and recent captures of diploid (i.e., reproductively viable) Grass Carp in the Great Lakes basin (U.S. Geological Survey 2015) have raised concerns over the potential invasion and ecological consequences of this herbivorous fish to the Great Lakes basin.

An earlier risk assessment of Asian carps, which included Grass Carp, identified broad potential risks to Canada, including the Great Lakes (Mandrak and Cudmore 2004). While this assessment provided insight into the risk faced by broad areas of Canada, knowledge gaps were identified. Given this, and the recent discovery of Grass Carp recruitment in Lake Erie, a binational ecological risk assessment of Grass Carp was proposed by Fisheries and Oceans Canada (DFO) and the Great Lakes Fishery Commission (GLFC) to the Asian Carp Regional Coordinating Committee (ACRCC) and was endorsed.

A non-native species risk assessment involves addressing the key concerns of a biological invasion, which includes assessment of the probability of introduction (Mandrak et al. 2012). The likelihood of spread within or between the Great Lakes is one element included in the probability of introduction (Mandrak et al. 2012). The purpose of this research document is to support the risk assessment by providing a modelling approach (using information available up to 2014) and an *in situ* assessment of fish movement between lakes through locks and canals to understand the likelihood of spread in the Great Lakes basin. Specifically, these approaches address the following questions on the likelihood of Grass Carp spread in the Great Lakes basin:

1) Can Grass Carp spread throughout the Great Lakes basin? If so, what is the timeline of spread through the Great Lakes?
2) Can fishes use canals and locks as pathways for spread throughout the Great lakes basin?

This document is structured into two sections, each addressing one of the aforementioned questions. In the first section (question 1, Section 1.0), an area-restricted individual-based model is used to predict spread rates and regions likely to attract Grass Carp when released from two of the most likely invasion sites: Chicago Area Waterway System, Lake Michigan; and Maumee, River, Lake Erie. In the second section (question 2, Section 2.0), the Welland Canal and St. Marys River were assessed as possible corridors for invasive species dispersal within the Great Lakes basin, by evaluating the ability of fishes to utilize canals and locks as a passage way between waterbodies.

1.0 GRASS CARP DISPERSAL MODEL

Warren J.S. Currie and Marten A. Koops

ABSTRACT

Grass Carp movement dispersal was modeled within the Great Lakes (using data available up to 2014), assuming two different arrival points: southern Lake Michigan near the Chicago Area Waterway System (CAWS) and southwestern Lake Erie near the mouth of the Maumee using an individual-based random-walk model. Modeled fish remained in the nearshore (<25 m depth) and used an area-restricted behaviour whereby they moved slower, at ¼ base speed when they encountered suitable habitat (given by GIS-based wetland data). Two conservative movement rates were used: a "fast rate" was 2,000 m (or 500 m in high food) every 2 hrs (effectively 22 cm •s^{-1}) and a very "slow" movement rate of 800 m (or 200 m in high food) every 2 hrs. These reasonable movement characteristics for Grass Carp (0.1–0.3 body lengths•s^{-1}), resulted in individuals reaching another basin from the one in which they were introduced within 5 years. By the end of 10 years, the model predicted that the second lake basin was likely to have multiple individuals, nearing 5–20% of the population; this was true for both the "slow" and "fast" movement scenarios of the model. The spread of Grass Carp in the model was reduced compared to bigheaded carps because Grass Carp are constrained to the nearshore areas and by the regular occurrence of high quality wetland habitat that exists in all of the lakes which effectively slow their rate of movement.

INTRODUCTION

The Fish Foraging and Movement model is an individual-based (DeAngelis and Gross 1992), Markov process movement model written for MatLab (Matlab 2014) that is based on the Bighead Carp (*Hypophthalmichthys nobilis*) and Silver Carp (*H. molitrix*) spread model introduced in Currie et al. (2011). The basis of the simulation model is that foragers use area-restricted search (ARS) (Kareiva and Odell 1987) on 2-D food fields acquired from GIS data on Great Lakes wetland quality (gllmimlbas_1km) (Gertzen et al. 2017). The use of ARS models (Kareiva and Odell 1987) has become common to investigate feeding behaviour and habitat use (Codling et al. 2008, Mueller and Fagan 2008) and is particularly useful for species invading new environments (Hastings et al. 2005). Individuals using this behaviour ("prey-taxis") tend to remain in regions with higher food resources so identification of likely habitats for new invaders is particularly suited to this approach.

METHODS

ARS movement was accomplished by using a threshold food field whereby the individual would move at ¼ the value of a normal step-length (distance travelled each time increment) when food was above a specific value. This simple approach results in only two behaviours for the individuals: searching for food (habitat) or feeding in good habitat. The wetland GIS layer categorized each pixel as a value of 0 (background habitat of little value) to 1.0 (an ideal habitat), so a threshold value of greater than 0.6 wetland suitability was used to change step-length. For the entire Great Lakes, 7.0% of the surface area was classified as a wetland habitat for Grass Carp, but only 1.4% was classified as ideal (above the threshold). For the initial run of the model, no seasonality was introduced to the habitat field (the values were the same the entire year).

At each time-step, the individuals always moved in a random direction so displacement in X and Y is determined by:

$$dx = d \cdot (\sin(z \cdot 2 \cdot \pi))$$

$$dy = d \cdot (\cos(z \cdot 2 \cdot \pi))$$

where d is the step distance (radius of the circle) and z is a random number (0–1).

Movement of fishes in pelagic or lacustrine environments are considerably different from those found in rivers (Anras et al. 1999) primarily due to the statistical differences between 1 and 2-dimensional walk paths (Codling et al. 2008). To more accurately estimate the dispersion, additional time-steps per day (12) were used to simulate movement, resulting in a time-step of 2 h for each new dispersal movement. This allows the carps to take smaller dispersals each step and ultimately retain their position in areas of high suitability. This is important because the “patches” of highly suited habitat are very small in comparison to the lake-wide distribution of chlorophyll used for bigheaded carps simulation. It is important to note that random walks in 2-dimensional environments are recurrent: individuals tend to remain in the same area because the direction of travel changes randomly each time-step. As a result, the actual displacement per day is much less than the distance per time-step added up for each day.

Two spread rates were used for Grass Carp, both of which are conservative. The “fast rate” is 2000 m (or 500 m in high food) every time-step (2 h) and a very “slow” movement rate of 800 m (or 200 m in high food) every time-step. With the random walk, the “fast” scenario gives a daily displacement of only 1.2 km/d ± 0.7 (sd) when searching for new habitat or 0.3 km/d ± 0.1 (sd) when feeding in good habitat. The “slow” speed gives a searching movement rate of 10 $cm \cdot s^{-1}$ and foraging movement of 2 $cm \cdot s^{-1}$, while the “fast” rate has a searching movement of 22 $cm \cdot s^{-1}$ and foraging movement of 5 $cm \cdot s^{-1}$. Both of these values are below the U_{crit} value of 3 $bodylengths \cdot s^{-1}$, which Grass Carp can easily sustain (Cai et al. 2014) and is still below the movement rates of other fishes. There is much dispute regarding the estimate of Grass Carp movement since there are very few direct measurements of real-time telemetry and movement rates are usually estimated by measuring activity or passage whereby the time between passing one receiver compared to the next, which erroneously assumes that the individual swims constantly directly from point to point. Cassani and Maloney (1991) noted these difficulties and the large variability in movement rate, but averaged ~180 m/h ± 113 (sd), which falls in-between the fast and slow rates. The “slow” movement rate used here can also assume that Grass Carp can use a background food (such as *Cladophora*) or tend to remain in place for half the day but is still likely to be an underestimate of actual movement.

An autocorrelated walk typical of pelagic fishes was used (see Currie et al. 2011 for details) whereby autocorrelated direction was added to the previous direction by averaging the newest movement with the previous one. Paths of an autocorrelated individual are more directional, exhibiting smoother arcs of longer distances than shown in non-autocorrelated movements, which tend to fill more of the available space. This autocorrelated movement tends to reduce the movement per time step, since it is averaged with the previous step which could have occurred in any direction. However, overall, autocorrelated movement tends to still have the same displacement as non-autocorrelated movements because paths tend to be directional. The random-walks were also constrained to the nearshore region defined by the 20–25 m depth isobath.

There were two possible introduction locations (Chicago-Area Waterway System (CAWS), Lake Michigan or Maumee River, Lake Erie). The CAWS start site is slightly offshore in Lake Michigan from the Chicago River. This location was chosen for comparison to the results found in Currie et al. (2011) for Silver Carp and Bighead Carp and represents a likely arrival pathway for Grass Carp to the Great Lakes basin. This is likely to be a conservative start point for Grass Carp introduced into Lake Michigan. The other start location is near the mouth of the Maumee River in Lake Erie. The western basin of Lake Erie would be a suitable site for Asian carp establishment, and juvenile diploid Grass Carp have been caught in coastal sites in Lake Erie (Chapman et al. 2013).

To include the influence of Great Lakes currents on the dispersal of Grass Carp, average flow conditions were taken from historical reviews and circulation models (e.g., Beletsky et al. 1999, see Currie et al. 2011 for more detail). The intent was not to create a coupled bio-physical model, but rather to investigate how flow might influence dispersal. The underlying current directions within the lakes were converted to the 1 km spatial grid and a mean pass 2-D smoothing filter (smooth2a) in MatLab and were not varied. Current intensity ranged from 0–0.25 km/h (0–7 cm/s) and the current vector could be added to each individual's movement using a multiplier. A very low multiplier value of 0.1x indicating little flow influence was always used for the Grass Carp scenario since the individuals are constrained to the nearshore region.

RESULTS

Locations visited and "food" habitat for 100 individuals were tracked every 2h for 20 years of simulation. Only rates of speed per time-step (fast or slow) and site of introduction (CAWS or Maumee) were varied.

For each scenario a series of figures were produced:

1. Histogram of distance traveled per time-step (in km)
2. Histogram of displacement distance from site of introduction
3. Bar graph of percent occupation of lake or large embayment for years 1, 5, 10, 20, and 50.
4. Time series of percent of individuals occupying a site above the food threshold of 0.6.
5. Contour map of log-transformed visits over the 50 year simulation to visualize rare visits.
6. A series of six maps showing the dispersal for 1, 5, 10, 20, 35 and 50 years.

The first graph (distance per time-step) indicates how many of the individuals are traveling at the slower "feeding" speed rather than the "searching" speed. If the food patches were found in a random manner, the distribution would be a normal curve. The graphs typically have a peak in the shorter distances which corresponds to the speed of "feeding" of either 200 m ("slow") or 500 m ("fast") per time-step.

The second graph indicates the dispersion of the 100 individuals after 50 years. Lakes that have suitable nearby habitat will tend to retain some individuals resulting in a peak at smaller distances. A bimodal distribution will occur if a significant number of individuals leave the lake and large distance indicate that most individuals have left the lake of introduction.

The third graph illustrates the spread of Grass Carp from the lake basin of introduction. All individuals will usually be in the starting lake by year 1 but, by year 20, many of the individuals may be found in other sites. The main waterbodies are: Superior, Michigan, Huron, Georgian Bay, St Clair, Erie, Ontario, and the Saint Lawrence. To identify occupancy of some large embayments likely to be suitable habitat for Grass Carp, these sites are dealt with separately from the main lake: Green Bay and Traverse Bay (Lake Michigan), Saginaw Bay (Lake Huron), Bay of Quinte (Lake Ontario), and Black/Thunder Bay (Lake Superior).

The fourth graph is a time-series of percent of individuals in suitable food habitat (wetland values > 0.6) and indicates the degree of success of the introduced population of Grass Carp over time (in years). Higher values indicate that more individuals have found and are retained in areas of high food suitability (generally about 25–30% of the population for this set of simulations).

The fifth graph is a contour map of log-visits allows comparison to the results found in Currie et al. (2011). Since the number of times a pixel is visited over the 50-year simulation is log-transformed, sites that have been transitorily visited or rarely visited at the edge of a movement front have a low but detectable value on the map.

The sixth and last figure is a panel of four maps for 1, 5, 10, 20, 35 and 50 years of simulation, which illustrates the invasion front by filling in the pixels that have been occupied up to 20 times (shown in dark blue).

CAWS Release

The rate of speed per time-step was an important predictor for dispersal, but the presence of suitable wetlands in the starting lake was extremely important in slowing the rate of spread (Figures 1.1 to 1.4). With an initial release near Chicago at the "fast" movement rate, only a small percentage of individuals would leave Lake Michigan for Lake Huron by Year 5 (Figure 1.1c). At the "slow" rate of movement, this was delayed only by a couple of years (Year 7). For both scenarios, more than 40% of the individuals were retained in Lake Michigan by Year 20, with approximately half in Green or Traverse Bays but, by Year 50, less than 20% of the individuals were retained in Lake Michigan (Figures 1.1, 1.3). By Year 10, in both movement scenarios, almost 20% of the individuals had moved into Lake Huron and Georgian Bay. In the "fast" scenario, by Year 20, Grass Carp had visited all of Huron and Georgian Bay nearshore, while in the "slow" scenario, only the North Channel of Georgian Bay was visited (Figure 1.2b). Only 2–3 individuals moved into lakes St Clair or Erie by 20 years in the "fast" simulation and there were few added individuals in Lake Erie since most of the population was primarily occupying quality sites in Georgian Bay and Lake Huron (~70%) at the end of 50 years.

For the CAWS release scenario, the percent of individuals locating high-quality habitat (>0.6) peaked around Year 5 with 25% of the individuals in the best habitats for the "fast" movement scenario (Figure 1.1d). This decreased and plateaued around Year 10 at 15–20% as Grass Carp began to enter new lakes (Lake Huron). The peak was earlier and greater in the "slow" scenario with >40% of individuals finding the best habitats by Year 4 (Figure 1.3d). This decreased to about 20% by Year 12 as individuals began leaving good habitat (e.g. Green Bay) in Lake Michigan. The higher percentage of individuals in good habitat during the "slow" simulation is due to the fact that individuals were less likely to move away from the best habitats once they located them.

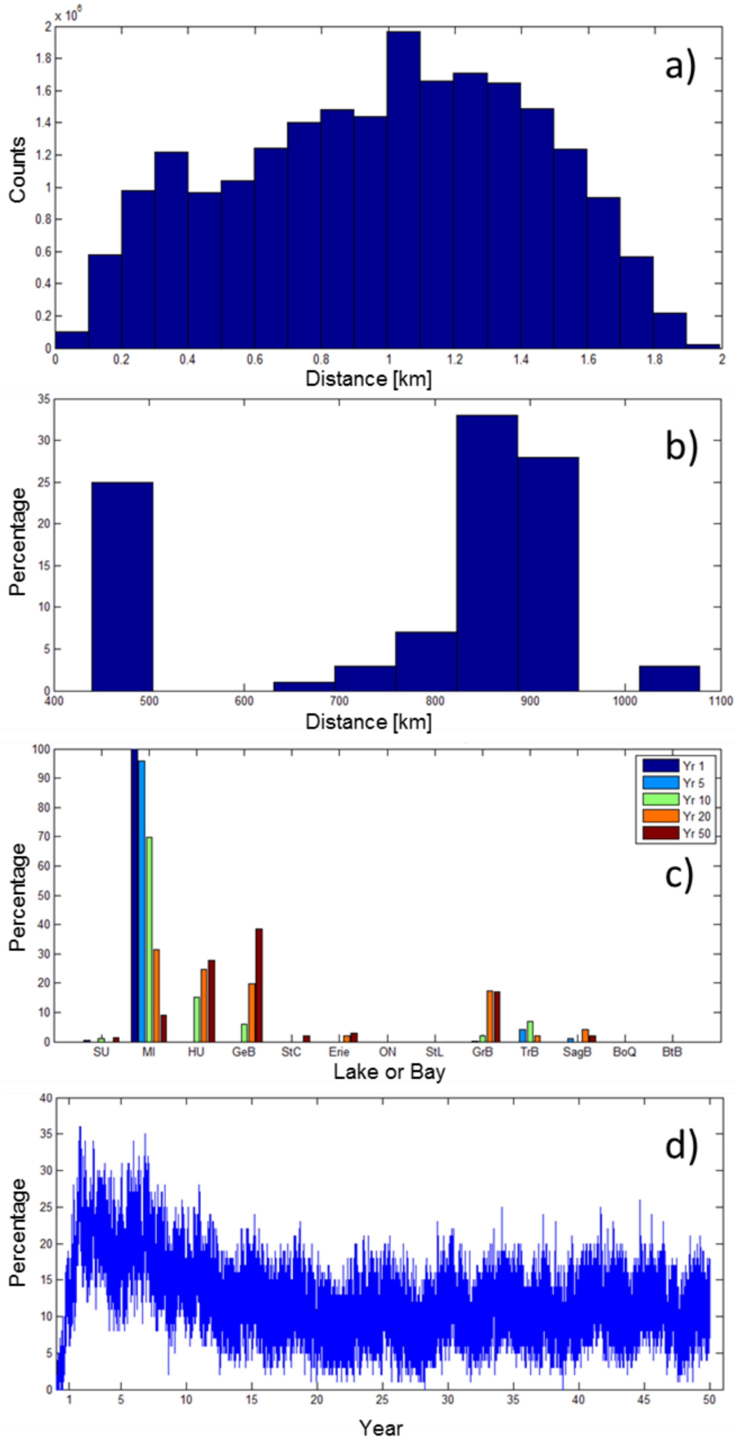

Figure 1.1. Grass Carp dispersal simulation, release at Chicago-Area Waterway System (CAWS). "Fast" movement is 2000 or 500m per time-step. a) Histogram of distance traveled per time-step; b) Histogram of displacement distance from site of introduction after 50 years; c) Bar graph of percent occupied by lake or large embayment for Years 1, 5, 10, 20 and 50; d) Time-series of percent of individuals occupying a site above the food threshold of good wetland habitat (0.6). Lakes or Bays in c) are: Superior, Michigan, Huron, Georgian Bay, St Clair, Erie, Ontario, Saint Lawrence River, Green Bay, Traverse Bay (MI), Saginaw Bay (HU), Bay of Quinte (ON), Black/Thunder Bays (SU).

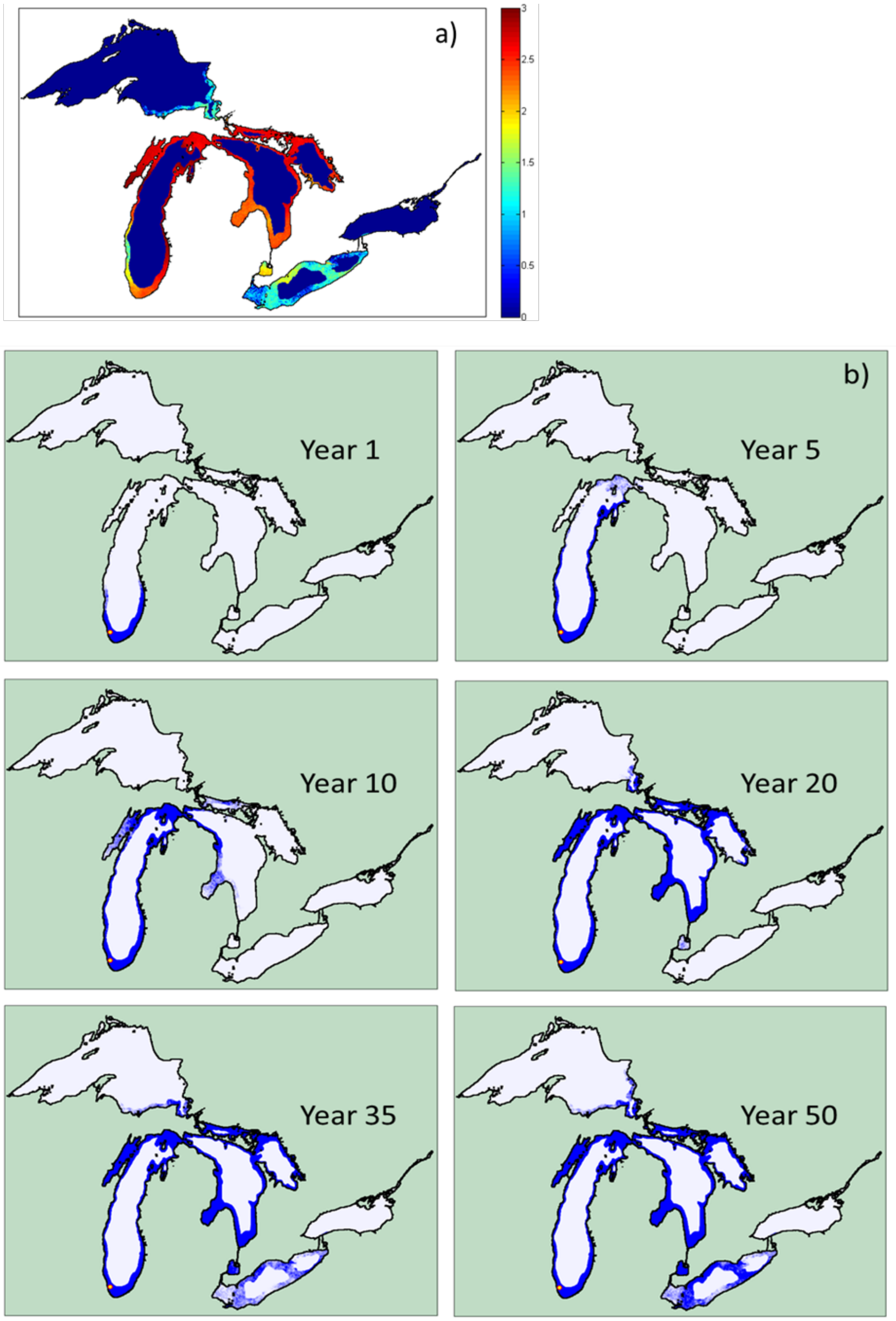

Figure 1.2. Grass Carp dispersal simulation, release at CAWS (○). "Fast" movement is 2000 or 500 m per time-step. a) Log-transformed visits at end of 50 years of simulation; b) Spread by year (in blue).

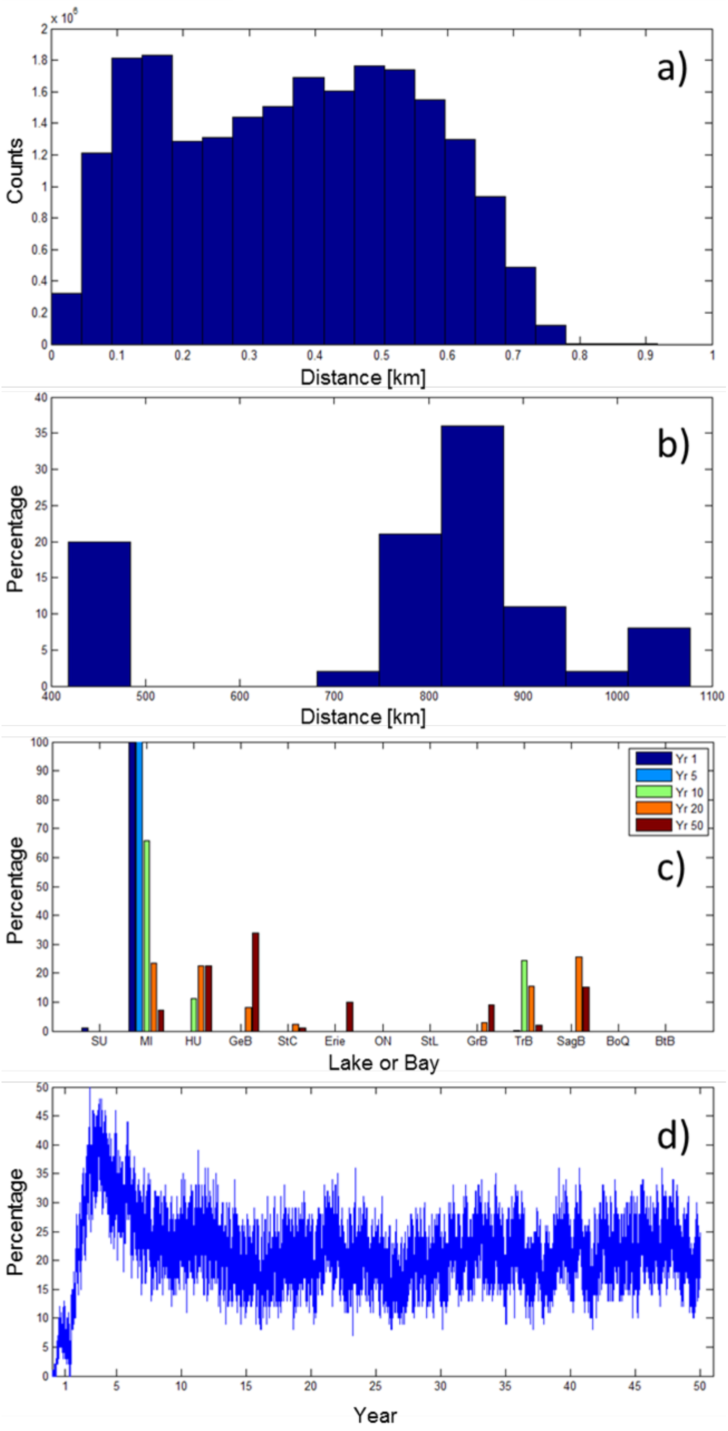

Figure 1.3. Grass Carp dispersal simulation, release at CAWS. “Slow” movement is 800 or 200m per time-step. a) Histogram of distance traveled per time-step; b) Histogram of displacement distance from site of introduction after 50 years; c) Bar graph of percent occupied by lake or large embayment for Years 1, 5, 10, 20 and 50 (see Figure1.1 for Lake or Bay axis information); d) Time-series of percent of individuals occupying a site above the food threshold of good wetland habitat (0.6).

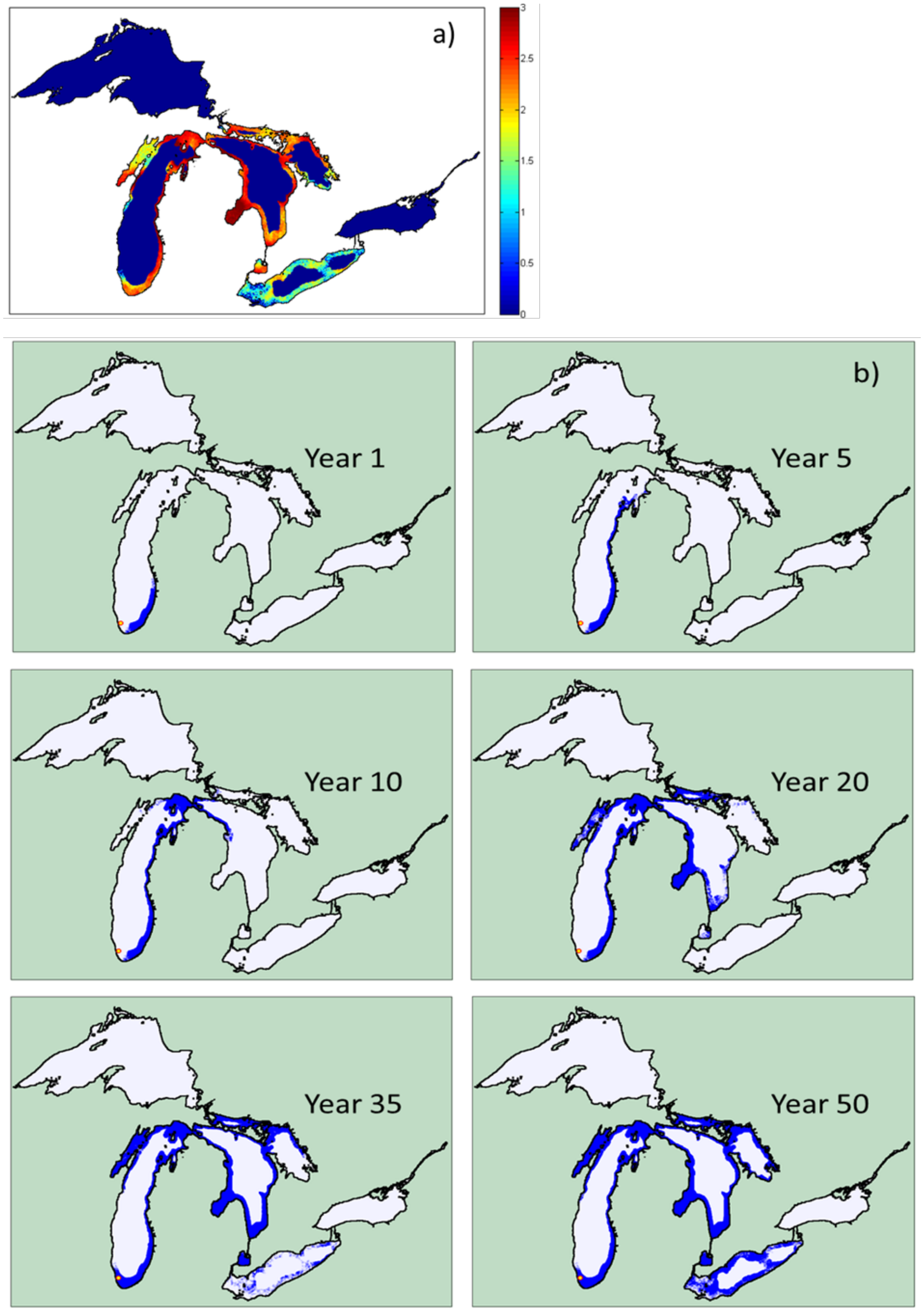

Figure 1.4. Grass Carp dispersal simulation, release at CAWS (○). "Slow" movement is 800 or 200 m per time-step. a) Log-transformed visits at end of 50 years of simulation; b) Spread by year (in blue).

Maumee Release

Similar to the results for the CAWS release, the extensive presence of high-quality wetlands in Lake Erie (Figure 1.9) was very important in slowing the spread of individuals to other locations (Figures 1.5 to 1.8). For both movement scenarios, the nearshore of Lake Erie was completely or nearly completely visited by Year 5 of the simulation (Figures. 1.6, 1.8). By Year 10, some individuals had entered into Lake Ontario and the Saint Lawrence River, 10% of the population in the “slow” and 7% in the “fast” scenarios (Figures 1.5b, 1.7b). For the “fast” scenario, the movement speed of Grass Carp was capable of moving some individuals upstream into Lake St Clair but most individuals stayed in the high quality habitat in Lake Erie (Figure 1.5b). In the “slow” scenario, by Year 50, slightly more than half of the individuals had moved into Lake Ontario and the Saint Lawrence River.

For the Maumee River release scenario, the percent of individuals locating high quality habitat (>0.6) slowly climbed from 10–15% to a peak and plateaued around Year 10 with 20% of the individuals in the best habitats for the “fast” movement scenario (Figure 1.5d). The rise to the peak was similar for the “slow” scenario but with much greater percentage (25–30%) of individuals finding the best habitats by Year 8 (Figure 1.7d). The slight depression in the success for the “slow” scenario is due to transport away from the western basin of Lake Erie by the average currents. Again, the higher percentage of individuals in good habitat during the “slow” simulation is due to the fact that individuals were less likely to move away from the best habitats once they located them.

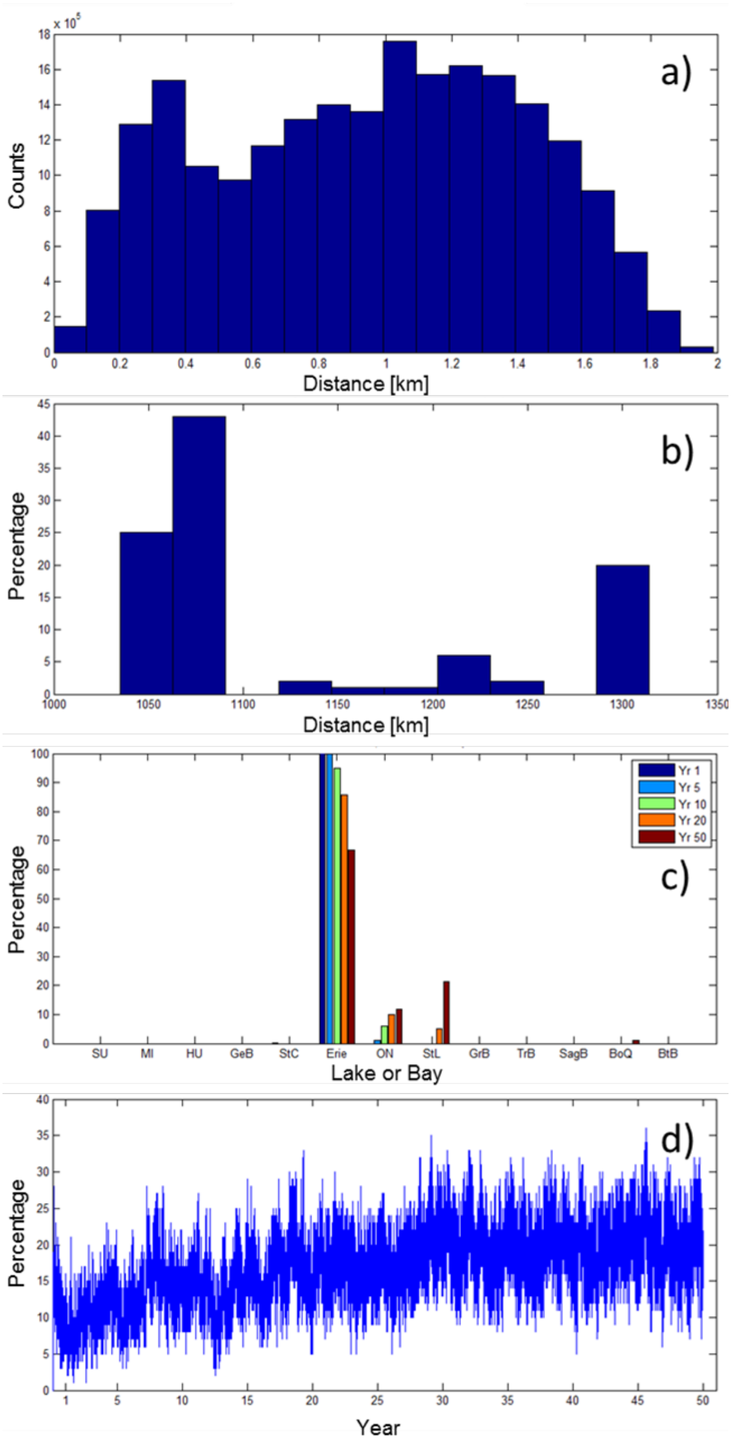

Figure 1.5. Grass Carp dispersal simulation, release at Maumee R. "Fast" movement is 2000 or 500m per time-step. a) Histogram of distance traveled per time-step; b) Histogram of displacement distance from site of introduction after 50 years; c) Bar graph of percent occupied by lake or large embayment for Years 1, 5, 10, 20 and 50 (see Figure1.1 for Lake or Bay axis information); d) Time-series of percent of individuals occupying a site above the food threshold of good wetland habitat (0.6).

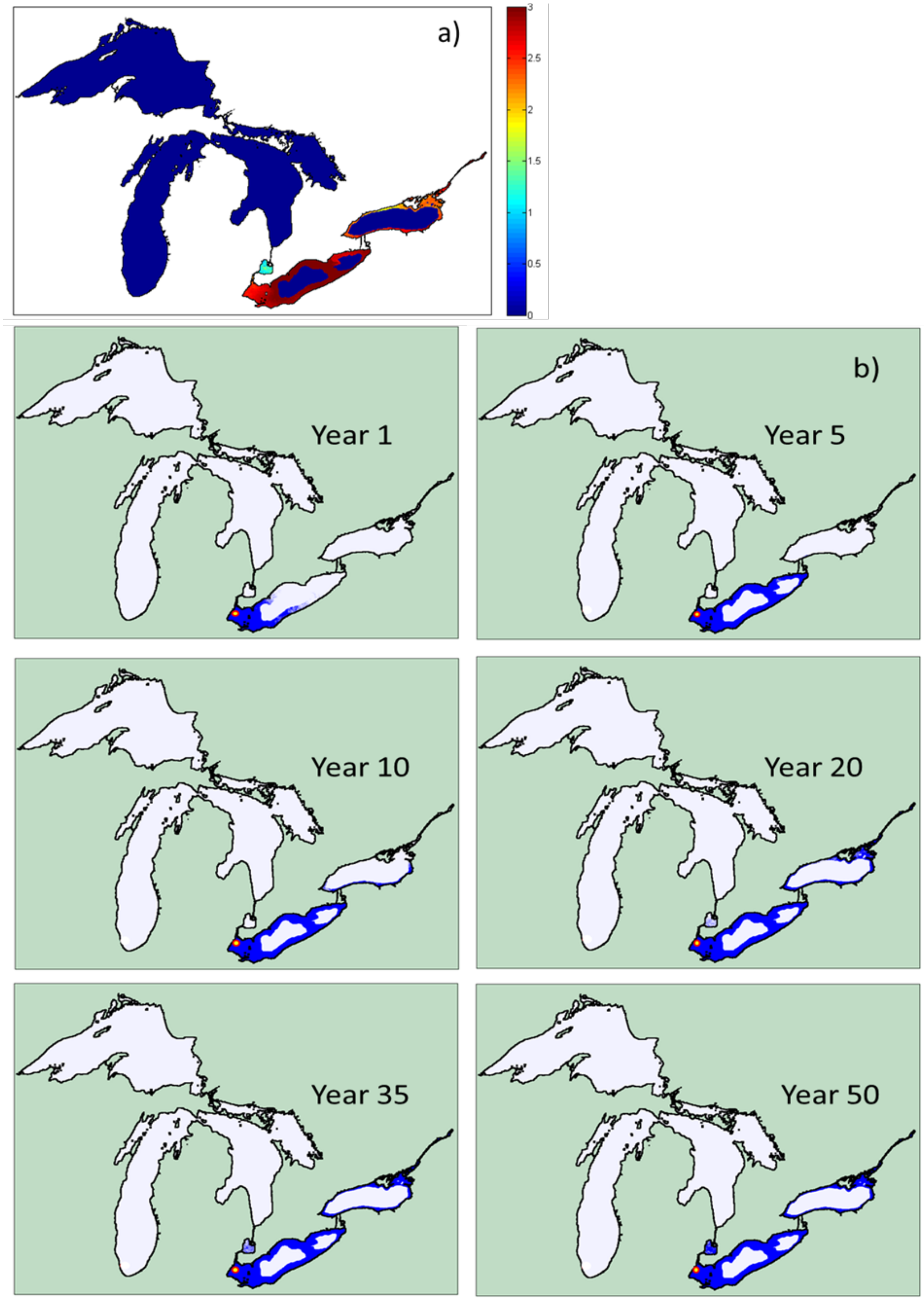

Figure 1.6. Grass Carp dispersal simulation, release at Maumee River (○). "Fast" movement is 2000 or 500 m per time-step. a) Log-transformed visits at end of 50 years of simulation; b) Spread by year (in blue).

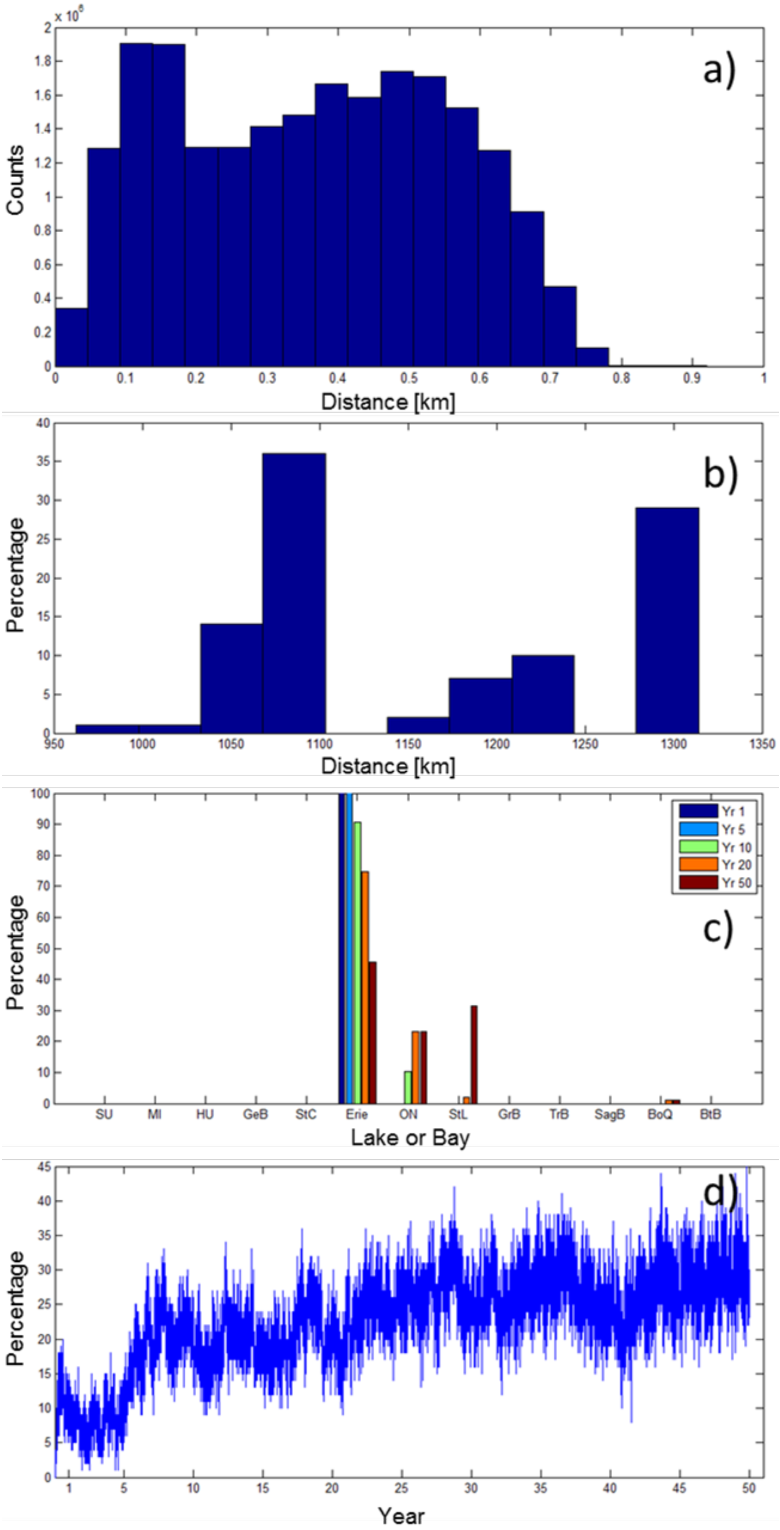

Figure 1.7. Grass Carp dispersal simulation, release at Maumee R. "Slow" movement is 800 or 200m per time-step. a) Histogram of distance traveled per time-step; b) Histogram of displacement distance from site of introduction after 50 years; c) Bar graph of percent occupied by lake or large embayment for Years 1, 5, 10, 20 and 50 (see Figure1.1 for Lake or Bay axis information); d) Time-series of percent of individuals occupying a site above the food threshold of good wetland habitat (0.6).

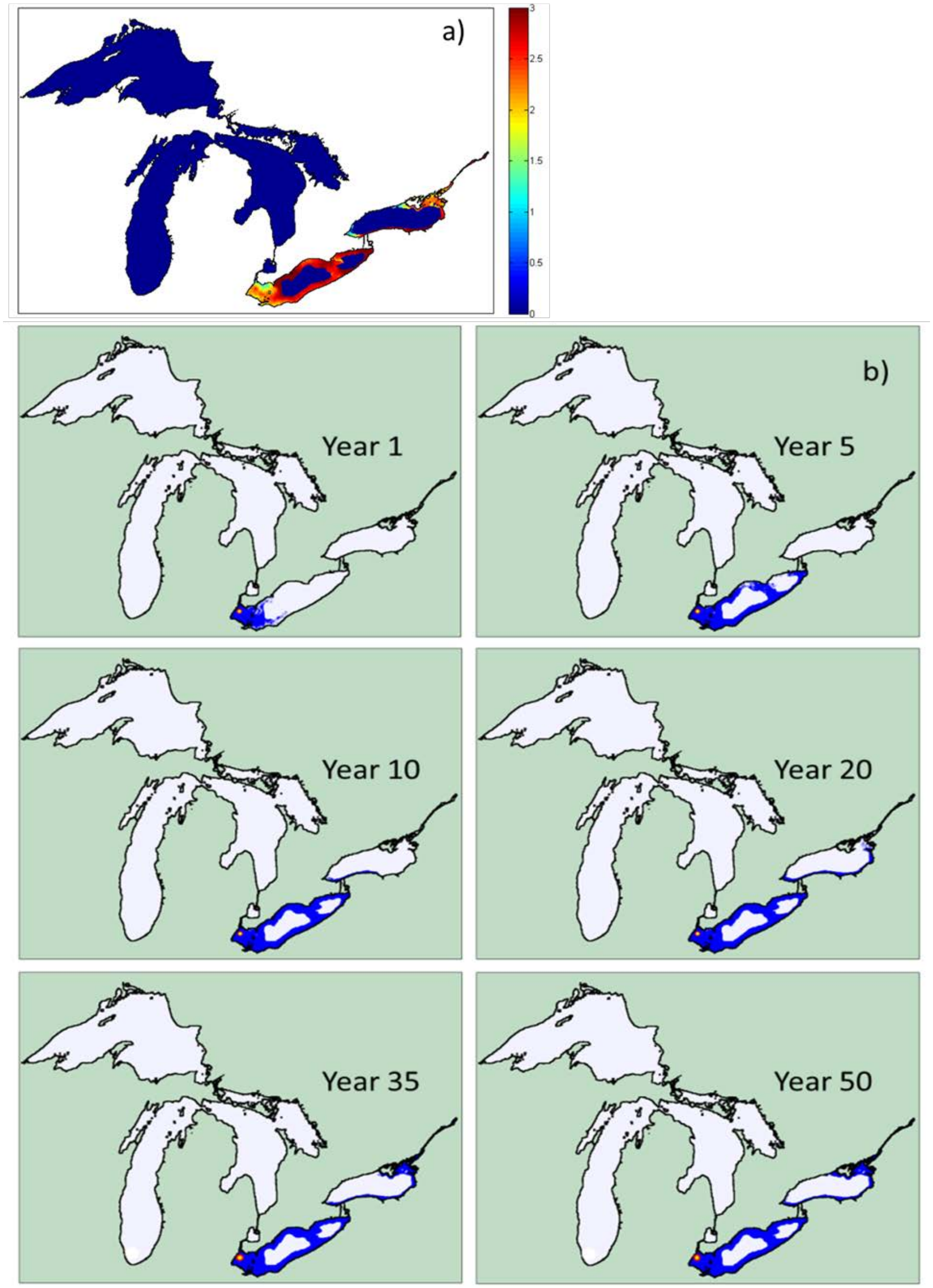

Figure 1.8. Grass Carp dispersal simulation, release at Maumee R (○). "Slow" movement is 800 or 200 m per time-step. a) Log-transformed visits at end of 50 years of simulation; b) Spread by year (in blue).

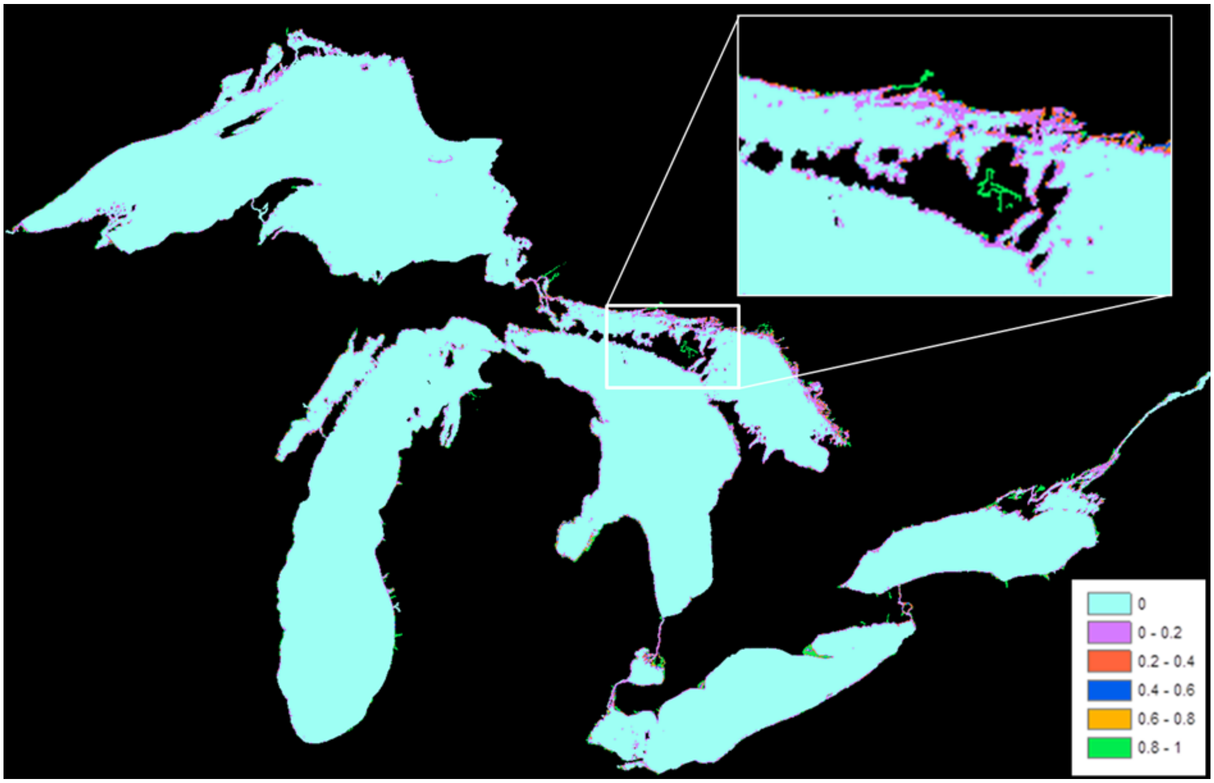

Figure 1.9 The wetland layer (gllmimlbas_1km) at 1km resolution used as the arena for the Grass Carp movement model (Gertzen et al. 2017). The inset for Georgian Bay North Channel illustrates the patchwork of wetland habitat. Suitability for Grass Carp habitats are given by the colours in the legend. A pixel with green or orange (threshold of 0.6) indicates an optimal habitat which changes the movement of the individual to a slower foraging speed (¼of the searching rate).

CONCLUSION

Given modest movement characteristics for Grass Carp (0.1–0.3 body lengths per second), individuals are expected to reach another basin from the one they were introduced within 5 years. By the end of 10 years, the second lake basin is likely to have multiple individuals nearing 10–20% of the population. This is true for both the “slow” and “fast” movement scenarios of the model. The spread of Grass Carp is slowed by the fact that individuals are retained in the nearshore of the lakes and the numerous sources of good wetland habitat that occur in all of the lakes (see Figure 1.9). It is also likely that a ready supply of *Cladophora* in the nearshore of most lakes will provide a source of food, which is likely to slow the rate of dispersal. Once the carps have been stabilized after a couple of years, generally 20–30% of the individuals are remaining in optimal habitat (given by the food threshold of 0.6, see Figure 1.9). Grass Carp has been shown to occasionally undergo rapid long-distance dispersal (e.g., during migration for spawning), which would not be captured by this model.

2.0 ASSESSING THE EXTENT OF DIRECT MOVEMENT OF FRESHWATER FISHES THROUGH THE WELLAND CANAL AND ST. MARYS RIVER

Jaewoo Kim, Nicholas E. Mandrak, Lisa M. O'Connor, Thomas C. Pratt, Evan Timusk, Monica Choy

ABSTRACT

Aquatic invasive species have become one of the most serious threats to Ontario freshwater biodiversity due to the severe negative impacts they can have on native ecosystems. The Asian carps (Bighead Carp, Silver Carp, Grass Carp, and Black Carp [*Mylopharyngodon piceus*]), in particular, are an encroaching threat, as these species have already colonized and impact many waterbodies in the United States. Examining the potential pathways that Asian carps may use to invade and spread throughout the Great Lakes basin is a critical step in preventing their northward movement. This study focused on the Welland Canal and St. Marys River as possible corridors for invasive species dispersal within the Great Lakes basin; specifically, evaluating the ability of fishes to utilize canals and locks as a passage way between water bodies. In both systems, a variety of fish species was caught and tagged using acoustic telemetry technology. Hydrophone arrays were set up in strategic locations within the systems to determine the extent to which fishes were moving in the canals and through the locks. In the Welland Canal, seven out of 179 tagged fishes (3.9%) moved through the canals and locks, ultimately, ending up in lakes Ontario or Erie. In the St. Marys River, eight (seven distinct fish) out of 152 tagged fishes (5.3%) were detected moving from Lake Huron to Lake Superior using several pathways and of those tagged fishes, 62.5% were detected returning from Lake Superior to Lake Huron. Although the number of fishes detected moving between the basins was low, these results indicate that fishes can use these artificial waterways as corridors between the Great Lakes basins.

INTRODUCTION

Freshwater fishes in Canada are particularly vulnerable to a wide range of threats including habitat degradation and loss, overexploitation, and pollution. Aquatic invasive species (AIS) have become a major recent concern because of their increasing numbers and the negative impacts they have on our native ecosystems. The establishment of AIS have played a role in the endangerment of Canadian freshwater fishes in 26 out of 41 freshwater fish species assessed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) (Dextrase and Mandrak 2006). The Great Lakes region, the largest freshwater lakes system in the world, is one of the most severely affected areas with an estimated 182 established invasive species (Ricciardi 2006). Once an AIS population has been established, eradication is often impossible and, if the population is to be managed, the costs involved are generally extremely high. Prevention is currently viewed as the most effective at keeping AIS from further damaging Canada's aquatic ecosystems (Kerr et al. 2005). Examining the pathways in which these AIS enter novel aquatic systems has become a key focus for preventing their spread, as the migration of aquatic species is heavily dependent on human facilitation. Canals and shipping channels have been identified as a potential vector as these artificial waterways can be used by invasive species to reach ecologically suitable areas that were not historically accessible to them (Kerr et al. 2005).

One AIS group of concern is the Asian carps: Bighead Carp; Silver Carp; Grass Carp; and, Black Carp. These potential invaders have been present in the United States since the 1970s and have been extremely successful in establishing reproducing populations and having impacts on native biodiversity. Asian carps have a very high likelihood of successful establishment should they enter the Great Lakes system and their spread will negatively affect natural lake ecosystems in the long term (Cudmore and Mandrak 2011, Cudmore et al. 2012). Potential pathways for their movement must be assessed to fully understand how these AIS could invade and spread in the Great Lakes, and what can be done to prevent their establishment. If Asian carps arrive in the Great Lakes, their spread may be facilitated in part by a section of the St. Lawrence Seaway, the Welland Canal, the connecting channel between Lakes Huron and Superior, and St. Marys River.

The Welland Canal is a pathway of concern. It has been identified as a mode for direct (dispersal) and indirect (shipping) bi-directional movement of AIS, between Lake Ontario and Lake Erie (Mills et al. 1993). It is an active shipping canal that extends 43.4 km from Port Weller on Lake Ontario to Port Colborne on Lake Erie (Figure 2.1A). The canal has a total lift of 99.5 m through a series of eight locks that enable ships to ascend and descend the Niagara Escarpment to bypass Niagara Falls. The locks are 233.5 m long by 24.4 m wide, with an average lift of 14.2 m. They can accommodate vessels up to a maximum of 225.5 m in length and 23.8 m in width to (Figure 2.1B). This route could be a future vector for Asian carps spread into lakes Erie or Ontario, depending on their origin. While fishes are known to move through the Welland Canal system (Pearce et al. 1980), no tagging research has been conducted on fish movement through the Welland Canal (Cudmore et al. 2012); this study examines the ability of tagged fishes to navigate the canal’s lock systems.

The St. Marys River is another potential pathway for AIS dispersal as it is the main connecting waterbody between Lake Huron and Lake Superior. The river spans 112 km from Whitefish Bay in Lake Superior to De Tour, Michigan where it meets Lake Huron (Duffy et al. 1987). There are locks and canals on both sides of the river: two hydroelectric canals and four locks on the U.S. side, and one hydroelectric canal and one lock on the Canadian side. There is also a connecting water system through the upper Canadian locks, through the Whitefish River, and into the rapids on the Lake Huron Side. At the head of the St. Marys Rapids there is also the Compensation Works, a series of 16 gates that can be opened and closed to control the current and divert water flow to the shipping locks or to nearby hydroelectric power plant canals (Duffy et al. 1987). Although several AIS and many other species are known to have used the St. Marys River to move between the two Great Lakes, other than the movements of Sea Lamprey (*Petromyzon marinus*) (Smith and Tibbles 1980), no research has been specifically conducted to determine the extent of movement for other tagged fish species (Cudmore et al. 2012).

METHODS

Hydrophone Array Deployment

To monitor the movement of freshwater fishes throughout both the Welland Canal and St. Marys River, hydrophone arrays were deployed in strategic locations to track any fish movements that occurred between the two main basins connected by the canal systems.

In the Welland Canal, hydrophone arrays were deployed 2012 to 2015. Their placement was focused around three potential entrances and exits for fish movement: Port Weller (Lake Ontario); Port Colborne (Lake Erie); and Port Dalhousie (Lake Ontario; long side channel through Lake Gibson and Twelve Mile Creek to Port Dalhousie) (Figure 2.2a). From Lake Gibson to Port Dalhousie, there are two Ontario Power Generation dams (Decew I, II) and Heywood Generating Station (St. Catharines Hydro). Within the Welland Canal, there are eight locks; seven locks are located closer to Lake Ontario, and one lock is near Lake Erie. The flight locks (locks 4, 5, and 6) represent a major barrier within the canal as they operate adjacently with no open canal between them. These locks have a combined lift of about 50 m in height (Figure 2.2b).

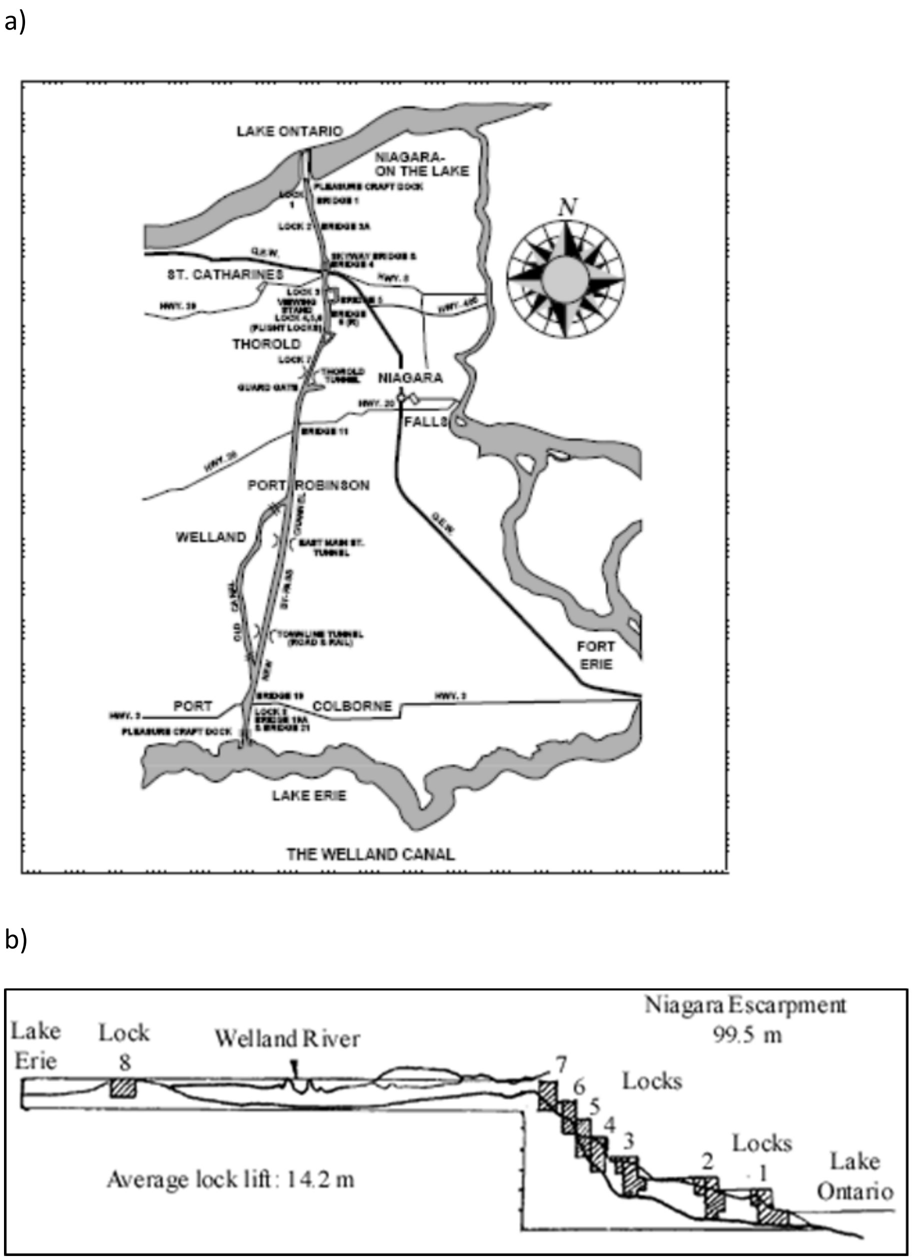

Figure 2.1. (a) Welland Canal and (b) profile of the Welland Canal (from The St. Lawrence Seaway Management Corporation).

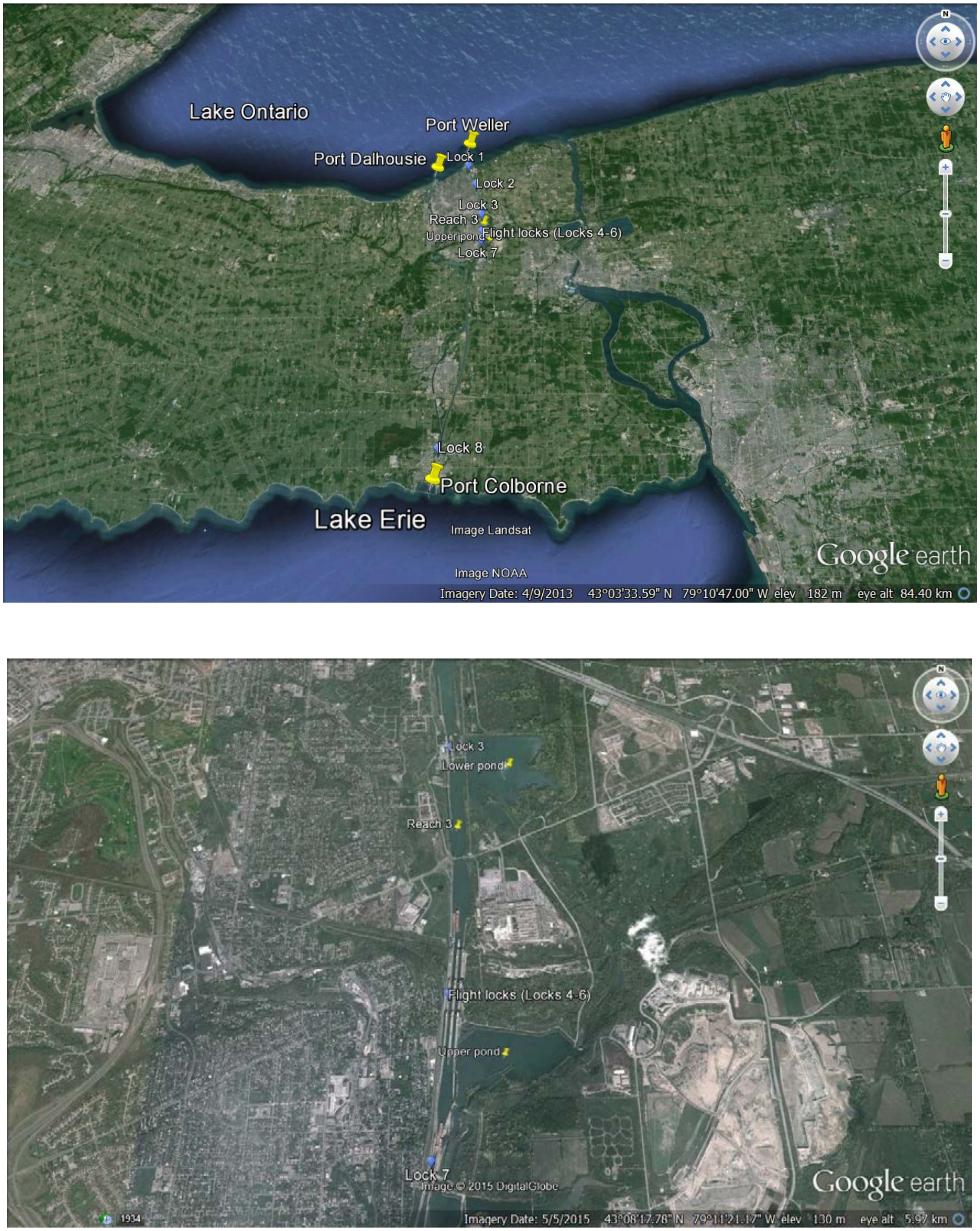

Figure 2.2. (A) Map of the Welland Canal and (B) closer view of the flight locks, reach 3, and the upper pond within the Welland Canal.

Within the St. Marys River, there are three potential corridors for fish movement: the U.S. shipping locks, which operate for 10 months of the year; the Canadian locks, which operate for six months of the year; and, the Compensation Works, operate year round (but are often closed), diverting water to the locks, the four hydroelectric dams located on the river, and the remaining rapids area (Figure 2.3). It is not expected that fishes can move up through the power plants directly. There is also a potential pathway through the Whitefish River on the Canadian side, which connects the upper and lower basins by an underground piping system that connects the upper river, through the Canadian locks, into the Whitefish River, and then into the rapids on the Lake Huron side.

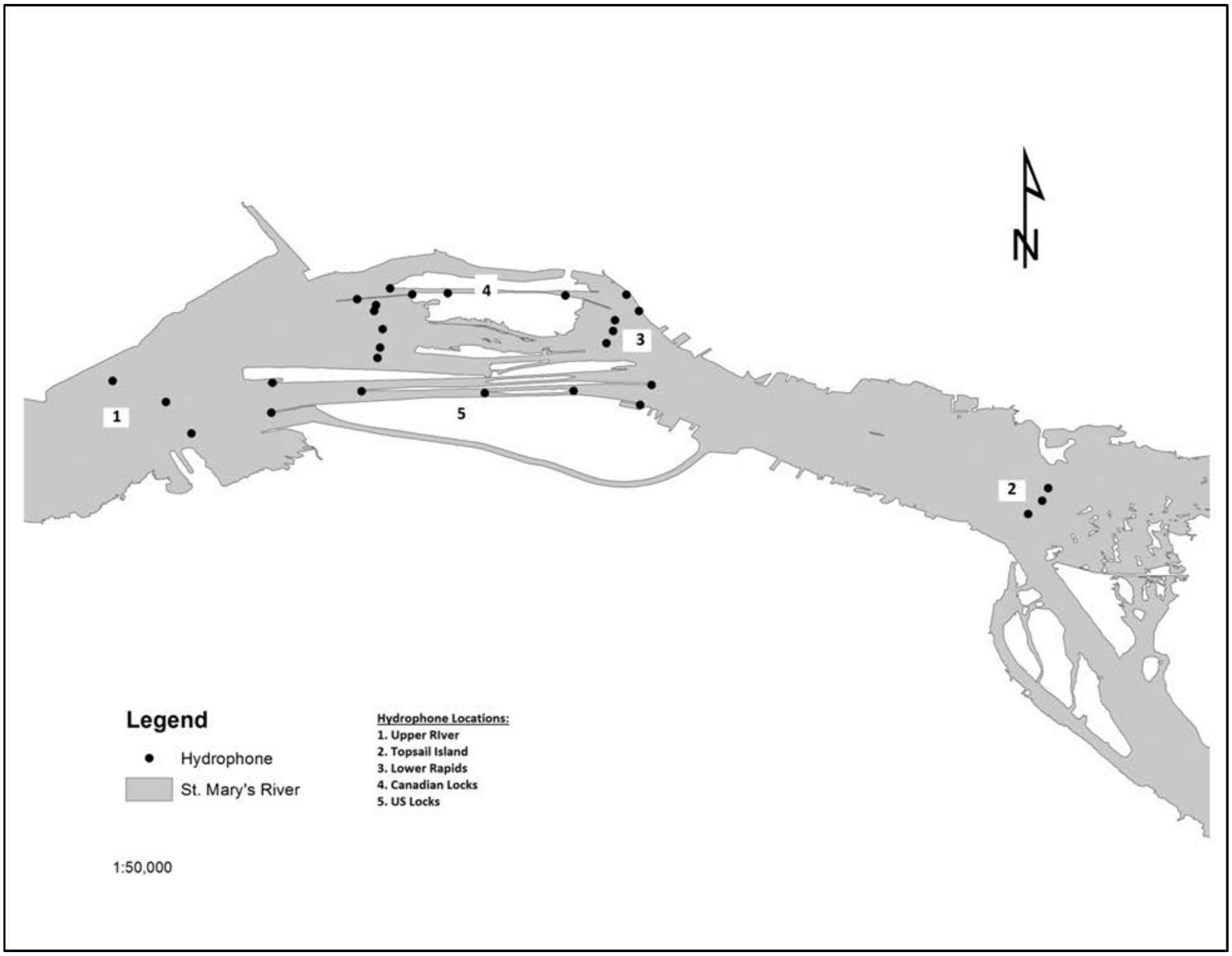

Figure 2.3. Layout of hydrophones in the St. Marys River from 2013 to 2014.The locations for all hydrophones were the same both years, with the exception of one hydrophone in the upper south-west corner of the U.S. locks. The loss of the fastening cables due to ice shear over the 2013–2014 winter prevented the re-establishment of this hydrophone in 2014.

Welland Canal

In 2012, a total of 21 hydrophone receivers (Vemco Model VR2W 69 kHz) were deployed throughout the year. Receiver sites were selected to cover the entrances and exits to all locks in the canal, the major reaches between locks, the major side channel that leads to Port Dalhousie, and to cover where the canal meets lakes Erie and Ontario in Port Colborne and Port Weller, respectively. The receivers were moored by attaching each to a steel cable with a buoy on one end and cinderblock on the other end, which fixed them to the bottom of the canal.

To place the receivers, a mooring steel cable connected the receiver to a point at the surface. This cable was used to deploy and retrieve the receivers by hand. Six receivers went missing and/or were damaged; these were replaced with new receivers.

In 2013, a total of 34 hydrophone receivers were deployed throughout the year. During the draining operation period (January to March), eight receivers were retrieved from the sites from the reach 2 (between locks 2 and 3) to reach 6 (between locks 6 and 7) that were drained. These receivers were redeployed in the spring (April to June) when the canal was filled and shipping operations had resumed. Four receivers went missing and/or were damaged; these were replaced with new receivers.

In 2014, a total of 34 hydrophone receivers were deployed throughout the year. There were no receivers lost or damaged.

St. Marys River

In 2013, a total of 28 hydrophone receivers were deployed in three main areas between May 27 and May 30 (Figure 2.3). A lower curtain in the Topsail Island area marked the lower river boundary and an upper curtain above the U.S. and Canadian locks marked the upper river boundary. Within the U.S. locks, the U.S. Army Corps of Engineers (USACE) assisted in the placement of seven hydrophones as 340 kg blocks were used to anchor the hydrophones to prevent loss within the canal; three were placed in the lower river locks and four were placed in the upper river locks. In the Canadian locks, one hydrophone receiver was placed in the lower river section and four were positioned in the upper locks. Given the Canadian locks are not operated for commercial shipping, the hydrophones were set similar to those in the Welland Canal. Hydrophones that were set within the river used a concrete block ranging in size from 23 – 50 kg, with the hydrophone attached to a buoy to keep the hydrophone upright and a floating line and anchor for grappling. Above the Compensation Works, a total of five hydrophones were placed so that the entire Works width would be covered. Below the gates, five hydrophones were positioned to cover the lower rapids area between the U.S. and Canadian locks. In addition to the hydrophones directly surrounding the locks and canals, we placed an additional array of three hydrophones above the canal and lock system where the river narrows (Figure 2.3). This allowed us to determine if fish moved beyond the influence of the canal and lock system into the upper river. We also placed an array approximately 3 km below the canal and lock system in the lower river, to determine if fish left the lower study area. This array was in operation from May 27 to the end of October, with the exception of the hydrophones above the Compensation Works and upper Canadian locks, which were removed in early November.

In total, 24 functioning hydrophones were recovered in 2013. One hydrophone located above the Compensation Works and one from the upper curtain were never relocated during the fall retrieval. One of the hydrophones in the upper U.S. locks was recovered with the plastic casing cracked due to the pressure of the cables on the housing due to the passage of ships. Any data stored on this hydrophone were unrecoverable. The last hydrophone was situated in the lower U.S. locks and the cables were twisted due to the force of ship movements. This hydrophone was still attached to the cables and left to overwinter in the lower locks area.

In 2014, a total of 27 hydrophone receivers were deployed. Set dates ranged from April 24 through June 23, with the majority of the hydrophones being set on May 7 and 15. Late ice cover in the spring of 2014 prevented an earlier start date and also damaged the cables holding the hydrophones in the U.S. locks. All but one cable needed to be repaired by the USACE and one (upper lock, south side) was not repairable for the 2014 season. Repairs within the locks could not be completed until mid-June, at which time the remaining hydrophones were put into place. The hydrophones remained in the river until early November 2014 and, when they were retrieved, a total of 25 hydrophones were recovered. The lower river hydrophone that was unrecoverable in 2013 was recovered and still operational, but two of the hydrophones above the Compensation Works were not recovered and were considered lost.

Fish Tagging

In the Welland Canal, fishes were tagged with acoustic transmitters (Vemco V9 tag) through surgical implantation (Table 2.1). As surrogates for Asian carps, a range of species were targeted including Common Carp (*Cyprinus carpio*) and other large-bodied individuals (mean weight = 1.97kg, n = 179).

Table 2.1. Summary of fishes tagged and detected in the Welland Canal in 2012 and 2013.

Common Name	**Scientific Name**	**2012**			**2013**		
		Tagged	**Detected**		**Tagged**	**Detected**	
			2012	**2013**		**2013**	**2014**
Common Carp	*Cyprinus carpio*	68	27	42	63	56	
Freshwater Drum	*Aplodinotus grunniens*	2	2	1	7	7	
Smallmouth Bass	*Micropterus dolomieu*	5	5	2	4	4	
Largemouth Bass	*Micropterus salmoides*	1	1	1	5	4	
Northern Pike	*Esox lucius*	1	1	1	6	6	
White Sucker	*Catostomus commersonii*	1	-	-	3	3	
Brown Bullhead	*Ameiurus nebulosus*	1	1	1	6	6	
Channel Catfish	*Ictalurus punctatus*				3	2	
Goldfish	*Carassius auratus*				2	2	
Shorthead Redhorse	*Moxostoma macrolepidotum*				1	1	
	TOTAL	**79**	**37**	**48**	**100**	**91**	**55**

In the St. Marys River, fishes were tagged with Vemco V9 tags and were then released in the lower river to determine if fishes move from the lower basin to the upper and, if they do, at what locations do they attempt to pass and where they are successful. A wide range of species were targeted as there are few Common Carp in the area (Table 2.2).

Table 2.2. *Summary of fishes tagged in the St. Marys River in 2013 and 2014.*

Common Name	**Scientific Name**	**2013**		**2014**	
		Number Released	**Moved Basins**	**Number Released**	**Moved Basins**
White Sucker	*Catostomus commersonii*	62	2	3	1*
Sea Lamprey	*Petromyzon marinus*	25			
Atlantic Salmon	*Salmo salar*	15	1	18	2
Silver Redhorse	*Moxostoma anisurum*	7		1	
Freshwater Drum	*Aplodinotus grunniens*	2		2	
Chinook Salmon	*Oncorhynchus tshawytscha*	1	1		
Pink Salmon	*Oncorhynchus nerka*	1			
Northern Pike	*Esox lucius*	9			
Walleye	*Sander vitreus*	2			
Smallmouth Bass	*Micropterus dolomieu*	3	1		
Brown Bullhead	*Ameiurus nebulosus*	1			
TOTAL		**128**	**5**	**24**	**3**

*One White Sucker that was tagged in 2013 moved to the upper basin in 2013 returned in 2014 and moved both to the upper basin and returned to the lower river in 2014.

Welland Canal

In 2012, a total of 79 fishes of seven different species were tagged and released (Table 2.1). All fishes were collected using gill netting. All tagged fishes were released in late June and early July. There were three release sites; one site was located below the flight locks and two sites were located above the flight locks. Forty-one fishes were released in the lower pond found between locks 3 and 4, 26 fishes were released in the upper pond found between locks 6 and 7, and 12 fishes were released in the canal between locks 7 and 8 (Figure 2.2a).

In 2013, a total of 100 fishes of 10 different species were tagged and released. All fishes were collected by boat electrofishing. To facilitate fish movement, 50 tagged fishes were released in the canal between locks 2 and 3 (below the flight locks), and 50 tagged fishes were released in the canal between locks 7 and 8 (above the flight locks) (Figure 2.2b).

St. Marys River

In 2013, fishes were collected for tagging using several methods. In early June, fishes were collected in trap nets set in the lower river. Smallmouth Bass (*Micropterus dolomieu*) and Sea Lamprey were collected from traps operated by DFO Sea Lamprey Control Centre (DFO-SLCC) with the Smallmouth Bass collected in the DFO-SLCC trap in the upper St. Marys River, and the

Sea Lamprey collected in the traps at the hydroelectric facility on the Canadian side. In the fall, fishes were collected using an electrofishing boat in the lower rapids area. A total of 128 tagged fishes of 11 different species were released (Table 2.2). The majority of fishes were tagged and released in early and mid-June and then in September. All fishes, with the exception of three Smallmouth Bass, were collected in the lower river basin. These three Smallmouth Bass were tagged and released in the lower river on June 13. The majority of fishes tagged were expected to live longer than one season with the exception of Sea Lamprey (25), Chinook Salmon (*Oncorhynchus tshawytscha*) (1), and Pink Salmon (*Oncorhynchus nerka*) (1). While these fishes were not expected to live beyond one year due to their semelparous lifecycle, they are species that have a strong desire to migrate as far upstream as possible during their spawning run. These fishes were tagged as they were expected to challenge any river obstacles more actively than other species.

In 2014, 24 additional fishes of four species were tagged and released in September to supplement the fishes expected to still be alive in 2014 (Table 2.2). As the majority of the fishes tagged in 2013 (79%) had the potential to live longer than one year, we did not want to overwhelm the hydrophone array with too many additional tags, which can cause false or non-reads when tag collisions occur. All fishes were collected using boat electrofishing in 2014.

RESULTS

Welland Canal

To date, a total of 1,069,440 detections were collected between July 2012 and January 2015. Thirty-one receivers, covering the time period from September 2014 to July 2015, still need to be downloaded.

In 2012, 37 of the 79 tagged fishes (six species) were detected within the canal (Table 2.1): 27 Common Carp; five Smallmouth Bass; two Freshwater Drum (*Aplodinotus grummierns*); one Largemouth Bass (*Micropterus salmoides*); one Brown Bullhead (*Ameiurus nebulosus*); and one Northern Pike (*Esox Lucius*). Two fishes (one Freshwater Drum and one Common Carp) were detected leaving the Welland Canal towards Lake Erie, where they passed through 1 or 2 locks and moved about 20 km upstream towards Lake Erie (Figure 2.2a). In addition, three fishes (two Common Carp and one Freshwater Drum) moved through the flight locks from the upper pond (above the flight locks) to Reach 3 between locks 3 and 4 (Figure 2.2b).

In 2013, 48 of 79 fishes tagged in 2012, and 91 out of 100 fishes tagged in 2013, were detected within the canal (Table 2.1). Releasing fishes in the middle of the canal, adding more receivers, and maintaining the receivers and periodic downloads improved the detection rate. Five fishes (four Freshwater Drum and one Common Carp) were detected leaving the Welland Canal and three fishes (two Freshwater Drum and one Common Carp) were detected moving 7 km downstream towards Lake Ontario through two locks (Figure 2.2a). In addition, two Freshwater Drum were detected moving towards Lake Erie through one lock and travelling about 25 km upstream (Figure 2.2a).

In 2014, 11 fishes tagged in 2012 were detected in January, and 55 fishes tagged in 2013 were detected within the canal. Of these 66 fishes, four fishes were detected re-entering the Welland Canal; one Common Carp and one Freshwater Drum were detected re-entering from Lake Ontario, and two Freshwater Drum from Lake Erie. Two Freshwater Drum were also detected moving across Lake Erie to the western basin and then back to the Welland Canal by other receivers in the Great Lakes Acoustic Telemetry Observation System (GLATOS). No fishes were recorded passing through the flight locks. Through GLATOS, acoustic data revealed that a tagged Common Carp released in Toronto Harbour had been detected in Lake Erie. We are currently examining our data to determine if this fish travelled through the Welland Canal.

Detection data for all years are being analyzed using multi-state mark-recapture models to estimate survival, detection, and transition probabilities at various spatial and temporal scales. GLATOS, which compiles acoustic telemetry data, will also be consulted to determine if any fishes from this study have been detected in other parts of the Great Lakes basin.

Overall, a total of seven fishes (3.9%) out of 179 tagged fishes moved out of the Welland Canal to either Lake Ontario or Lake Erie in 2012 and 2013. Only two species left the canal: a Freshwater Drum and a Common Carp. Throughout the three-year study, a total of three fishes (1.7%) out of the 179 tagged fishes moved through the flight locks from the upper pond to Reach 3; however, this movement only occurred in 2012 and was not detected again in 2013 or 2014.

St. Marys River

Of the 129 fishes tagged in 2013, 128 were released, as one died prior to release; however, additional fish were not available for tagging in 2013. All of the fishes tagged were recorded at least once after their release back into the lower river. A total of four fishes (Northern Pike, Smallmouth Bass, Walleye [*Sander vitreus*], Atlantic Salmon [*Salmo salar*]) were captured by anglers in the river between July 2013 and July 2014, and one Sea Lamprey was recovered in the DFO-SLCC traps in the lower river in July 2013. The majority of fishes remained in the lower rapids and lower lock areas for at least part of their recorded movements before dispersing in the lower river or moving past the lower river curtain. Fishes were recorded in the lower river throughout the year, based on data from the lower river hydrophone operational over the winter of 2013–2014. In total, five fishes (3.9%) of four species moved from the lower basin to the upper basin including: White Sucker (*Catostomus commseronii*), Smallmouth Bass, Atlantic Salmon, and Chinook Salmon. The Chinook Salmon was also recorded returning to the lower river basin. The fishes were recorded using a variety of paths to reach the upper river. Listed below are detailed accounts of the individual fish that moved from the lower to upper basin.

White Sucker (A69-1601-8208)

This fish was tagged on June 05 and released on June 06. It moved around the lower river area (lower rapids and down to Topsail Island area) and then returned to the lower rapids area on June 17. It traveled through the Canadian locks to the upper river where it remained through the remaining summer months. It was recorded returning to the upper Canadian locks in November; however, the Canadian locks close to ship traffic around October 12, 2013. This individual was recorded in the area of the Compensation Works in November, at which time the hydrophones were removed from the river.

White Sucker (A69-1601-8182)

This fish was caught and tagged on June 06. It was recorded in the lower river and Topsail Island area throughout much of the summer. On August 25, it was recorded in the rapids and lower U.S. locks area. It was then recorded on the upper U.S. locks receivers overnight on August 28. It most likely travelled through the U.S. locks as the Canadian locks are not open at this time (overnight). It was last recorded at 04:03 in the upper U.S. locks on August 28.

Smallmouth Bass (A69-1601-8172)

This fish was captured in the upper river on June 13 and then tagged and released on June 14 in the lower river. The fish was recorded in the rapids and lower locks areas (both U.S. and Canadian) before it moved towards the curtain at Topsail Island. It returned to the rapids area and remained until June 24, at which time it was recorded moving through the U.S. locks and on to the upper river. It passed the upper corridor hydrophones on June 25 and was not recorded again.

Chinook Salmon (A69-1601-8230)

This fish was captured with the boat electrofisher on September 10 and then tagged and released on September 12. This individual moved around the lower rapids and the Topsail Island area until mid-September, when it moved back to the lower rapids. It was recorded in the rapids on September 27/28. On October 03, it was recorded on the hydrophones above the Compensation Works. Chinook Salmon are known to school at this time in the rapids at the Compensation Works gates and it is most likely that the fish passed through the gates directly. The fish was recorded in the upper river area during October 03 and then on the upper U.S. locks receivers that night. It was then recorded leaving the lower U.S. locks at 05:32 on October 04, whereby, it returned to the lower rapids area and then past Topsail Island on October 19.

Atlantic Salmon (A69-1601-8222)

This fish was captured with the boat electrofisher on September 10 and then was tagged and released on September 11. It was recorded in the lower Canadian locks and rapids area until October 13. It was recorded in the Topsail Island area on October 21, at which point, the hydrophones were removed in the area. This individual was next recorded on November 03 in the upper Canadian locks area. The Canadian locks closed in mid-October and the fish was not recorded moving up through the Compensation Works or across the Works (from U.S. waters to the upper Canadian canal). It is possible that the fish moved up river via the Whitefish Channel, which connects the lower river with the upper Canadian canal via a passage into the Canadian locks in this area. As the hydrophones were removed from the upper Canadian canal at this time, the fish was not recorded further.

In 2014, 24 fishes were collected with the electrofishing boat, tagged, and released between August 25 and August 27. All of these fishes were recorded moving in the lower rapids area post-release. In addition to the fishes collected in 2014, 48 fishes tagged in 2013 were recorded in the array in 2014. This only included fishes that were recorded moving within the array area as several (five) were recorded on the hydrophones, but were not considered to be alive during the 2014 season. A total of three fishes (4.2%) were recorded moving from the lower to upper basin in 2014, including one that had moved to the upper river in 2013. In total, one White Sucker and two Atlantic Salmon moved from the lower basin to the upper and returned in 2014. Listed below are detailed movements of these three individuals.

White Sucker (A69-1601-8208)

This fish was tagged in 2013. We do not have a record of how it returned to the lower river as it was last logged in the upper river in the upper Canadian canal on the day the hydrophones were removed. It is possible the fish returned via the Compensation Works, as it was not recorded on the hydrophone that remained in the U.S. locks over the winter. This individual was first recorded on the lower river curtain in the Topsail Island area on June 02. It then moved up the rapids area and was subsequently recorded in the lower Canadian locks on June 16, followed by a movement in the upper Canadian locks, showing a clear movement upstream. The fish was recorded in the upper river and Canadian locks on October 16 when it then moved back through the locks to the lower river. The Canadian locks closed on October 15. However, diver inspections were conducted on October 16, which resulted in the locks opening and closing throughout the day; this flushing action likely facilitated lock passage for this fish.

Atlantic Salmon (A69-1601-25047)

This fish was tagged on August 26, 2014 and was then released in the lower rapids area. The fish was recorded in the rapids area on August 27 and shortly after, proceeded to drop back towards the Topsail Island area. On August 31, it moved to the upper river via the U.S. locks where it remained until September 21. It then returned to the lower river, most likely through the Compensation Works, and was recorded in the rapids area on October 15. This individual was recorded in the rapids and locks area until November 23.

Atlantic Salmon (A69-1601-25048)

This fish was tagged on August 26 and was released in the lower rapids area. This individual was recorded in the rapids area, and was then detected moving up the U.S. locks and past the upper curtain area on September 22. The fish returned to the lower river through the U.S. locks on September 23 and remained in the rapids area until October 17. On October 30, the fish was captured by Lake Superior State University fisheries students. The fish was used as part of the stocking program and released in good health back into the river in November 2014.

DISCUSSION

Canal systems have been used by AIS as pathways to travel into novel environments (Eshenroder 2014). Invasive species, such as Sea Lamprey and White Perch, have used both the Welland Canal and St. Marys River as corridors, allowing them to colonize new basins within the Great Lakes area (Pearce et al. 1980, Smith and Tibbles, 1980, Cudmore et al. 2012). However, there has been limited research on how effectively fishes move through lock and canal systems as dispersal corridors (Eshenroder 2014). Understanding how locks differentially facilitate fish movement between basins is important to inform future management decisions regarding how to prevent the spread of AIS through this pathway.

By examining fish movement through the Welland Canal, our results demonstrate that freshwater fishes do use the canal to move between Lake Ontario and Lake Erie. Although only a small percentage of fishes moved into the Great Lakes from the canal, species that exhibited this type of movement included Freshwater Drum and Common Carp. Of the 68 Common Carp tagged in 2012 and 63 tagged in 2013, two were detected leaving the canal and another two were observed passing through the flight locks. This low number suggests that, although Common Carp can use the Welland Canal as a route between the Great Lakes, such movement is not common. Freshwater Drum appear to be the most mobile fish species tagged. Although only nine specimens were caught in 2012–2013, eight individuals moved through locks, one of which was able to move through the flight locks. Records from the Muskingum River in Ohio and Rideau Canal in Ontario have shown that Freshwater Drum are capable of moving through canal systems with dams and locks, so perhaps this species is more proficient at navigating these barriers than the others that were tagged (Watters 1996, Phelps et al. 2000).

While only non-surrogate fishes were tagged in St. Marys River due to the lack of Common Carp in the rapids area, it is clear that a variety of species will use the available pathways to move between the upper and lower basins, moving both up and down river. Fishes used both the U.S. and Canadian locks to move up and down the river. They also used the Compensation Works, despite the expectation that high flows through this area are an impediment to many species. Historically, before any hydroelectric development and lock infrastructure installation, the entire river consisted of rapids (MacDonald 1977, Conway 1980, Duffy 1987) and supported an immense natural Lake Whitefish fishery, in addition to many other species (Conway 1980). As in Welland Canal study, only a small percentage of tagged fishes (5.3%) made their way from the lower basin to the upper basin; however, of those tagged fishes that moved to the upper basin, 62.5% returned to the lower basin using a variety of pathways, indicating that movement between the upper to lower basin can be quite high. Despite the low number of tagged fishes that moved upstream in this study, previous research have shown that other species, such as White Sucker (L. O'Connor, DFO-Great Lakes Laboratory for Fisheries and Aquatic Sciences, pers. comm.), Sea Lamprey (R. McDonald, DFO-SLCC, pers. comm.), and some salmon species (A. Frappier, USACE, pers. comm.), move between the lower and upper river on a regular basis. Despite the low number of tagged fishes that moved from the lower to upper river, based on past AIS dispersion studies and this study, which shows that fishes do use these canals and locks to move between the Great Lakes (Pearce et al. 1980, Smith and Tibbles 1980, Mills et al. 1993), the St. Marys River is a potential dispersal corridor into Lake Superior should Asian carps or other AIS invade Lake Huron.

As with any telemetry study, there are potential limitations to the use of acoustic telemetry for fish movement studies. By using the latest state-of-the-art acoustic telemetry technology, there is the potential for unpredictable technical issues. It is possible that the acoustic receivers did not detect all of the tagged fish due to defects with the equipment, sub-optimal placement of the receivers, missing and lost receivers, damage from being deployed throughout all seasons, and the possibility of theft or tampering. There may have also been issues with the tags themselves as there is always the risk of defective tags and inefficiently functioning batteries. In terms of environmental factors that may have interfered with the telemetry system, there is the possibility of uncontrollable influences such as ambient noise, shipping traffic, and regular lock operations. Lastly, as with all tagging studies, there is always the chance for mortalities or unanticipated expulsion of tags, which would have led to skewed observations as the collected data would not have matched the actual movement of fishes.

From both studies, it has been shown that fishes can move through canals and lock systems to travel between waterbodies. AIS, such as Asian carps, known to successfully move upstream, may exploit these pathways to enter other basins within the Great Lakes system if they arrive. Monitoring these potential dispersal corridors is a vital step in preventing the spread of future AIS through the Great Lakes region, as a rapid response is essential to ensure AIS do not proliferate if they arrive.

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GENERAL CONCLUSIONS

The research presented here in support of the Grass Carp risk assessment indicate that under current lake conditions, the movement and spread of Grass Carp within and between lakes in the Great Lakes basin is possible. More specifically, the following main summary points are:

Grass Carp Dispersal

- Individuals are expected to reach another basin from the one in which they were introduced within 5 years.
- By the end of 10 years, the second lake basin is likely to have multiple individuals nearing 10-20% of the population.
- Spread of Grass Carp is slowed by strong preference for the nearshore of the lakes and the numerous sources of good wetland habitat.

Movement of Fishes through the Welland Canal and St. Marys River

- Fishes can move through canals and lock systems to travel between waterbodies; Asian carps, which are known to successfully move upstream, may exploit these pathways to enter other lakes within the Great Lakes system.
- Only a small percentage of tagged individuals managed movement of this extent (between lakes Superior and Huron through the St. Marys River and lakes Erie and Ontario through the Welland Canal).

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