The fate of farmed rainbow trout (*Oncorhynchus mykiss*) released from commercial aquaculture operations in Lake Huron

by

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ABSTRACT

The fate of farmed fish after escape is poorly understood. The extent to which these fish might impact freshwater ecosystems is dependent upon their survival and distribution in the wild. I simulated small- and large-scale escape events from two commercial aquaculture operations in Lake Huron over 2 years. I combined the use of telemetry (120) and Floy (1000) tags to determine the fate of escaped farmed rainbow trout (*Oncorhynchus mykiss*). Once released, escapees dispersed rapidly, showed low site fidelity (~15% after 3 months) and were capable of long distance movements (up to 360 km). Rainbow trout experienced low survival (~50%) but maintained high growth rates both at and away from the farms. The results of this study provide a strong basis for understanding the potential risks that farmed fish may pose to the Lake Huron fish community and ecosystem in an escape event.

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CHAPTER 1: Introduction

1.1 Aquaculture

A change is happening in worldwide fisheries acquisition with an expansion in aquaculture and declining reliance on capture fisheries. Aquaculture production increased over 2 million tonnes (t) annually from 2000 to 2005, while capture fisheries declined at a rate of 300,000 t annually during the same period (FAO 2007). A driving force is the present global demand for fish for human consumption not being met by the commercial harvest of natural populations. This fact, coupled with declines of wild fish stocks (Pauly 2009), and continued human population growth, indicates that aquaculture may be an ideal industry to provide high protein food source (Boghen 1989).

Aquaculture is the farming of aquatic organisms including fish, molluscs, crustaceans and plants (Pillay 1990). Asia is widely recognized as the birthplace of aquaculture, dating back more than 2,000 years ago in China where carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*) were cultivated in flooded rice fields (Li 1994). Presently, aquaculture is practiced worldwide with the species and biomass produced varying by region, dependent upon suitable conditions for growth and market demand. The farming of aquatic species has seen unprecedented expansion as an industry in the past half century. In fact, the contribution of aquatic organisms to global supplies is growing more rapidly than all other animal producing food sectors, contributing ~4% production by weight in 1970 to more than 30% by 2004 (FAO 2007). One of the factors contributing to the substantial growth of aquaculture production is related to the decline of wild fish stocks. A classic example is the over-fishing of northern cod (*Gadus morhua*) off the east coast of Canada, collapsing the population, and bankrupting the entire province of Newfoundland and Labrador (Hutchings 1996). Similar exploitation of reproducing Atlantic salmon (*Salmo salar*) adults combined with habitat degradation (increase of dams in spawning rivers) greatly reduced the Baltic stocks of wild salmon (Eriksson and Eriksson 1993). The decline of Atlantic salmon led to a rapid expansion of salmonid husbandry research, stocking programs, and the development of the salmon aquaculture industry, led largely by Norway.

The majority of current salmonid aquaculture production, and the focus of my M.Sc. study, is the open-pen (cage) industry. Open-pen aquaculture dates back almost two centuries to when commercially valuable fish were held in bamboo cages to be sold live in the Great Lakes area of Kampuchea in Southeast Asia (Pillay 1990). Traditional cage culture, defined by the reliance on natural or waste feeds and cage construction of only natural materials is still practised in many parts of Indonesia and Southeast Asia (Beveridge 1987). Pen- or cage-culture has gained much attention in research and development due to its highly productive potential in large open waters, both in freshwater and marine environments (Pillay 1990). Today, cages fall under four general groups: fixed, floating, submersible, and submerged, with the dimension varying for different species (Beveridge 1987). For example, blue fin tuna (*Thunnus thynnus*), a valuable species with declining stocks, are grown in large off-shore floating cages accessed only by boat (Beveridge 1987), while salmonids are commonly reared in a series of attached pens that are anchored (fixed) and include floating walkways to access cages for ease in feeding, care, and harvesting (Brown and Gratzek 1980).

A majority of fin-fish production in Europe and North America is through cage farming of salmonid fishes, especially Atlantic salmon in the marine environment. The use of salmonids in aquaculture is well developed as their life histories are both well known and easily manipulated to meet the needs of profitable cage rearing. As of 2006, 68 of the 159 countries practicing fish-based aquaculture were rearing salmonids (e.g. Atlantic salmon; Arctic char, *Salvelinus alpinus*; rainbow trout, *Oncorhynchus mykiss*), with the greatest production occurring in Norway, Chile, the UK, Canada and Turkey (FAO 2008). The extensive growth in the Atlantic salmon fisheries industry in the past 15 years, from ~200,000 t in 1990 to >1 million t in 2006, is almost completely attributed to aquaculture production (Jones 2006). A large portion of this recent growth in Atlantic salmon production is from Norway and Chile, which presently account for two thirds of Atlantic salmon production (Weir and Fleming 2006), although all other dominant producing countries are increasing, albeit at a slower rate (FAO 2008). Production in Canada has more than tripled over the past two decades, from ~ 34,000 t in 1991 to over 100,000 t in 2008 (Statistics Canada 2009).

Although Atlantic salmon dominates finfish production in North America and Europe, other species have a valuable niche as well. The production of rainbow trout in freshwater has been occurring since as early as the 1950s, and global production has steadily increased from 4200 t in 1950 to 322,925 t in 2007 (FAO 2009). Commercial freshwater aquaculture occurs in a majority of Canadian provinces but Ontario leads the industry, contributing ~4000 t of rainbow trout (~70% of total Canadian production) to the global market annually (Statistics Canada 2009). A majority of this production (75%) is carried out by a small number (<10) of open-pen operations located in Lake Huron (DFO 2007).

Freshwater aquaculture in Canada reached its peak of expansion in the mid to late 1990's, but the industry has reached a plateau and production has been constant over the past decade (Figure 1.1). With initial industry growth came increasing concern regarding impacts on the local environment, focused largely on the nutrient inputs, and the escape of domestic fish to the wild (reviewed in Yan 2005; Podemski and Blanchfield 2006). These concerns have halted the expansion of commercial aquaculture in Ontario and the need for scientific research to assist governing bodies in appropriate regulatory decision making in the industry is apparent.

1.2 Occurrence of aquaculture escapees

A historically significant problem and present day concern with open-pen farming in both marine and freshwater environments is the escapement of farmed fish into the wild (often termed escapees). Although husbandry practices and cage design strive to minimize escapement to the wild, there is always a possibility of accidental release from open-pen operations. Escapement of aquaculture fish can be classified as either acute or chronic (Bridger and Garber 2002). Chronic leakage is the continuous slow loss of fish by various means such as small tears in the cages from wear, localized predation, or improper farm practices; whereas acute escapement is a larger scale loss of fish over a short period of time and can be caused by storms, vandalism or predation (Bridger and Garber 2002). For example, in the Faroe Islands in 2002 600,000 salmon escaped after storm damage (McGinnity *et al.* 2003).

Accidental release of fish is possible at all stages of rearing. Globally, escaped farmed fish can account for up to 48% of the total catch in marine and freshwater fisheries, with a majority being sexually mature salmonids (Bridger and Garber 2002). An estimated 2 million farmed Atlantic salmon escape into the North Atlantic every year, equalling ~50% of the pre-fishery abundance of wild salmon (McGinnity *et al.* 2003). In the Norwegian fishery, at least a quarter of the fish caught at feeding grounds in the north east Atlantic are farmed Atlantic salmon (Hansen *et al.* 1993; Jacobsen *et al.* 2001). In Norwegian rivers, one third of adult salmon entering rivers have escaped from commercial farms; farmed fish account for up to 80% of the run in some rivers (Fiske and Lund 1999).

The North American story is similar to that of Norway. A 20 year survey (1987-2006) of rivers on the east coast of North America in close proximity (300 km) to marine aquaculture facilities showed that 87% contained farmed Atlantic salmon (Morris *et al.* 2008). In some rivers, farmed salmon outnumber wild conspecifics 10-fold (McGinnity *et al.* 2003). Similarly, on the west coast of Canada, farmed Atlantic salmon have been located in over 80 rivers in British Columbia, including the presence of feral juveniles in three different regions (Volpe *et al.* 2000). The Atlantic Salmon Watch Program, which documents aquaculture escapement on the west coast of North America, reported losses of 452,049 salmon between 1991 and 2002 in British Columbia (DFO 2002). These numbers should be taken as a minimum estimate as they only reflect large scale escape events, and not the numbers of fish escaped through chronic leakage, which are less likely to be reported (Skaala *et al*. 2006; Weir and Fleming 2006).

1.3 Impacts of aquaculture escapees

The loss of farmed fish to the wild not only represents a significant financial loss to the operators, but also poses a number of environmental concerns regarding interactions with native or naturalized fish communities (Naylor *et al.* 2005). To date there have been a variety of studies examining the incidence, effects, implications, and potential mitigation of escapees (e.g. Hansen *et al*. 1993; Volpe *et al.* 2000; Jacobsen and Hansen 2001; Carr and Whoriskey 2006; Fiske *et al*. 2006; Skaala *et al.* 2006; Walker *et al.* 2006). Not surprisingly, a majority of aquaculture research has focused on the Norwegian experience; however, North America has contributed to research, specifically on the areas of interactions with native populations and ecosystem disruption upon escapement of farmed fish (Clifford *et al.* 1998; Jacobsen and Hansen 2001; Whoriskey and Carr 2001; Skaala *et al.* 2006; Thorstad *et al.* 2008). The three main areas of concern with escapement of farmed fish can be broadly categorized as: genetic, disease, and ecological impacts. Here I only briefly discuss genetic and disease-related effects of aquaculture as these areas are well studied and not the main focus of this thesis.

1.3.1 Genetic implications

The first commercial salmonid open-pen operation began in Norway in the 1960s, when rainbow trout were successfully cultured in marine cages (Saunders 1989). The production of salmonids to smolt stage had been perfected during the 1940's and 1950's due to the aforementioned decline in wild Atlantic salmon numbers. Captive salmonids are easy to spawn artificially by applying pressure to their bodies to extrude the female ova (eggs) and male milt (sperm) and mixing them to allow fertilization (Saunders 1989). Once fertilized, the eggs are incubated, most commonly in trays, with gently flowing 8-13 ºC fresh water (Bardach *et al.* 1972). The trays are often made of a special type of wire screen with oblong openings that retains eggs, but allows alevins to pass through (Bardach *et al*. 1972). Once the yolk sac is depleted, the fry are fed a commercial feed which increases in size as they grow into fingerlings. Eventually fingerlings undergo major physiological changes (smoltify) in preparation for migration to salt water (Steelhead trout, Atlantic salmon) or freshwater lakes (rainbow trout) (Willoughby 1999; Negus 2003). Once the smolts reach a desirable minimum size they are transferred to open-pen farms to complete their growth to market size. Salmonids typically reach market size after 2-2.5 years.

Species used in aquaculture today have undergone selective breeding for traits that favour the 'aquaculture environment' (Bridger and Garber 2002). Phenotypic traits commonly selected for aquaculture production include large body size, late maturation, disease resistance, flesh quality, and high growth rate (Skaala *et al.* 2006). Selective breeding is a controlled process where the hatchery operator isolates and propagates those genotypes that control for the desired traits (Donaldson and Olson 1957). Due to the selective breeding process, farmed and wild salmon today differ genetically (Skaala *et al.* 2006).

A number of studies have examined differences in phenotypic traits, such as growth rate and behaviour, between wild and farmed salmon (Einum and Fleming 1997; Fleming and Einum 1997; Johnsson *et al.* 2001, Fleming *et al.* 2002). Many of these studies highlight the variation in growth rates between wild and domestic fish (Fleming and Einum 1997; Fleming *et al.* 2002; Biro *et al*. 2004, 2006; Reinbold et al. 2009). Selection for higher than normal growth rate coupled with constant food availability and absence of predators, now standard in aquaculture, can make farmed fish maladapted to the wild environment (Gross 1998). For example, studies on domesticated age 1+ rainbow trout and Atlantic salmon, age 2+ Atlantic salmon, and juvenile steelhead trout, showed domestic fish have decreased predator avoidance compared to their wild counterparts (Johnsson and Abrahams 1991; Berejikian 1995; Johnsson *et al.* 2001; Biro *et al.* 2004, 2006). Lifetime success (the ability of an adult to have an offspring who survives to reproduce) of domesticated salmon is 16% of that of wild salmon (Fleming *et al.* 2000), and there has been a 37.5% fitness decline per captive reared generation demonstrated in steelhead trout (Araki *et al.* 2007).

It follows then, that a major concern associated with the escape of farmed fish is their potential negative impact if able to successfully breed or hybridize with wild or naturalized fish stocks (Bridger and Garber 2002; Naylor *et al.* 2005). Successful breeding and hybridization of farmed fish with wild fish has been demonstrated in the

Atlantic and Pacific oceans (Lura and Seagrov 1991; Carr *et al.* 1997a; Clifford *et al.* 1998; Volpe *et al.* 2000). With successful breeding of escapees an influx of traits selected for in aquaculture are passed into wild populations. Studies have shown that domestic and hybrid domestic-wild salmon life history adaptations can lower the overall fitness of the wild population if successfully integrated (Fleming *et al.* 2000). The gene flow from farmed fish to native populations can significantly reduce the productivity and fitness of native populations which are already struggling (Fleming *et al.* 2000; McGinnity *et al.* 2003). If genetic variation in wild populations were homogenized, as done with aquaculture fish, the capacity to evolve and adapt to environmental change would be reduced (Hindar *et al.* 1991).

1.3.2 Disease implications

For aquaculture in general and escapement in particular, disease transmission is, or has been a primary concern. In marine habitats epidemic patterns have been traced back to farmed fish in Canada, Norway, Ireland, and Scotland (Naylor *et al.* 2003; Krkošek *et al.* 2005). Many studies have linked parasitism of wild salmonids to the presence of fish farms (Tully et al. 1999; Bjørn and Finstad 2002; Carr and Whoriskey 2004). Current examples include the outbreak of sea lice (*Lepeophtheirus salmonis* and *Caligus elongatus*), the transfer of highly virulent salmon anemia (ISA), infectious hematopoietic necrosis (IHN), whirling disease, and furunculosis (Naylor *et al.* 2005).

Furunculosis is a bacterial disease that can cause haemorrhaging at fin bases and erosion of pectoral fins, which in the past has accounted for a high percentage of wild fish losses attributed to infectious disease (Schachte 1974). Johnsen and Jensen (1994) found that Norwegian Atlantic salmon escapees infected with furunculosis have been responsible for the spread of the disease in other farmed and wild stock. Within a few years of fish escape, furunculosis was found in 74 Norwegian rivers, in some cases reaching epidemic proportions (Johnsen and Jensen 1994). This issue has been mostly mitigated with antibiotics. A recent concern in North America is the sea lice infestation of native Pacific salmon due to aquaculture. Krkošek *et al.* (2007) showed that recurrent louse infestations of wild juvenile pink salmon (*O. gorbuscha*), due to the presence of Atlantic salmon farms, have depressed these populations, potentially leading them to rapid local extinction on the west coast of Canada. Most infestation of wild populations has been linked to their juvenile migration past sea cages, although the transfer of disease from escaped farm fish to wild fish is possible (Lund and Heggberget 1992).

1.3.3 Ecological implications

Ecological consequences associated with escapement of farmed fish represent the least well studied area of concern and is the focus of this thesis. Escapees potentially compete with native fish populations for food, space, and mates, all of which can be limited in a natural system. The key to quantifying the potential risks that escaped farmed fish pose to native fish communities and ecosystem function, is an assessment of their fate once released. Parameters of escapee fate: their distribution once released, the ability to adjust and successfully forage in the wild, and their overall survival, are key in addressing the potential risk associated with an escape event. The importance of genetic and disease related effects may be greatly reduced if escapees have poor survival and exhibit high levels of site fidelity to the release farm. Alternatively, if fish exhibit high survival, and have long distance dispersal their effects will be greater. The presence of large numbers of escaped farmed fish in the wild indicates that at least some portion of them are able to successfully forage and live outside of the aquaculture environment (Lund *et al.* 1991; Hansen *et al.* 1993; Hansen *et al.* 1997; McKinnell *et al.* 1997).

There is strong evidence that escaped fish can readily adjust to the wild. Farmed Atlantic salmon recaptured around the Faroe Islands after 1-3+ years in the wild exhibited selective evidence of foraging behaviour (Jacobsen and Hansen 2001). The ability to rapidly learn to respond toward novel prey has also been shown in domestic Atlantic salmon parr which allows them to maintain a high foraging efficiency when released into foreign habitats (Reiriz *et al.* 1998). Age at escape may be an important factor, as younger fish adjust more quickly to natural feeding after escape than adults (Rikardsen and Sandring 2006). Species used in aquaculture have been chosen because of their ability to quickly adapt and succeed in a variety of environments. It is not surprising that fish escaped from farms can adjust to local environments, even when outside of their native range (see McKinnell *et al.* 1997; Volpe *et al.* 2000; Soto *et al.* 2001; Toledo Guedes *et al.* 2009).

The area impacted by the release of farmed fish to the wild depends largely on the distribution of escapees. Site fidelity of escaped fish may reduce their impacts on the local system as their home range becomes limited to the area in and around the cage sites, opposed to the entire water body. Escaped fish could have reduced impact if they remain at the cages, consuming waste feed and applying limited pressure to local food availability (Phillips *et al.* 1985; Carss 1990). Other escaped fish have been shown to remain at the cage site but prey on local fish populations (Toledo Guedes *et al.* 2009). The degree of site fidelity and nature of food consumption would determine the resource driven consequences of an escape event.

Competition for space can occur in all life stages, but due to the interest in genetic interactions, has been most widely studied during the reproductive period (eg. Carr *et al.* 1997; Fleming *et al.* 2000; Volpe *et al.* 2000). Escapees may not directly compete with wild fish for mates but can indirectly affect their success by entering spawning streams late and disrupting spawning beds, reducing the already low reproductive success of a diminishing population (Lura and Saegrov 1993). In regions where farmed fish hybridize with wild populations, escapees, particularly males, have reduced breeding success (Fleming *et al.* 2000). Domesticated fish have been shown to cause more damage during the spawning period through resource competition and competitive displacement than through the production of viable offspring, depressing the reproductive success of the native wild fish by more that 30% (Fleming *et al.* 2000).

A major concern for competition and potential displacement of native species arises when aquaculture species are grown outside of their native range. If there are repeated releases the chance of escapees establishing themselves as an invasive species increases (Naylor *et al.* 2005). Invasive species can alter competitive interactions, reduce native populations, and the hybridization of invasive species with native species can cause loss of fitness, leading to a possible threat of extinction (Mooney and Cleland 2001). At a global level, exotic introductions are considered second only to habitat loss as the major threat to marine biodiversity and the integrity of natural communities (IUCN 1997). Nearly one third of farmed Atlantic salmon are raised in regions where the species is exotic (Thorstad *et al.* 2008). The successful breeding of escaped Atlantic salmon has also been documented on the west coast of Canada, which has raised concerns of establishment of feral populations that could further endanger the fragile state of native Pacific salmonids (Volpe *et al.* 2000).

1.4 The Canadian freshwater aquaculture industry

Although the focus of aquaculture research has been on marine systems, similar problems exist for the freshwater industry. As an example, the amount of wild fish used to produce high nutrient fish feed is a concern in both the marine and freshwater industries where large quantities of oils and protein are acquired from wild fish stocks for the culture of carnivorous fishes (Naylor *et al.* 1998). However, some effects are of greater concern in freshwater than marine environments. The effect of fish waste on habitat surrounding an aquaculture operation is of greater concern in freshwater aquaculture due to the smaller area and reduced flushing compared to marine operations, causing waste to have a more localized impact (Yan 2005). The nutrient increase caused by excess feed and faecal matter directly affects wild populations when ingestion of these materials occur, or indirectly through food web changes (Podemski and Blanchfield 2006). An increase in phosphorus inputs as a result of aquaculture production in freshwater systems can increase algal abundances, decrease water clarity, and subsequently increase profundal oxygen consumption (Yan 2005). This is of greatest concern in small systems, such as freshwater lakes that have limited mixing of the water layers and inadequate flushing around the cage site to prevent eutrophication of the lake (Yan 2005).

Causes of freshwater escapements are similar to marine systems, but the implications of freshwater escapement are not yet understood. To date, no comprehensive study on the potential impacts of escaped farmed fish at sites of commercial freshwater aquaculture in Canada has been done. The potential impact of escaped farmed fish to freshwater ecosystems represents a significant gap in present knowledge that needs to be addressed (Podemski and Blanchfield 2006). Sound scientific research conducted to fill these gaps can inform policy makers and allow for sustainable practices in the freshwater cage-culture industry in Canada.

The fish most commonly produced in freshwater Canadian aquaculture is the rainbow trout, accounting for approximately two thirds of production (DFO 2007). Like the Atlantic salmon, rainbow trout is a highly adaptable species whose range has been greatly extended; from freshwaters west of the Rocky Mountains to its current occupancy on every continent (MacCrimmon and Gots 1972). There are approximately 700 freshwater aquaculture operations in Canada; however, most of these are land-based. While small in number (2%), open-pen farms produce more than 45% of Canada’s freshwater aquaculture output (DFO 2007). They occur in Newfoundland, Prince Edward Island, Ontario, Saskatchewan, and British Columbia. Rainbow trout production is concentrated in Ontario contributing ~$16 million to the economy annually (Moccia and Bevan 2007).

A majority of this production (>75%) is carried out at less than 10 commercial operations in the North Channel and Georgian Bay of Lake Huron (Masser and Bridger 2007) (Figures 1.2, 1.4).

1.4.1 Rainbow trout (*Oncorhynchus mykiss*)

In Lake Huron rainbow trout is considered a “naturalized” species, having been originally introduced in 1876 (OMNR 2006). Significant stocking of rainbow trout over the past century (3 million + in past years) has resulted in the establishment of self-reproducing populations in the Laurentian Great Lakes. Annual stocking of rainbow trout into Lake Huron over the past three decades ranged from ~ 500,000 to >3.5 million fish (Figure 1.3). Today, stocked and naturalized rainbow trout provide significant recreational opportunities, especially in Lake Huron (OMNR 2006).

The life history of naturalized trout begins with the deposition of fertilized eggs into gravel riffle area of a stream or river. Once hatched, the fry will stay in the stream for a few months to four years before moving into Lake Huron at the size of 10-15 cm, where they grow rapidly in the new abundance of food, and can mature in under a year (MacCrimmon and Gots 1972). In this time fish travel between near and off-shore regions, with the switching between areas driven by food availability, optimal temperatures, or dissolved oxygen levels (eg. Haynes *et al.* 1986; James and Kelso 1995; Warner and Quinn 1995; Barrow and Peters 2001). Once mature, rainbow trout return to the stream/river to spawn. Rainbow trout reproduce in the spring, spawning in inlets and outlet streams of lakes, or smaller tributaries of rivers if they are stream-resident.

Spawning can occur from March to August, but largely mid-April to late June (Hartman *et al.* 1962). Some populations in the Great Lakes enter spawning streams from late October to late May and spawn from late December to late April (Dodge and MacCrimmon 1970), in water temperatures between 10.0 – 15.5 ºC (Scott and Crossman 1973). In Georgian Bay, Lake Huron, spawning generally starts in April, and finishes in April or May, with most of the population (63%) spawning in 4 weeks or less (Biette *et al.* 1981). In general, rainbow trout spawn once, but have been found to spawn up to 5 successive years (Scott and Crossman 1973). The average life span is variable by region, but tends to be 6-8 years in the Great Lakes (Scott and Crossman 1973). Fish surviving to these ages can grow to be upwards of 75 cm in length, and weigh 1.3-2.5 kg, although a couple 7 kg fish are reported by anglers each year (MacCrimmon and Gots 1972).

Naturalized rainbow trout prefer water temperatures <20.0 °C, dissolved oxygen levels >6 mg/L, and areas with high densities of aquatic and terrestrial insects, molluscs, crustaceans, fish eggs, minnows and other small fishes (Wegner *et al.* 1985; Haynes *et al.* 1986; James and Kelso 1995; Warner and Quinn 1995; Barrow and Peters 2001). Specifically, juvenile rainbow trout (<300 mm) have been found to feed largely on invertebrates (taxa Chironomidae, Tricoptera, and unidentified aquatic insects), with some incidence of piscivory on alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), and other small fishes (Nilsson and Northcote 1981; Jude *et al.* 1987). There are ontogenetic shifts in diet as trout grow, feeding shifts from plankton to insects and crustaceans and finally to fish (Scott and Crossman 1973). Larger fish are more piscivorous, with diet consisting mainly (60% +) of available fishes such as alewife, rainbow smelt, and spottail shiner (*Notropis husdonius*), as well as fish eggs, particularly salmon (Jude *et al.* 1987; Scott and Crossman 1973).

1.4.2 Incidence of escape in Lake Huron

Ontario's aquaculture industry is focused in the North Channel and Georgian Bay regions of Lake Huron (Figures 1.2, 1.4). The annual production of the open-pen farms in this region has been hovering around 4000 t over the past decade (Figure 1.1). If fish are being grown to ~1 kg before harvest, then there are ~ 4 million fish produced annually in the open-pen operations of the North Channel and Georgian Bay. Escapement of farmed fish in freshwater aquaculture is estimated to be 2-5% of total commercial fish farm production (Phillips *et al.* 1985). With 4000 t of fish produced each year, an estimated 80,000 to 200,000 1 kg fish could be entering the waters of Lake Huron annually. Annual stocking in recent years has been hovering around 500,000 juvenile fish per year, so even the minimum loss estimate of 2% would increase the stocked population by 16%. This could put significant pressure on resource availability in this oligotrophic system.

1.4.3 Concerns of escapes in Lake Huron

While literature on the incidence and implications of marine escapees if extensive, the differences between marine and freshwater systems bring to question the applicability of this information. Aside from one study at a small experimental fish farm (Blanchfield *et al.* 2009), there have been no studies examining the distribution, habitat use, and survival of escaped rainbow trout at commercial aquaculture sites in Canadian freshwaters. Thus, we lack even the most basic of data on escaped fish in the wild, including movement patterns, dispersal, foraging habits, habitat selection, and survival. A recent incident in Saskatchewan, where ~400,000 steelhead trout escaped into Lake Diefenbaker when shifting ice during spring melt tore holes in nets, highlights the need for a better understanding of escapee impacts in freshwaters.

There have been an increasing number of studies employing telemetry to monitor the movements, and survival of fishes released from aquaculture operations. Biotelemetry involves the measurement of physiological, behavioural or energetic data, while tracking telemetry is the more basic form that involves determining where an animal is spatially (Cooke *et al.* 2004). Recent advances have resulted in dramatic improvements in the range of technology available for quantifying the spatial behaviour of fishes in their natural environment (Lucas and Baras 2000). Animals can be monitored passively, removing biases associated with conventional practice including handling and sampling of organisms (Bridger *et al.* 2008). Telemetry, in comparison to conventional tagging methods, allows for the monitoring of fish behaviour continuously over large temporal and spatial scales with a single handling event for transmitter insertion. A combination of stationary receivers and roaming manual tracking receivers make it possible to determine fine-scale movement and activity patterns of radio- or acoustically-tagged individual (Cooke *et al.* 2004). These systems are commonly being employed in aquaculture research to assess fish behaviour once escaped from a farm, and their subsequent movement patterns. A basic review of tagging studies relevant to this project, in both marine and freshwater systems, are summarized in Table 1.1. To examine site fidelity, dispersal, and survival of escaped farmed fish, researchers have employed both conventional tagging methods (Lea tags, t-bar external), as well as telemetry, and a combination of the two.

I highlight a study from the east coast of Canada because of it’s relevance to my research. The study, carried out in Bay d’Espoir, Newfoundland, involved the tagging and release of large steelhead trout (1.5-2 kg) directly from commercial aquaculture pens and from 1 km away in both summer and winter to determine site fidelity (Bridger *et al.* 2001). Fish released in the summer showed high site fidelity, with 75% of individuals remaining within 500 m of the farm for 1 month after release. A majority of fish released 1 km from the site (65%) were present there in the same time period. The winter released fish showed lower site fidelity, with only 16% of fish remaining at the release site 2 days after release and of those released off site, 6.7% returned to the cages. The researchers noted a directed movement of fish once dispersed in the direction of a nearby hatchery (within 40 km). They also noted fish utilized other aquaculture operations as habitat once they dispersed from their release site. The authors suggest that the high degree of site fidelity shown over a 1 month period here (summer) with directed movement of fish once they dispersed resulted in concentrations of escaped fish in small areas that would also allow for viable recapture strategies, lowering the impact of escapees on the local environment.

Presently, there is a small body of work on freshwater systems from which to draw upon for understanding ecosystem-level impacts of escapees. These involve experimental studies carried out in confined systems, 1.5-23 ha Canadian lakes (see Biro *et al.* 2004; Blanchfield *et al.* 2009) and one recent Norwegian study highlighting the seasonal distribution of farmed rainbow trout released from a well established farm (Lindberg *et al.* 2009). The only detailed study of rainbow trout escapes in freshwater involved the release of acoustically-tagged farmed fish from a small-scale commercial operation (1 cage; 10 t operation) into an isolated 23 ha lake at the Experimental Lakes Area (ELA) in north western Ontario (Blanchfield *et al.* 2009). The researchers found low survival of escaped fish with a majority of surviving fish remaining at the cages. Similarly, Lindberg *et al.* (2009) found low survival in their study with 21% of fish removed by angling, and 31% of the fish never being detected. The surviving fish dispersed widely (Lindberg *et al*. 2009), and exhibited high growth rates in the wild (Blanchfield *et al.* 2009). High growth rate of escaped farmed fish has been documented in lakes containing aquaculture operations. For example, abnormally large rainbow trout (>18 kg) have been caught in both Lake Huron and Lake Diefenbaker, Saskatchewan. Similarly, in replicated whole-lake studies in small lakes located in south-central British Columbia, domestic rainbow trout achieved 100% greater growth than wild strains by utilizing richer yet riskier feeding grounds (Biro *et al.* 2006). The utilization of riskier habitat to achieve high growth was linked to greater predation of domestic fish, such that domestic trout survival was half that of wild trout (Biro *et al*. 2006). There is strong evidence that age 1+ domestic rainbow trout have greater growth, but much reduced survival compared to their wild counterparts (Biro *et al.* 2004), but their specific action and interactions with local biota in the event of an escape is poorly understood.

The escape of farmed rainbow trout from commercial aquaculture operations and their potential interactions with the fish community and food web of the Lake Huron/Georgian

Bay region is a controversial yet poorly-studied issue that requires further research. As rainbow trout are an introduced species to Lake Huron, interbreeding between escaped farmed fish and now "naturalized" stocks is not a management concern (C. Wilson, Ontario Ministry of Natural Resources, personal communication, (2009)). Upon accidental escapement within Lake Huron, competition for food resources with local naturalized rainbow trout are of primary concern, but escapees could potentially affect other fish species, such as brown trout (*Salmo trutta*) and lake trout (*Salvelinus namaycush*). There is a heightened concern around resources available to fish in this oligotrophic system, particularly if there was an influx of fish with increased growth rates such as escaped farmed rainbow trout to the local food web. The present body of scientific research is limited and primarily marine based, which may not be entirely applicable to freshwater systems, yet these data are crucial to understanding the potential risks that escapees may pose on the environment they are released into. A goal of this study is to provide strong scientific evidence on the fate of escapee rainbow trout from commercial aquaculture operations as a first step towards estimating their potential impacts. This information will be beneficial to the industry economically in their possible recapture of escaped fish. Most importantly, this research is intended to assess the potential risks that escaped rainbow trout may pose in an effort to contribute to the ongoing sustainable management of this industry.

1.5 Objectives

The main goal of this study is to determine the fate of rainbow trout released from commercial open-pen aquaculture operations in Lake Huron. I simulated small and large scale releases of telemetry and Floy tagged rainbow trout from two commercial aquaculture operations in Lake Huron over two field seasons to address the following objectives:

1. determine what proportion of escaped fish remain at commercial farm sites and for how long (site fidelity)
2. determine dispersal patterns and habitat selection of escaped fish
3. quantify the survival and growth of escaped fish in the wild
4. provide a better understanding of the potential impacts of escaped farmed fish to the Lake Huron ecosystem, especially the native fish community

1.6 Thesis organization

This thesis will consist of five chapters. Throughout this thesis I use ‘domestic’ and ‘farmed’ interchangeably when referring to fish bred for the use in aquaculture. The remainder of this chapter provides information on the study area and the general methods used throughout the study. The following three chapters are independently written as self-contained articles in the format of the Canadian Journal of Fisheries and Aquatic Sciences. Chapter 2 examines objective 1 and explores site fidelity of farmed rainbow trout to commercial aquaculture cages in Lake Huron in using detailed presence/absence data collected on 90 telemetry tagged fish. Data on the returns of angled fish (telemetry and Floy) from the near farms (<500 m) is also incorporated in an overall estimate of site fidelity. Chapter 3 addresses objective 2 and examines dispersal of escaped fish on both an individual and population level. The movement patterns of escapees are explored through the manual location and angler returns of tagged fish. The third data chapter,

Chapter 4, highlights the third objective by investigating survival and growth of escaped fish over time through manual locations of telemetry fish and information gained from angler returns of tagged fish, both telemetry and Floy. The final chapter is a synopsis of the main findings of the previous chapters and the implications of escapee rainbow trout to the Lake Huron ecosystem.

1.7 General Methods

1.7.1 Study Area

Manitoulin Island separates Lake Huron, Ontario, into three distinct basins: the North Channel to the north, Georgian Bay to the east, and the main basin to the south (Figure 1.4). The North Channel has a maximum length of 150 km, is 35 km at its widest, with a surface area of 3950 km^2 and a mean depth of 22 m (Sly and Munawar 1988). The maximum length and width of Georgian Bay is 215 km, and 95 km respectively, and has a surface area of 15,111 km^2 and a mean depth of 44 m (Sly and Munawar 1988).

All but one of the open-pen commercial freshwater aquaculture operations in Lake Huron is located around Manitoulin Island. I conducted my research at two of these active commercial farms. These farms consist of a number of square cages or pens that are all connected to a central walkway, which is attached to shore (see Figure A1.1). There is a separate smaller walkway that encircles each pen and allows full access for the farmers. The North Wind Fisheries farm is a small operation (8 pens total, each 15 m x 15 m x 15 m) with an annual production ranging from 160-180 t. The farm is located in the Wabuno Channel of the North Channel, which is 1-1.5 km wide and has a maximum depth of 50 m (Figure 1.2). This farm is typical of most of the other commercial operations in Lake Huron. I consider this farm to be in an ‘open’ system as it is located in a large open body of water with minimal geographical restrictions between itself, Georgian Bay, and the main basin of Lake Huron. The second site, Meeker’s Aquaculture, is located in Lake Wolsey (area 23.2 km^2, max. depth 26 m) which connects to the North Channel of Lake Huron through a narrow, 5-7 m deep channel (Figure 1.2). The farm has been in operation since 1986 and is one of the largest in Lake Huron with a total of 19 pens, each 15 m x 15 m x 15 m, although not all are continually in use. Production ranges from 350-400 t annually. This farm is an anomaly compared to the other freshwater open pen operations because it is contained within a smaller lake. Although the lake itself connects to the North Channel, I refer to this system as ‘closed’ compared to the North Channel and the rest of Lake Huron. Both operations raise all female and regular stock (male and female) domestic rainbow trout from fingerlings (provided by Jim Taylor, Cedarcrest Trout, or Spring Hills), to market size, which varies depending on demand. Throughout this thesis I refer to North Wind Fisheries as Farm 1 and Meeker’s Aquaculture as Farm 2.

1.7.2 Fish tagging

In July 2008 and May 2009, I surgically implanted transmitters into 20 and 40 farmed rainbow trout at each of the study farms, respectively. Fish were seined into the corner of a net pen by farm staff, dip netted into a transfer container, and transported to the surgery area (maximum distance 120 m) as needed. The fish were randomly selected, with the requirement that transmitter weight be <2% of body weight. Transmitter specifications are listed in Table 1.2. Fish size and numbers for all tagging events are listed in Table 1.3.

Fish were individually placed in an anaesthetic bath of 60 mg/L of tricaine methanesulfonate (TMS)(Argent Laboratories, Redmond, WA) buffered with sodium bicarbonate in ambient temperature lake water. Once anaesthetised, fish wet weight (g) and fork length (mm) were recorded, and the transmitters were implanted as detailed in Wagner and Stevens (2000), with the use of monofilament suture material (MONOCRYL, Ethicon Inc., Piscataway, NJ) to make three sutures. Fish gills were continually rinsed with a 30 mg/L TMS anaesthetic bath. Fish handling time (measuring, weighing, and time in surgery until placed in recovery bath) averaged 9 min 40 sec in 2008, and 6 min 11 sec in 2009. Once upright and active, fish were placed into a second larger recovery pen and held overnight. Fish were individually released to the wild by dip net on 2, 4 and 12 July 2008 and 12, 13, 15 and 16 May 2009.

On May 25-28, 2009 an additional 1000 rainbow trout, 500 at each farm, were tagged with an external T-bar anchor tag (Floy Tag Manufacturing, Seattle, WA) to simulate a large scale escape. Each tag was individually marked with contact information to enable individual identification and provide return information upon recapture.

Prior to release of all fish, interviews with local media describing the study were printed in local newspapers and signs detailing the tagged fish appearance and instruction upon recapture were placed in popular local angling spots (boat launches, resorts, bait shops).

1.7.3 Telemetry monitoring system

Prior to the release of the rainbow trout in 2008 and 2009, Lotek receiving stations (Lotek Engineering Inc., Newmarket, ON) were installed to detect fish presence at each farm site. Each farm telemetry station was equipped with the following: a 6-element Yagi radio antenna placed perpendicular to the shoreline; an omnidirectional hydrophone (LHP_1); a sonic upconverter to convert the ultrasonic transmitter signals to a frequency that can be received and logged by the receiver; multiple antenna switching (ASP_8) enabling the receiver to gather information by alternating scan times of the radio antenna and hydrophone; and an SRX_400 receiver. An additional three receiving stations (called "gate" stations) were strategically placed in narrow areas to monitor the movement of fish through two of the major passages between the North Channel of Lake Huron into Georgian Bay, and one from Lake Wolsey into the North Channel (Figure 1.2). The gate stations only monitored radio signals and consisted of a 5-element Yagi antenna and an SRX_400. Each of the five receiver stations was powered by a sealed 12 v marine battery; farm stations additionally included a solar panel for continual charging. All stations were housed in lockable 36 L Rubbermaid Action Packers and chained to the surroundings.

In 2009, four Sonotronics submersible ultrasonic receivers (SURs) (Sonotronics Inc., Tucson, AZ) were strategically placed throughout Lake Wolsey to monitor fish presence within the lake, and fish moving out of the lake. In addition to maintaining the original Lotek receivers at the farm and "gate" station, I incorporated this second telemetry system at Farm 2. In essence, the four SUR's replaced manual tracking of transmitter fish in Lake Wolsey in the second field season by providing broad spatial distribution of all tagged fish (see Figure 3.1 for locations and coverage of each receiver). This allowed for greater manual tracking effort at Farm 1 during the second field season, as it is a more representative aquaculture operation of the industry.

Table 1.1 Summary of studies focused on site fidelity, dispersal, movement patterns, and survival of fish escaped from a fish farm.

Species	System	Study area	N	Release season	Size (cm), and/or Wt.	Study duration	Tagging method	Study
Steelhead trout	marine	farms (2), bay	240	July/August, December	1.5-2 kg	77 d	telemetry	Bridger *et al.* 2001
Rainbow trout	freshwater	experimental farm, lake, 23 ha	14	September	.87-1.1 kg	3+ yr	telemetry	Blanchfield *et al.* 2009
Rainbow trout	freshwater	farm, lake, 4700 ha	48	November	48-58, ~2 kg	9 mo	telemetry	Lindberg *et al.* 2009
Atlantic salmon	marine	farm, Atlantic ocean (NA)	273	January, April/May	39-58	1+ yr	telemetry	Whoriskey et. al 2006
Atlantic salmon	marine	farm, fjord	132	July, Aug./Sept., Dec./Jan., March/April, June	54-72.4, 2.8-4.3 kg	4 wk	telemetry	Skilbrei *et al.* 2009
Atlantic salmon	marine	farms(2), fjord	4495	Nov., Dec., Feb., March, April	68.3-76.4	unclear	external (Lea tags)	Hansen 2006
Atlantic cod	marine	farm, fjord	45	August, February	47-65.5, 1.9-3.1 kg	13 wk	telemetry and T-bar external	Uglem et al. 2008

Table 1.2 Transmitter model, specifications, and numbers implanted into farmed rainbow trout and released into Lake Huron at Farm 1 and 2 in the 2008 and 2009 study period.

	Farm 1 & 2 2008		Farm1 - 2009		Farm 2 - 2009	
	Lotek radio	Lotek CART	Lotek radio with pressure and temperature sensor	Lotek CART	Sonotronics acoustic with pressure sensor	Sonotronics acoustic
Model	MCFT-3A	CART 16-1	SR-TP-16-25	CS-16-25	DT-97-L	CT-82-2-1
Length (mm)	46	60	55	57	80	53
Diameter (mm)	16	16	11	16	15.6	15.6
Weight in water (g)	6.7	13.5	8	14	11	9
Number implanted	20(10 at each farm)	20(10 at each farm)	10	30	10	30
Battery life (days)	641	663	1095	791	365	420

Table 1.3 The number, mean (± 1 S.E.) weight (g) and fork length (mm) of rainbow trout released into Lake Huron from two commercial farms. Fish were implanted with a telemetry transmitter or Floy tag in both study years 2008, and 2009. The number of tagged fish reported angled is noted.

	Telemetry				Floy	
	2008		2009		2009	
	Farm 1	Farm 2	Farm 1	Farm 2	Farm 1	Farm 2
# fish tagged	20	20	40	40	500	500
Mean Wt (g)	884 ± 30	1384 ± 69	775 ± 14	965 ± 25	732 ± 7	710 ± 8
Mean FL (mm)	387 ± 4	434 ± 7	354 ± 2	389 ± 3	344 ± 1	351 ± 1
# fish angled	1	1	4	9	33	46

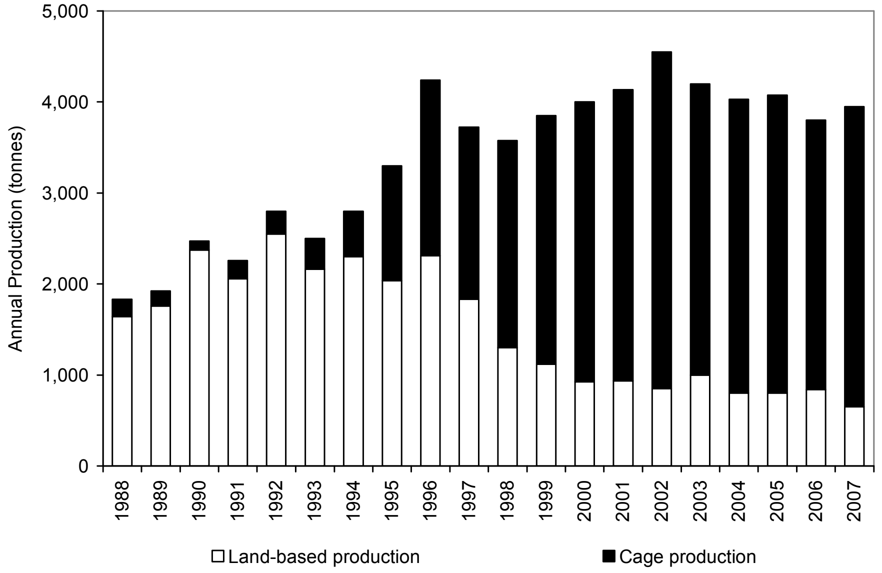

Figure 1.1 Comparison of Ontario land-based aquaculture and open-pen aquaculture production between 1988 and 2007. (Moccia and Bevan 2009).

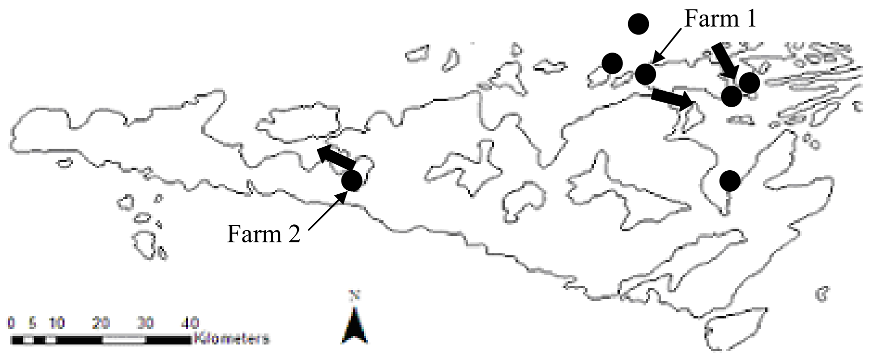

Figure 1.2 Approximate locations of commercial aquaculture facilities (farms) in and around Manitoulin Island are shown (solid circles). The operations used in this study are labelled; Farm 1 (North Wind Fisheries) and Farm 2 (Meekers Aquaculture). There in one other operation in Georgian Bay not shown. Radio telemetry gated stations used to monitor fish movement are indicated by solid arrows. Refer to Figure 1.4 for location of Manitoulin Island within Canada.

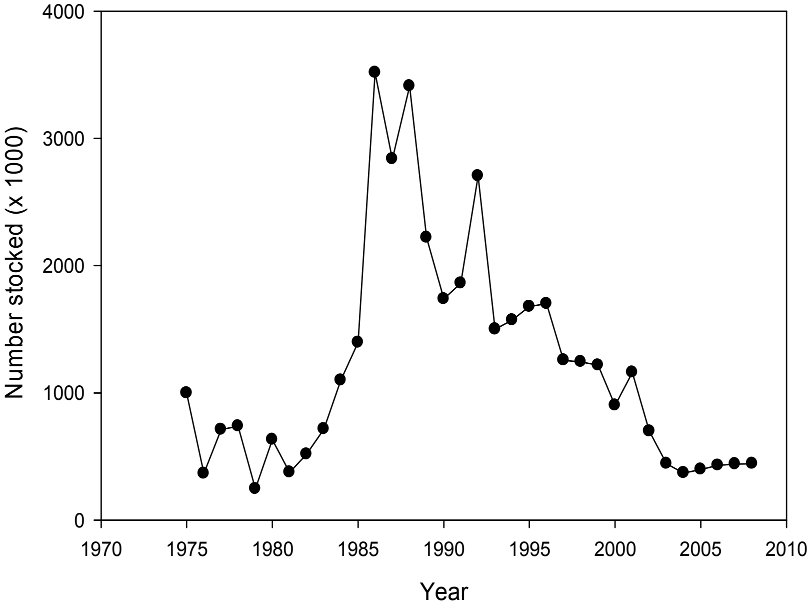

Figure 1.3 Records of rainbow trout stocked into Lake Huron by the Michigan Department of Natural Resources, USA, and Ontario Ministry of Natural Resources, Canada from 1975 to 2008. (adapted from FWS/GLFC (2010)).

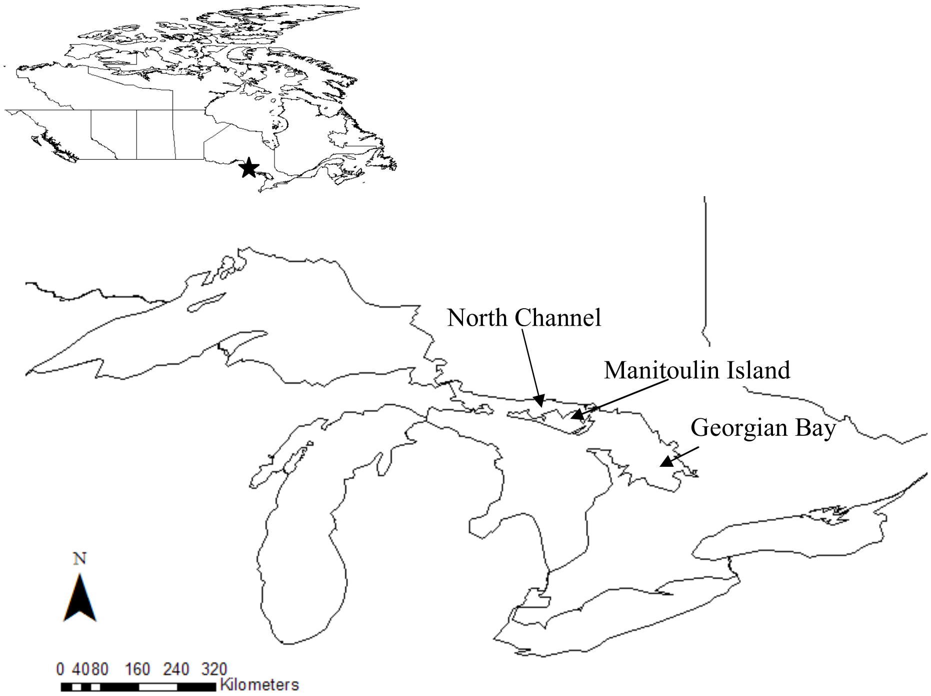

Figure 1.4 Map of Canada showing the location of Manitoulin Island in Lake Huron within the Great Lakes (inset). The North Channel and Georgian Bay regions are shown where a majority of Ontario's aquaculture production occurs.

CHAPTER 2: Fidelity of farmed rainbow trout to commercial aquaculture cages in Lake Huron

2.1 Introduction

The escape of farmed fish into the wild from open-pen commercial aquaculture operations remains one of the major ecological concerns of fish farming (Naylor *et al.* 2005; Weir and Fleming 2006). Of the genetic and ecological concerns related to the escape of farmed fish to the wild (reviewed in Ch. 1.3), the potential impact to native fish communities and their supporting food web is the least studied. The extent to which escaped fish can result in ecological perturbation is dependent upon a host of factors that include their survival rate, life history, and dispersal, among others. The preponderance for escaped fish to remain at the site of release, termed site fidelity, is believed to minimize the impact of these fish by reducing competition with local fish for food and habitat (Phillips *et al.* 1985). Further, site fidelity by escaped fish may decrease the overall environmental impact of commercial operations as these fish are known to consume waste feed and faeces at cage sites (Phillips *et al.* 1985; Carss 1990). Finally, if escaped fish display high fidelity to sites of escape, there is potential for their subsequent recapture, thereby further lessening any potential impact.

Our present understanding of the degree to which escaped farmed fish remain at sites of commercial aquaculture operations is limited. The fate of farmed fish in marine systems is variable and can differ by species, age, and season. For example, large Atlantic salmon (40-74 cm) released from a farm into a high current area had low site fidelity, leaving the farm rapidly and following dominant currents (Hansen 2006; Whoriskey *et al.* 2006), while smolts (13-35 cm) exhibited variable responses, either remaining at the site or dispersing large distances (>500 km) over a three month period (Hansen and Jonnson 1991). Fate of tagged Steelhead trout (*Oncorhynchus mykiss*) released from farms in Atlantic Canada was dependent on season and local factors; escaped trout showed higher fidelity to the release site in summer than in winter, with a tendency to disperse in the direction of a resident hatchery (Bridger *et al.* 2001). In contrast, Atlantic cod (*Gadus morhua*) released in a Norwegian fjord displayed low site fidelity upon release (>80% dispersed within first 3 days), rapidly becoming distributed over large areas, regardless of release season (Uglem *et al.* 2008). These examples show highly variable attraction of escaped farmed fish to sites of release and the subsequent limitations in our ability to predict the response of fish escaped from commercial aquaculture operations. Further, these studies have all occurred in marine environments, highlighting the lack of research in freshwater ecosystems.

The potential for escaped fish to alter native fisheries and food webs is of greater concern in freshwaters, where commercial aquaculture operations occur in oligotrophic systems with much fewer species than in marine ecosystems. In Canada, the rearing of rainbow trout dominates the freshwater open-pen commercial aquaculture industry. Escape of farmed fish in freshwater aquaculture is estimated to be 2-5% of total commercial fish farm production (Phillips *et al.* 1985). A concern regarding the escape of farmed rainbow trout is that they have undergone selective breeding for a number of desirable traits for cage rearing, specifically increased growth rate (Tymchuk & Devlin

2005). Upon release, domesticated hatchery fish forage in risky habitats to maintain high growth rates (Tymchuk *et al.* 2007), attaining up to two to three times the mass of wild strains (Biro *et al.* 2004, 2006). This behaviour allows them to achieve growth uncommon in wild fish, but also increases their susceptibility to predators which lowers their overall survival (Biro *et al.* 2004, 2006; Reinbold *et al.* 2009). There is evidence of escaped rainbow trout reaching large sizes (>18 kg) in Lake Huron, Ontario and Lake Diefenbaker, Saskatchewan, both sites of commercial aquaculture operations producing rainbow/steelhead trout. The extraordinary size of these rainbow trout highlights the potential of escaped farmed fish to exploit local resources to maintain high growth rates in the wild and to attain sizes unmatched in naturalized rainbow trout in Lake Huron (avg. size = 1.3-2.5 kg) (MacCrimmon and Gots 1972). The experimental work carried out in a small northwestern Ontario lake showed the escapee rainbow trout were able to maintain the same high growth rates as they would in the cages, allowing for continued accelerated growth (Blanchfield *et al.* 2009).

Data on site fidelity by escaped rainbow trout in freshwater systems are scarce. Rainbow trout released from an experimental farm (10 t operation) in a small boreal lake (23 ha) spent a majority of time at the cage site after initial rapid dispersal (Blanchfield *et al.* 2009). In contrast, in a Norwegian study with a well established farm, high dispersal was found with seasonal shifts in habitat selection with a concentration of fish in the middle of the lake in winter, and a wider distribution of fish in spring and summer (Lindberg *et al.* 2009). Seasonal shifts have been shown to correspond to fish farm operation in other studies where fish were more often found near the cages if feeding was continually occurring (Bridger *et al.* 2001; Blanchfield *et al.* 2009). The high site fidelity in these studies may be attributed to the smaller water bodies as long range movement (100-2000 km) of escaped salmonids has been confirmed in ocean studies (Jonsson *et al.* 1993; Hansen 2006; Whoriskey *et al.* 2006), but no studies have been undertaken in large bodies of freshwater to answer these questions.

The objective of this study is to quantify the extent to which farmed rainbow trout released from commercial aquaculture operations in Lake Huron, remain at those sites. Because site fidelity has important implications for assessing the potential ecological impacts of escapees, as well as their potential for recapture, I first examine this behaviour and in the subsequent chapter (Chapter 3), I deal with patterns of dispersal. Based on previous research available on freshwater rainbow trout escapees, I hypothesized that a majority of fish will exhibit site fidelity to their release site. From past research I anticipated higher site fidelity to the farm in the semi-contained system, and lower site fidelity when fish are released into the cooler spring waters. Here I 1) quantify site fidelity of escapees released from two commercial farms in Lake Huron over two seasons (3 mo), 2) examine the influence of farm location and season of release on degree of site fidelity, and 3) explore variation in individual patterns of site fidelity.

2.2 Methods

Study site, fish tagging procedures (including transmitter size and details and mean fish sizes per tagging event (Tables 1.2 and 1.3)), and the telemetry monitoring system are detailed in section 1.7.3. Information on tagged fish (individual size, release date, # farm detections, etc.) can be found in Tables 2.1-2.4. In this chapter, I use telemetry information from the farm receivers, as well as angler recaptures of tagged fish to examine fish attraction to release sites. In 2009, 20 pressure-sensing transmitters, 10 at each site, were employed to record fish distribution in the water column to evaluate whether escaped fish were feeding on waste feed/faeces at the cage sites.

To determine site fidelity of escaped farmed rainbow trout, fish presence at both commercial aquaculture operations was monitored by stationary receivers from 2 July to 18 October 2008 (108 days), and 12 May to 19 September 2009 (130 days). Continual monitoring was inconsistent between farms after ~100 days, so here I report data on the first 14 weeks in detail. Radio only transmitters were not consistently picked up by the farm receivers (Appendix I), so I focus my analysis on data obtained from rainbow trout implanted with combined acoustic and radio transmitters or acoustic only transmitters (n = 90). Of the 90 fish implanted with transmitters, three were never detected by any means and thus excluded from all analysis. Transmitters inserted in 2008 remained active throughout the 2009 season allowing for the assessment of long term fidelity (>1 y).

2.2.1 Site fidelity

I considered an individual rainbow trout to exhibit site fidelity if it was detected at a stationary receiver located at the farm site from which it was released. I first established that stationary receivers were able to detect transmitters within 140-500 m of the farm; this distance was dependent upon transmitter location relative to the receiver (Appendix I). The 140-500 m detection range covered the entire farm area at both commercial aquaculture sites (Appendix 1). I considered an individual fish to be detected at a farm site only if 2 detections within 3 min or 15 min (depending upon Sonotronics or Lotek equipment) were recorded on a farm receiver. If a fish was detected at the farm anytime during the 24 h of a day, it was categorized as being "present" on that day, regardless of whether it spent 1 h or 24 h at the farm site. Fish tagged with external Floy tags were considered to be demonstrating site fidelity if they were reported angled within 500 m of the release farm.

I examined site fidelity in several ways. First, I treated all released fish with telemetry tags (n=87) as a single group (irrespective of year and site of release) to estimate of site fidelity over time of all fishes. Next, I examined how year and site of release influenced patterns of site fidelity. In 2008, fish were released in summer (July) compared to a spring (May) release in 2009. Likewise, I compared differences in site fidelity between fish released at the open commercial operation (Farm 1) versus the aquaculture operation located in an enclosed lake system (Farm 2) (see Fig. 1.2). I examined seasonal and location influences on site fidelity at three distinct periods, representing initial (7 d), mid (30 d) and final (90 d) estimates of site fidelity. To compare between proportions of fish present at the farms at these times, I took the average site fidelity of the six days surrounding the periods chosen (e.g. for site fidelity 30 d post release I took the mean of days 27 to 33).

Detailed daily estimates of fish presence or absence at sites of release allowed for an in-depth assessment of individual patterns of site fidelity. I examined site fidelity through time-specific queries of all individual detections of farm receiving stations (Microsoft Access). I classified fish into groups based on the number of days they were present at the farm site of their release: “resident” fish were present >50% of all days monitored; “frequent” fish were present 25-50% of days; “infrequent” fish were present 12.5-25% of days; and “rare” fish were present <12.5% of days at the farm site. These groups were used for examining variation among release sites and seasons. I specifically queried times of fish absence from the farm to explore the time fish spent away from the farm before returning.

Initial fork length (mm) and weight (g) were used to determine if size of fish at release influenced site fidelity among fish.

2.2.2 Statistical Analysis

I compared the site fidelity of rainbow trout between release sites and release seasons. I arcsine-square root transformed all proportional data before analysis in an attempt to normalize the data set. All data sets were tested with the Shapiro-Wilk’s test for normality, and the Brown-Forsythe test for homogeneity of variances. Depending on the outcome, the data were analyzed in Statistica v. 6.1, (Statsoft, Inc., Tulsa, USA) using parametric (t-test, ANOVA) or non-parametric (Mann-Whitney U) tests (specified in results). Bonferroni correction was applied when multiple comparisons were made within the same data. To examine a periodicity pattern detected in the site fidelity of all fish, I examined each year of data separately to determine if the pattern was being driven by the lunar cycle. I performed non linear regression (exponential decay) to these transformed data sets, and plotted the residuals of these regressions against both days after release, and day in the lunar cycle (1-29), to determine if that was the driving force.

2.3 Results

2.3.1 General trends in site fidelity

Overall, farmed rainbow trout implanted with acoustic transmitters and released from commercial aquaculture operations (n=87), showed an immediate and rapid decline in presence at the site of release, followed by a more gradual decline over the first month until the establishment of a "resident population" at the farms during the last two months of monitoring (Figure 2.1). Within the first week after release a majority of rainbow trout (~50%) had dispersed from the farms. The number of tagged fish remaining at the commercial aquaculture sites steadily declined over the next 3 weeks, with only 26% remaining 30 d post release (Figure 2.1). Over the next 60 d there appeared to be the establishment of a resident population that consisted of, on average, 17% of released fish; however, the proportion of escapees present at cages during this time was variable and ranged from 9-28% (Figure 2.1). The variability in daily numbers of fish observed at the farm sites is indicative of departed fish occasionally returning to sites of release.

Proportions of tagged rainbow trout present at each farm after release were variable between sites and years, but for each release event I observed a similar pattern of initial dispersal, steady decline, followed by a stable but lower number of fish remaining at the site. When considering the farms as separate release sites in two separate years, site fidelity was typically higher at Farm 2 (closed site) than Farm 1 (open site), particularly in 2009, and higher at both farms in 2008 (summer release) compared to 2009 (spring release) (Figure 2.2). In 2008, site fidelity was generally higher at Farm 2, although the difference between the two farms was not large (Figure 2.2a). The trend was similar in 2009 with a more rapid initial reduction of site fidelity, particularly at Farm 1, where 60% of fish departed in the first 24 h, compared to the 35% that left Farm 2 (Figure 2.2b). Fish continued to depart and at the end of the first week only 18% of escaped fish remained at Farm 1 and 55% at Farm 2 (Figure 2.2b). Fish released in 2009 followed a similar pattern of declining site fidelity over time, with 0-25% of fish remaining 3 mo post release (Figure 2.2b).

2.3.2 Factors affecting site fidelity

Fish released from Farm 2, the semi-enclosed aquaculture operation located in a 2300 ha lake attached to the North Channel, showed higher site fidelity compared to fish released from Farm 1 in both 2008 and 2009 (Figure 2.2). Farm 2 fish exhibited a higher degree of site fidelity when compared to Farm 1 at 1 wk, 1 mo, and 3 mo after release in both 2008 (Mann-Whitney U test, $Z = -2.87- -3.13$, $Ps < 0.005$) and 2009 ($Z = -3.13$, $Ps < 0.005$) (Figure 2.3). Over time (3 mo), fish released from Farm 2 showed an increased presence at the fish farm compared to fish released from Farm 1 in both 2008 and 2009. This increased site fidelity is particularly obvious between farm sites in 2009 (Figures 2.4-2.7).

Differences in site fidelity of released rainbow trout did not only occur between farms, but was also apparent between study years within an individual farm site (Figures 2.2, 2.3). Fish released in July 2008 (summer) demonstrated greater reliance on the farm than those released in May 2009 (spring) at Farm 1 and Farm 2. Fish exhibited a higher degree of site fidelity in 2008 than 2009 at 1 wk, 1 mo, and 3 mo after release at both Farm 1 (Mann-Whitney U tests, $Z = 2.87\text{-}3.13$, Ps <0.01) and Farm 2 ($Z = -3.13$, Ps <0.01) (Figure 2.3). Fish released in 2008 showed a higher degree of site fidelity over time (98 days) to both farms compared to fish released in 2009. Site fidelity was consistently higher at Farm 2 but long term use of the cage site was only apparent at Farm 1, with 20% of fish released in 2008 showing reliance on the cage 14 mo after release (Figure 2.6).

Another factor potentially affecting site fidelity of escaped fish is body size. Fish released from both farms were significantly larger in 2008 than 2009 (Mann-Whitney U test, Farm 1: $Z = -3.31$, $p < 0.001$; Welch's t-test, Farm 2, $t = -5.74$, $p < 0.001$) and fish from Farm 1 were significantly smaller than fish released from Farm 2 in both years (Welch's t-test, 2008: $t = -6.63$, $p < 0.001$; Mann-Whitney U test, 2009: $Z = -5.20$, $p < 0.001$)(see Table 1.3 for mean sizes, and Tables 2.1-2.4 for individual sizes). Due to the different release dates between years, July versus May, the fish would have been 2-3 mo older in 2008.

2.3.3 Individual variation in patterns of site fidelity

Declines in rainbow trout site fidelity over time were not wholly attributed to permanent departures of individuals. Instead, it was common for individual fish to depart from and return to farm sites on a number of occasions, particularly at Farm 2. This individual variation is highlighted in Figures 2.4-2.7 where, for example, you can note reappearance of individuals after >1 mo absence at Farm 1 in 2008, and both farms in 2009. Examples include fish #38 (Figure 2.4), #72 (Figure 2.6) and #34 (Figure 2.7). I classified individual trout into four groups characterizing their site fidelity. Fish that were classified as rare were only present at the farm for up to approximately 2 weeks (12 d in 2008, 15-16 d in 2009). In 2008, 80% of fish were frequent or resident fish at Farm 2 while only 50% of Farm 1 fish were occupying the farm area (Figure 2.8). In 2009, rainbow trout released from Farm 2 showed a pattern opposite to that observed in 2008, with most fish rarely detected at the cage site, and less than one third of fish (32%) were categorized as resident and frequent visitors (Figure 2.8). Site fidelity of released fish from Farm 1 was skewed, with a majority of fish (89%) rarely present at the site of release, and just 4% of fish showing resident or frequent visitation to the farm (Figure 2.8). Initial body weight at time of release did not differ significantly among the four fish presence categories (ANOVA, P's > 0.1).

Among all fish (n=87), presence at the farm sites was not continual, even among resident fish (Figures 2.4-2.7). Every individual left the farm for at least 1 d before returning, and one resident fish was absent from the cage site for 42 d before returning (Figure 2.9). On average, resident rainbow trout spent the shortest time away from the farms before returning (3.4 ± 0.5 d) compared to all other groups. The amount of time between return visits to release sites increased with declining farm presence. Frequent and infrequent visitors spent, on average, 4.7 d (± 0.8 d) and 6.7 d (± 1.8 d) away, respectively, from farm sites prior to returning. Maximum time between visits for frequent and infrequent visitors was 71 d and 102 d, respectively. Fish that were rarely present at the farm sites spent the greatest time away from farms on average, (11.5 ± 2.3 d), but did not have the greatest maximum time away from the farm between visits (93 d).

2.3.4 Recaptures of Floy-tagged fish

As of 360 d after release from the two commercial aquaculture operations, 8.6% of the 1,000 externally tagged rainbow trout have been reported captured by anglers. Roughly equal numbers of fish were captured from each of the releases (n=500) in 2009 (Farm 1, n=35; Farm 2, n=49) (two returns did not indicate Id #); however, there were notable differences between farms in the proximity of capture relative to the site of release. Almost all (95%) released rainbow trout were caught within a 5 km radius of Farm 2, the semi-enclosed aquaculture operation, of which approximately half (53%) were captured within 500 m of the fish farm. At Farm 1, the open site, approximately one third (n=11) of released trout were captured within 500 m of the farm while the majority of fish were captured >5 km away from their site of release. Some rainbow trout exhibited extended attraction to commercial aquaculture operations as they were angled at both farms 130 d after release.

2.4 Discussion

The commercial rearing of salmonid fishes in open-pen cage aquaculture operations can result in the escape of farmed fish to surrounding water bodies (Naylor *et al.* 2005; Thorstad *et al.* 2008). The ecological impacts associated with an influx of domestic fish into aquatic ecosystems remains one of the largest problems faced by open-pen aquaculture today (Weir and Fleming 2006; Thorstad *et al.* 2008). An obvious concern associated with the escape of farmed fish is that they are capable of competing with local conspecifics and other species for food, habitat, and mates. If fish exhibit high fidelity to commercial aquaculture sites, then the potential impacts to surrounding areas may be localised, and thus reduced. Also, if fish remain in close proximity to their escape site there is potential for their recapture, subsequently reducing financial loss to the farmer and lessening any impact to the local ecosystem. I examined site fidelity of farmed rainbow trout tagged and released from two commercial aquaculture operations in the North Channel of Lake Huron over a 2 year period. I found that the vast majority of trout rapidly dispersed upon release while low numbers remained in close proximity to the farms by the end of the monitoring period. A second important finding of this research was that except for a few fish that dispersed rapidly and were never seen again, most fish returned to the commercial farms on several occasions.

Contrary to my prediction that a majority of rainbow trout released from active commercial aquaculture operations would exhibit site fidelity, I found rapid dispersal away from the commercial farms. Half of the released fish left the farms in the first 2 days, followed by a steady decline in fish presence. At the end of the monitoring period (3 mo), <20% of released fish showed fidelity. It is worth noting that at no point throughout the study did 100% of fish disperse from the farms. At a minimum, 10% of released rainbow trout were present (9 fish) throughout the monitoring period. Release of adult domestic salmonids on the east coast of North America (open ocean) and in Norway (contained lake) found lower site fidelity than found in this study. In these studies, all fish had departed within 3 d and there was no continual use of the farm site (Whoriskey *et al.* 2006; Lindberg *et al.* 2009). Adult Atlantic cod tagged and released from a fish farm in a

Norwegian fjord had similar rapid declines in site fidelity as the salmonid studies; all fish had dispersed within 4-13 d post release (Uglem *et al.* 2008). Similar to the present study, however, 40% of released cod returned to the farm with some individuals remaining at the farm site until the end of the 12-13 week monitoring period (Uglem *et al.* 2008). Bridger *et al.* (2001) initially found a high degree of site fidelity of adult released Steelhead trout in a Newfoundland bay. In that study, 75% of fish were present at the farm 1 month post release, but similar to rainbow trout released into Lake Huron, fish presence decreased over time and <10% remained after only 2.5 months (Bridger *et al.* 2001).

I noticed a cyclical pattern in the site fidelity data in presence of fish at the farm sites. It appeared to be ~30 days in length and so I investigated to see if this fluctuation (seen in Figures 2.1 and 2.2) was related to the monthly lunar cycle. By examining the residual values of a non-linear regression of the site fidelity data over days after release against the days of the lunar cycle I saw no pattern to support this idea (Figure 2.10a). The periodicity was still apparent in the residuals of the regression and days after release suggesting the lunar cycle was not the cause of the monthly cyclical nature of increased rainbow trout presence at the farms (Figure 2.10b). One hypothesis is that the fluctuating pattern observed in site fidelity is being driven by the cyclical pattern found in growth rates of rainbow trout, following a 4-5 week period (Noel and Le Bail 1997). Fish may have been returning to the farm sites at the heightened growth periods of the cyclical pattern as fish farms are thought to be an ideal feeding habitat.

2.4.1 Site factors influencing levels of site fidelity

Specific factors influencing site fidelity of escapees at sites of commercial aquaculture production are not well known, although it is generally believed that farm processes, especially feeding regime, may act as an attractant to escaped and native fish (Bridger *et al.* 2001; Blanchfield *et al.* 2009; Johnston *et al.* 2010). Escapees and native fish are attracted to and remain at sites of commercial aquaculture operations for access to waste food and faeces (Fernandez-Jover *et al.* 2008). Consumption of waste feed is prevalent and researchers estimate anywhere from 40-80% of waste food and faeces are consumed by escaped farmed fish and native fish species (Vita *et al.* 2004; Felsing *et al.* 2005). The reliability on cage sites as a food source is not restricted to excess feed pellets and waste, but may also include the aggregations of fish which can be attracted to cage sites (Toledo Guedes *et al.* 2009). In the case of freshwater aquaculture in oligotrophic systems, it is possible for the addition of nutrients to the surrounding water to increase productivity (Yan 2005). In Lake Huron, large aggregations of prey and top predator fishes have been found at cage sites (Johnston *et al.* 2010); similar patterns of fish distribution occur around cage sites in marine systems (Dempster *et al.* 2002, 2009; Fernandez-Jover *et al.* 2009). Recaptures of escaped sea bass near farms found with no pellets in the gut content, but only local prey items supports this idea (Toledo Guedes *et al.* 2009), but pellets have been found in stomachs of rainbow trout around freshwater farms, saithe (*Pollachius virens*) around marine farms in Scotland, and a variety of wild Mediterranean species (Carss 1990; Fernadez-Jover *et al.* 2008).

In the case of freshwater aquaculture production in north-temperate ecosystems, like Lake Huron, the time of year of escape may be important factor. Commercial production cycles, and hence feeding, typically follow seasonal water temperature patterns. In freshwater, commercial fish production increases throughout the summer, with maximal feeding occurring as the optimal temperature for rainbow trout growth is reached, ~15 ºC (Mäkinen 1994). Feeding rates can be reduced in high temperatures but otherwise continue at a high rate and then are slowly reduced as temperatures decrease through the fall. Fish released in mid-summer (July 2008) would be present at the farms during a period of peak production and feed availability, as well as when water temperatures were optimal for growth. In contrast, fish released in the spring (May 2009) were present at the farm at a period of low feeding and when the metabolic rates of rainbow trout were comparatively low. I observed both a longer time to dispersal and higher levels of site fidelity when fish were released in warm waters (15-18 ºC) in summer (July 2008) versus when released in colder spring water (4-7 ºC) the following year (May 2009), particularly evident at Farm 1 (open site). Similarly, steelhead trout released from farms on the east coast of Canada took longer to depart in summer versus winter (Bridger *et al.* 2001). This pattern has also been observed between winter and spring released Atlantic salmon (Whoriskey *et al*. 2006). Increased site fidelity of released rainbow trout to the farm in summer may be attributed to the increased feeding levels at the farms as this time of year metabolic rates and growth are high for rainbow trout. A combination of feeding regiment and optimal water temperature for growth could explain the differences in rainbow trout fidelity to the cage site between years.

A lack of attraction to abandoned cage sites has been seen in both marine and freshwater studies. Blanchfield *et al.* (2009) specifically monitored fish presence at a cage site at three different operational times; full feeding (normal operation), pre-harvest, a brief period (1-2 weeks) when fish are still in cages but not being fed, and post-harvest when all fish are removed from cages. They found a reduction in escapee presence at the farm during the pre-harvest halt of feeding and further lack of attraction to the cage post-harvest compared to during normal operation, suggesting that fish presence at the cage site is driven largely by food availability. Similar results were seen in a Norwegian lake where escapee rainbow trout were not present at the farm site after the caged fish had been harvested (Lindberg *et al.* 2009). Likewise, site fidelity of steelhead trout was considerably lower following a winter release (10%) compared to a summer release (75%) from a commercial operation (Bridger *et al.* 2001). Feeding at commercial aquaculture operations, in general, is minimal throughout the ice covered season and the limited presence of escapees at cage sites during winter when production is low suggests the attraction is primarily driven by food availability.

Physical characteristics of the farm site may influence the behaviour of farmed fish once released. In the present study, the commercial farms were situated in distinct water bodies that could have differentially influenced site fidelity. Commercial aquaculture operations located in small-or medium-sized lakes, such as Farm 2 in this study, may favour site fidelity as escaped fish may not be able to leave the system or, alternatively, can easily return to the cages site after departure as the distance may not be great. I observed at least 10% greater presence of fish at the semi-contained operation (Farm 2) than at the open site (Farm 1). Studies on escapees in small semi- or fully contained systems have found that fish depart immediately, disperse as widely as possible and return to the cage site, often within 24 hours (Phillips *et al.* 1985; Blanchfield *et al.* 2009). In this study, fish released from Farm 2 would be able to disperse as widely as possible within Lake Wolsey and return to the cage within a 24 hour period. Also, the passage from Lake Wolsey into the North Channel (see Figure 3.1) is small compared to the lake size, and may potentially limit the ability of fish to leave the system. Fish released from Farm 1 have no similar physical constraints to Farm 2, and this may have contributed to their reduced site fidelity. The growing number of studies on site fidelity of escaped farmed fish, including the findings from this study, suggests a negative correlation between site fidelity and water body size; a greater proportion of escaped fish remain at farm sites in small contained lakes (eg. Blanchfield *et al.* 2009), compared to the low site fidelity observed in marine studies (eg. Whoriskey *et al.* 2006).

Water temperatures combined with lake bathymetry at sites of commercial aquaculture operations can exert an influence on escapee site fidelity. Specifically, warm water temperatures can create a thermal barrier to fish movement during the warmer months of the year (July, August). I observed greater site fidelity of rainbow trout at Farm 2 in 2008, when released during the warm summer than in the spring release the following year (Figure 2.3). One explanation of this could be that the channel connecting Lake Wolsey to the North Channel is very shallow (<5 m) and is a thermal barrier (>20 ºC) to departing rainbow trout in summer. In support of this, more rainbow trout were detected leaving Lake Wolsey when released in May 2009, when water temperatures were cooler (4-7 ºC), compared to releases in July 2008 when temperatures were higher (15-18 ºC). In contrast to the potential thermal barriers to Farm 2 fish, those released from Farm 1 had no such boundaries, allowing for uninhibited movement away from the release site. However, the fact that 65% of depth detections at the farm were in the top 3 m of the water column when temperatures reached upwards of 22 ºC would suggest that temperature is perhaps not the only factor influencing levels of site fidelity between farms.

It is apparent that both the geographic location of the commercial aquaculture operations and the seasonal timing of escape were important factors influencing site fidelity of released farmed rainbow trout in Lake Huron. An interesting and unexpected finding of this study was that long-term site fidelity was only observed at Farm 1, the open site. Forty percent of rainbow trout released in 2008 were detected at the farm in 2009, with half (20%) continuing to show a high degree of site fidelity throughout the 2009 monitoring season (Figure 2.6). In fact, these fish released in 2008, were present on enough days at Farm 1 in 2009 to be classified as resident fish. In contrast, 40% of fish released from Farm 2 in 2008 were manually located within Lake Wolsey in 2009 within 5 km of the fish farm, but never detected at the farm site. Given the consistently lower site fidelity of released rainbow trout at the open site (Farm 1), the finding of long-term (>1 yr) fidelity to this site was counter to my expectations. Blanchfield *et al.* (2009) found escapee rainbow trout incorporating the cage site into their home range up to 3 years after release from an experimental farm into a small lake. However, this is the first report of long term site fidelity at commercial operations.

2.4.2 Site factors influencing fidelity to alternative fish farms

Sites of commercial aquaculture are considered optimal (feeding) habitat for fish (Tuya *et al*. 2006; Uglem *et al.* 2008) and attract both wild and domestic fish (Carss 1990; Bridger *et al.* 2001; Dempster *et al.* 2002, 2009; Uglem *et al*. 2009). Within Lake Huron, rainbow trout farms have similarly been found to be an attractant of many wild fish species, such as yellow perch (*Perca flavescens*), lake whitefish (*Coregonus clupeaformis*), as well as rainbow trout and lake trout (Johnston *et al.* 2010). There are two other rainbow trout aquaculture operations within a 5 km radius of Farm 1 that offer an alternative location for residency by escaped rainbow trout. Using manual tracking, one to three tagged rainbow trout were detected at both fish farms in close proximity to Farm 1 (see Chapter 3). Similar observations were made by Bridger *et al.* (2001) whereby escaped fish targeted nearby fish farms once dispersed from the release site. Uglem *et al.* (2010) found that farmed cod showed site fidelity to a foreign cod farm and neighbouring mussel farm when released there. With respect to the present study, a rainbow trout would need to travel ~90 km from Farm 2 before encountering another fish farm, which I did not observe. The lack of other commercial aquaculture operations in close proximity to Farm 2 may be another factor that could explain the higher degree of site fidelity there, and contribute to the variation in site fidelity found between the two release sites.

2.4.3 Individual patterns of site fidelity

Use of telemetry in this study allowed for an exploration of individual variation in the patterns of site fidelity among individuals of a population of released farmed fish. This level of detail in escapee behaviour has not been examined before in relation to commercial aquaculture, but is important for understanding levels of reliance and attraction to cage sites. I observed low site fidelity in rainbow trout released from two commercial farms in Lake Huron, but it was not entirely explained by a mass exodus of fish from the farm. After release there was an initial sharp decline with only 50% of fish remaining at the cage sites after 6 days. This rapid dispersal of tagged fish was followed by a steady decline over the next 3 months. In this latter period, a number of individuals continued to show fidelity to the cages, but also made excursions away from the release site that lasted from one day to more than one month in length. This occurred across all presence categories. For example, of the 16 “resident” fish, which I defined as being detected at the farm for >50% days, seven of them left the farm for 10 or more consecutive days before returning. One resident fish was away for 42 days before returning and remaining at the farm. Uglem *et al*. (2008) found up to 40% of released farmed cod returning to the farm once dispersed. This study has demonstrated that while low proportions of fish permanently inhabit the area surrounding the farm, larger proportions of escapees frequent the farm sites. This information is important in assessing the feasibility and timing of a recapture event.

Understanding the movements of fish and the mechanisms underlying them are challenging questions. Tagged rainbow trout in the present study showed similar behaviour to escaped cod (Uglem *et al.* 2008) and rainbow trout in an experimental study (Blanchfield *et al.* 2009) by returning to the cage site once dispersed. I largely attribute this behaviour to the attractiveness of the cage site as a food source. Beyond these examples, detailed telemetry studies on patterns of site fidelity have primarily addressed the effectiveness of Marine Protected Areas (MPAs). Recent studies on giant manta ray (*Manta birostris*), ocean whitefish (*Caulolatilus princes*), and California sheephead (*Semicossyphus pulcher*), found high site fidelity to either release sites or aggregation sites, and multiple short term excursions within or outside of the MPA related to seasonal changes and resource availability (Topping *et al.* 2006; Bellquist *et al.* 2008; Dewar *et al.* 2008). My findings contrast the observed high site fidelity in the MPA studies, but the short term ventures (80% fish dispersal lasted ≤5 days) away from the site before returning is paralleled. This pattern of high site fidelity with short movements away from aggregated areas has also been shown in red drum (*Sciaenops ocellatus*) in a salt marsh where movements were largely accounted for by both tidal and diel cycles (Dresser and Knieb 2007). Collectively, the MPA studies ascribe movements away from aggregation site for the acquisition of mates.

The reasons behind the movement of escapees away from sites of commercial aquaculture production are not fully understood. One idea is that fidelity to cage sites may be density-dependent. With the attraction of fish to cage sites it is reasonable to assume overcrowding occurs, and in turn competition for waste feed or other prey may become intense. Subsequently, fish may disperse to lower density waters. This idea could explain the relatively stable proportion of escaped rainbow trout remaining at the farm after one month; a pattern observed across all years and sites of this study. Blanchfield *et al.* (2009) estimated that even a very low rate of feed loss (0.09%) at their single experimental pen (10 t) would be capable of supporting the growth of 10 escaped fish at the same rates as those inside the cage. Larger farms (180-400 t), like the ones in this study, would be capable of supporting the high growth rates of approximately 200-400 trout, assuming similarly low rates of feed loss. In the 2008 season, the numbers I released were only a fraction of what a farm could support, but there would also be competition for food among other fish attracted to the site; potentially other farmed fish from previous chronic losses, that could drive escaped fish to disperse. Our study group (telemetry and Floy) was larger in 2009, and the proportion of fish exhibiting site fidelity was also lower. This coincides with the idea that site fidelity in escaped fish may be in part driven by density of fish around the cage sites.

2.4.4 Angler returns of Floy tagged fish

The large-scale release of Floy-tagged rainbow trout (n=500) at each farm provided further insight into the site fidelity of escapees through angler returns in 2009. Over half of the farmed fish that were released from Farm 2 were recaptured near the fish farm. The nature of the data do not allow for classification of Floy-tagged fish as “resident” because there is only one location collected at time of angling, but their capture at release sites is highly indicative of fidelity. Of those rainbow trout released from Farm 2, 95% of fish were caught within a 5 km radius of the farm which suggesting that they could have been frequenting the farm for shorter or longer periods of time as we saw in the telemetry-tagged fish. Visual sightings of Floy tagged fish were also regular occurrences at both farm sites by myself and farm staff. Fewer Floy-tagged fish from Farm 1 were angled at the farm (~1/3), which coincides with the lower site fidelity seen in telemetry fish. Angler returns of tagged fish also provided novel data on long term site fidelity of escapees. Floy-tagged escapees have been captured at the commercial farms a year after release, and will continue to be monitored throughout the life span of the fish, providing long term insight into site fidelity that would not be possible with telemetry monitoring alone.

This study quantified site fidelity of escaped rainbow trout at commercial aquaculture operations in Lake Huron. Within a month site fidelity was low (25%), with a majority of fish having left the farm sites. This was particularly apparent of fish released from Farm 1, located in the North Channel, which is a more typical aquaculture operation in Lake Huron. Although there was variation between release sites and season, overall site fidelity of all tagged individuals was lower than expected from experimental work done on escapee rainbow trout. Findings of low site fidelity suggest that the potential impacts to the local ecosystem may be higher than originally anticipated, assuming a larger area is affected by the presence of farmed trout. The limited site fidelity observed in this study suggests a greater potential for habitat overlap with local species, as well as increased competition for food resources outside of the farm sites. In an oligotrophic system where there is a concentration of nutrients and prey species around a fish farm, the departure of fish to exploit limited resources in the surrounding system could be highly detrimental, especially in the event of a large escape of farmed fish. Concerns surrounding the potential ecological impacts of an escape event, especially those related to competition for food, appear valid when only considering the lack of site fidelity observed in this study. However, the survival, dispersal, and specific effects of farmed rainbow trout in Lake Huron still need to be examined before an appropriate risk assessment of impacts can be produced.

Table 2.1 Summary information for all 20 farmed rainbow trout implanted with telemetry transmitters at Farm 1 in 2008. CART = combined acoustic radio transmitter. All detection data are from the farm receiver only and encompass the period from release date, 7/2/2008 to the end of the monitoring period 10/18/2008. The number of days detected and total number of detections at the farm are shown. Days at liberty is the number of days a fish was detected once released until it was last detected by any means (i.e. farm receiver, angling or manual tracking).

Tag ID	Tag type	FL(mm)	Wt. (g)	# days detected	% of days detected	# of days at liberty	# detections	Fate
10	Radio	375	820	5	5	328	214	
11	Radio	390	1006	8	8	99	519	Dead
12	Radio	394	1040	8	8	353	248	
13	Radio	371	753	9	9	101	639	
14	Radio	375	771	1	1	0	17	
15	Radio	373	873	26	27	129	701	Angled
16	Radio	411	957	43	45	108	5317	
17	Radio	374	708	2	2	1	116	
18	Radio	409	969	1	1	0	179	
19	Radio	390	820	5	5	106	196	
30	CART	418	1112	3	3	2	704	Dead
31	CART	372	800	13	14	15	3590	
32	CART	413	1068	6	6	8	401	
33	CART	380	896	87	91	481	13751	
34	CART	378	892	1	1	406	314	
35	CART	358	723	61	64	84	9034	
36	CART	383	798	76	79	480	3752	
37	CART	383	785	27	28	380	3066	
38	CART	380	763	6	6	107	221	
39	CART	408	1133	66	69	392	16060	

Table 2.2. Summary information for all 20 telemetry transmitters implanted at Farm 2 in 2008. CART = combined acoustic radio transmitter. All detection data are from the farm receiver only and encompass the period from release date, 7/4/2008 or 7/12/2008 to the end of the monitoring period 10/18/2008. The number of days detected and total number of detections at the farm are shown. Days at liberty is the number of days a fish was detected once released until it was last detected by any means (i.e. farm receiver, angling or manual tracking).

Tag ID	Tag type	FL(mm)	Wt. (g)	# days detected	% days detected	# of days at liberty	# detections	Fate
20	Radio	444	1393	31	29	128	1754	
21	Radio	380	826	29	27	66	8265	Dead
22	Radio	440	1320	4	4	9	58	
23	Radio	448	1568	1	1	1	7	
24	Radio	444	1281	4	4	37	181	
25	Radio	448	1511	5	5	27	373	Dead
26	Radio	430	1407	8	7	11	3784	
27	Radio	492	1950	18	17	83	1760	
28	Radio	376	874	2	2	8	72	Predated
29	Radio	393	1184	7	6	7	702	
40	CART	431	1343	5	5	377	285	
41	CART	477	1718	90	83	127	13192	
42	CART	450	1620	26	24	31	2968	
43	CART	426	976	61	56	62	16599	
44	CART	475	1980	22	20	369	3576	
45	CART	427	1354	27	25	377	2995	
46	CART	448	1462	54	50	134	6655	Angled
47	CART	411	1182	98	91	156	61811	
48	CART	396	1153	97	90	364	47617	
49	CART	439	1575	77	71	369	22885	

Table 2.3. Summary information for all 37 telemetry transmitters implanted at Farm 1 in 2009. CART = combined acoustic radio transmitter. All detection data are from the farm receiver only and encompass the period from release date, 5/12/2009 or 5/13/2009 to the end of the monitoring period 9/19/2009. The number of days detected and total number of detections at the farm are shown. Days at liberty is the number of days a fish was detected once released until it was last detected by any means (i.e. farm receiver, angling or manual tracking).

Tag ID	Tag type	FL(mm)	Wt. (g)	# days detected	% days detected	# of days at liberty	# detections	Fate
1	Sensor(R)	343	343	0	0	n/a	1	
2	Sensor(R)	358	358	3	2	103	504	
3	Sensor(R)	335	335	24	19	38	289	
4	Sensor(R)	354	354	0	0	70	0	Dead
5	Sensor(R)	348	348	4	3	145	548	Angled
6	Sensor(R)	373	373	1	1	69	188	
7	Sensor(R)	340	340	0	0	63	309	
8	Sensor(R)	337	337	3	2	86	861	
9	Sensor(R)	360	360	0	0	n/a	0	
15	Sensor(R)	360	360	15	12	86	5112	
50	CART	381	381	1	1	0	14	
51	CART	374	374	2	2	92	9	
52	CART	343	343	2	2	1	45	
53	CART	345	345	1	1	92	3	
55	CART	345	345	1	1	0	4	
56	CART	355	355	31	24	129	5744	
58	CART	345	345	31	25	98	3130	Angled
59	CART	360	360	10	8	41	1098	
60	CART	342	342	12	10	91	511	
61	CART	355	355	0	0	91	1	
62	CART	382	382	1	1	48	7	
63	CART	359	359	1	1	0	37	
64	CART	342	342	0	0	91	4	
65	CART	349	349	43	34	157	9794	Angled
66	CART	348	348	2	2	66	22	
67	CART	346	346	12	9	73	881	
68	CART	351	351	7	6	10	228	
69	CART	346	346	1	1	66	13	Dead
70	CART	351	351	1	1	78	3	
72	CART	399	399	13	10	73	1899	
73	CART	360	360	0	0	87	14	
74	CART	361	361	9	7	74	651	
75	CART	360	360	1	1	1	16	
76	CART	362	362	16	13	132	1046	
77	CART	364	364	13	10	36	726	Angled
78	CART	343	343	4	3	97	144	
79	CART	332	332	1	1	57	45	Predated

Table 2.4. Summary information for all 40 telemetry transmitters (Sonotronics) implanted at Farm 2 in 2009. CT = straight acoustic transmitter, DT = pressure sensing acoustic transmitter. All detection data are from the farm receiver only and encompass the period from release date, 5/15/2009 or 5/16/2009 to the end of the monitoring period 9/19/2009. The number of days detected and number of detections at the farm are shown. Days at liberty is the number of days a fish was detected until it was last detected by any means.

Tag ID	Tag type	FL(mm)	Wt. (g)	# days detected	% days detected	# of d. liberty	# detections	Fate
3	DT (sensor)	393	950	50	40	141	10495	
4	DT (sensor)	410	1150	67	54	141	13676	
5	DT (sensor)	410	1200	62	50	141	14312	Angled
6	DT (sensor)	392	1040	17	14	125	3279	
7	DT (sensor)	417	1175	72	58	140	9587	
8	DT (sensor)	384	1052	28	23	123	5686	
9	DT (sensor)	438	1370	21	17	26	3355	Angled
10	DT (sensor)	385	1050	72	58	140	19122	
11	DT (sensor)	383	992	13	11	25	1888	
12	DT (sensor)	376	1020	25	20	32	1604	
18	CT	359	672	7	6	123	113	
19	CT	394	880	5	4	14	121	
20	CT	390	987	18	15	35	1240	
21	CT	364	755	127	102	140	46623	
22	CT	402	942	14	11	20	366	Angled
23	CT	378	838	15	12	15	4416	
24	CT	358	694	13	11	50	758	
25	CT	387	830	30	24	105	2264	
26	CT	354	695	27	22	31	11602	
27	CT	388	932	4	3	8	716	Angled
33	CT	394	940	7	6	14	661	Angled
34	CT	403	1010	52	42	140	16803	
35	CT	378	870	34	27	105	1348	
36	CT	404	1032	21	17	31	1128	
37	CT	418	1294	38	31	75	3123	
38	CT	389	1006	0	0	0	2	
39	CT	389	1020	2	2	26	51	Angled
40	CT	422	1132	57	46	84	24247	
41	CT	370	811	22	18	101	1346	
42	CT	383	950	12	10	32	348	
48	CT	395	855	13	11	14	5406	Angled
49	CT	375	738	19	15	36	471	
50	CT	398	1041	19	15	27	882	
51	CT	360	910	59	48	140	1869	
52	CT	394	1037	83	68	99	42011	
53	CT	377	729	5	4	64	269	
54	CT	392	971	106	86	140	39937	
55	CT	378	790	14	11	15	967	Angled
56	CT	379	960	3	2	6	357	Angled
57	CT	401	1100	18	15	28	486	

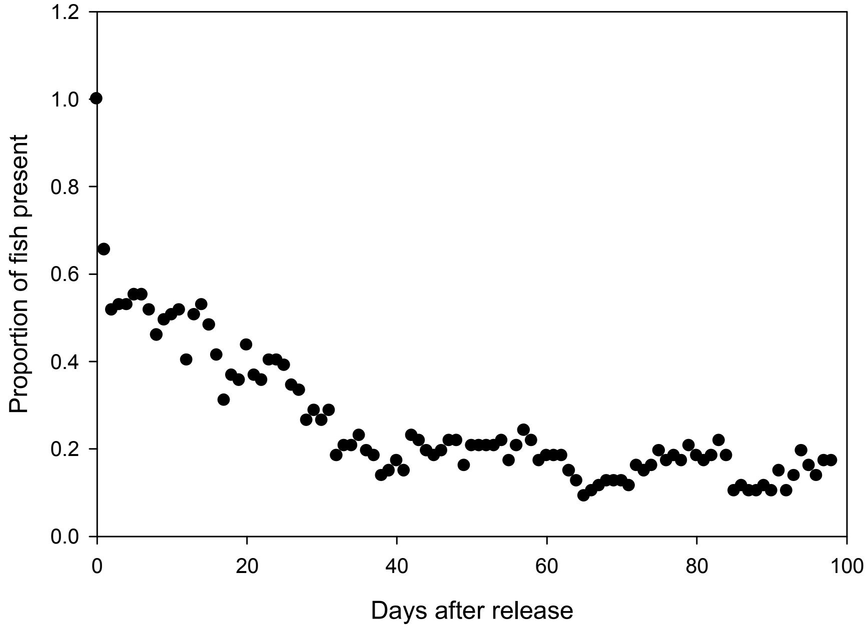

Figure 2.1 Proportion of acoustically-tagged farmed rainbow trout (n = 87) present at the commercial aquaculture sites from which they were released. Daily rainbow trout presence at farm sites was determined by a receiving station at each of the two cage sites of release (see Figure A.1). Fish releases occurred in 2008 and 2009 and presence was monitored from 2 July through 18 October 2008 and 15 May through 19 September 2009.

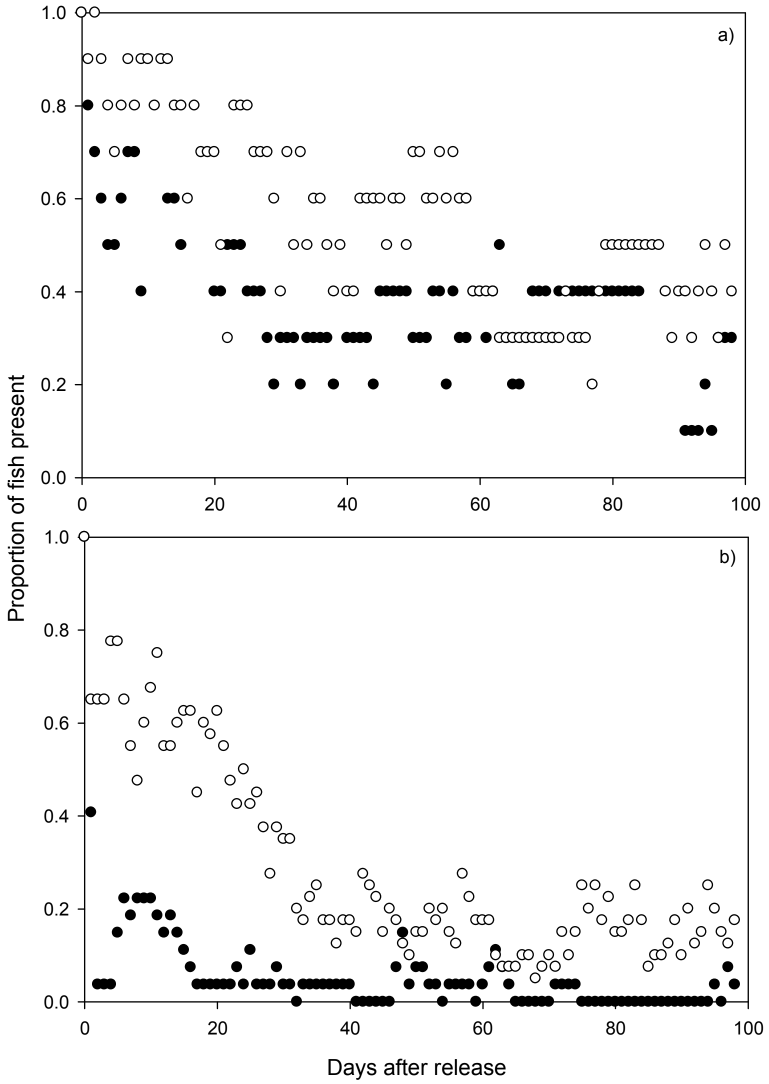

Figure 2.2 Daily proportions of acoustically-tagged farmed rainbow trout present at commercial aquaculture sites in Lake Huron from which they were released. Fish presence at Farm 1 (solid circles) and Farm 2 (open circles) were detected by the receiving station set up at each cage site. Fish were monitored from (a) 2 July through 18 October 2008 (n=20) and (b) 15 May through 19 September 2009 (n=67).

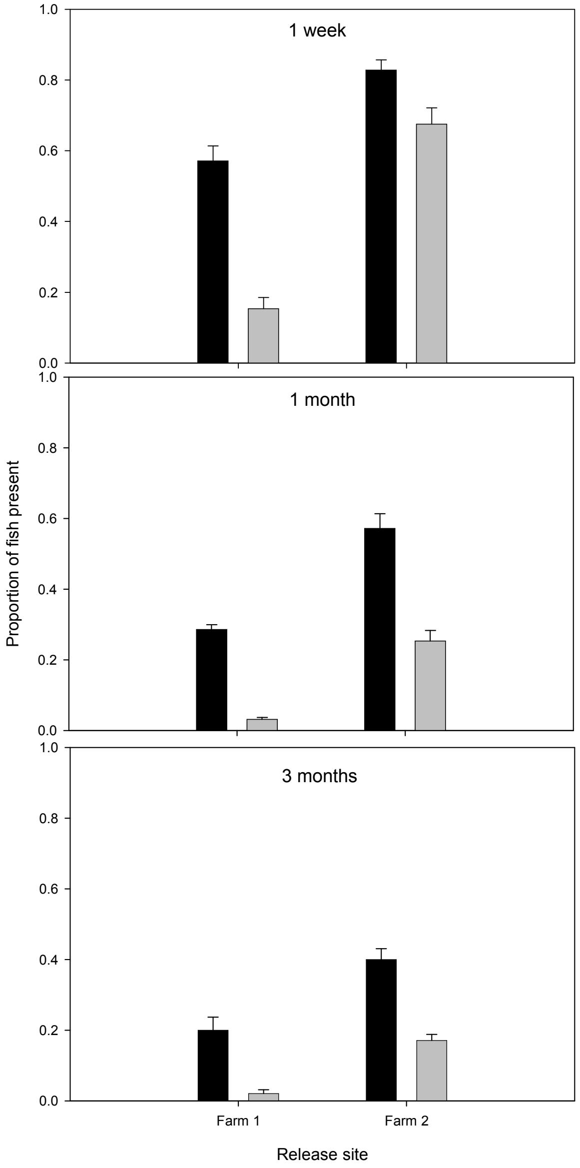

Figure 2.3 Proportion of acoustically-tagged farmed rainbow trout (n = 87) present at the commercial aquaculture sites from which they were released. Fish presence (7 d mean ± 1 S.E.) at Farm 1 and Farm 2 are shown at 1 wk, 1 mo, and 3 mo after release in 2008 (black bars, July release) and 2009 (grey bars, May release).

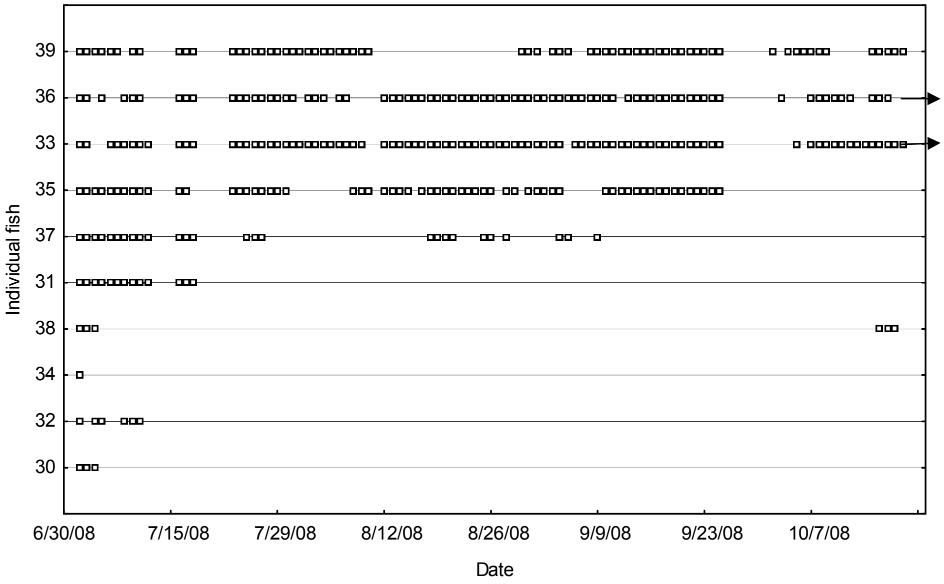

Figure 2.4 Site fidelity patterns for all 10 rainbow trout implanted with CAR transmitters at Farm 1 (see Table 2.1) as detected by farm receiving station from 2 July - 18 October, 2008. Each coloured block symbolized presence on that day and the colouration of the block denotes presence category; green = resident, clear = frequent, yellow = infrequent, and red = rare (see text for details). Arrows denote continued site fidelity of 2008 released fish in 2009 (see Figure 2.6).

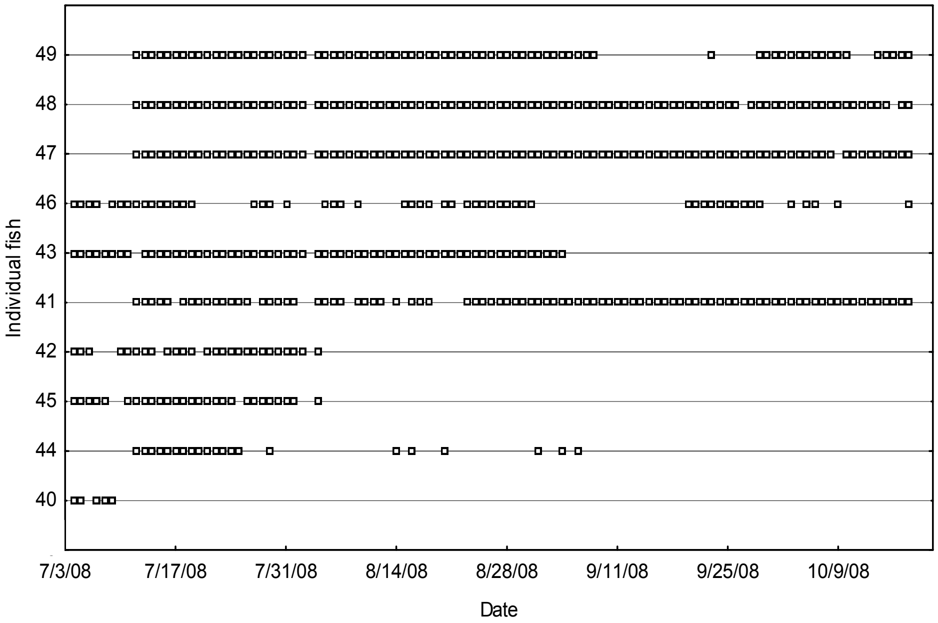

Figure 2.5 Site fidelity patterns for all 10 rainbow trout implanted with CAR transmitters at Farm 2 (see Table 2.2) as detected by farm receiving station from 4, 12 July - 18 October, 2008. Each coloured block symbolized presence on that day and the colouration of the block denotes presence category; green = resident, clear = frequent, yellow = infrequent, and red = rare (see text for details).

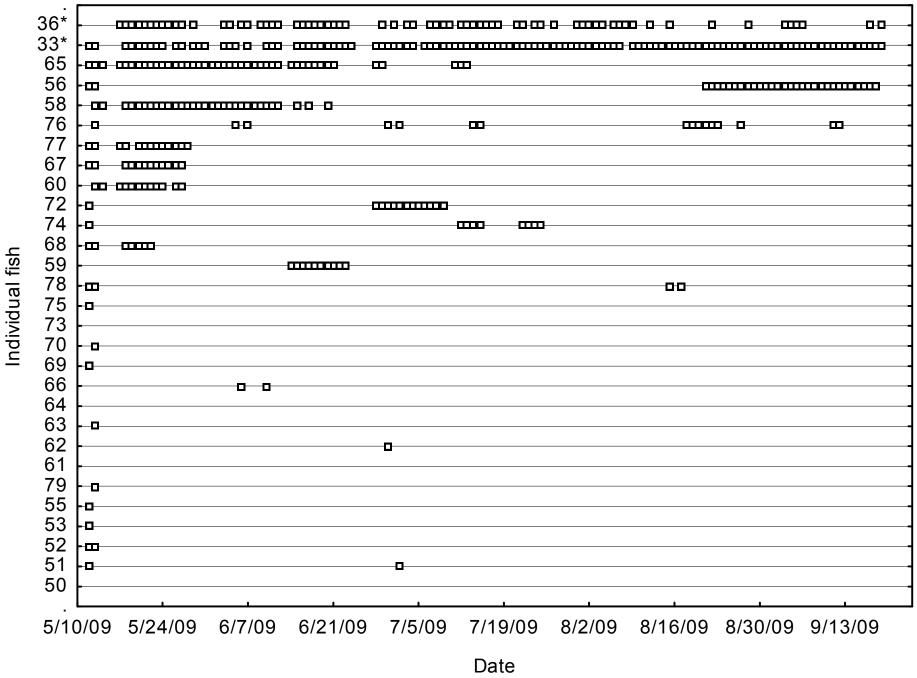

Figure 2.6 Site fidelity patterns for all 27 rainbow trout implanted with CAR transmitters at Farm 1 (see Table 2.3) as detected by farm receiving station from 12, 13 May - 19 September, 2009. Each coloured block symbolized presence on that day and the colouration of the block denotes presence category; green = resident, clear = frequent, yellow = infrequent, and red = rare (see text for details). * fish numbers and blue blocks indicate fish released in 2008.

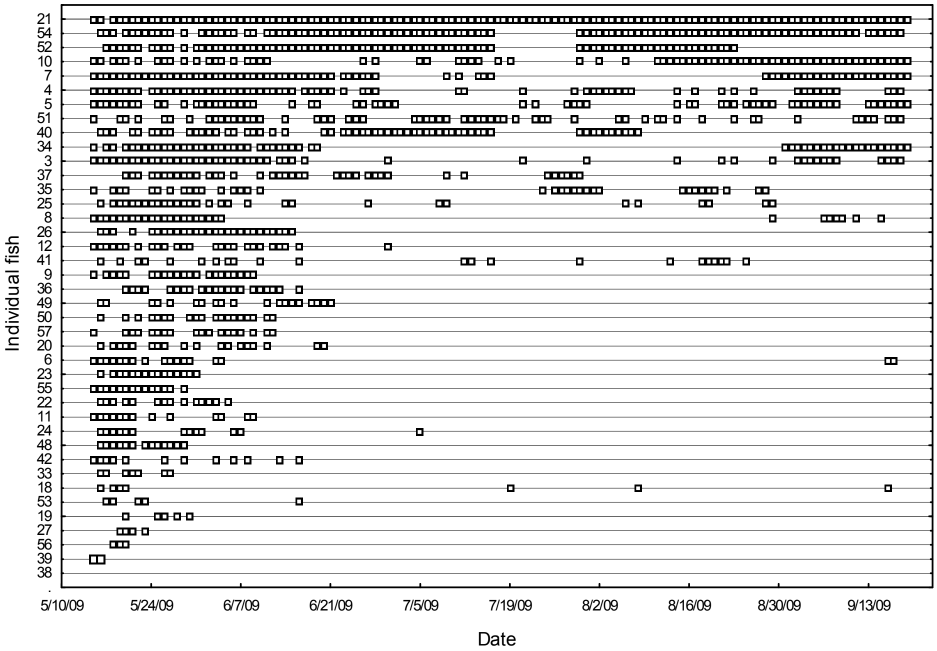

Figure 2.7 Site fidelity patterns for all 40 rainbow trout implanted with acoustic transmitters at Farm 2 (see Table 2.4) as detected by farm receiving station from 15, 16 May - 19 September, 2009. Each coloured block symbolized presence on that day and the colour denotes presence category; green = resident, clear = frequent, yellow = infrequent, and red = rare (see text for details).

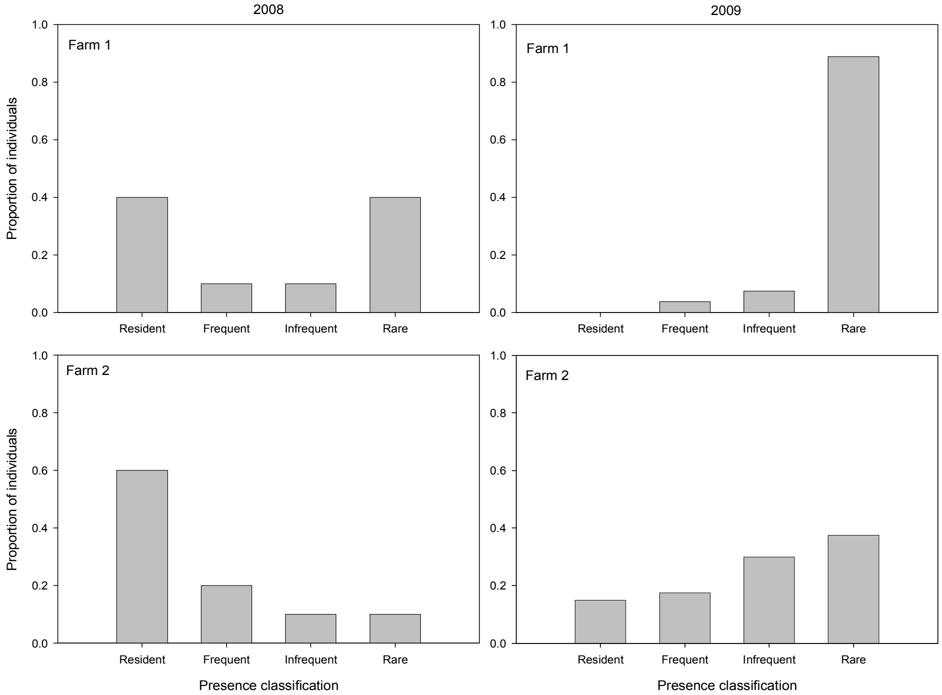

Figure 2.8 Proportion of acoustically tagged farmed rainbow trout (n=87) classified as exhibiting resident, frequent, infrequent or rare site fidelity at Farm 1 and Farm 2 in 2008 and 2009 based on their detection at the farm receiver stations (see text for details) after being released into Lake Huron, Ontario.

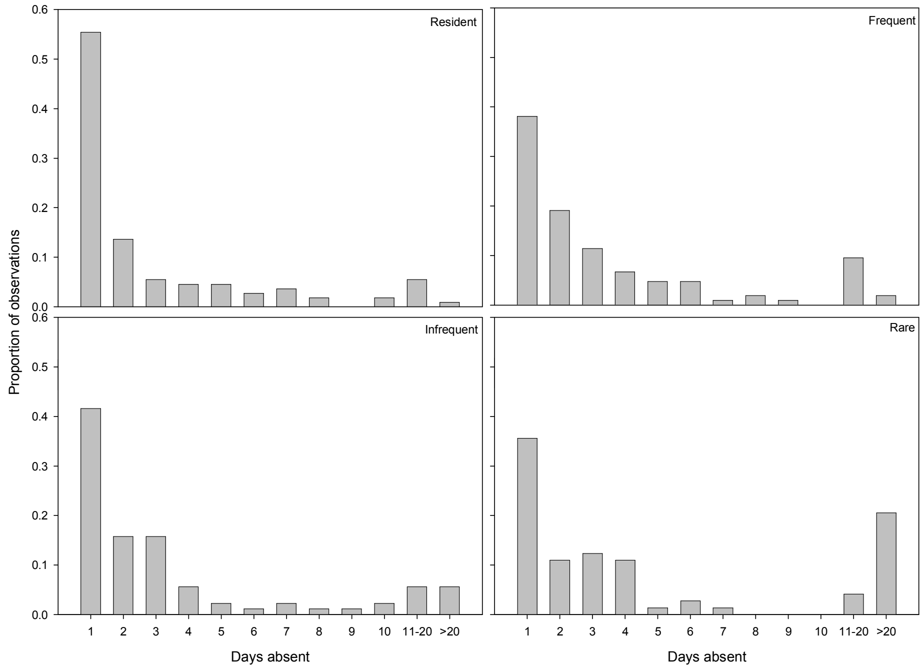

Figure 2.9 Frequency distribution of the number of days individual tagged rainbow trout (n=87) were absent from commercial aquaculture operations of release prior to returning. Days absent shown here is separated by presence category: resident, frequent, infrequent, and rare (see text for details). For time line specific absence from the farm sites see Figures 2.4-2.7.

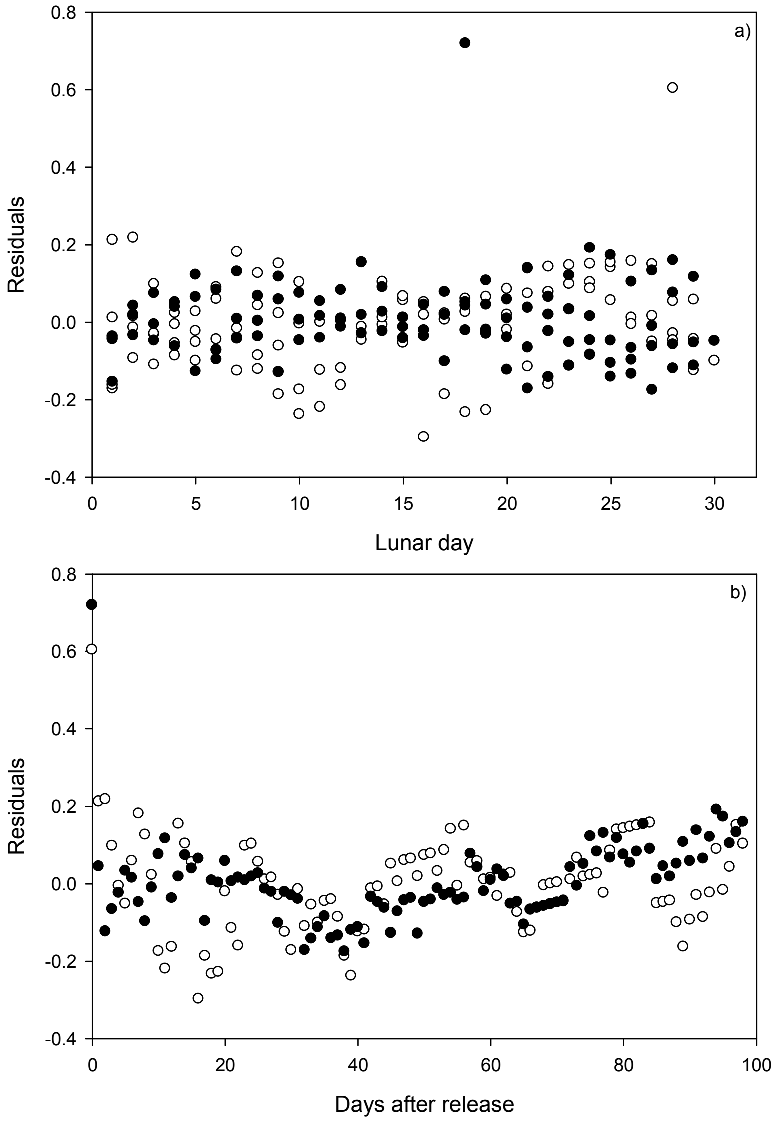

Figure 2.10 Residual values from the non-linear regression of proportion of fish present against days after release of fish released in 2008(open circles)($y=0.9672*e^{-0.03x}$, $r^2= 0.50$) and 2009 (dark circles)($y=0.8516e^{-0.03x}$, $r^2=0.72$) plotted against day in the lunar cycle a), and days after release b).

CHAPTER 3: Dispersal and movement of fish released from an aquaculture cage

3.1 Introduction

A major concern associated with the escape of farmed fish is their potential negative ecological impact if able to survive in the wild and compete with wild or naturalized fish stocks (Jacobsen and Hansen 2001; Naylor *et al.* 2005). The potential ecological risks of escaped farmed fish include competition with conspecifics and other local species for resources, namely food, space, and breeding partners. There is evidence that escaped farmed fish disperse from commercial aquaculture operations, exhibit selective foraging and successfully adjust to feeding in the wild (Jacobsen and Hansen 2001). The level of risk associated with the escape of farmed fish will be highly dependent on the degree to which escapees disperse from aquaculture operations (Naylor *et al*. 2005). If dispersal distances of escaped fish are minimal, any effects of increased competition through an increase in numbers of farmed fish may be highly localized. Alternatively, if farmed fish disperse widely from commercial operations, the area of impact, and hence risk associated with escapees, will be significantly larger. A rapid and/or wide dispersal of fish also limits the opportunity for recapture by the farmers.

There is strong evidence that farmed salmonids undertake long-distance dispersal movements away from commercial farms upon escape. Escaped Atlantic salmon from commercial fish farms around Vancouver Island, British Columbia (BC) have been found around the entire island, in inland freshwaters of BC, and have travelled distances >4500 km to Alaskan waters (McKinnell *et al.* 1997). Similarly, Atlantic salmon escaped into the Atlantic Ocean have been found entering rivers from 100 km to over 420 km away from release sites on the east coast of North America and the west coast of Norway (Jonsson *et al.* 2003; Whoriskey *et al.* 2006). Intentional releases of tagged farmed Atlantic salmon in Scotland and Norway resulted in some released fish travelling 1600 km from the Scottish farms, while a majority of Norwegian escapees were angled within 150 km of the release sites (Hansen and Youngson 2010). Domestic rainbow trout are also capable of long-distance dispersal, travelling up to 1760 km after their release in a Norwegian fjord (Jonsson *et al.* 1993). Collectively, these studies show farmed salmonids are capable of long-distance dispersal following escape from sites of commercial open-pen aquaculture production, but the numbers of escapees that undertake these movements is unclear. Studies generally report on the distance from the farm that a fish was angled, with limited consideration for the remaining population. Habitat utilization is also poorly understood for similar reasons, and when examining migratory species, the vastness of the area travelled provides obvious limitations in examining fine scale habitat use.

Given the potential negative consequences of escapees to natural fish populations, there are surprisingly few studies that have examined the question of dispersal in any detail. Most of the detailed studies that have attempted to quantify dispersal have implanted farmed fish with telemetry transmitters and released them from commercial open-pen aquaculture operations to simulate an escape event (see Table 1.1). Atlantic salmon released from a farm in Maine, USA, rapidly dispersed with no fish detected at the farm by the end of the first day (0-21 h) (Whoriskey *et al.* 2006). Once dispersed, fish made directed movements with the local currents and broad-scale dispersal pathways (Whoriskey *et al.* 2006). A recent Norwegian study on Atlantic cod (*Gadus morhua*) found that most fish (52-84%) rapidly dispersed from the farm in the first day (Uglem *et al.* 2008). In contrast to the salmonid studies, there was no directionality to the Atlantic cod movements after being released from the farm (Uglem *et al.* 2008). Blanchfield *et al.* (2009) found rapid dispersal of farmed rainbow trout released into an experimental lake (23 ha), with all fish departing the site within 1-2 days. Similar results were seen with farmed rainbow trout released into a larger Norwegian lake (4700 ha), when 94% of fish had left the farm within 3 days. Another study tracked the movements of tagged Steelhead trout (*Oncorhynchus mykiss*) released into Bay d'Espoir region of Newfoundland, Canada and found that individuals tended to congregate around fish farms, disperse slowly with directed movements toward a spillway with a hatchery (Bridger *et al.* 2001). This is the only study that observed slow dispersal rates, with only 25% of fish leaving the cage site in the first month post release. All other studies reported a majority, if not all fish having left the release farm within hours to 3 days post release, regardless of the size of the system, or species used.

At present, there are only two studies that have examined dispersal of escaped fish from freshwater farms, and both have taken place in small- to medium-sized lakes. A study by Blanchfield *et al.* (2009), at the Experimental Lakes Area in northwestern Ontario, found that farmed rainbow trout rapidly dispersed throughout the 23 ha lake and were observed at the maximum distance from the release farm within 1-2 days. Similarly, a Norwegian study of farmed rainbow trout released into a lake found that 94% of fish dispersed from the farm site within 3 days (Lindberg *et al.* 2009). In both studies, farm operations ceased within one month after the release of farmed fish to the wild. To date, there has been no large scale dispersal study conducted of freshwater escapees. Based on the long distance movements observed in ocean run salmonids, the results of farmed fish released into a large system such as the Canadian Great Lakes could differ dramatically that what has been observed in the .

Information on the dispersal of escapees from marine and small-scale freshwater studies may not be directly applicable to larger freshwater systems. This was apparent from my examination of site fidelity of escaped rainbow trout from commercial aquaculture operations in Lake Huron (Chapter 2). The low overall site fidelity (<20% after 3 months) of tagged trout that I observed after their releases from the Lake Huron farms is indicative of high dispersal rates. Here, I assess dispersal by including the timing, rate and directionality of movement away from fish farms. These are key points that need to be addressed to form a realistic assessment of the impact of escapees. The rate at which fish disperse from a farm and their subsequent movements will determine if it is possible to organize and implement a recapture effort post escape. Knowing that a low number of fish remain at the farm suggests that a majority of escapees are occupying other habitats, enlarging the area of impact. The goals of this portion of the study are to monitor the initial dispersal of rainbow trout and their subsequent distribution and habitat use after release from commercial open-pen aquaculture operations in Lake Huron. Specifically, I 1) quantify dispersal of fish released from two commercial farms, 2) explore the effect of farm site location, (located within an open water body compared to a semi-contained lake) and seasonal variation in release dates, and, 3) examine individual and population post-dispersal movements over time.

3.2 Methods

3.2.1 General methods

Study site, fish tagging procedures (including transmitter size and details (Table 1.2) and mean fish sizes per tagging event (Table 1.3)), and the telemetry monitoring system are described in detail in section 1.7.3. Information on all rainbow trout surgically implanted with transmitters, such as individual size and release date can be found in Tables 2.1-2.4.

To quantify the dispersal of farmed rainbow trout away from release sites, I use telemetry data collected by stationary receivers located at each farm and three others strategically located at sites of passage into larger water bodies (called “gate stations”, see Fig. 1.2 for details). I also collected data on the location of telemetry-tagged farmed fish when dispersed from the farms by manual location (details to follow) and by angler recaptures of both telemetry and Floy-tagged fish. Continual monitoring of fish presence at each release site allowed me to determine how long individuals remained at the farm before initial dispersal (departed for > 1 d), and how long they remained away from the site before returning. Gate receiving stations provided the date and time at which tagged rainbow trout moved outside of the system I was actively monitoring via manual location or stationary receivers. Once a fish passed through a gate station they were considered to have left the system, and were categorized as “departed”.

3.2.2 Manual location of telemetry fish

Manual location of telemetry fish (termed “tracking”) was undertaken to locate rainbow trout once they had dispersed from the commercial farms. The Lotek manual location system was comprised of a 5-element Yagi antenna, directional hydrophone (LHP_1), sonic upconverter, SRX_400 receiver, and a 12 v battery. The manual tracking system could be easily transported between boats to track in the areas around each cage operation. The boat used to track the fish released from North Wind Fisheries in the North Channel was an 18’ Hourston Glascraft with a 150 HP outboard motor, and was harboured in Little Current. An 18’ Crestliner equipped with a 50 HP outboard motor, harboured at Twilight Isle (<10 km from Farm 2), was used in Lake Wolsey. I was able to search for fish up to a maximum distance of 30 km away from the release sites. Manual tracking followed the general methods of Blanchfield *et al.* (2005). In brief, the boat would be brought to a complete stop and the motor disengaged. UTM coordinates would be noted and the GPS unit (GPSMAP 520; Garmin Ltd., Olathe, KS) was turned off to reduce interference. A directional scan was done with the radio antenna, listening for 15-20 s at each stop of N, E, S, and W. If a transmitter was detected, the antenna would be adjusted toward the strongest signal. An identical scan with the hydrophone would follow. For both the radio and hydrophone scans, if a fish was detected, we would re-position the boat as necessary to decode the fish and pinpoint its approximate location. I considered a fish to be located when I obtained the highest power reading at the lowest gain possible. At this point, I would record the GPS position. I recorded all locations scanned, regardless of detection, as well as general weather conditions, time, water depth, and a count of boats actively fishing in view. Manual locations of telemetry tagged fish were used for general dispersal and movements away from the release site and not fine scale habitat use. Manual tracking was carried out at both farms in 2008 with focused efforts at Farm 1 in 2009 (see Table 3.1).

3.2.3 Dispersal

Time to initial dispersal of rainbow trout was calculated as the number of days from the time of release that an individual moved outside of the detection range of the farm receiver for a period of at least 24 h. Dispersal distance was calculated as the maximum linear distance (km) an individual was located away from the farm via manual location, gate station detection or angler recapture of both telemetry- and Floy-tagged fish. All detections of individual fish were used to calculate the mean distance away from the release site that a fish was manually located (Table 3.1).

In 2009 I did not manually track escaped rainbow trout in Lake Wolsey (Farm 2). Instead, I used an array of four stationary receivers placed at the farm and throughout the lake that allowed for sufficient coverage of this system based on the manual location of fish released in 2008 (Figure 3.1). One of these receivers was outside the lake to monitor fish passing through the small channel connecting Lake Wolsey to the rest of Lake Huron. These receivers were attached to buoys moored to the bottom of the lake, and were placed 1.5 to 3 m below the surface. From detections of telemetry fish at one or more of the four receivers, I estimated individual daily movement patterns. Fish could be detected at none or all of the receivers over a 24 h period. Because the receivers recorded the date and time of individual fish detections, I was able to monitor movement out of one receivers range and into another in a short period of time.

3.2.4 Spatial Distribution

I evaluated the spatial distribution of telemetry tagged rainbow trout in the study area using the program FishTel 1.4 (Rogers and White 2007). To determine if fish were randomly distributed within the search area, I constructed a perimeter of the area in which I was able to manually search for fish. I used the random function of FishTel to compare actual fish locations to an equal number of randomly generated locations. The resultant variance, based on 1000 iterations, was then compared to the variance generated by another 10,000 iterations of randomly distributed points (n=18, the number of observed fish locations) to determine the P-value (Rogers and White 2007). Because some fish were located more than once, I randomly dropped observations until all fish had the same number of locations as suggested by Rogers and White (2007).

I examined the directionality of fish locations via manual location of telemetry tagged Farm 1 fish in 2008 and 2009, as well as angler returns of Floy tagged fish in 2009. I employed the Rayleigh test to determine whether the fish locations were randomly distributed or there was a directional preference in the locations as described in Zar (1997).

3.2.5 Statistical analysis

Three of the 90 telemetry-tagged rainbow trout released from the two commercial operations in Lake Huron during the 2008 and 2009 field seasons were never detected and therefore not included in subsequent statistical analyses. I first examined the initial time to disperse (mean ± 1 S.E.) of all fish (n=87) from the release farm, and quantified the dispersal distances of escaped trout (objective 1) from manual location, gate station detections, or angler returns. I then compared mean initial dispersal and distance travelled data separated by release site (Farm 1 and 2) and release season (summer 2008, spring 2009) to assess any influence these factors may have on dispersal of escaped fish (objective 2). Data on distance away from the farm of fish manually located, multiple relocations of fish manually, detection at a gate station, or returned from anglers was combined with the movement data of Farm 2 fish collected by the receiver array deployed in Lake Wolsey to examine specific movements of fish once released (objective 3). These results were also compared between site and season of release. All data sets were tested with the Shapiro-Wilk's test for normality, and the Brown-Forsythe test for homogeneity of variances. The results were analyzed in Statistica v. 6.1, (Statsoft, Inc., Tulsa, USA) using a combination of parametric and non-parametric tests (specified in results) depending on the outcome of the aforementioned tests for normality in the data sets. Bonferroni correction was applied when multiple comparisons were made within the same data.

3.3 Results

3.3.1 Timing of dispersal

Most individuals (72 of 87) were detected on the farm site receivers immediately after release. The remaining 15 telemetry-tagged rainbow trout were later detected either by stationary receivers, manual location, or via angler return at some point throughout the study period. I did not include these 15 fish in my analysis of initial dispersal. Time to initial dispersal of tagged rainbow trout from release sites at commercial farms in Lake Huron ranged from hours to months with a mean of 6.3 ± 1.8 d (range: 0.001 - 88.5 d). The time to initial dispersal of fish from release sites was significantly longer in 2008 (range: 0.02-88.5 d) than in 2009 (range: 0-35.8 d) at both farms (Mann-Whitney U test, Farm 1: $Z = 3.07$, $P = 0.002$; Farm 2: $Z = 2.62$, $P = 0.009$) (Table 3.1, Figure 3.2). Taking the location of the release site into account, there were no significant differences in initial dispersal of fish between release sites (Mann Whitney U tests, $Ps > 0.025$) (Table 3.1, Figure 3.2).

Once initially dispersed, 18% of fish never returned, while all other fish remained at large from anywhere between 1 d and 102 d (mean ± 1 S.E.: 12.4 ± 3.4 d) before returning to their release site. Although fish were slower to initially disperse when released in July 2008, there was no difference in the amount of time fish spent away from the release site before returning in 2008 (10.0 ± 6.3 d) compared to when released in the spring of the following year (May 2009) (13.3 ± 4.1 d) (Mann-Whitney U-test, $Z = -0.008$, $P = 0.99$) (Figures 2.4-2.7).

Within the first weeks after release of tagged rainbow trout from Farm 2 in 2009, fish were detected on all receivers monitoring the lake, including the farm and this pattern continued for a number of fish throughout the monitoring period (Figure 3.3). Fish released from Farm 1 in 2009 were quick to disperse outside of monitoring range (absent), where large proportions of fish remained over the 14 wk period (Figure 3.3). Of the dispersed fish, 44% never returned to the farm site. A quarter of the fish (7 of 27) were never detected by any means once they left the farm. Greater numbers of fish were detected moving into the larger bodies of water adjacent to Farm 2 (from Lake Wolsey into the North Channel) when released in May 2009 (n=7) than July 2008 (n=0) (Figure 3.3). Tagged rainbow trout released from Farm 2 in 2009 were detected at the gate station moving into the North Channel from Lake Wolsey 2-36 d post release.

3.3.2 Dispersal distances

Manual location of released fish took place around both farms in 2008, and Farm 1 in 2009. In 2008, fish released from Farm 1 were located, on average, three times as far away from the release site as Farm 2 fish in 2008 (Table 3.1). This difference was due to our sampling efforts as we only attempted to manually locate fish dispersed from Farm 2 within Lake Wolsey (up to 5 km from the release site) as there was no evidence of fish exiting the lake system from our gate station receiver. A much greater manual location effort at Farm 1 in 2009 yielded detections up to 23 km away from the release site (Table 3.1, Figure 3.4). The spatial distribution of Farm 1 fish locations was non-random within the search area (P=0.02) which was reflective of the non-random search effort. Focused efforts also allowed for multiple relocations of individual fish. Some individuals were relocated up to four times on different dates with a maximum distance of 16.2 km between two relocations of a single fish. The distance away from Farm 1 that manual tracking efforts encompassed (mean ± 1 S.E.: 12.0 ± 0.5 km, range 1.4-26.4 km) was greater than the distance fish were successfully located away from the release site (6.9 ± 0.8 km, range 1.1-22.9 km) (Figure 3.4). Some of the detections of fish were at the farthest distance of daily manual tracking efforts. Thus, distance away from the farm that fish were detected may have been limited by daily travel distance (Figure 3.4). All angler returns of telemetry fish were reported within the area searchable through manual location (0-21 km from release sites).

3.3.3 Post-dispersal movements – Farm 1

Manual location of telemetry tagged rainbow trout released from Farm 1 in 2008 showed no directional preference in movement of fish, instead showing that individuals were randomly dispersed from the commercial aquaculture operation (Rayleigh's test, $z = 2.76$, $P > 0.05$) (Figure 3.5a). In contrast, telemetry fish released in 2009 displayed directional preference, moving more often west than east of the release site (Rayleigh's test, $z = 5.87$, $P < 0.05$)(Figure 3.5b). Also in 2009, three individuals were detected at two different fish farms located within 6 km of Farm 1. One of these escapee trout displayed a degree of site fidelity to a foreign farm, as I detected it there on three different occasions. One additional fish was angled at these neighbouring farms 36 d after release. I also detected two fish released from Farm 1 in 2008 ranging from 2-13 km away from the farm in 2009. All locations of Farm 1 fish detected by manual location are displayed in Figure 3.6. No fish were found in rivers known to host salmonid spawning on the north side of Manitoulin Island and the north shore of the North Channel when scanned in October 2008 (Fort La Cloche, Kagawong, Mississagi, Serpent, Spanish, and Whitefish rivers). No spawning rivers were monitored for released fish in the spring of 2009.

3.3.4 Post-dispersal movements – Farm 2

Using the array of passive receivers located throughout Lake Wolsey in 2009, I conducted detailed post-dispersal movements of telemetry-tagged rainbow trout released from Farm 2 in 2009 (Fig 3.1). Of the 40 rainbow trout released from Farm 2 in 2009, 7 left the lake through the channel (departed) and a further 8 fish were angled in the monitoring period. As a result, the total number of fish monitored was continually adjusted to account for these losses when assessing movement patterns of this tagged group (Figure 3.3). A common trend within the remaining population was for fish to occupy the south basin, mid lake, and farm monitoring regions of Lake Wolsey, especially over the first four weeks (Figure 3.3). The most common movement pattern of rainbow trout observed during the 14 wk monitoring period appears to involve travel from the farm site to the south basin of Lake Wolsey and returning once more to the farm (Figure 3.7).

Although general movement patterns were apparent, there was also large variation in post-dispersal movements among individuals within Lake Wolsey. Throughout the monitoring period fish were commonly detected on more than one receiver per day, (Figures 3.3, 3.7). For example, Fish #48 frequented the detection range of the Farm, South Basin, and Mid Lake receivers for up to 90 days before becoming resident at the farm. Fish #'s 58 & 74 favoured the Mid lake and/or South basin area, and infrequently visited Farm 2 in the case of Fish #74, or left the farm permanently two weeks post-release in the case of fish #58 (Figure 3.7). Interestingly, fish #62 travelled between the South basin, and Mid lake regions for over a month before leaving Lake Wolsey in late June only to return more than two months later to the Mid lake region (Figure 3.7).

3.3.5 Dispersal of Floy-tagged fish

As of May 2010, 86 of the 1000 (8.6%) externally tagged domestic rainbow trout had been reported as captured by anglers since their release in May 2009. Of the 500 fish released from each farm, 35 and 49 were recaptured from Farms 1 and 2, respectively (two returns did not indicate Id #). Many recaptures occurred at the commercial aquaculture release sites but also ranged up to 360 km away (Figure 3.8, 3.9). A majority of fish released from Farm 2 (93%), were angled within a 5 km radius of the release site, with half of all recaptures occurring within 500 m of the farm. Floy-tagged fish from Farm 1 were angled significantly farther away from their site of release (mean ± 1 S.E.: 53.7 ± 16.4 km,) than fish released from Farm 2 (6.3 ± 4.7 km) (Mann-Whitney U test, Z = 2.79, P = 0.005). The distances away from release sites at which fish were captured by angling were more variable for trout released from Farm 1 (0-360 km) compared to those from Farm 2, which had only one individual recaptured >12 km away (Figure 3.8). There was no linear relationship between distance away from site of release and time upon recapture (Figure 3.8). Apart from those fish captured in close proximity to their site of release at the commercial farms, the distances that released rainbow trout were captured were much greater than that of our limited manual tracking efforts (Figures 3.6, 3.8, 3.9).

Floy-tagged fish released from Farm 1 in 2009 were found to have no directional preference in their movements, based on their recapture location (Rayleigh's test, z = 1.05, P > 0.05) (Figure 3.5c). There was no difference in initial body weight between fish that dispersed from the farm compared to those who exhibited site fidelity at either farm (t-test: Farm 1, P = 0.75; Farm 2, P = 0.85).

3.3.6 Habitat of recaptured fish

Angler returns of Floy-tagged rainbow trout were generally reported from near shore areas (<1 km from a shoreline). Including only fish with precise recapture location (n=75), 43% of escapees were caught in the near shore area, 44% at release sites, 5% at other cage sites and 8% were angled in rivers. Floy-tagged fish released from Farm 1 were primarily angled in the near shore area (37%) and at the release farm (33%), but also at other farms (12%) and in rivers (18%). Fish from Farm 2 were split evenly between the farm and the near shore area. Similar numbers of telemetry tagged fish were manually located in both near and off shore areas ($\chi^2 = 0.14$, $p = 0.71$) suggesting sampling bias in the angler returns. Of the Floy returns of Farm 1 fish, 17% were angled in streams and rivers, varying in distance from the mouth to 12.5 km up river. Recaptures were in Whitefish River (23 km from release site), Sauble River (2 fish on separate occasions) (192 km), Nine Mile River (263 km), Riffle River, MI (340 km) and Elk River, MI, (360 km). Five of these recaptures were in the fall or early winter (9 October to 15 December, 2009), and one tagged rainbow trout was caught in the spring (24 April, 2010).

3.4 Discussion

The growing of fishes in open-pen aquaculture operations has resulted in the presence of increased numbers of farmed fish in the wild (Naylor *et al.* 2005, Thorstad *et al.* 2008).

The ecological effects of a release of farmed fish to the surrounding water bodies is one of the largest concerns surrounding open-pen aquaculture, but remains the least well studied, especially in freshwaters (Podemski and Blanchfield 2006; Weir and Fleming 2006). I conducted small- and large-scale escape events of tagged farmed fish at commercial aquaculture operations in the North Channel of Lake Huron to quantify the extent to which escaped rainbow trout disperse from cage sites. I found that most fish dispersed rapidly from the release sites and there were a variety of individual movement patterns as well as population trends. A second key finding was that escaped fish were capable of travelling long distances (>350 km) and occupied a variety of habitats once dispersed.

3.4.1 Dispersal rates

There has been an increase in aquaculture production of salmonids world wide, and a majority of this growth has been in the open-pen industry, which has resulted in greater numbers of farmed fish escaping into surrounding water bodies (Naylor *et al.* 2005, Thorstad *et al.* 2008). The effects of escaped farmed fish to the wild hinges on their behaviour and distribution once released. If a majority of escaped fish remain near the release site their area of impact will be concentrated, and their potential to compete with local species for food, mates, and habitat will be reduced. Therefore, understanding the potential impacts of escaped farmed fish requires quantifying the rate and distance of dispersal away from aquaculture sites. Earlier, I showed that only a small portion (<20%) of telemetry-tagged rainbow trout released from two commercial farms in Lake Huron exhibited site fidelity (see Chapter 2). Concurrent with this finding, I observed that released fish rapidly dispersed away from the farm, within days of release. All fish released dispersed from the farm.

Knowing how quickly fish disperse once released is important in determining feasibility of recapture. Dispersal of fish from Farm 1 in 2009 was especially rapid, with all fish dispersing within 40 hours of release. Similar rapid dispersal of fish has been seen in Atlantic salmon released off the coast of North America, where all fish had dispersed from the release sites within 21 hours, as well as in Atlantic cod released from a Norwegian farm, where over half of the released fish had dispersed in the first 24 hours, and all fish had left the farm in the next 4 days (Whoriskey *et al.* 2006; Uglem *et al.* 2008). Blanchfield *et al.* (2009) also found rapid initial dispersal, with almost all rainbow trout dispersing the farm within the first 2 days after release. My results concur with the literature provided on dispersal of escapees and found rapid dispersal of fish, sometimes within a matter of hours.

Rates of dispersal of farmed fish once released may be influenced by a number of biological and physical processes. As described in the previous chapter, seasonal differences in feeding regimes associated with annual production cycles at aquaculture facilities and water temperatures can both influence levels of site fidelity (Chapter 2). Likewise, I predicted that dispersal rates would be influenced by these same factors. I found differences in dispersal between releases that occurred in different seasons (spring versus summer) at both farms. Dispersal was slower when fish were released in the summer (July 2008) than in spring (May 2009) regardless of release site. Fish released in the summer of 2008 remained at the cage site for approximately two weeks (17 days) prior to initial dispersal, but when released in spring of 2009, left the farm within three days. More rapid dispersal of escapees from aquaculture sites in cooler seasons has been found with summer versus winter release of both Steelhead trout (Bridger *et al.* 2001) and Atlantic cod (Uglem *et al.* 2008) as well as spring versus winter release of Atlantic salmon (Whoriskey *et al.* 2006). It has been suggested that the more rapid dispersal of winter released trout may be associated with a reduced feeding regime at aquaculture sites at this time (Bridger *et al.* 2001). My data on initial dispersal support this idea, as escaped rainbow trout had a more rapid dispersal in spring when production, and hence feeding, at the Lake Huron farms is lower than in summer.

Location of the release site may also influence dispersal and movements of escaped farmed fish. If there are physical or thermal barriers to fish movement within a system, rates of dispersal from a farm, and their subsequent movement decisions may be altered. I found more rapid dispersal and greater distribution of dispersed fish at Farm 1, located in open channel, compared to fish released from Farm 2, which is contained in a lake on Manitoulin Island with only a narrow connection to the North Channel (Fig 1.2). Telemetry-tagged rainbow trout released from Farm 1 dispersed three-fold faster than those from Farm 2 when released in summer and more than six-fold quicker in a spring release. It is possible that fish released from Farm 2 were not able to detect the small channel to larger waters and subsequently returned to the farm within 24 hours. If so, these fish would not be considered as dispersed. This quick lake survey and return to farm was seen with domesticated rainbow trout in the experimental study carried out by

Blanchfield *et al.* (2009). In the present study, high water temperatures (>21 ºC) in the shallow channel (<5 m) and attached bay would have presented a thermal barrier to fish passage in summer months. There are no similar physical or thermal barriers to movement in any direction from Farm 1. There are currently no studies that have examined whether the physical, thermal, and bathymetric parameters of the farm site affect dispersal rates. The low dispersal and limited distances moved of rainbow trout released from Farm 2 compared to Farm 1 suggests that the characteristics of the surrounding water body that fish are released into is an important factor to estimating dispersal rates.

Salmonid fishes have strong olfactory abilities and the presence of other fish farms, hatcheries or rivers are believed to influence patterns of movement by escaped fish (e.g. Bridger *et al.* 2001). In the present study, there are no other fish farms within 90 km of Farm 2; however, there were two other fish farms within ~6 km of Farm 1 that appeared to have influenced fish movement. In 2009, four escaped rainbow trout were located at these neighbouring fish farms. Each of these fish was detected at a farm at least twice, with one fish detected four times over a one month period. Four of the Floy tagged fish released from Farm 1 were also angled at these two farms. Acoustic telemetry studies have shown that escaped farmed fish are present around sites of commercial aquaculture different from their site of original release (Bridger *et al*. 2001; Uglem *et al.* 2010). Escaped fish are attracted to farm sites by the abundance of waste feed (Dempster *et al.* 2009), high densities of natural prey items (Dempster and Taquet 2004), and because a farm may provide shelter from predation (Bridger *et al.* 2001; Dempster and Taquet

2004). Any of these influences could explain the escapees directed movement toward farms in this study.

As I highlighted in the previous chapter on site fidelity, almost all telemetry-tagged rainbow trout released into Lake Huron from commercial sites returned to the farm sites once dispersed. Repeated visits to sites of release by escapees were influenced by the release season, and rates of initial dispersal. After dispersal from the release site, fish were not only quicker to return to the farm in summer than in spring, but more fish returned to the release site. Even at the large open site, Farm 1, the majority of trout (75% and 63% in 2008 and 2009, respectively), returned to the farm after initially dispersing, while almost all (100% and 97%) dispersed fish returned to Farm 2 throughout the monitoring period. Rainbow trout were able to return to their original site of release after spending more than three consecutive months away (Farm 1: 93 days; Farm 2: 102 days). Blanchfield *et al.* (2009) found a similarly high percentage of rainbow trout returning to the cage site in their experimental study, whereas only 40% of farmed cod released in an open fjord returned to the cage site (Uglem *et al.* 2008). Open ocean releases of Atlantic salmon off the coast of Maine, USA, saw no returns of fish to the cage site (Whoriskey *et al.* 2006). The few studies to date show a large variation in return rate of escaped farmed fish to sites of release. In general it is thought that increasing size of water body equates to lower return rates of escapees (see Whoriskey *et al.* 2006; Uglem *et al.* 2008; Blanchfield *et al.* 2009). The findings from this study, carried out in a large system, the Great Lakes, saw a minimum of ~60% of escaped fish returned to the cage site. This suggests that dispersal is likely more complex than water body size alone and that olfaction and the proximity of neighbouring aquaculture operations may also play critical roles.

3.4.2 Movement of fish

The second key question I addressed in this study is how far fish disperse away from aquaculture facilities. I used manual location to find tagged fish once they dispersed from the farms. Maximum dispersal distances were four times greater for rainbow trout from Farm 1 (12 km away) than for fish from Farm 2 (3 km from the farm) in the summer release (2008). This reduced movement of trout from Farm 2 is attributed to the single, relatively small passage to larger waters, as well as an unavoidable shallow region (<5 m) beyond the passage that was a thermal barrier for fish movement at the time they were released (July). No tagged rainbow trout were detected moving through this channel in the 2008 season, restricting them to Lake Wolsey. Fish from Farm 1 had no such geographical or physical barriers to movement and subsequently they were detected farther from the farm. It is important to note that my estimate of the maximum distance rainbow trout dispersed is a conservative estimate because of limitations imposed by equipment and weather.

Increased manual tracking efforts of rainbow trout released from Farm 1 in 2009, I was able to monitor a larger area of the North Channel. Subsequently, trout were located over twice the distance (23 km) away from the farm than they were in 2008. These efforts also allowed for multiple locations of individual fish, providing a glimpse into movement patterns in a larger system. For example, one fish had travelled 19 km from release site over the first 44 days at liberty, and then was detected only 2.7 km from the farm 29 days later. In 2009 the locations of fish displayed a directional preference, with more fish located west of the farm site than east. Manual location was directed to areas with the greatest likelihood of fish detections, potentially biasing the directionality of relocations. These manual location choices were based on where we had previously detected fish, and sites considered to be an attractant to fish, such as other fish farms. Fish locations were also heavily influenced by the restricted daily tracking distances and weather conditions. Having to return to port allowed for maximum daily travel distances of 25-30 km away from the farm site. This distance was often reduced by high afternoon winds, which the North Channel is prone to. Likewise, our routes would often be planned to allow for shelter if required by a change in weather. Both of these factors limited the opportunity to for more extensive forays to examine the distribution of escapee rainbow trout. Longer distance movements of escaped fish than could be detected through manual tracking did occur as evidenced by fish leaving our search area (through gate stations) and by angler returns of both telemetry- and Floy-tagged fish throughout the season. Nonetheless, relocations of fish through manual tracking provided data unparalleled by single return information describing the movements of fish once dispersed from the release site.

Working in the large system of Lake Huron presented limitations to locating escaped rainbow trout. As a result, varying numbers of tagged fish (0-96%) were located only early in the study, or very rarely, if at all throughout the 14 week monitoring period (Figure 3.3). An individual was considered absent when not detected at the release site, during manual location scans, at the gate stations, or reported angled within a period of one week. A majority of fish released from Farm 1 (60-96%) in 2009 fell under this category. The high number of absent fish is likely a reflection on the limited area I was able to search by manual tracking in this large open-water system with many physical barriers (i.e. islands) to fish detections. Further, I observed tagged rainbow trout traveling up to 16 km between detections, so high rates of fish movement likely also contributed to low detections. I located a majority or all of the fish released into Lake Wolsey from Farm 2 in 2008 during a single day of manual tracking, providing confidence in the ability of the manual tracking system to detect fish if they are present. The absence of fish is commonly seen in telemetry studies, and is often categorized as fish that have departed the system (see James and Kelso 1995; Uglem *et al.* 2008, 2010; Lindberg *et al.* 2009).

The manual location of telemetry-tagged fish is a labour-intensive venture that typically allows for limited amounts of data on individual fish, especially when attempting monitoring multiple fish at the same time. Instead, the use of multiple passive receivers allows for an estimate of general movement patterns. In 2009 I installed monitoring stations to follow the movements of escaped rainbow trout within the lake surrounding Farm 2, and to determine if they exited through the narrow channel which connects Lake Wolsey to the North Channel of Lake Huron. This portion of the study allowed a detailed description of post release individual and population movements of escaped fish. Movements between the farm and the south basin were most common in fish, but examples of individual variation such as fish #'s 74 and 58 who travelled more between the mid lake and south basin regions with minimal time spent at the farm were also found

(Figure 3.7). Interesting individual movement was seen in fish #62 who dispersed from the farm, occupied the mid lake and south basin regions for over a month before leaving the lake via the narrow channel only to return to the lake over 2 months later and occupy the mid lake region (Figure 3.7). This variation in individual and population movements is important in assessing potential impact on the local ecosystem as well as providing insight into feasibility of recapture. Knowing the movement of fish between lake regions and the movement patterns between the farm sites and other areas of a lake provide a base of information to organize a recapture effort. Although data of this nature does not pinpoint factors controlling fish movement, it provides a starting point for examining frequented areas and patterns of movement which can give insight to the forces driving fish movement, as well as a better understanding of interaction and competition with other species occupying these habitats.

Because of the limitations of manually locating escapee rainbow trout in a large open-water system, such as the North Channel of Lake Huron, I conducted large-scale releases of externally-tagged fish from the same commercial aquaculture operations to extend the breadth of information on escapee dispersal distance and distribution. Returns of these fish, particularly those released from Farm 1, revealed a much broader distribution than determined through telemetry. For example, Floy-tagged fish were angled up to 78 km away from the release site within two weeks of release. Rainbow trout from the large-scale releases were captured up to 360 km away from their origin and included locations on the south side of Manitoulin Island, on the eastern shores of Lake Huron, and in Lake Michigan (Fig. 3.9). Studies of naturalized rainbow trout movement in the Great Lakes found fish travelling up to 290 km in 94 days in Lake Ontario (Haynes *et al.* 1986) and 20-201 km in Lake Erie (Wegner *et al.* 1985). The range at which Floy-tagged fish from both farms were angled at (0-360 km) shows the ability of escapees to undertake long distance movements on the same scale as naturalized populations, as well as highlighting the limitation of using telemetry data alone. This result shows the rapid ability of farmed fish to pervade the habitat of wild fish, increasing the likelihood of interaction and competition with the Lake Huron fish community.

Incorporation of two complementary approaches – fine-scale telemetry and large-scale external tagging – were necessary to assess initial dispersal and long distance movements made by farmed rainbow trout upon release from commercial aquaculture operations in Lake Huron. Trout dispersed rapidly from the farms and once dispersed showed no directed movement patterns. Fish made both long and short range movements, taking refuge in rivers, near and offshore areas, as well as occupying the release and other near by fish farms. Variation in dispersal rates and aptitude to undertake long distance movements was partially attributed to the difference in location of the farm in a water body and the season of release. Both farm location and release season are important factors when planning a recapture effort. Although small in number compared to a typical escape event, the combination of telemetry and Floy tagging of farmed rainbow trout has provided insight into escapee dispersal in Lake Huron. This study is the first to tackle the initial dispersal, post dispersal movement patterns, and effects of release site and time of escapees to the wild. It highlights the possible range escaped fish can travel in the Great Lakes and saw escaped fish moving into waters far from their release location and into areas where there is no cage culture such as Lake Michigan. This increases the potential area impacted by escaped fish, broadening the implications of a farm release to include management groups well beyond the farming region which needs to be considered in the assessment of effects of escaped fish from Lake Huron.

Table 3.1 Summary information of tagging, initial dispersal, and movement of acoustically tagged rainbow trout released from two commercial aquaculture operations in Lake Huron, Ontario. Movement data (mean distances, range) were collected by manual location of fish. Initial departure and return time data was collected by the farm site receivers.

	2008		2009	
	Farm 1	Farm 2	Farm 1	Farm 2
# fish tagged	10	10	30	40
Mean Wt (g) ± 1 S.E.	897±48	1436±94	780±17	960±25
Mean FL (mm) ± 1 S.E.	387±6	438±8	356 ± 3	389±3
Mean time to initial departure (days) ± 1 S.E.	6.6±2.4	25.6±10.9	4.1±1.4	0.6 ± 0.1
Mean time to initial return (days) ± 1 S.E.	20.5±16.5	3.7 ± 1.3	35.0±11.6	5.2 ± 2.6
# of fish detected at gates	0	0	0	7
# of days manually tracked	9	8	13	1
# fish detected during manual tracking	7	9	18	n/a
# of 2008 fish detected in 2009	n/a	n/a	5	5
Mean distance (km) manually located	4.3±0.8	1.5±0.2	6.9±0.8	n/a
Range of distances (km) fish were manually tracked	0.8-11.9	0.5-2.7	1.0-22.9	n/a

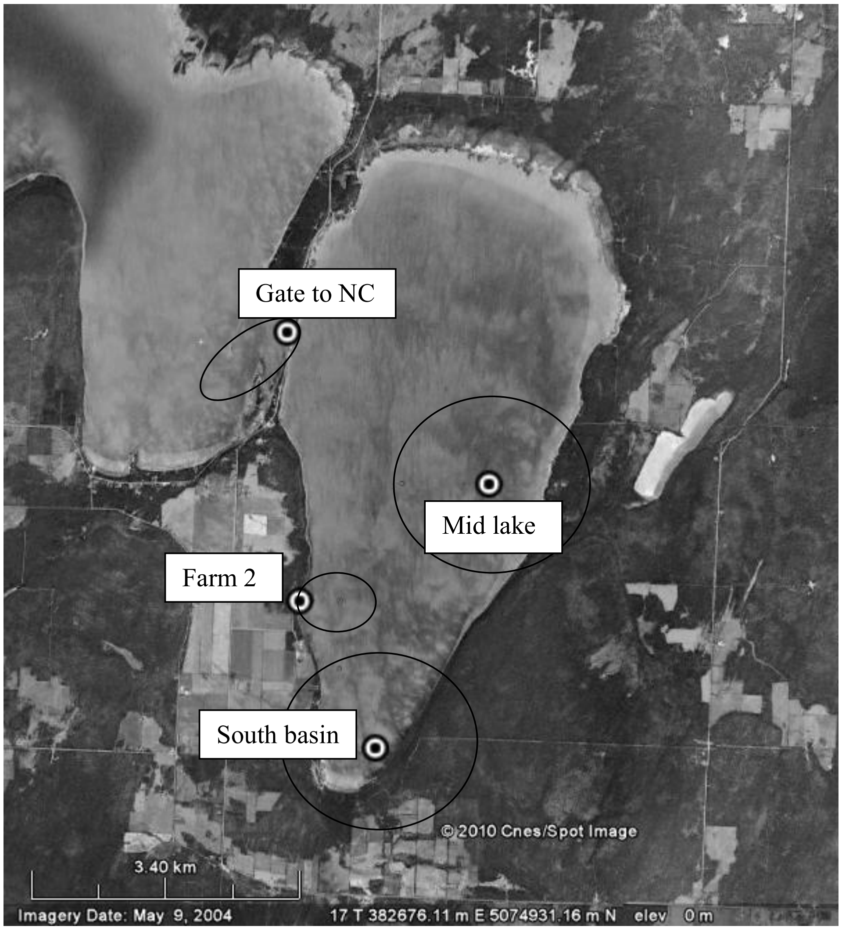

Figure 3.1 Map of Lake Wolsey showing the positions of the four acoustic receivers (black and white circle) used to monitor fish movement throughout the lake. Each receiver is labelled for the area it covered and the large black circle surrounding each receiver indicates the area in which it could detect transmitters.

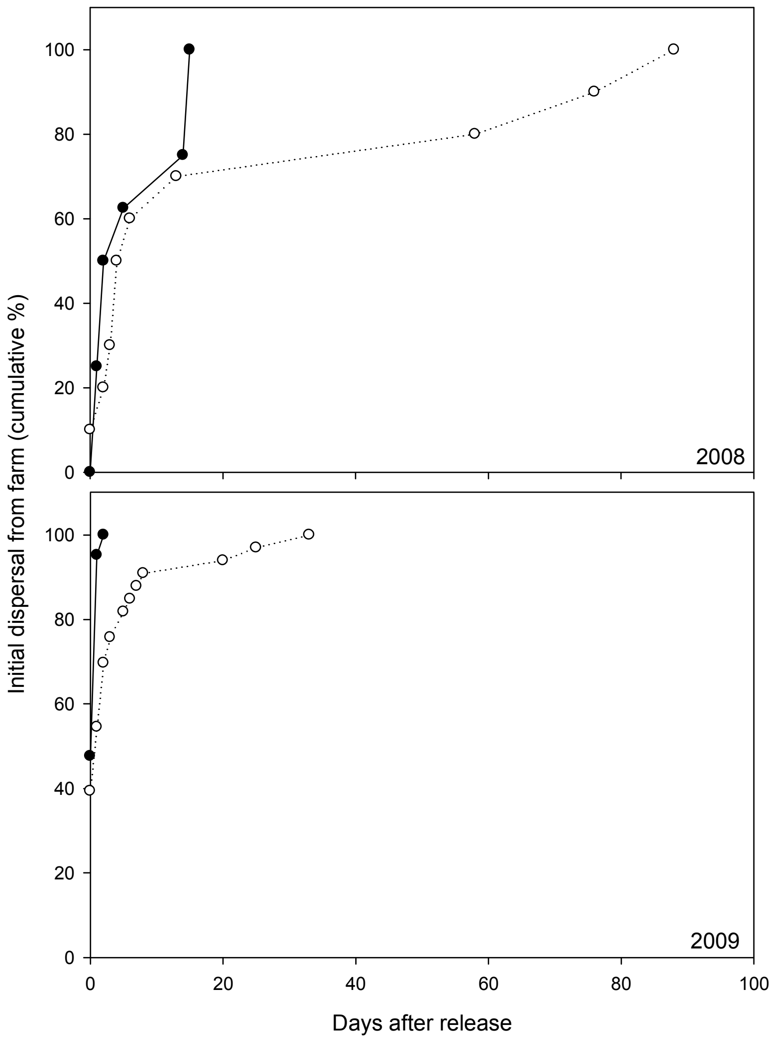

Figure 3.2 Cumulative percentages of acoustically (acoustic and CART) tagged and released domestic rainbow trout that dispersed from Farm 1(2008: n=8, 2009: n=21) (solid circles) and Farm 2 (2008: n=10, 2009: n=33) (open circles) in 2008 and 2009. Initial dispersal was defined as the first time an individual was not detected on the farm receiver for a period of 24 hours.

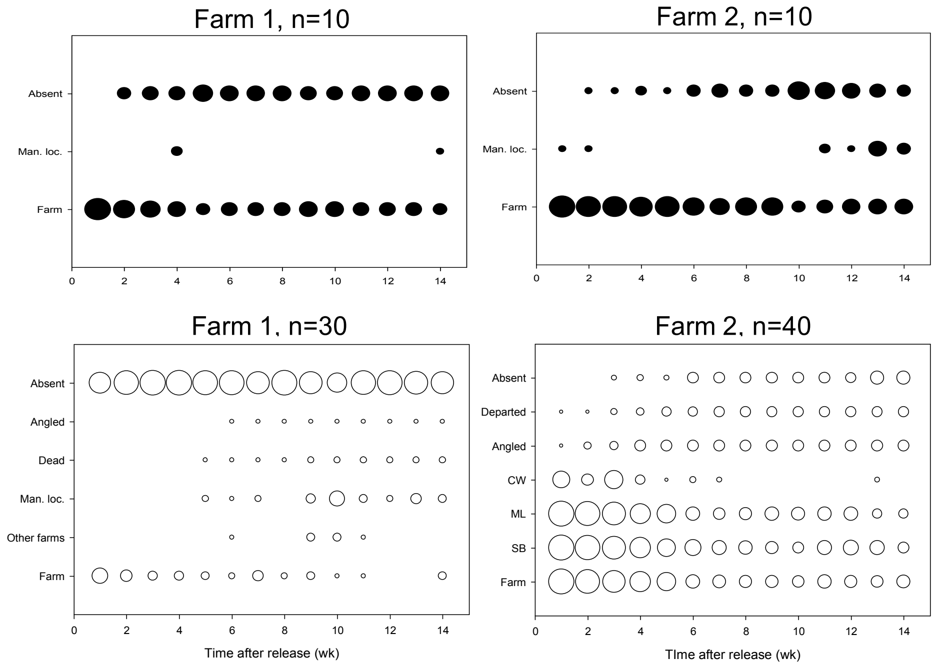

Figure 3.3 Fate and movement of telemetry tagged rainbow trout released from two farms in the North Channel of Lake Huron in 2008 (solid circles) and 2009 (open circles). The size of the circles show the proportion of fish observed in each category, with the smallest circle indicating a single fish, the largest circle representing all fish in 2008, and 26 of 30 at Farm 1 and 39 of 40 at Farm 2 in 2009. Absent = fish was not located within the week by any means, departed = a fish was detected moving out of the system via a gate station receiver, Man. loc. = manually located, Farm = release site. In 2009 at Farm 2 there were 3 other receiving stations set up throughout the system to monitor fish movement (refer to Fig. 3.1). SB = South basin, ML = Mid lake, CW = the gate station from Lake Wolsey to the North Channel.

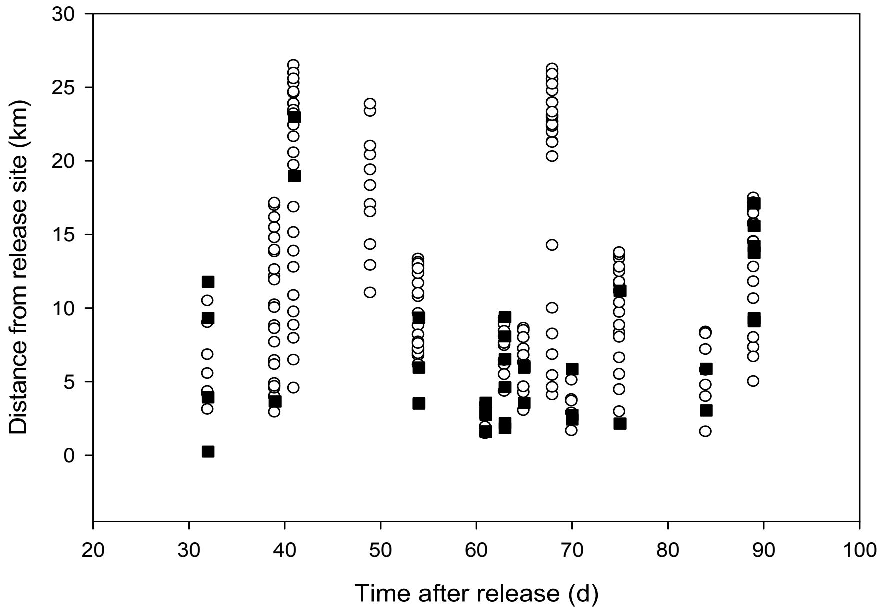

Figure 3.4 Manual locations of rainbow trout with acoustic (CAR) transmitters released into Lake Huron from Farm 1 in 2009. Solid squares indicate fish detection; open circles indicate a sampling location with no fish location.

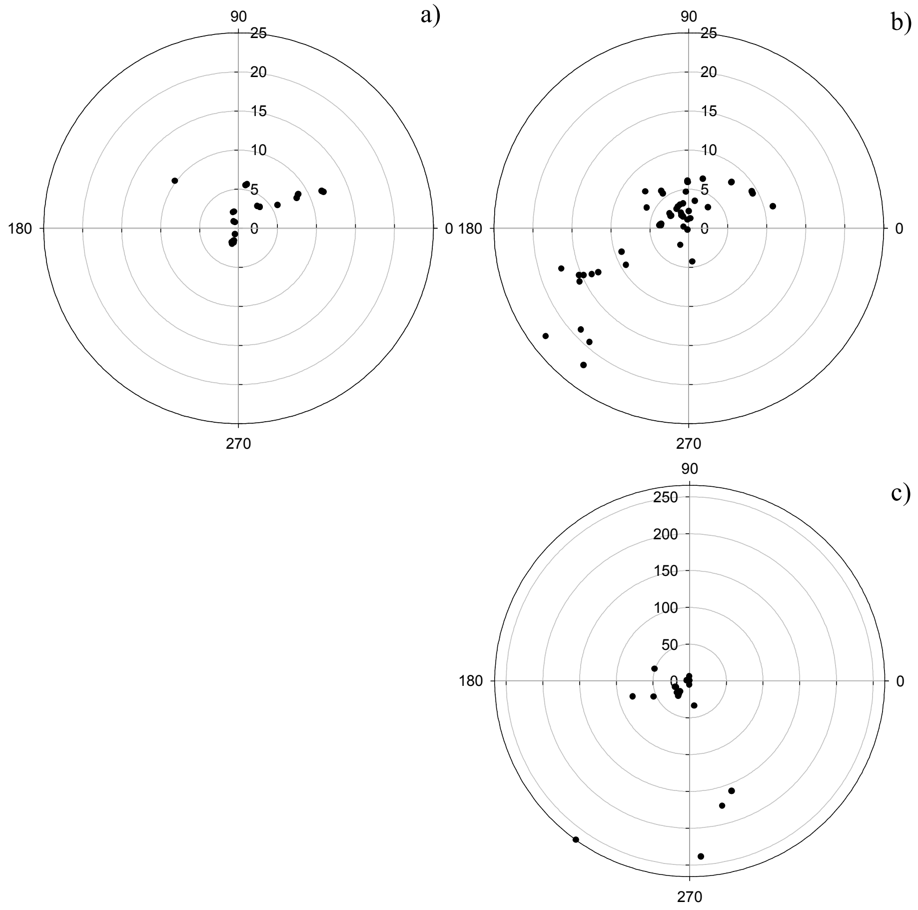

Figure 3.5 Manual location of telemetry tagged domestic trout dispersed from Farm 1 in 2008 a), and 2009, b). Recapture location within Lake Huron of Floy tagged fish released from Farm 1 in 2009 c). The center point of each circle is the location of Farm 1 with the small closed circles representing recapture/manual location position in both distances (km) from release site and direction (degrees from true north) from Farm 1.

a)

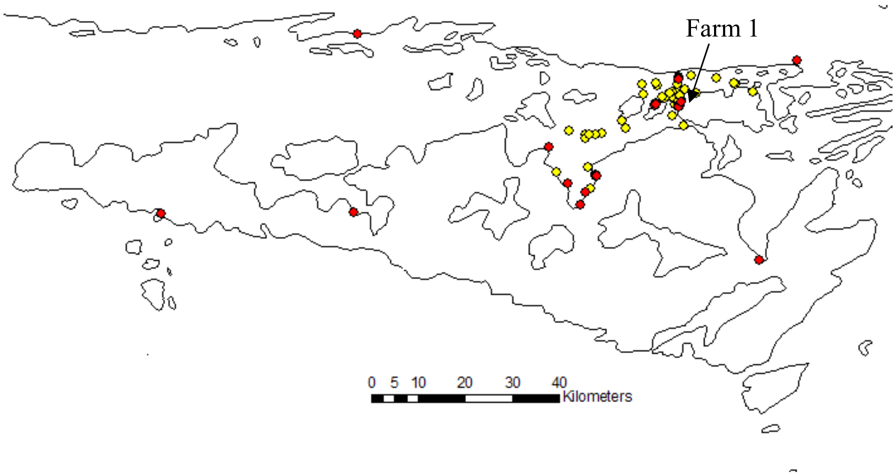

Figure 3.6 Map of Manitoulin Island showing the locations of telemetry tagged fish found manually (yellow circles), and location of angled Floy-tagged fish reported by anglers between May 2009 and May 2010 (red circles). All locations are of tagged rainbow trout released from Farm 1 (location left of the arrow).

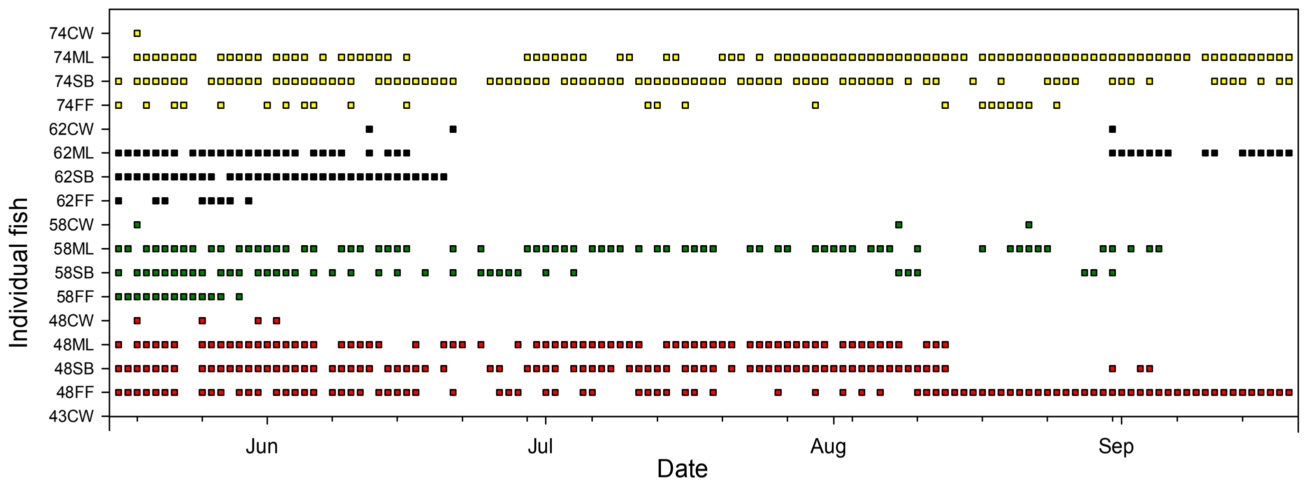

Figure 3.7 Detections of four individual rainbow trout released from Farm 2 in 2009. Fish presence was monitored at each of the four receiver stations set up in Lake Wolsey from 5/16/2009 until 09/19/2009 (CW- the gate station from Lake Wolsey to the North Channel, ML- Mid lake, SB-South basin, FF- Farm 2) (see Figure 3.1). Presence of an individual at each receiver is indicated by a coloured square (Fish #'s 48(red), 58(green), 62(black), 74(yellow)).

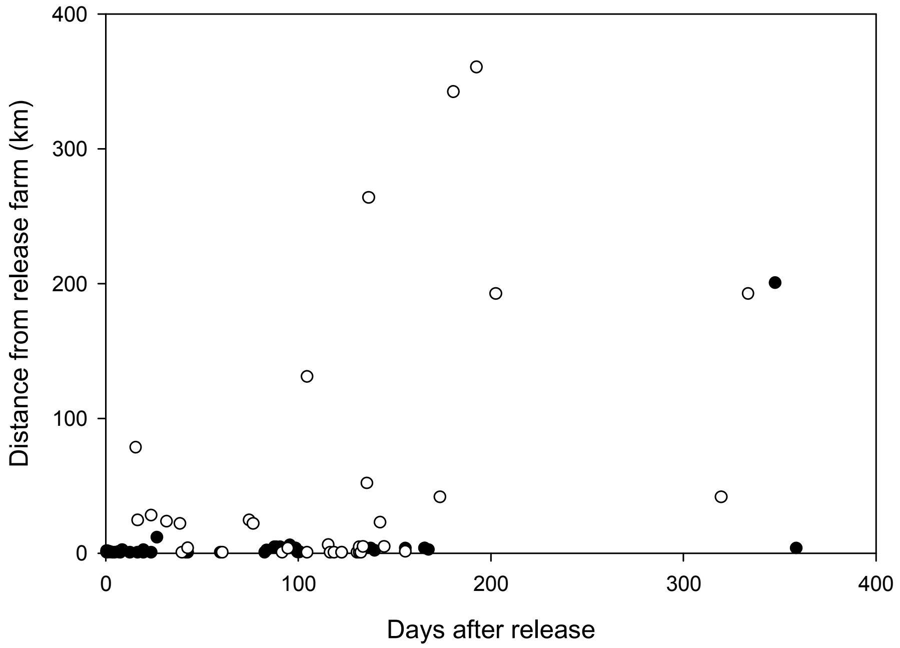

Figure 3.8 Distance away from release sites (km), that Floy-tagged rainbow trout released into Lake Huron from two open-pen aquaculture operations, Farm 1 (open circles) and Farm 2 (closed circles), were angled over time.

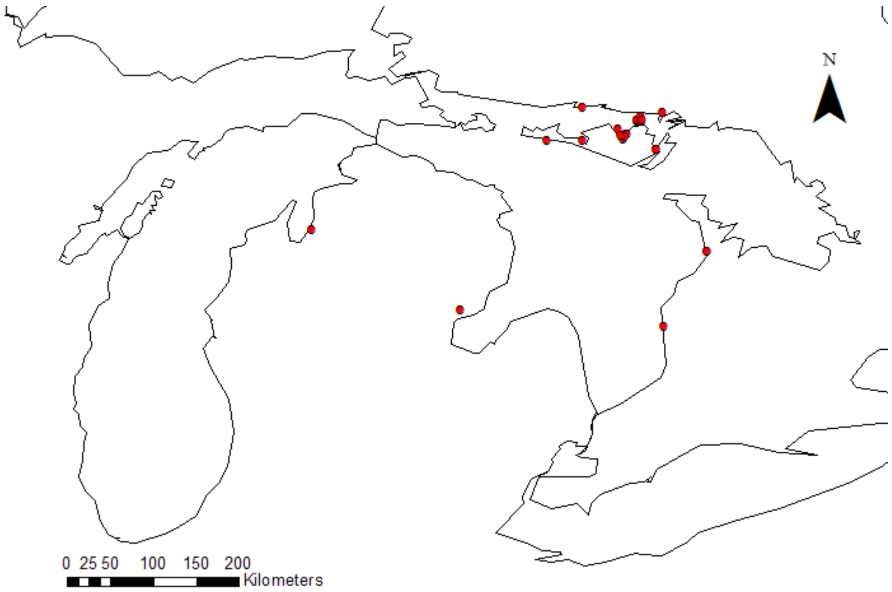

Figure 3.9 Map of Lake Huron (right) and Lake Michigan (left) where Floy tagged farmed rainbow trout were reported angled (red circles). Fish were released from Farm 1 in May 2009 and angler returns were reported until May 2010.

CHAPTER 4: Growth and survival of rainbow trout released from commercial aquaculture operations in Lake Huron

4.1 Introduction

The degree to which farmed fish have the potential to effect their local environment is dependent, in part, on their movement once escaped from commercial aquaculture operations (discussed in Chapters. 2 and 3). These impacts are dictated by the ability of escapees to successfully forage, grow, and survive in the wild. The capacity of escaped fish to successfully forage is central in estimating competition with other species as well as potential food web shifts if specific prey items are being exploited. There exists evidence of lower survival rates of hatchery-reared salmonids compared to their wild counterparts (Fraser 1981; Einum and Fleming 2001; Biro *et al.* 2004, 2006); however, similar studies on escaped farmed fish that quantify survival rate and life-span in natural environments are lacking. Much focus has been directed at the impacts caused by escaped farmed salmonids when they move into rivers during spawning by wild populations, (see Naylor *et al.* 2005; Weir and Fleming 2006; Thorstad *et al.* 2008), but the portion of their life spent in open waters has received little attention. There have been no studies on the impacts of escapees from commercial aquaculture operations in Lake Huron where the Canadian freshwater industry is concentrated.

Rainbow trout have been domesticated since the early 1870's in the USA and have been part of a selective breeding program at the University of Washington, Seattle, since the early 1930's (Donaldson and Olson 1957; Hershberger 1992). As part of these breeding programs, growth was being selected for and the largest fingerlings were used for broodstock (Donaldson and Olson 1957). As a result of long-term hatchery rearing, morphological, physiological, and behavioural changes now exist in hatchery strains of rainbow trout used in aquaculture (Fleming *et al.* 1994; Jonsson and Jonsson 2006).

Long-term fish breeding programs in a hatchery environment has resulted in significant behavioural differences between wild and domestic fish. Specifically, generations of breeding in a predator-free environment has resulted in reduced anti-predator behaviour for a number of salmonid species used in commercial aquaculture operations (Johnsson and Abrahams 1991; Berejikian 1995; Einum and Fleming 1997; Biro *et al.* 2004). Anti-predator behaviour provides a differing competitive ability in domestic fish compared to their wild counterparts (Jonsson and Jonsson 2006). For example, rainbow/steelhead trout have been shown to be more willing to take risks when foraging in the presence of predators, allowing for higher growth rates but in turn significantly reducing their survival rates compared to their wild counterparts (Johnsson and Abrahams 1991; Biro *et al.* 2004). Reduced anti-predator behaviour has also been noted in Atlantic salmon (Einum and Fleming 1997; Fleming and Einum 1997), and brown trout (*Salmo trutta*) (Johnsson *et al.* 1996). Evidence for increased growth rate in farmed fish could lead to increased survival compared to their wild counterparts, but the reduced anti-predator behaviour documented in escapees reduces their survival significantly.

Accurate assessments of survival of escaped farmed fish are a logistically complicated and often resource demanding undertaking. This is especially true in the large water bodies where most open-pen commercial production occurs and when monitoring fish species used in aquaculture that make long distance movements, such as salmonids. To examine the survival of escaped farmed fish, many researchers use mark-recapture studies that rely on returns of marked fish from commercial and recreational anglers, or targeted netting. For example, recaptures of fin clipped Atlantic salmon allowed Saloniemi *et al.* (2004) to estimate survival of domestic fish to be 4.5 times lower than that of wild smolts. Similarly, higher rates of recapture in farmed versus wild cod, suggests an increased susceptibility to angling in domestic fish (Uglem *et al.* 2008). Recapture of marked escapees provides valuable survival information, but selective recapture methods can inherently bias the data and survival estimates derived in this way should be treated with some caution. To date most studies have estimated survival of farmed fish based only on the numbers of fish recaptured through fishing effort. Other sources of mortality, such as predation and natural mortality can make up a significant proportion of losses (Hvidsten and Mǿkkelgjerd 1987). Thus, estimating survival without incorporating other causes of mortality will not provide a complete estimate of survival of escaped farmed fish in the wild.

Compared to conventional mark-recapture programs, telemetry studies allow for repeated detections of individuals over time. As such, the use of telemetry can permit assessment of alternate causes of mortality to escaped farmed fish in addition to only those caused by fish harvest. For example, Whoriskey *et al.* (2006) tagged and released adult Atlantic salmon from a farm in Maine, USA. They observed high rates of mortality (56% and 84%), which they related to the relative abundance of seal predators in the area (Whoriskey *et al.* 2006). Farmed rainbow trout released from a small-scale commercial farm into a small boreal lake in north-western Ontario with no angling pressure had high annual mortality (~50%), with no fish surviving longer than three years post release (Blanchfield *et al.* 2009). They observed most mortality was natural although, predation was also suspected as a cause of mortality of farmed fish (Blanchfield *et al.* 2009). Detailed information on the causes of mortality is only possible with telemetry approaches, whereas conventional tagging methods allow for determination of the fate of farmed fish captured through commercial or recreational harvest. A combination of both mark-recapture and telemetry approaches would provide the strongest estimate of survival because together they encompass a number of pathways through which mortality of escaped farmed fish can occur (Pine *et al.* 2003; Pollock *et al.* 2004).

A strength of conventional mark recapture programs is in the returns of tagged fish released to obtain growth data on escapees. A common disparity between domestic fish used in commercial aquaculture and their wild counterparts is in growth rates. In rainbow trout, the increased growth rate of domestic fish compared to their wild counterparts is well documented (Biro *et al.* 2004, 2006; Reinbold *et al.* 2009) as well as in other salmonids, such as Atlantic salmon (Fleming and Einum 1997; Fleming *et al.* 2002). For example, domestic or hatchery rainbow trout were found to grow to masses twice that of their wild counterparts in laboratory growth trials and in experimental lakes in British Columbia (Biro *et al.* 2006). The greater growth is due to increased appetite and a higher food conversion ratio that has been selected for in the domestic strain of rainbow trout (Biro *et al.* 2006). An increase in appetite aids in driving domestic fish to forage on novel prey in the wild to satisfy their needs once released (Reiriz *et al.* 1998). Successful foraging of domestic fish in the wild has been documented in both Atlantic salmon (Reiriz *et al.* 1998; Jacobsen and Hansen 2001) and rainbow trout (Rikardsen and Sandring 2006) which allows domestic fish to maintain their high growth rates.

The objective of this study is to estimate survival and growth of farmed rainbow trout tagged and released from commercial aquaculture operations in northern Lake Huron. I conducted small- and large-scale releases of farmed rainbow trout to simulate escape events and used a combination of telemetry and conventional tagging approaches to provide the most thorough estimate of survival. My examination of the spatial distribution of escapee rainbow trout showed that farmed fish had low site fidelity to the commercial sites (see Chapter 2). Their recapture in areas far away from any commercial operations more than one year after release, shows that they are able to successfully live in the wild (see Chapter 3). I hypothesize that fish will exhibit low survival (<50%) throughout the monitoring period, and will maintain high growth rates once released to the wild. Specifically, I 1) estimate survival of domestic rainbow trout released from two commercial farms, 2) measure growth rate of domestic fish released to the wild through angler returns, and 3) examine the influence of release site and size at release on both growth and survival of farmed trout. This information is crucial in assessing the potential impact of escapees to the Lake Huron ecosystem.

4.2 Methods

Study site, fish tagging procedures (including transmitter size and details and mean fish sizes per tagging event (Tables 1.2 and 1.3)), and the telemetry monitoring system are detailed in section 1.7.3. In this chapter, I use telemetry information I collected at the farm and gate station receivers, manual location of fish/transmitters, and angler recaptures of tagged fish to examine survival and growth of escaped fish. Telemetry transmitters and Floy tags each contained e-mail or phone contact information along with information to provide on the recapture (length, weight, location). ‘Reward’ was also written on each tag and monetary compensation was offered in return for angler cooperation. Prior to the release of fish, notices were posted in localities with high angler traffic, e.g. resorts, bait shops, boat launches. Interviews with regional newspapers were also conducted throughout the study.

A shore-based creel survey occurred twice a week (once a week at each farm), for 8 hours a day, for 3 months in 2009 (June, July, and August). I designed the schedule and interview forms and my field assistant and project collaborator ran the creel survey. Information was collected via interview regarding the fishing effort (area targeted, number of anglers, hours fished), species sought, angling method, and approximate depth of fish when angled. If tagged rainbow trout were angled, measurements of length, weight and general condition of the fish was recorded. Date and times of each interview were also recorded. A call-in phone number was placed on each tag to receive angler reports outside of the creel census. This phone line is still active and monitored for angler returns year round. A majority of interviews (~70%) were carried out at the shore creel located near Farm 2, and 22% of those interviewed anglers reported targeting the farm area specifically.

In 2009, I also set up wildlife cameras to help assess angling pressure at each farm. These cameras took a time/date stamped snapshot of each farm once an hour, 24 hours a day. Each photo was examined for fishing boats, and then numbers of anglers were counted. This took place from May 8 to August 31, 2009.

4.2.1 Survival

Mortality of rainbow trout once released into Lake Huron was determined as follows: 1) angler return of a telemetry transmitter or a Floy tag (see below); (2) lack of movement of a telemetry transmitter; the tag remains in same location, determined by manual location or farm receiver stations, with a consistent power reading; or 3) recovery of a transmitter, e.g. on shore or shallow waters. I considered the time of death of individual fish as the date of initial detection for the latter two scenarios, which I confirmed with either tag retrieval, or reoccurring detection of a transmitter. Transmitters were recorded at the farm sites from 2 July to 18 October 2008 (108 days), and 12 May to 19 September 2009 (130 days). Manual location of transmitters took place from release until October 13 2008 and August 12 2009. Survival and fate of fish released in each season was determined at the end of each full monitoring period. In 2008 this ran from July 2 to October 18 2008 and from May 15 to August 25 in 2009. Any fish detected after the monitoring period was considered alive in our monitoring period. For example, if I had not detected a fish manually or at the stationary receiving stations by the end of the monitoring season, then it would be categorized as “unaccounted for”. If that particular fish was angled past the end of the monitoring period, it would instead be categorized as “alive”. Transmitters inserted in 2008 remained active throughout the 2009 season and the location of those individuals in the following year was used to estimate long-term survival.

4.2.2 Growth

Growth (and survival) information on recaptured escapees was collected through angler cooperation at a shore-based creel census, or reporting of fish captures through e-mail or a phone call. Once an angler reported a captured fish I would initiate a phone or e-mail interview to obtain required details, which followed the same format of the shore-based creel interview. All information gathered from angler returns was standardized into metric units and compared to initial fork length (FL) (mm) and weight (Wt.) (g) taken at tagging time. Measurement of length (methodology unknown) reported by anglers was assumed to be total length (TL) and was calculated to fork length (FL) through the following equation:

$FL = 0.9391*TL+0.155$ (Sturgess and Moyle 1978).

These steps were taken to provide the best estimate of rainbow trout growth from their initial release to time of recapture. Because I was not able to weigh and measure recaptured rainbow trout there are potential inconstencies in angler-reported measurements and the results I present should be interpreted as a best estimate of growth in escaped fish.

4.2.3 Statistical analysis

I estimate survival of domestic rainbow trout released from two commercial farms. In this analysis I include all telemetry-tagged fish released into Lake Huron from the two commercial farms (Farm 1 and Farm 2) over the two field seasons (2008 and 2009)(n=120). Three of the 120 telemetry fish were never detected after release and have been omitted from all subsequent analyses. At each farm 500 Floy-tagged fish were released. Angler returns of farmed fish provided an approximation of fishing mortality in Lake Huron, and the recapture locations allowed estimates of numbers of escapees leaving the system. This information was combined with known mortality detected through telemetry monitoring to provide realistic estimates of overall survival. Correlation between initial size at release and time to mortality was examined with a Spearman's rank correlation coefficient to look at influence of release size on survival.

The growth of domestic fish released to the wild was documented through angler returns. Absolute growth rates (g/d, mm/d) were calculated for fish returned with length, weight, and recapture date information provided. Initial size at release was regressed against growth rate in a linear fashion to determine if there was any effect on the growth of fish based on their starting weight. Mean growth rates of escapees were compared between farm sites to determine the influence of release location on growth in the wild.

All data sets were tested for with the Shapiro-Wilk's test for normality, and the Brown-Forsythe test for homogeneity of variances. All results were analyzed in Statistica v. 6.1, (Statsoft, Inc., Tulsa, USA) using a combination of parametric and non-parametric tests (specified in results). Bonferroni correction was applied when multiple comparisons were made within the same data set.

4.3 Results

4.3.1 Survival

The fate of all telemetry-tagged rainbow trout (n=117) released into Lake Huron from the commercial farms at the end of each 3 month monitoring period showed 52% of fish alive, 15% dead, and the remaining fish (33%) unaccounted for (Figure 4.1a). Of the mortalities (n=17), five were due to unknown causes, two caused by predation, and the majority (n=10) were attributed to angling. Beyond the monitoring period (>3 mo) there were 7 further recorded mortalities. These new cases of mortality were largely angling (6 of 7), with one unknown cause of death. Based on these additional returns, overall mortality of telemetry-tagged fish was 21% at the end of the study (May 2010).

Specific fates of all released fish are listed in Table 4.1. Predation on farmed rainbow trout occurred in both years with tags recovered from the nests of an osprey (*Pandion haliaetus*) and a double-crested cormorant (*Phalacrocorax auritus*). These were first detected 7 d and 54 d after release. The osprey nest was in close proximity (< 3 km) to Farm 2, where that fish originated. However, the tag found wound into the cormorant nest was 8 km away from Farm 1, where the fish had been released from. Angling accounted for the largest fraction of known mortality, a majority of which were from Farm 2 (8 of 10). An additional 4 fish (2 from 2008, 2 from 2009) were angled in the post monitoring period. Mean angling time for all telemetry tagged fish was 95 ± 25 d post release (range 6-351). Angling pressure assessed by the wildlife cameras captured 18 boats fishing near the Farm 1, with an estimated 23 anglers in the 115 days monitored (~1 boat/week). The camera located at Farm 2 captured 278 boats with a possible 550 anglers (~17 boats/week). One-third of fish were 'unaccounted for' (25% in 2008, 40% in 2009), meaning that they were not reported angled throughout the season nor detected by any telemetry means anytime in the last two weeks leading up to the end of the monitoring period.

Considering all telemetry-tagged fish, size at release did not appear to influence survival. There was no difference in initial fish size between fish that survived (n=54) and those known to be dead (n=24) (t-test, FL: t = 0.71, P = 0.48; Wt.: t = 0.70, P = 0.49). Fish mass at release was not correlated with how long a fish survived before being angled (Spearman r = -0.29, P = 0.32).

There was variation in fate of fish between farms, and between release seasons. A majority of fish (80%) released from Farm 1 in 2008 were alive at the end of the monitoring period compared to the 50% known survival from Farm 2 (Figure 4.2). The fate of telemetry tagged fish released from Farm 1 dramatically differed in 2009, with less than half of the known survival rate of 2008 (38%), an increase in mortality (from 5% to 13%), and large increase in numbers of "unaccounted" fish. Fish tagged and released from Farm 2 held similar fates between the two seasons (Figure 4.2). For those that were angled, fish released from Farm 1 survived longer (mean ± 1 S.E.: 153 ± 43) before angling than those from Farm 2 (53 ± 23) (t-test: t = -2.04, P = 0.04).

Four fish released from Farm 1 were still alive and present at the farm from 328 to 480 d post release. These fish were located at both the farm site and also manually located within 5 km of the farm. Three additional fish (7 total) were located manually 306 to 406 d after their release up to 13 km away from the Farm 1. No fish from 2008 were detected at Farm 2 in 2009, but one day of manual location in Lake Wolsey found four surviving fish (alive 369-377 d post release). All 2008 fish detected in 2009 were considered alive and continuing to survive past these dates.

From time of release, 25 May 2009, until 22 May 2010, 86 of the 1000 (8.6%) Floy-tagged fish have been angled (all returns are from angling). Details and analysis of angling location are discussed in Chapters 2 and 3. Four of the returns had incomplete recapture data information and have been excluded from further analysis. Floy-tagged fish (n=82) were angled, on average, 92 ± 10 days after release (mean ± 1 S.E). Body mass at release influenced survival of Floy tagged fish. Angled rainbow trout were significantly larger (772.3 ± 19.3 g) upon initial release than those not captured by angling (n=914) (716.5 ± 5.4 g) (t-test, $t = 2.94$, $P = 0.003$). Within the group of fish that were angled, a larger fish mass at time of release was correlated with how long a fish survived before being angled (Spearman $r = 0.22$, $P = 0.049$).

Floy-tagged fish released from Farm 1 (n=500) were significantly larger than those released at Farm 2 (n=500)(t-test, $t = 2.03$, $P = 0.043$)(see Table 1.3). Farm 1 tagged fish survived longer before being caught (mean ± 1 S.E.: 120 ± 12 d, median 123 d) than fish released from Farm 2 (70 ± 13 d, median 24 d)(Mann-Whitney U test, $Z = 3.82$, $P < 0.001$). The first fish from Farm 1 was angled 16 days after release, with only 3 fish reported in the first 30 d. In contrast, 40% of fish angled from the Farm 2 release were recaptured in the first 2 weeks post release and over half (53%) of all returns occurred within the first month (Figure 4.3). There was no release site specific correlation between how long a fish survived and size at release (Spearman r, F1: $p = 0.12$; F2: $P = 0.56$).

My estimate of survival has been adjusted based on the location of angler returns of Floy-tagged fish. Of all Floy tag returns, 15% were from outside of the range in which I was able to successfully monitor via manual location, gate stations, and the farm receivers. Based on the finding that 15% of Floy-tagged fish dispersed outside of the monitoring range, I assume that similar numbers of telemetry tagged fish from the same population could have also dispersed outside of range. Incorporating the Floy-tagged data with the telemetry data, my revised estimate of rainbow trout survival (up to 3 mo) is ~67% (Figure 4.1b).

4.3.2 Growth

A total of 16 telemetry-tagged fish were angled 6-351 days post release. Three of these returns were excluded from analysis as they were angled in the first two weeks post release (acclimation period), two returns provided no recapture information, and one return only provided the recapture mass, leaving ten fish with complete growth information (length and mass). On average there was positive growth in both length (FL) (60 ± 35 mm) and mass (Wt.) (306.7 ± 181.7 g) of all fish. The greatest growth was seen in a fish recaptured 351 d after release who had grown from 360 to 715 mm and more than tripled in mass from 705 to 2381 g. Mean growth rates were positive, yet highly variable, for fork length (0.17 ± 0.19 mm/d) and mass (0.50 ± 1.17 g/d).

A majority of Farm 1 fish maintained positive change in length (5 of 6) and mass (4 of 6) compared to Farm 2 (2 of 4 for length, 1 of 4 for mass) (Figure 4.4). While fish recaptured from Farm 1 had positive growth rates (0.30 ± 0.25 mm/d and 1.91 ± 1.65 g/d) and Farm 2 fish did not (-0.02 ± 0.28 mm/d and -1.62 ± 0.99 g/d) there was no significant differences in growth rates between the two groups (length: t-test, t = -0.84, p = 0.43; mass: Welch's t-test, t = -1.62, p = 0.15).

Of the 86 Floy-tagged fish recaptured, 61 returns provided full recapture information (date, mass, length). Eight of these 61 returns were excluded from analysis as they were angled in the first two weeks post release (acclimation period), leaving 53 fish with complete growth information. On average there was positive growth in both length (FL) (68 ± 8 mm) and mass (399.7 ± 56.7 g) of all fish (mean ± 1 S.E.). The greatest growth was seen in an individual fish recaptured 320 d after release who had grown from 332 to 573 mm and tripled in mass from 770 to 2325 g. Mean growth rates were positive for both fork length (0.52 ± 0.07 mm/d) and mass (3.13 ± 0.66 g/d) of all recaptured Floy-tagged fish.

Floy-tagged fish released from Farm 1 obtained similar overall growth to those released from Farm 2 in both FL (Farm 1: 79 ± 10 mm; Farm 2: 53 ± 12 mm) and mass (Farm 1: 396.2 ± 63.2 g; Farm 2: 404.6 ± 105.6 g) (t-tests, FL: t = 1.66, P = 0.10; Wt: t = -0.07, P = 0.94) (Figure 4.5). A majority of Farm 1 fish maintained a positive change in length (30 of 31) and mass (27 of 31) with a greater number of Farm 2 fish exhibiting individual negative growth (4 of 22 for length, 5 of 22 for mass) (Figure 4.5). The only notable difference in growth of fish released from two different farms was a significant difference in growth rate. Rainbow trout from Farm 1 grew almost twice as fast (0.64 ± 0.06 mm/d) as those from Farm 2 (0.35 ± 0.14 mm/d) (t-test, t = 2.08, P = 0.04). The initial size at stocking did not influence growth rate in escaped fish (regression, F = 0.10, P = 0.75). Based on recapture location, there was no difference in growth rates of fish who dispersed from the release sites compared to fish that were angled at the farms (mm/d: p = 0.27; g/d: P = 0.86) (Figure 4.6). There was also no difference in growth rates (mm/d or g/d) of fish tagged with telemetry or Floy tags (t-test, P > 0.05).

4.4 Discussion

The global demand for fish protein cannot be met by capture fisheries and subsequently there has been an increase in global aquaculture production (Bohgen 1989; Naylor *et al.* 2000). This industry growth has been met with many environmental concerns, particularly nutrient inputs and the introduction of farmed fish (native and non-native) to the local ecosystem through escape events (see Gross 1998; Yan 2005). Assessing the potential ecological impacts of farmed fish to aquatic systems requires an understanding of the fate of the escaped fish once they are released. This information is especially needed for the freshwater aquaculture industry in Canada, in which no assessment of escaped fish has occurred. I monitored the fate of telemetry- and Floy-tagged rainbow trout released from commercial operations in the North Channel of Lake Huron. I found that survival was low for escaped rainbow trout and most known mortality was through recreational angling. Fish were also capable of maintaining growth rates seen in cage culture once released in the wild.

4.4.1 Survival

Estimating the survival of escaped farmed fish is critical in assessing the potential risks these fish pose to native ecosystems. I estimated short-term survival (3 months) of farmed rainbow trout released from commercial open-pen aquaculture operations in Lake Huron, the site of most freshwater production in Canada. Overall, the survival of telemetry tagged rainbow trout was low, with about half of released fish surviving to the end of the three month monitoring period. Naturalized populations of rainbow trout in the Great Lakes generally have a life span from 3-7 years, which is longer than the < 2 years seen in the ~50% survival observed by farmed fish in this study (MacCrimmon and Gots 1972; Scott and Crossman 1973). Survival in the present study was slightly higher than survival of tagged Atlantic salmon released from a farm in Maine, USA, which found 16-44% of fish surviving once released into oceanic waters (Whoriskey *et al.* 2006), but substantially lower than results found in a study carried out in a small experimental lake in which no mortality was observed in the first 3 months of monitoring of escaped farmed rainbow trout (Blanchfield *et al.* 2009).

The low level of survival reported in this study (50%), would lead one to assume that the mortality of farmed rainbow trout released into Lake Huron was high. Contrary to this assumption, only 15% of released fish were confirmed dead. The primary source of mortality was through recreational angling, but predation was also observed. Predation of rainbow trout by both osprey and cormorant was confirmed in this study with the location and removal of telemetry transmitters from two nests. Susceptibility to predation may be attributed to the loss of behavioural and physical traits that have occurred through a century of domestication of salmonid fishes used in aquaculture. For example, decreased swimming behaviour (Reinbold *et al.* 2009) and a reduction in anti predator-behaviour (Johnsson and Abrahams 1991; Einum and Fleming 1997; Biro *et al.* 2004) observed in hatchery salmonids decrease their ability to escape a predator. Selection for reduced anti-predator behaviour has resulted in domestic rainbow trout selecting much riskier habitat and having reduced survival compared to their wild counterparts (Johnsson and Abrahams 1991; Biro *et al.* 2004). In the present study, 20 of the telemetry transmitters implanted had a pressure sensor to record fish swimming depth. Released rainbow trout were mostly found in the upper three meters of the water column (65% of fish depth detections). In fact, almost half (45%) of all escapee detections were in the upper 1 m of the water column. These observations suggest that farmed rainbow trout released into Lake Huron spent the majority of time in habitats that would make them highly susceptible to avian predation. A similar lack of appropriate habitat selection (surface waters) has been observed in other rainbow trout studies (Warner and Quinn 1995; Blanchfield *et al.* 2009).

Although there were cases of observed predation throughout this study, the estimate of 2% should be considered a minimum. I was able to detect predation only in rainbow trout that were implanted with radio transmitters, which constituted 66% of transmitters used in this study. All transmitters used at Farm 2 in 2009 were acoustic only, providing no estimate of predation from fish released into Lake Wolsey in that year. There are large double breasted cormorant colonies situated near each farm site and other nesting birds of prey throughout Manitoulin Island and the north shore of the North Channel. I also observed cormorants feeding directly on escaped rainbow trout at the cage sites. Because aquaculture operations are targeted by cormorants that may travel long-distances, I strongly suspect that mortality due to predation was under-estimated for the released fish in this study.

The release of a popular sport fish to a system will undoubtedly pique angler interest. I found angling to be the most common cause of mortality for telemetry-tagged rainbow trout released from the commercial farms in Lake Huron, even though angling deaths were only recorded in the 2009 season. Overall there were 16 fish angled, accounting for two-thirds of the mortality seen in the farmed rainbow trout. At the end of the three month monitoring period there was a 4-fold difference in angler returns of telemetry-tagged fish between release sites but by the end of the study in May 2010, 60% of angled rainbow trout were from Farm 2 and 40% from Farm 1. In 2009 Farm 2 also saw a greater number of Floy-tagged fish angled, although the difference is less substantial (Table 4.1). Rates of fish removal through angling are comparable to farmed rainbow trout released into a lake, 21% (Linberg *et al.* 2009), as well as with tagged adult cod released into a fjord, 28-52% (Uglem *et al.* 2008, 2010). The greater portion of fish angled at Farm 2 may be in part due to location. Farm 2 is the largest aquaculture operation in the North Channel of Lake Huron, and is situated within a 2300 ha lake. Fish farms have been shown to attract aggregations of wild fish and/or escaped fish (Carss

1990; Dempster *et al.* 2002, 2009; Johnston *et al.* 2010) and I consider this to be true at this farm, based on the large numbers of fish I observed around this site.

Aquaculture operations are an attractive destination for anglers because they attract large numbers of native and escaped farmed fish. Current Canadian regulations require anglers to remain 30 m away from freshwater farms in Lake Huron, and operators are required to place a series of buoys around their farms to denote this angling limit. The higher rate of angled fish released from Farm 2 can be attributed to increased angling pressure recorded from higher numbers of anglers frequenting the area and camera evidence of the increased presence of fishing boats and anglers. This evidence suggests that differences between angling between the farms is driven by angling pressure, and not a difference between farm stocks, although this difference is not apparent with Floy tag returns (58% Farm 2, 42 % Farm 1).

If fish are capable of long-term survival, their potential to impact the system they have escaped into is much larger. I was able to estimate long-term survival (1+ yr) for telemetry-tagged rainbow trout released in 2008 (n=40) as their transmitters continued to be functional through the following field season. Survival of this group of fish (~30 %) was lower than what has been found for farmed rainbow trout during a multi-year study in a small lake (33-50%, Blanchfield *et al.* 2009) and after ~9 months in a 4700 ha lake (48%, Lindberg *et al.* 2009). In my study, only 20% of those released in 2008 were known mortalities by the end of the monitoring period in 2009, while ~50% of fish were unaccounted for. Of the Floy-tagged fish released in May 2009, there have been 5 reports of fish exhibiting long-term survival; angled 320-359 days post release. Due to the nature of these external tags, information from angler returns of Floy tagged fish will continue to provide long-term survival information about farmed rainbow trout in the wild.

The difference in survival seen in my study compared to the other aquaculture research may be explained by the design and nature of the study system. I found low survival compared to the experimental work by Blanchfield *et al.* (2009) which can largely be attributed to angling and study system size. Although they found no mortality in the first three months after release, angling pressure was absent, and their study lake was a small and closed system. While survival was low in our released fish, mortality was not high, and a large proportion of tagged trout remained unaccounted for at the end of our study. Due to the large study area, I found overall that one third of released fish were unaccounted for after 3 months of monitoring. The addition of Floy-tagged fish provided evidence that farmed fish are capable of making long distance movements similar to naturalized species and the large proportion of unaccounted for fish could be alive and outside of our monitoring system. Based on these assumptions, survival rate should be considered a minimum estimate.

4.4.2 Growth

Growth of escaped fish in the wild is important as it is a direct measure of the ability of a farmed fish to forage in the wild. Recaptures of tagged fish showed positive growth rates, with individuals growing up to 15 g/d in the wild. This has been seen in both juvenile and adult farmed rainbow trout released into experimental lakes (Biro *et al.* 2004, 2006;

Blanchfield *et al.* 2009). Jonsson *et al.* (1993) found that growth in escaped rainbow trout in Norway varied inversely with size at release, but I saw no evidence of growth varying among different sized fish in my study.

Fish farms have been considered optimal feeding habitats (Tuya *et al*. 2006; Uglem *et al.* 2008), so higher growth rates for fish that remained at the farm would be expected. There was no evidence of growth benefit between fish that dispersed from the farm compared to those who showed site fidelity to their release site. The shallow depth distributions seen at the farms also do not suggest fish present are feeding on waste or excess feed fallen to the bottom of the cages, although it is possible they are taking up excess feed in the water column. The ability of these fish to maintain high growth rates demonstrates that escaped rainbow trout were able to forage and survive in the wild as fish were capable of tripling their initial mass and maintaining growth rates up to 15 g/day without relying on the farm for sustenance.

Rainbow trout released from aquaculture operations in Lake Huron showed high but variable growth while at large. Although growth was variable among individuals, the population of escaped fish exhibited positive growth rates overall. Some individuals grew at rates greater than achieved when held in aquaculture operations (see Austreng *et al.* 1987). A high growth rate of aquaculture escapees in the wild is a major concern for the competition and exploitation of resources. This study provides evidence of successful foraging in farmed fish once escaped from a fish farm in Lake Huron. Although fish were capable of successfully fulfilling their heightened appetite, the result of low survival found in domestic rainbow trout suggests that the potential impact of an escape event may be of less concern than originally anticipated.

Table 4.1 Fate of telemetry- and Floy-tagged rainbow trout released from two commercial aquaculture operations in Lake Huron in July 2008 and May 2009. Data on survival of telemetry fish is from the known fate of each group at the end of 108 and 102 day monitoring period, July 2 to October 18, 2008, and May 15 to August 25, 2009 when manual location of individuals ceased. Return of Floy tags by anglers occurred from May 25, 2009 through to May 22, 2010.

	Telemetry				Floy	
	2008		2009		2009	
Fate	Farm 1	Farm 2	Farm 1	Farm 2	Farm 1	Farm 2
# tagged	20	20	40	40	500	500
Alive	16	10	14	21	n/a	n/a
Unaccounted for	3	7	21	11	465	451
Angling	0	0	2	8	35*	49*
Predation	0	1	1	0	n/a	n/a
Unknown mortality	1	2	2	0	n/a	n/a

* there were 2 additional fish reported angled without tag Id information provided and not included in these angling numbers

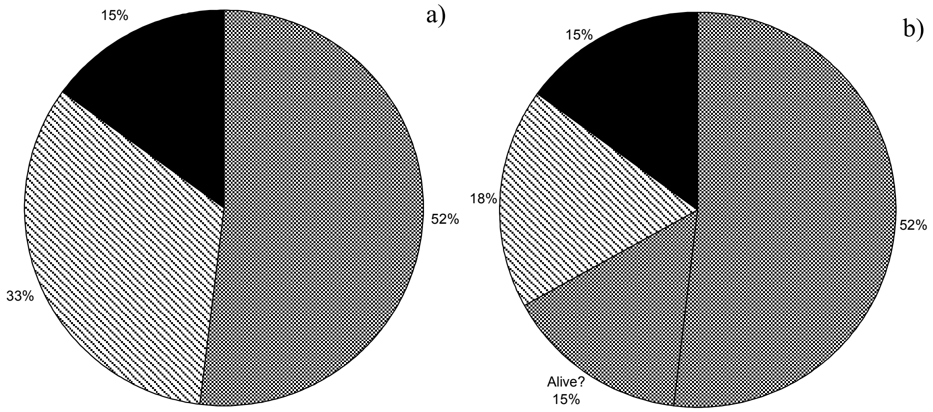

Figure 4.1 Fate of telemetry-tagged farmed rainbow trout (n=117) released from two commercial operations in Lake Huron and monitored from July 2 to October 18, 2008 and May 15 to August 25, 2009 a). Percentage of fish that were alive (dark grey), dead (black), and unaccounted for (white with black stripes) are displayed a), and b) takes into account the numbers of fish dispersed outside of the monitoring range based on returns of Floy-tagged fish (see Chapter 3) and categorizes them as ‘alive’ opposed to ‘unaccounted for’.

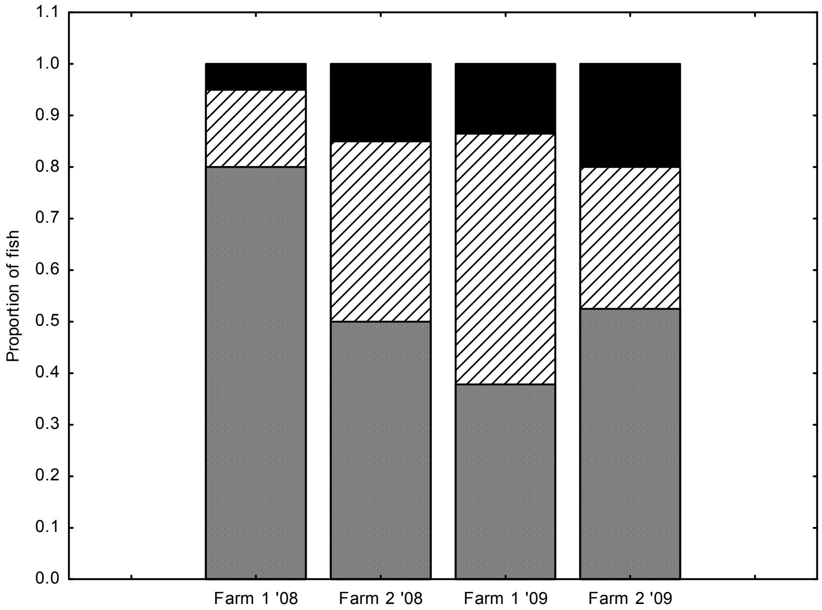

Figure 4.2 Fate of telemetry tagged farmed rainbow trout released from two commercial aquaculture operations in two release seasons in Lake Huron. Fish from Farm 1 and Farm 2 were monitored from July 2 to October 18, 2008 and May 15 to August 25, 2009. Proportions of fish that were alive (dark grey), unaccounted for (white with black stripes), and dead (black), are displayed.

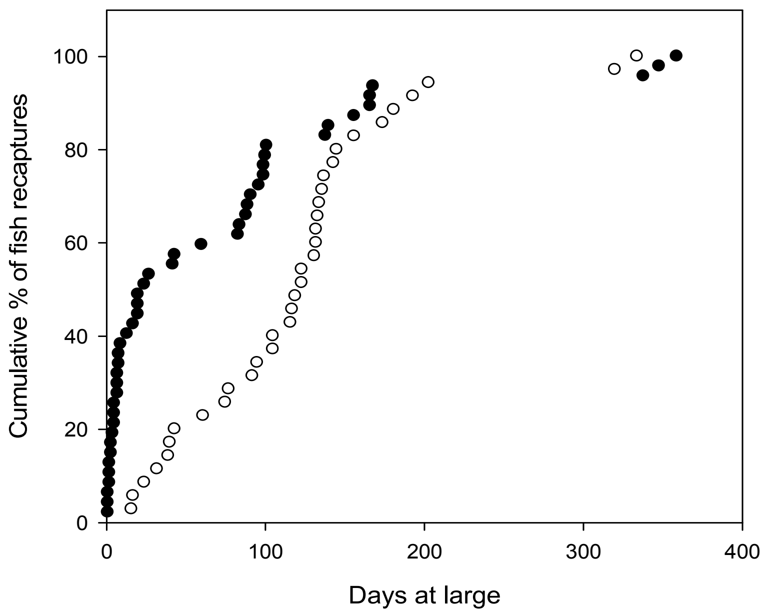

Figure 4.3 Cumulative percentages of angling recaptures of Floy-tagged farmed rainbow trout released in May 2009 from Farm 1 (solid circles) and Farm 2 (open circles), two commercial aquaculture operations in Lake Huron.

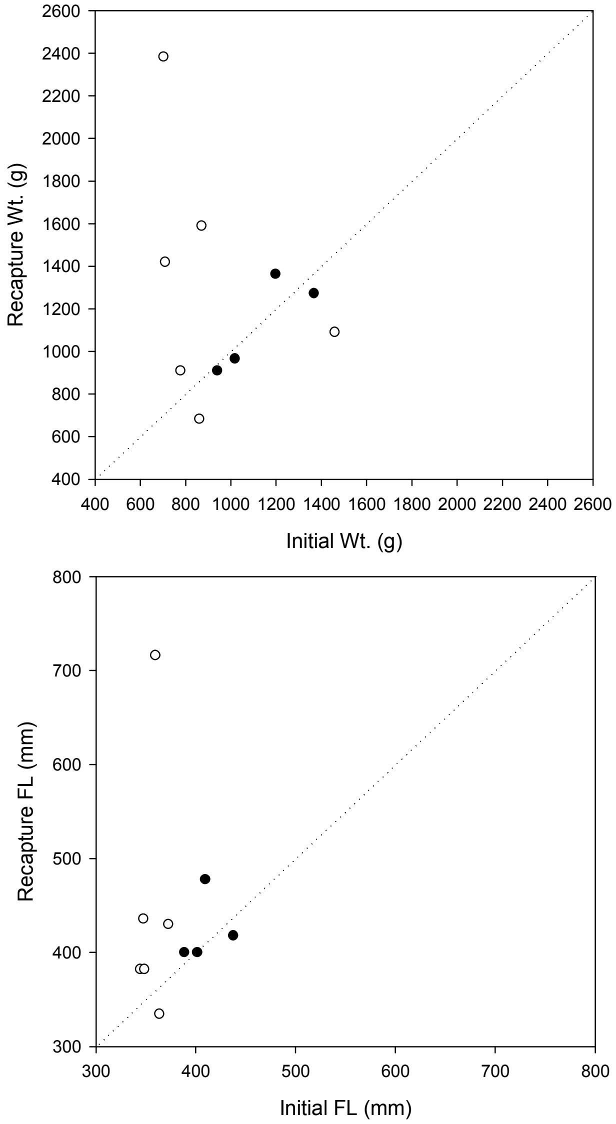

Figure 4.4 Growth of telemetry tagged rainbow trout released from two commercial aquaculture operations in Lake Huron: Farm 1 (open circles) and Farm 2 (solid circles). Fish were angled 6-351 days post release. Data points below the dashed line representing the one-to-one ratio indicate negative growth.

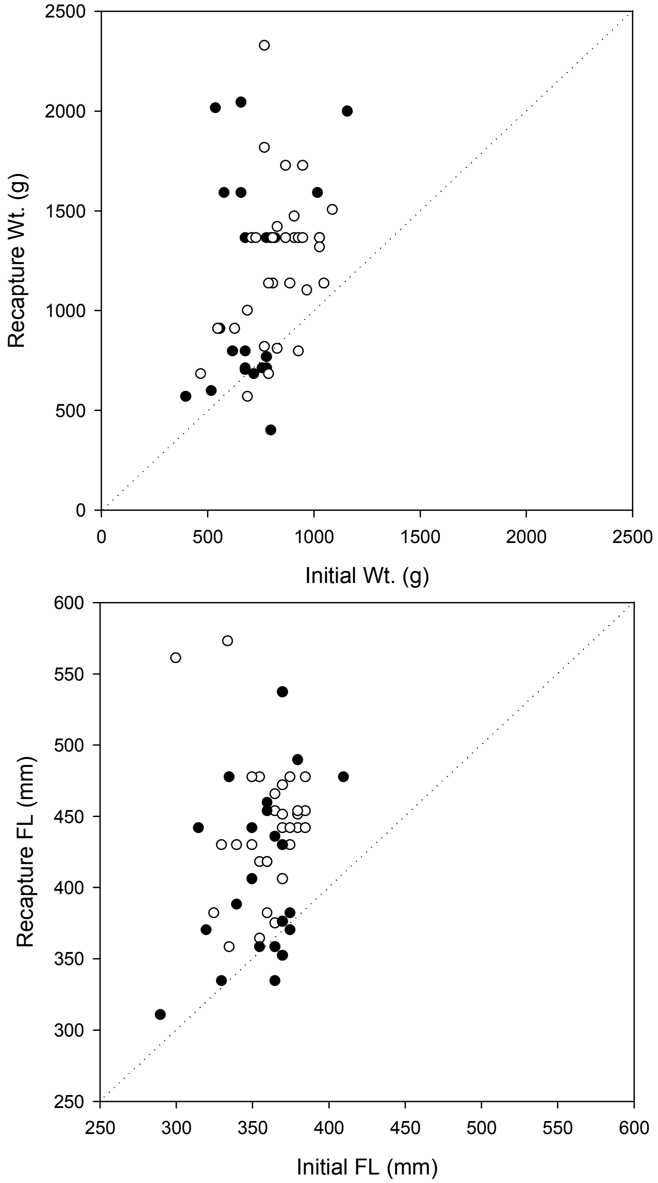

Figure 4.5 Growth of Floy tagged rainbow trout released from two commercial aquaculture operations: Farm 1 (open circles) and Farm 2 (solid circles). Fish were angled 1- 359 days post release. Data point below the dashed lines representing the one-to-one ratio indicates negative growth.

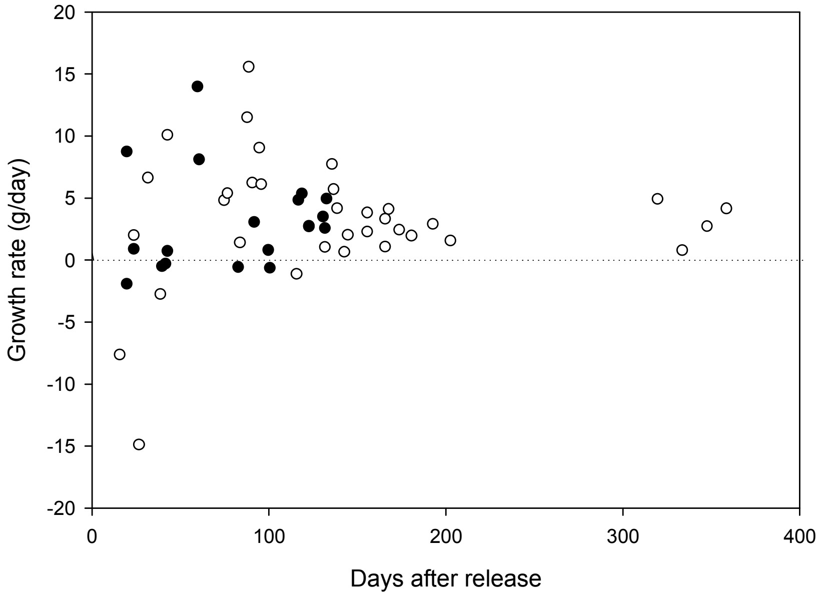

Figure 4.6 Growth rate of Floy- tagged rainbow trout released from two commercial aquaculture operations that were angled at the farm sites (solid circles) or away from the farm sites(dispersed)(open circles). Fish were angled 1- 359 days post release. Data point below the dashed line indicates negative growth rates.

CHAPTER 5: Synthesis

5.1 Overview

Since the mid-1960's, there has been a substantial increase in the commercial open-pen farming of salmonids. Despite preventative measures, growth in the aquaculture industry has resulted in increased numbers of escapees entering the wild (Naylor *et al.* 2005). The loss of farmed fish to the wild represents a considerable financial loss to the operator and poses a number of environmental concerns. The genetic and disease related effects of escaped fish have been well documented experimentally and in the wild (reviewed in Weir and Fleming 2006; Thorstad *et al.* 2008). The magnitude of these effects may be significantly reduced if escapees have poor survival and exhibit high levels of site fidelity to commercial aquaculture operations, yet examining factors such as these has received limited research interest. The regulatory bodies that govern the aquaculture industry need to understand the ecological impacts and potential risks that farmed fish pose to sustainably manage this industry.

Open-pen aquaculture has been occurring in Canadian freshwaters for over 30 years, contributing 45% of the freshwater production (DFO 2007). These farms produce rainbow trout and contribute ~$16 million annually to the Canadian economy (Moccia and Bevan 2007). The bulk of this production (70% or ~4000 t annually) is from a small number of farms located in the North Channel and Georgian Bay areas of Lake Huron, Ontario (Figure 1.2). It is estimated that 2-5% of farmed fish escape from freshwater operations each year (Phillips *et al.* 1985), which would be ~80,000 to 200,000 individuals at the present production values. A more recent estimate of escapees specifically entering Lake Huron suggested an annual loss of 7000 to 10,000 individuals (Dobiesz *et al.* 2005), which is equivalent to 0.25% of annual production.

Growth in the freshwater aquaculture industry has ceased, remaining at a near constant level of production over the past decade (Figure 1.1). Uncertainty surrounding environmental concerns associated with commercial freshwater aquaculture, and corresponding legislation, is a contributing factor to this lack of growth. In the wake of these concerns there have been recent reviews on the potential impacts of open-pen freshwater aquaculture to aquatic systems aimed at identifying gaps in our scientific knowledge (Yan 2005, Podemski and Blanchfield 2006). In response, the federal government has funded research directly aimed at trying to fill these gaps in scientific knowledge. A major experiment was conducted that involved running a commercial operation (10 t) in a small lake at the Experimental Lakes Area (ELA) for a 5-year period to examine the potential impacts of aquaculture on freshwater ecosystems (Findlay *et al.* 2009; Kullman *et al.* 2009; Rooney and Podemski 2009). The question of impacts of escaped rainbow trout were part of this whole-ecosystem study (Blanchfield *et al.* 2009); however, the small size of the study system (23 ha) did not allow for an assessment of large-distance fish movements or mortality through angling. The potential impact of escaped farmed fish remains one of the major concerns surrounding the Canadian freshwater aquaculture industry, yet there has been no large-scale study to assess these impacts in the water bodies where commercial operations occur.

The purpose of this study was to determine the fate of farmed rainbow trout released from commercial aquaculture operations in Lake Huron. I simulated small- and large-scale escape events with a combination of telemetry and external Floy tags over two field seasons. Receivers at each farm monitored site fidelity and allowed for estimates of time to dispersal of telemetry-tagged rainbow trout. I located fish by boat using a manual receiver to locate fish once dispersed from the farm sites. In addition, receiving stations were set up at small channels to document fish passage outside of the study area into larger bodies of water (Figure 1.2). Farmed rainbow trout were released and monitored by the above methods for 3 months in both 2008 and 2009. Growth and recapture location of escapees was collected through angler returns of Floy- and telemetry-tagged fish. This combination of approaches allowed for a thorough assessment of the movement, behaviour, survival and growth of farmed rainbow trout from commercial aquaculture operations.

The main findings of this study are as follows:

1. Site fidelity of escaped rainbow declined upon release. Within days of release only half of fish were present at the cage site. A stable resident population of escaped fish (~15-20%) remained at the cage sites.
2. Long-term site fidelity (>1 year) to the aquaculture pens was observed in telemetry fish.
3. A majority of released rainbow trout dispersed from the farm sites once released into the surrounding water body, and the initial dispersal of fish was rapid (hours).

4. A majority of escaped fish (82%) who dispersed returned to the release site at least once, even after departing for up to 102 days.
5. Rainbow trout exhibited long range movements, travelling up to 360 km away from the release site.
6. Escaped fish occupied near and off shore habitat and were detected at other commercial aquaculture operations and rivers.
7. Survival of escaped rainbow trout in the wild was ~50%, although individuals were found capable of long term survival (>1 year). Recreational angling and avian predation were the main sources of mortality to escaped fish.
8. Escaped farmed fish were capable of maintaining and surpassing growth rates found in cage culture once released to the wild.

Due to the nature and design of the study I was able to assess the influence of release season (summer versus spring) and farm location (semi-contained system of Lake Wolsey versus open water body- the North Channel of Lake Huron; Figure 1.2) to the fate of escapee rainbow trout. Although this was not the main focus of the study, the following observations on escapee behaviour were made:

1. Site fidelity was higher to a farm in a semi-contained system (Farm 2, 10-25%), compared to an open system (Farm 1 0-10%).
2. Site fidelity was higher when fish were released in summer than in spring, regardless of release site.
3. Dispersal was more rapid from Farm 1 than Farm 2 in both release years, and when fish were released in the spring.

4. Dispersal distances were significantly farther for fish released into an open system (Farm 1), compared to those released from Farm 2.

While not the main focus of this thesis, differences in the seasonal timing of release events between study years and the very different location of farms allowed for a broader understanding of escapee behaviour in my study. Moreover, inter-year and inter-farm comparisons helped to shed light on some potential factors that may influence escapee behaviour in Lake Huron-North Channel system. I point out that, while these patterns are interesting, findings should be treated with some caution as fewer individuals were monitored in the first pilot season (n=10) and there is no replication of study sites.

5.2 Site fidelity

The escape of farmed fish from commercial aquaculture operations presents an immediate financial loss to the farm operator and a threat to wild fish stocks with who the escapees would be in competition with for resources. A key question for the industry is how long escaped fish remain in close proximity to commercial operations in order to determine the feasibility of recapture. I simulated small- and large-scale releases of tagged farmed rainbow trout to quantify site fidelity to commercial farms. Fidelity to cage sites decreased rapidly; within days of release only half of the original population remained at the farms. A small proportion (~15%) of escaped rainbow trout remained around the cages and were considered to be a "resident" population that exhibited high site fidelity, Detailed monitoring of telemetry fish showed novel behaviours: >80% of fish returned to the release site once dispersed and individuals returned to the farm on 1-23 separate occasions over a three month monitoring period. Together, these findings suggest that any recapture effort by commercial operators would be most successful if done immediately following an escape event.

5.3 Dispersal

Understanding dispersal rates and patterns of escaped farmed fish is important for similar reasons to those of site fidelity. Initial dispersal of fish from a release site is vital in estimating recapture potential, but more importantly, quantifying dispersal allows for an assessment of the distance farmed fish can travel and the habitats they occupy outside of the farm, giving a more complete view of the potential area of impact. Farmed rainbow trout released into Lake Huron departed from the farms after 6.3 days after release, on average. Time to dispersal ranged from hours to months among individuals, but every fish departed the farm for at least 1 day. Fish were found to make long distance movements and 11% of returned Floy-tagged fish were angled >50 km from their release site (range 50-360 km). Angler returns of tagged fish allowed for a broad habitat use estimate. The majority of returns came from the release sites (44%), and near shore habitats (43%), and 5% of fish angled at other fish farms, and 8% in rivers.

5.4 Survival and Growth

Survival of escaped farmed fish once in the wild is the most important determinate of potential impacts. Quantifying fish movement, foraging ability, and habitat selection are vital in estimating the effect of farmed fish in the wild, but one first has to understand the probability of those fish surviving and contributing to such effects. I found low overall survival (~50%) of farmed rainbow trout at the end of a three month monitoring period.

Mortality (15%) was attributed to angling, predation, and unknown causes. Because one-third of fish were unaccounted for, my survival estimate should be considered a minimum value. The capture of escaped rainbow trout with Floy tags located outside of the monitoring range suggests that at least a portion of the ‘unaccounted’ telemetry fish were potentially alive (Figure 4.1b).

Fish bred for use in aquaculture have higher food conversion ratios and subsequently higher appetites and growth rates than wild fish. The growth of farmed fish in the wild is indicative of their ability to successfully forage and satiate their increased hunger outside of the pen. Recapture data of angled Floy-tagged fish revealed that escaped rainbow trout maintained high growth rates, similar to fish being held in cages, once released into Lake Huron. Based on the shallow depth distribution of fish at the cage, it is unlikely that escapees are feeding on waste faeces, but are likely feeding on waste feed suspended in the water column. There was no evidence of higher growth in escaped fish that were angled near fish farms compared to those that dispersed. My data show that escaped rainbow trout were able to maintain high growth rates while consuming native food sources.

5.5 Potential impacts of escapees

The large release of fish from commercial aquaculture operations in Lake Huron can result in substantial economic losses to the independent farmer. If a recapture effort can be organized prior to fish dispersion, the loss could be minimized. My findings of low site fidelity and rapid dispersal of farmed rainbow trout immediately after release suggest that any recapture effort would need to be done immediately to be effective. The time limitations to coordinate such an effort, and the large area into which fish disperse, make it is unlikely that recapture efforts would be very effective. Atlantic salmon (*Salmo salar*) recapture efforts employing both recreational and commercial fisheries after an escape event have yielded <3% of the escapees and the evidence suggests it may be unrealistic to recapture a significant amount of those released (see Thorstad *et al.* 2008). A more recent study suggested continued effort (up to 4 weeks) employing trawler fishing vessels and recreational fishers using gill nets in a 40 km area around the farm sites yielded much greater returns (40% of released fish)(Skilbrei and Jørgensen 2010). The observation that most released rainbow trout returned to the farm sites after leaving suggests that a sustained trapping effort in Lake Huron could be an effective strategy at reducing the number of escapees at large following an escape event. There is no commercial fishery for rainbow trout in our study area and the staff and equipment available to carry out a recapture effort is reduced compared to a large scale salmon farm.

Fish distribution in the water column was monitored at the farm sites in 2009. A majority of detections of fish were in the upper three meters, suggesting they are not consuming fish waste, but potentially waste feed. As high growth rates were maintained throughout the study where low site fidelity to the farm was observed, it is clear that farmed fish released into Lake Huron are actively foraging in the wild and, therefore, are expected to be competing with naturalized and wild fish stocks for resources. Escaped rainbow trout targeted nearby fish farms, as has been observed in another study on this species (Bridger *et al.* 2001), and suggests that they are attracted to these sites as a food source. However, only a small percentage of escaped trout were present at neighbouring farms, instead the majority of fish released from the commercial aquaculture operations were quelling their appetite with wild prey. Escaped fish were also located in a variety of habitats (near shore, off-shore, alternative fish farms, and rivers), increasing the likelihood of interaction and competition with wild conspecifics and other local species for food and space. Hatchery selective breeding programs produce rainbow trout with increased appetite and reduced anti-predator behaviour compared to wild conspecifics (Johnsson and Abrahams 1991; Einum and Fleming 1997; Biro *et al.* 2004). Subsequently, juvenile rainbow trout make use of risky, food-rich habitats that result in high growth but high mortality through predation (Biro *et al.* 2006). My data suggest this is also happening in large rainbow trout escapees (~1 kg), which were most often detected in shallow waters (0-3 m) and prone to avian predation. Increased appetite may also make farmed fish more susceptible to angling, which was the greatest source of known mortality. Survival of escaped fish was estimated to be ~50% after 3 months, although the high proportion of fish unaccounted for (~30%) could alter this statistic dramatically. Presently, I estimate survival of farmed rainbow trout to be low in the wild, which would lower any impact to the local ecosystem.

Although small in number compared to a typical escape event, the combination of telemetry- and Floy-tagging of farmed rainbow trout has provided valuable insight into escapee behaviour in Lake Huron. This study is the first to examine multiple factors influencing the impacts of rainbow trout escaped from freshwater commercial operations and illustrates limited site fidelity, high rates of dispersal, long-distance movements, low survival and high growth rates. These are fundamental data when attempting to estimate potential impacts of escapees in natural systems. A fine-scale habitat assessment and extensive monitoring of fish movements throughout the North Channel, Lake Huron and Georgian Bay was not possible in this study, but would be important in understanding competition and food web changes caused by escaped farmed fish. The positive growth rates estimated from angler returns of fish indicate successful foraging in the wild in a short period of time. The survival found in this study is to be taken as a minimum estimate, and future research should focus on obtaining precise survival rates and causes of mortality in escaped farmed fish.

5.6 Implications of this research to the aquaculture industry

There is no question as to whether farmed fish escape from their pens, but the impacts and concern related to such introductions are widely unknown. This study has provided a basis of evidence to state that escaped rainbow trout show low site fidelity to commercial operations, and instead disperse and travel, sometimes great distances, while successfully foraging to maintain elevated growth rates.

Rainbow trout is a non-native species to the Great Lakes and is stocked annually into Lake Huron. As such, interbreeding of aquaculture escapees and naturalized populations of rainbow trout is not a major concern for the maintenance of these populations (C. Wilson, Ontario Ministry of Natural Resources, personal communication). In the past decade over 5.7 million rainbow trout have been stocked into the lake by provincial and state governments (FWS/GLFC 2010). In recent years the numbers of naturalized rainbow trout being stocked into Lake Huron have decreased to ~500,000 per year. The recent estimate of the number of fish escaping from aquaculture operations in Lake Huron ranges between 7000 and 10,000 fish annually (Dobiesz *et al.* 2005) and other freshwater estimates suggest 2-5% of fish escape annually (Phillips *et al.* 1985). A release of 5% of production could account for half of the number of rainbow trout entering Lake Huron in a year. Escaped fish are able to maintaining high growth rates seen in cage culture once released to the wild which make them capable of growing twice the mass of a naturalized rainbow trout in the wild (Biro *et al.* 2006). This increased consumption of resources could put significant pressure on the Lake Huron ecosystem if the numbers of escaped fish is large.

In summary, I showed that rainbow trout released from commercial aquaculture operations in Lake Huron have limited site fidelity, high rates of dispersal, long-distance movements, low survival and high growth rates. As the first study assessing impacts of Canadian freshwater aquaculture escapees I feel that these data provide a strong basis for understanding the potential risks that farmed fish may pose to the Lake Huron fish community and ecosystem. Based on the findings of this study, low releases of farmed fish should have minimal implications to the Lake Huron ecosystem, but large releases, in the order of 5% of production, could put pressure on the available resources. I strongly urge the combination of stringent escapee reporting by commercial operators and the inclusion of escapees in population monitoring programs used in stocking density decisions by provincial governments to mitigate any potential impacts of escaped farmed fish to Lake Huron.

APPENDIX I. Transmitter trials to estimate fish presence at aquaculture field sites in Lake Huron

I.1 Background

Biotelemetry allows the remote sensing of a number of physiological and behavioural variables of an animal, or the environment surrounding it. This occurs through the transmission of a radio or acoustic signal from the transmitter attached to the organism in question. Transmitters are individualized by different frequencies of pulses that are detectable by acoustic or radio receivers. Noise pollution, water depth, and obstructions in the water column can all reduce or distort the transmission sent by the tagged fish and need to be accounted for to accurately assess the probability of detecting a fish in your study system.

Commercial aquaculture operations range in size, fish biomass, construction materials, and depth. Potential transmitter interference from the large numbers of fish held at each of the commercial aquaculture operations where I conducted this research (200 thousand fish) and associated industry noise required testing of all telemetry equipment to quantify distances over which transmitters could be successfully detected and decoded. I conducted a number of trials in varying environmental conditions to test the capacity of the receiving system with the specific goal of determining fish presence at the cage site, I used this transmitter trial data for decision making related to system deployment and data interpretation.

I.2 Methods

I.2.1 Detection range of farm receiver stations

I conducted a series of detections trails during each field season (2008 and 2009) to determine the ability of the stationary receivers to detect and decode transmitters in and around the aquaculture facilities (farms)(Figure 1.2). A Lotek receiving station was deployed at each farm and was comprised of the following: a 6-element Yagi radio antenna placed on shore; an omni directional LHP_1 hydrophone; a sonic upconverter to convert the ultrasonic transmitter to an RF frequency that can be received and logged by the receiver; an ASP_8 for multiple antenna switching so the receiver can gather information by alternating scan times of the radio antenna and the hydrophone; and an SRX_400 receiver. Each of the farm stations were powered by a sealed 12 v marine battery connected to a solar panel for continual charging. Thus, the Lotek receiving station at each farm continually monitored for both radio and acoustic signals being transmitted from Lotek radio or combined acoustic-radio (CAR) transmitters. In 2009, Farm 2 additionally had a Sonotronics submersible ultrasonic receiver (SUR) with internal power attached at the same location as the Lotek equipment. The Sonotronics SUR is equivalent to a hydrophone and detected only Sonotronics acoustic transmitters. The quantity and specifications of transmitters implanted into farmed rainbow trout and released at each of the farm sites are described in Table AI.1.

Trials were conducted at each farm and consisted of lowering a transmitter to varying depths (0-15 m) at 10-13 locations (Figure AI.1). Trials were conducted for all transmitter types: radio; acoustic; and CAR. Additional trails were conducted by boat from 0-15 m away from the cages. To determine the ability of the farm receivers to successfully decode a transmitter, a trial was run in a specific time slot, and the receiver was downloaded and processes for tag detections within that time frame.

I.2.2 Detection rates between acoustic and radio transmitters

In August 2009, transmitters previously returned by anglers were placed at a depth of ~7 m at each farm (locations 10 at Farm 1 and 14* at Farm 2; Figure A1.2). One radio and one CAR transmitter were placed at Farm 1, while one pressure-sensing acoustic and one straight acoustic transmitter were placed at Farm 2. All stationary transmitters were left in place for a period of 3 weeks to determine variability in detection and decoding.

Comparisons between numbers of radio and acoustic detections were made for CAR transmitters at each farm in 2008, and Farm 1 only in 2009. This information was gathered from both dummy transmitters and tagged fish showing site fidelity.

I.3 Summary of results

I.3.1 Detection range of farm receiver stations

In the 2008 trials, the radio transmitter was detected at 6 of the 10 locations on Farm 1 and 7 of the 13 locations on Farm 2. The maximum distance to which the radio transmitter was detected and decoded by the receiver was 34 m at Farm 1 and 91 m at Farm 2. The trials conducted off of the cage site by boat resulted in no detections at either Farm 1 or 2. Overall, the farm radio receivers had a limited detection range (<150 m) and an inability to detect and decode radio tags at depths >3 m (Table AI.2).

In the 2009 trials using CAR transmitters, the acoustic portion of combined transmitter had a greater range than the radio, being decoded at 7 of 10 locations around Farm 1 at depths up to 15 m compared to the 3 locations with reduced depths that the radio component was decoded (Table AI.2). At Farm 2, where the Sonotronics acoustic system was employed, the range of the straight acoustic transmitters was 144 m (locations 5 and 6) from the receiver consistently at depths of 8 m (Table AI.2, Figure AI.1). This detection distance for the Sonotronics acoustic transmitter was equal to complete coverage of Farm 2, including all cages and walkways. Acoustic trials conducted on the outside of the cage demonstrated that the aquaculture operation was a barrier for successful decoding of transmitters. The maximum distance a Sonotronics acoustic transmitter was decoded on the opposite side of the farm as the receiver was 139 m, and up to 497 m when on the same side of the farm as the receiver.

I.3.2 Detection rates between acoustic and radio transmitters

The radio-only transmitter deployed at Farm 1 in 2009 was never detected by the farm receiving station during its 3-week deployment. The CAR transmitter was detected an average of 206 ±12 (mean ±1 S.E.) times per day, which is equivalent to once every 7 min. If the transmitter was decoded each scan of the receiver, it would be detected once every 1.8 min. The two Sonotronics acoustic transmitters (pressure sensor, straight acoustic) were detected on average 765 ± 56 and 1551 ± 35 times per day respectively. Generally, detections are considered valid, non errors, when the power of a transmitter decoded is above 50 (communication with Lotek representative).

Of the 10 CAR transmitters implanted in domestic rainbow trout at each farm in 2008, 15% of all detections of individuals were from the radio component of the tag, while 85% were detected by the acoustic hydrophone. The trend was similar between farm sites; 90/10 acoustic/radio ratio at Farm 1, 85/15 ratio at Farm 2. In 2009 however, the 30 fish with CAR transmitters released at Farm 1 were detected 42% of the time by the radio antenna and 58% of the time by the acoustic hydrophone.

I.4 Contribution to decision making

1. Fish presence at the farm sites may be underestimated, particularly with straight radio transmitters.
2. Based on the results of these trials, the deployment of a stationary tag, and correspondence with Lotek representatives, I considered a rainbow trout with Lotek transmitter type (radio or CAR) to be ‘present’ at Farm 1 in 2008 and 2009, and Farm 2 in 2008 if the radio detection has a power greater than 50, or an acoustic detection occurs twice in 15 min with power level greater than 50.
3. Due to the higher detection rates seen in the straight acoustic transmitters, fish will be considered ‘present’ at the Farm 2 in 2009 if there are at least two detections in 3 min.
4. Fish presence may be biased by the receiver location on the farm sites, with an increased rate of detections for fish visiting the same side of the farm as the receiver.

Table AI.1 Transmitter model, specifications, and numbers implanted at Farm 1 and 2 in the 2008 and 2009 study period.

	Farm 1 & 2 2008		Farm 1 - 2009		Farm 2 - 2009	
	Lotek radio	Lotek CART	Lotek radio with pressure and temperature sensor	Lotek CART	Sonotronics acoustic with pressure sensor	Sonotronics acoustic
Model	(MCFT-3A)	(CART16-1)	(SR-TP-16-25)	(CS-16-25)	(DT-97-L)	(CT-82-2-I)
Length (mm)	46	60	55	57	80	53
Diameter (mm)	16	16	11	16	15.6	15.6
Weight in water (g)	6.7	13.5	8	14	11	9
Number implanted	20(10 at each farm)	20(10 at each farm)	10	30	10	30
Battery lifetime (days)	641	663	1095	791	365	420

Table AI.2. Successful decoding of transmitters from trails carried out in 2008 and 2009. The three transmitter types tested were radio (R), acoustic (A) and combined acoustic-radio (CAR) from either Lotek (L) or Sonotronics (S) (see Table 1). Maximum distance from receiver to edge of farms is ~ 65 m at Farm 1 and ~150 m at Farm 2.

Year	Farm	Transmitter type	Location	Distance from receiver (m)	Maximum depth decoded (m)
2008	1	L-R	1	33.5	3
2008	1	L-R	2	0.0	0
2008	1	L-R	3	16.5	2
2008	1	L-R	9	20.0	0
2008	1	L-R	10	36.4	0
2008	1	L-R	7	64.3	1
2008	2	L-R	12*	24.4	2
2008	2	L-R	13*	60.2	0
2008	2	L-R	2	62.3	1
2008	2	L-R	1	32.3	2
2008	2	L-R	11*	34.0	1
2008	2	L-R	10	60.4	1
2008	2	L-R	9	91.8	0
2009	1	L-CAR	3	16.6	5
2009	1	L-CAR	4	35.4	10(acoustic) 5 (radio)
2009	1	L-CAR	5	63.1	10(acoustic) 5 (radio)
2009	1	L-CAR	7	64.3	5
2009	1	L-CAR	8	31.1	15
2009	1	L-CAR	9	20.0	10
2009	1	L-CAR	10	36.4	5
2009	2	S-A	1	34.1	8*
2009	2	S-A	2	38.2	8
2009	2	S-A	3	62.0	8
2009	2	S-A	4	101.6	8
2009	2	S-A	5	133.0	8
2009	2	S-A	6	144.9	8
2009	2	S-A	7	127.6	8
2009	2	S-A	8	94.6	8
2009	2	S-A	9	60.4	8
2009	2	S-A	10	30.6	8

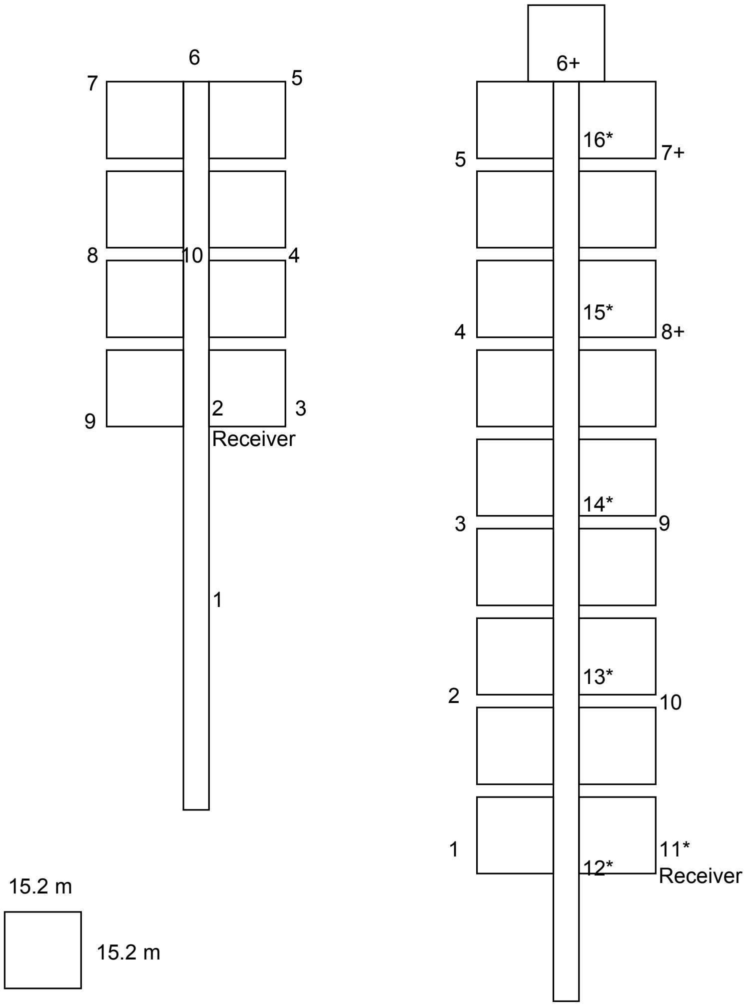

Figure AI.1 Radio and acoustic transmitter trial positions on the farm sites in 2008 and 2009. Transmitter was lowered and held at 1-5 m increments. (*) indicates trial locations in 2008 only, (+) 2009 trials only.

APPENDIX II. Detection range of stationary ‘gate’ receivers and manual tracking system

II.1 Background

I tested the detection capabilities of the various telemetry systems employed to monitor the fate and movement of domestic rainbow trout released into Lake Huron at two sites of commercial aquaculture operation. Knowing the capacity of the equipment to effectively detect and decode transmitters is vital to planning and executing a successful study, and interpretation of data collection.

I conducted trials to determine the ability of the stationary receivers to detect and decode transmitters at three narrow channels. Each of the three stationary receivers was strategically placed in a narrow channel to monitor the movement of fish through “gates” from two possible passages between the North Channel of Lake Huron into Georgian Bay, and from Lake Wolsey into the North Channel (Figure 1.2). I refer to these three stationary receivers as “gate stations”. The goal of the trials was to determine the ability of the radio only receivers to detect transmitters passing through the channels at a variety of depths and distances from the receiver.

To determine the ability of the manual tracking system to detect and successfully decode transmitters I ran a series of trials with a both radio and combined radio acoustic tags at a wide range of depths and distances between the tag and the receiver. Information from trials of this nature are integral in determining the limitations of the telemetry system in you water body.

II.2 Methods

II.2.1 Detection range of stationary gate receiver stations

In the summer of 2009, I conducted trials to determine the ability of the Lotek stationary receivers to detect and decode transmitters at the gated channels (Figure 1.2). The gate stations were radio only monitoring stations consisting of a 5-element Yagi antenna and an SRX_400. Each of the three receiver stations was powered by a sealed 12 v marine battery.

At each gate station a transmitter was slowly towed (3-5 km/h) through the water column behind a non-motorized vessel. Each trial occurred over depths ranging from 0 m to 5 m. Transmitter specifications can be found in Appendix I (Table AI.1). I assessed the ability of the stationary receiving station to successfully decode a transmitter by comparing the known time and location of a transmitter in trial, and the receiver recordings for the time period over which the trial was conducted. This was unnecessary in the manual location trials as the receiver was with you and you were collecting real time data.

II.2.2 Detection range of manual tracking system

In the summer of 2008, three trials were run to assess the maximum range at which the acoustic hydrophone and radio antennas could detect and decode a radio and a combined acoustic-radio (CAR) transmitter. Two trials were run in a large open, deep-water basin from a stationary boat. One further trial was conducted around a small rock island in the

North Channel of Lake Huron (UTM ,WGS84 - 0425273, 5099460), with the boat stationary, and under power. Specifications of the boat can be found in Chapter 3.2.2.This was done to determine detection rates in an obstructed environments, and determine if, and at what speed the boat could travel and still successfully monitor fish presence. Favourable conditions were chosen to determine maximum range. Weather was optimal; calm, no waves, and there were no permanent obstructions between the tag and the radio antenna/hydrophone and receiver, except in the previously mentioned case. Range was determined by lowering a transmitter at a minimum of 1-m increments and motoring away with a radio antenna and/or hydrophone and receiver pointed at the transmitter location until the receiver could no longer decode the transmitter. We continued to increase the distance between the transmitter and the receiving unit until the transmitter pings were no longer audible (detectable). Distance between the tag and the boat were measured using the UTM coordinated recorded at the tag site, and every scanning location.

II.3 Summary of results

II.3.1 Detection range of stationary receivers

When towed through the gated channels, radio, acoustic, and CAR transmitters were all successfully decoded at least once during each trial. A successful decoding with the Lotek equipment was considered to have occurred when the power level was above 50 for a tag ID. The radio-only transmitters were decoded more often than the radio component of the CAR transmitters at all three of the gate stations. The Sonotronics acoustic trials at the gate station between Lake Wosley and the North Channel proved to be most effective, decoding the transmitter for the entire path it was towed through.

II.3.2 Detection range of manual tracking system

If tagged fish were in waters <4 m deep, Lotek radio transmitters could be detected at best ~600 m away by the Lotek manual tracking receiver, but the ability to decode transmitters and obtain individual data occurred at one-quarter of this distance (150 m; see Figure AII.1). I also found that to detect radio signals it was necessary to turn the motor off as there was too much noise interference (creates multiple error readings on the receiver) to be able to travel and scan with the radio antenna.

Field trials using stationary radio transmitters showed that the ability to detect fish decreased with increasing fish depth, and that radio signals cannot be detected once fish are deeper than ~12 m in depth (Figure AII.1). Obstruction in the water (boulders, islands, etc.) reduced the ability to decode a transmitter, but the radio signal was still detected, allowing a change in boat position to successfully locate fish.

Transmitter trials were also conducted for the acoustic components of the telemetry system. When a CAR transmitter was lowered from 1-30 m below the water surface, it was decoded, on average 1677 m away and detected 1874 m away from the hydrophone/receiver. There was little difference between the distance to which tags could be detected and individuals identified (Figure AII.2). The ability of the receiver to detect acoustic signals from the stationary transmitter was not affected by transmitter depth (Figure AII.2).

II.4 Contribution to decision making

Based on the results from the trials carried out at the gate stations and open water, the following criteria regarding the successful location of telemetry fish were made:

1. Single detections from a transmitter at gate stations will be considered to be a fish passing.
2. When attempting to manually locate fish, the boat should be stationary and not under motor while scanning with telemetry equipment.
3. When manual tracking, successful decoding of an acoustic transmitter does not necessarily give most accurate current fish position. Power levels should be monitored for greatest levels while moving in the direction of the strongest signal.
4. When manual tracking, the distance between scanning locations should be no greater than ~400 m for radio transmitters, and ~1 km for acoustic transmitters. (Figures AII.2)

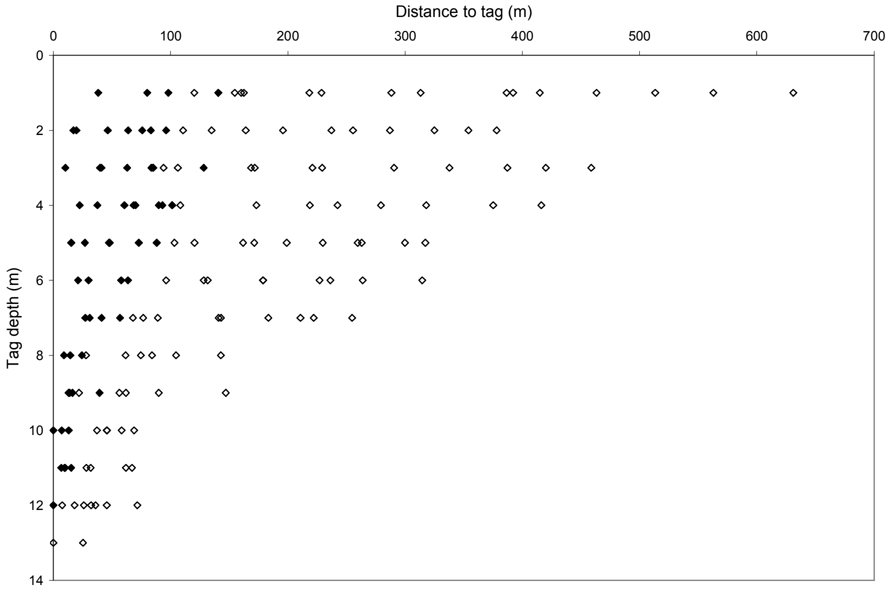

Figure AII.1 Maximum distance to which a Lotek stationary radio transmitter could be decoded (solid diamond) or detected (open diamond) by Lotek manual tracking receiver SRX_400 as a function of water depth (maximum detection depth of 13 m). Data are the average of two trials run by lowering a radio tag in 1-m increments and moving away with a radio antenna and receiver until the receiver could no longer decode the transmitter, and continuing until the transmitter signals could no longer be detected.

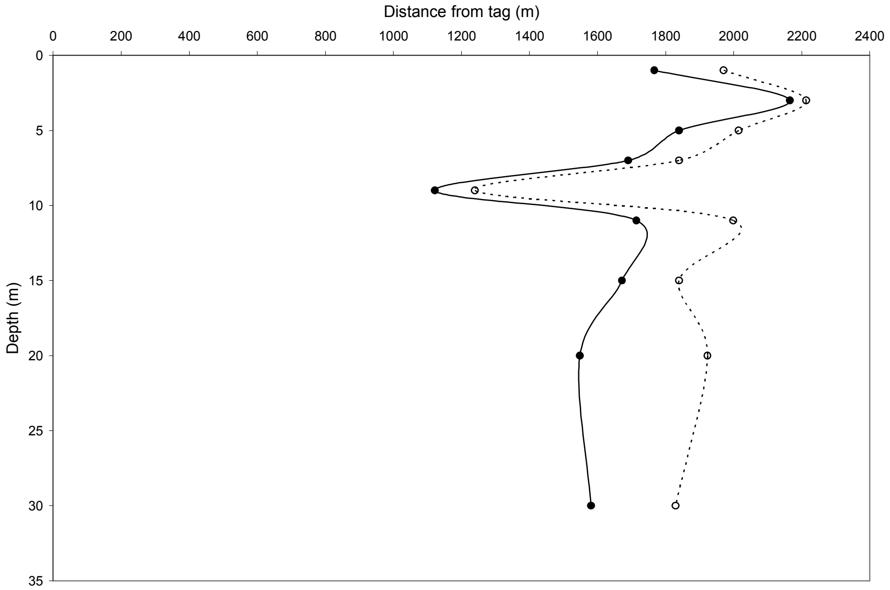

Figure AII.2 The maximum distance a Lotek CAR transmitter could be decoded (solid line) and detected (dashed line) by Lotek manual tracking receiver SRX_400 at various depths (to a maximum of 30 m).

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