MOVEMENT, HOME-RANGE, AND HABITAT SELECTION OF MUSKELLUNGE (*Esox masquinongy* Mitchell) IN THORNAPPLE LAKE, MICHIGAN

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A thesis submitted in partial fulfillment of
requirements for the degree of
Master of Science

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Central Michigan University
Mount Pleasant, Michigan
May 2008

Accepted by the Faculty of the College of Graduate Studies,
Central Michigan University, in partial fulfillment of
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ACKNOWLEDGEMENTS

I would like to thank my committee members, Dr. Tracy Galarowicz, Kregg Smith, Dr. Mic Hamas, and Dr. Tom Gehring for the support and advice offered during this project. Special thanks go to Dr. Galarowicz who offered endless advice, support, and assistance. I also need to thank all the volunteers who assisted in data collection in the field. A special thanks to my wife, Laura, whom I could always count on as a field assistant if no one else was available to help out. This project could not have been completed without your help. All of the members of the Michigan Muskie Alliance were very supportive of this project and offered excellent advice and suggestions. William Schultz, DVM, helped by training me in surgical techniques, and Will Schultz offered his great understanding of muskellunge behavior and biology. Chris Barton allowed me the use of his dock during my second field season. Pierce Cedar Creek Institute in Hastings, MI, provided housing. The Central Michigan University Biology Department, The Office of Research and Sponsored Programs at Central Michigan University, and The Michigan Muskie Alliance also provided funding for this project. Telemetry equipment was supplied by Walleyes for Tomorrow.

ABSTRACT

MOVEMENT, HOME-RANGE, AND HABITAT SELECTION OF MUSKELLUNGE (*Esox masquinongy* Mitchell) IN THORNAPPLE LAKE, MICHIGAN

by Christopher David Eilers

Muskellunge (*Esox masquinongy*) are an important sport fish in the Great Lakes region. As a result of large growth potential, a "fearsome" appearance, and a powerful fighting ability once hooked, muskellunge have become popular with anglers, who contribute to the economy through equipment purchases and license sales. Muskellunge are top predators in many systems and influence the lake ecosystem through interactions with other fish species.

Thornapple Lake is a unique system in Michigan in that it is formed by a natural flooding of the Thornapple River and is connected to multiple stream systems. Muskellunge in the lake are managed with a 127 cm minimum length limit in an attempt to provide a large spawning population. Determining if fish move between lentic and lotic habitats is important, as fish that move into the river are no longer protected by the 127 cm regulation.

Using ultrasonic telemetry techniques and GIS analysis, I examined muskellunge movement patterns, home-ranges, and habitat selection. Annual home-range estimates were compared and available habitat was classified and measured using GIS techniques. Water quality (temperature, dissolved oxygen concentration, and Secchi disk transparency) was measured and analyzed to determine if muskellunge selected for or against certain water quality characteristics within the lake. Fish communities and biomass in the lake were also assessed to determine available muskellunge prey.

Fish movement out of the lake was not observed. Muskellunge primarily used vegetated habitats in the spring, early summer, and late fall. As water temperatures increased, muskellunge moved to deeper offshore habitats or near stream inlets. Mean MCP and Kernel home-range estimates were 39 ha and 18.8 ha respectively. Female fish primarily used the western end of the lake while male fish occupied home-ranges within the central lake basin. Prey species in the lake were found to be numerous and adequate for muskellunge survival. As fish can potentially move between lake and river habitats, knowledge of movement patterns is necessary to properly manage the system to ensure a viable adult spawning population in the system for the future.

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CHAPTER I

INTRODUCTION

Animal movement has long been of interest to fish and wildlife managers. Animals move for numerous reasons: to spawn or search for mates, to search for food, to seek more optimal habitats, or to avoid other organisms such as predators, diseases, humans, and competitors (Brown et al. 1999). Animal movement plays a large role in population dynamics as individuals are constantly entering and leaving the population through immigration and emigration. Moving organisms also expend more energy than sedentary organisms. However, an organism that moves from sub-optimal habitat to optimal habitat will experience an increase in energy intake and will most likely experience a net energy gain (Howard 1960). Similarly, dispersing individuals may experience increased risk of predation, but the benefits gained (reduced competition for food and breeding territory, access to more optimal habitat) by moving to a new area outweigh the risk of predation (Howard 1960).

Habitat determines the composition of an assemblage as well as the potential productivity of a system. A habitat is a place where an organism lives and is defined by the physical, chemical, and biological variables present in the environment. All animals have certain habitat requirements. Although they may be able to tolerate a wide range of environmental conditions, their growth, survival, and reproductive success varies depending on how well the environment matches the organism's needs. Identifying the basic habitat needs of organisms is a common goal of fish and wildlife managers. Understanding the habitat requirements of a species and the relationship between a species and its environment are required before managers can begin to understand and mitigate the impacts that humans have on an area.

Management is further complicated by the fact that individuals of the same species may have different habitat requirements at different life stages (e.g., anadromous fish spawn in freshwater and yet grow and mature primarily in a marine environment) (Rosenfeld 2003). Further problems arise from confusion of terminology when studying habitat selection.

Habitat associations are often mistaken for habitat selection, are correlative, and easily misinterpreted. Population density can be a misleading indicator of habitat quality (Van Horne 1983). Habitat quality should instead be defined using survival and production characteristics, as well as population density of the species of interest. It is often assumed that habitat selection implies a requirement of that particular habitat. This assumption is rarely validated, as removal of the selected habitat may have little or no immediate effect on the growth or reproduction of the animal (Sogard 1994). Individual growth may decline but still remain positive; alternatively, sub-optimal habitat may cause the animal to lose weight and eventually die (Sogard 1994).

Though this may seem fundamentally simple, it is important to remember that habitat selection may change from one area to another, as habitat selection of an animal in one area is highly dependant on the biotic and abiotic factors in that area (Rosenfeld 2003). For example, in the absence of competitors and predators, an animal exhibits true habitat selection (the fundamental niche, Hutchinson 1957). As predators are added to this system, the animal must change its behavior to avoid predators (such as spending more time hiding). As competitors are added to the system, the animal must become more efficient in the utilization of acquired resources to survive. In the presence of competitors or predators, the animal occupies what has been called the “realized niche” (Hutchinson 1957), in which true habitat selection has been altered in the presence of predators, humans, and competitors. Habitat selection is often determined by observing animals during their day to day activities, through an area that is called an animal’s “home-range” (Bolen and Robinson 2003).

Home-ranges are important concepts in fisheries and wildlife management as they help to describe animal movement, the temporal use of resources by animals, and provide insight into what resources are necessary to support a population (Seaman and Powell 1996). Although similar, home-ranges are not the same as territory. A territory is a space that is actively defended by an organism (Noble 1939). Home-ranges are typically larger than territories and although the home-ranges of two animals may overlap, a territory is exclusive (Galbraith et al. 1987).

As habitat suitability ultimately impacts the survival of animals in a given area, it is important to consider any changes to the habitat when investigating animal movement and habitat selection studies (Rosenfeld 2003). If preferred or suitable habitat is not available due to habitat alteration by humans, animals will move out of the area if possible (Berteaux and Boutin 2000). Large terrestrial animals may be able to travel across the landscape between habitat patches in the search for more suitable habitats (Simberloff and Abele 1982). Some animals, such as fish, are unable to do so, and thus the impact of habitat destruction is more profound.

Life History, Habitat, and Distribution

The muskellunge is the largest member of the family Esocidae, which is comprised of five species all belonging to the genus *Esox*. Throughout its range, muskellunge occur more frequently in streams and rivers than other esocids and are thought to be better adapted to living in riverine environments (Crossman 1978). Muskellunge are endemic to freshwater lakes and streams in eastern North America; their range has expanded in recent years due to stocking efforts, and muskellunge now occur in twenty-seven states and four Canadian provinces (Becker 1983).

All esocids are highly predaceous and feed primarily on fish. Common prey items include catostomids, cyprinids, percids, and centrarchids (Bozek et al. 1999). In southern reservoirs beyond the native range of muskellunge, gizzard shad (*Dorosoma cepedianum*) and common carp (*Cyprinus carpio*) are also important prey items (Axon 1981). Muskellunge may also eat rodents (Becker 1983, Bozek et al. 1999) and small birds (Becker 1983).

Muskellunge are ambush predators, commonly associated with underwater structures such as the edges of weed beds, logs, stumps, drop-offs, and rocky ledges, which they use for cover and ambush sites (Crossman 1977, Dombeck 1979, Miller and Menzel 1986a). Large individuals may also occur in deep water where vegetation is sparse or absent (Miller and Menzel 1986a). Muskellunge rely on sight as a primary means of acquiring food (New et al. 2001). Habitat suitability index models suggest that clear water (Secchi depth $\geq$ one meter) is required for optimum muskellunge growth and survival (Cook and Solomon 1987). Muskellunge occupying less suitable habitat need to spend more energy searching for prey, which affects behavior and movement patterns.

Esocids spawn in the spring, scattering eggs across the substrate and vegetation. Common spawning substrates include sand, silt, coarse woody debris, and decaying vegetation (Crossman 1977, Dombeck 1979, Dombeck 1986). Fertilized eggs are left to develop without parental care. Muskellunge spawn near the shoreline, in shallow (≤1 m) water amidst vegetation (*Chara* spp. or *Potamogeton* spp.) (Strand 1986). Muskellunge eggs, unlike the eggs of other esocids, are non-adhesive and sink to the substrate, where they are particularly vulnerable to fungal (*Saprolegnia* sp.) infection and anoxic conditions (Dombeck et al. 1984). Muskellunge eggs exhibit lowest mortality on organic substrates such as coarse woody debris (Dombeck et al. 1984).

There are currently many areas where natural populations of muskellunge are extirpated or sustained only by stocking. One possible cause for decline is the introduction of northern pike (*Esox lucius*) into lakes containing muskellunge. Northern pike spawn earlier in the spring than muskellunge, and the consequent "head start" allows the young-of-the-year northern pike to prey on muskellunge fry (Inskip 1986). There is also evidence that adult muskellunge and northern pike compete for food (Inskip and Magnuson 1986) and cover (Inskip 1986). Poor reproductive success and habitat loss are also thought to be major causes in the decline of muskellunge populations (Craig and Black 1986, Dombeck 1986).

Habitat loss occurs due to human development of lakes and streams. Vegetation beds are commonly destroyed with herbicides, effectively eliminating muskellunge habitat and polluting the lake. The loss of spawning habitat is particularly detrimental because the population is unable to recruit new individuals.

Muskellunge in Thornapple Lake

Thornapple Lake, Michigan, has been negatively impacted by human development, with more than 45% of the shoreline altered by dock installments and residential lawns (Wesley 2000). Currently, the muskellunge population in the lake is maintained wholly through stocking efforts by the Michigan Department of Natural Resources (MDNR), in which 1600 juvenile fish are put into the lake every other October (Wesley 2000). Adult muskellunge in the lake are able to produce gametes and exhibit spawning behavior, but the eggs do not survive once they have been broadcast across the lake substrate (K. Smith, MDNR, personal communication).

The lake has also been one of two source populations for muskellunge brood stock egg collection (the MDNR captures and collects eggs from adult fish every April) for the MDNR state-wide muskellunge rearing program since 1999. Although adult muskellunge are returned to the lake after their gametes are collected, the MDNR has observed that the number of spawning fish caught each year is declining. The MDNR is therefore concerned that current stocking rates may not be high enough to support a viable adult spawning population in the lake in the future. If the number of adult fish spawning in the lake declines further, the MDNR will need to spend more time and resources gathering the number of eggs necessary for a successful rearing program. If the spawning population in the lake reaches very low levels, a new source lake may need to be selected for the brood stock program.

Knowledge of the movements of adult fish is necessary to determine if current stocking rates are high enough to maintain a large adult population. In other studies, adult muskellunge have been observed moving out of lakes and into the adjoining river systems after they spawn (Crossman 1977). If fish move out of the lake and no longer spawn in the lake, they are no longer susceptible to MDNR netting efforts. This will decrease the effective spawning stock size within the lake. As Thornapple Lake is a natural lake, there are no barriers to prevent fish movement between the lake and adjoining rivers. While muskellunge in the lake are protected by a 127 cm minimum length limit, fish moving out of the lake are not protected by this conservative regulation and may be subject to increased harvest mortality. If many adult fish move into the river and are harvested, the spawning population in the lake could be reduced. Knowledge of adult movements will provide MDNR managers with data to determine if muskellunge fishing regulations need to be changed in adjacent river systems. Additionally, spawning muskellunge may exhibit homing behavior. Individuals have been reported returning to the same spawning site every year (Crossman 1990). Thus, knowledge of adult movement patterns will allow managers to capture muskellunge more efficiently and determine and protect spawning areas vital to the population.

There has been interest in the muskellunge population in Thornapple Lake since 1999, when MDNR began using Thornapple Lake as a brood stock source for the muskellunge rearing program. Length and age frequency distributions have been prepared from MDNR data collected from 1999 through 2003. Growth models developed from these data indicate that muskellunge in Thornapple Lake are growing at a faster rate than the state average (Kregg Smith, MDNR, personal communication).

Additionally, mean length frequency distributions in Thornapple Lake are greater than mean length frequency distributions calculated from data taken from eight northern Wisconsin lakes (Hanson 1986).

Previous Research

Fish movement is most often studied using radio or ultrasonic telemetry. Many researchers (Crossman 1977, Dombeck 1979, Miller and Menzel 1986a, Miller and Menzel 1986b, Strand 1986) have used telemetry as a means to quantify muskellunge spawning movements, home-ranges and habitat selection. Crossman (1977) used radio telemetry to describe muskellunge home-ranges in a river system to be 300-800 m linear distances. However, muskellunge in river systems are capable of extensive movements (27 km) outside of this home-range (Younk et al. 1996). Other studies have estimated muskellunge home-ranges in lakes where home-ranges were 0.2-6100 ha (Dombeck 1979, Strand 1986).

One problem with home-range estimates is that little agreement exists on how to quantify home-ranges. Numerous techniques have been developed to quantify home-ranges and the estimate can vary based on the technique used. Miller and Menzel (1986b) estimated muskellunge home-ranges to be 39-443 ha when calculated using the minimum convex polygon (MCP) technique. In the same study, home-range estimates decreased to 27-73 ha when using the grid-square technique (Miller and Menzel 1986b).

Biotic and abiotic factors that can influence home-range size include lake size and the abundance and size of prey species (Dombeck 1979). It is assumed that if forage species are present, muskellunge may stay near the food source (Johnson 1963). This behavior could result in small home-ranges if the forage species are plentiful and do not exhibit long movements. Alternatively, this same behavior could result in large home-ranges if the prey species are highly migratory, as muskellunge may follow schools of prey species in the lake. In addition, dissolved oxygen levels below 3 ppm can prevent many fish species from using parts of the water column (Wesley 2000). This factor can limit muskellunge movements, preventing them from using parts of the water column in their home-range. Seasonal changes in dissolved oxygen concentration cause changes in home-range size or location.

CHAPTER II

OBJECTIVES

The goals of this study were to evaluate movement, home-range, and habitat selection of muskellunge in Thornapple Lake, and to identify the potential factors that contributed to these patterns. Thornapple Lake was selected because the muskellunge population is an important component of the Michigan Department of Natural Resources muskellunge rearing program. Movement, home-range, and habitat selection were examined using:

1) Ultrasonic telemetry and GIS techniques to digitally plot animal locations so that they could be examined and analyzed statistically. Fish movement was examined specifically to determine if there is evidence to support the hypothesis that adult fish are leaving the lake and contributing to the observed population decline.

2) Variables that influence fish movement and habitat selection by collecting habitat data at fish selected sites and comparing it to habitat data from "non-fish" sites. Habitat abundance data was collected for littoral habitat structures to allow the calculation of habitat selection. Fish assemblages were also sampled and compared between sites to determine if prey availability could affect fish movement.

CHAPTER III

METHODS

Study Site

Thornapple Lake is a natural, 165.5 hectare lake in Barry County, Michigan. It is formed by a natural widening of the Thornapple River 8.4 km southeast of Hastings, Michigan (Figure 1). The maximum depth of the lake is 9.14 m; however, dissolved oxygen concentrations drop below 3 ppm between depths of 3.7 and 4.0 m, effectively limiting most fish to the upper 4.0 m of the water column (Wesley 2000). The Thornapple River flows into the lake at the eastern end out through the western end. Dams at Irving and Nashville prevent fish movement in both directions (upstream and downstream). The Nashville Dam is 10 km upstream from the lake, and the Irving Dam is 29 km downstream. Other tributaries entering the system are Mud Creek and Highbanks Creek.

Fish Collection and Surgery

Adult muskellunge were captured with trap nets (3.8 cm mesh, with 22.9 cm throat and 91.5 cm pot) in April 2004 and 2005. The nets were set April 1, 2004 and 2005, and checked every 48 hours until enough gravid females were captured to provide eggs for the MDNR muskellunge stocking program. Net locations that captured muskellunge were marked, and GPS coordinates were recorded (Figure 2). Muskellunge were transported to shore where they were weighed (nearest 0.1 kg), measured (nearest 0.01 cm), and surgically implanted with an ultrasonic transmitter (IACUC approval # 12-04).

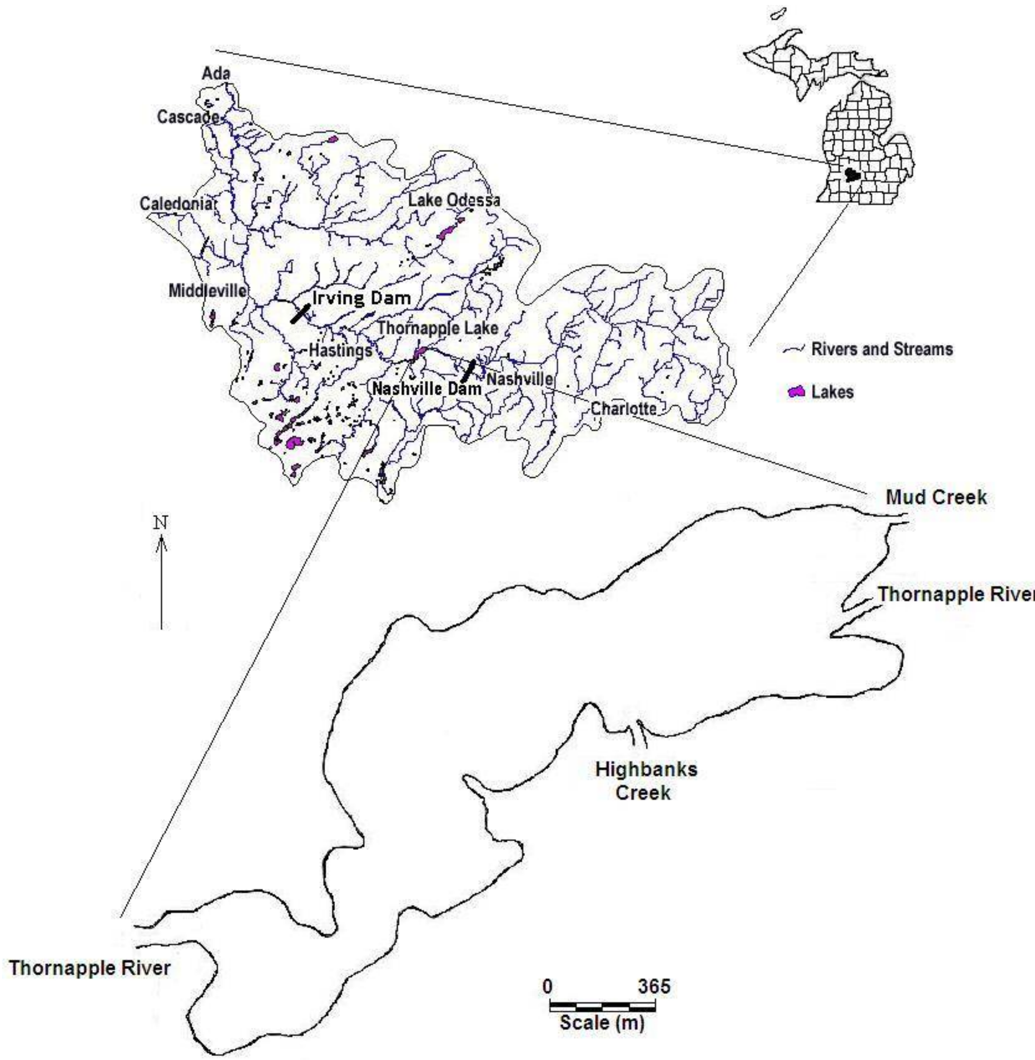

Figure 1. Map of the Thornapple River Watershed, Thornapple Lake, and tributaries. The Thornapple River and its watershed are part of the Grand River watershed, which eventually empties into Lake Michigan.

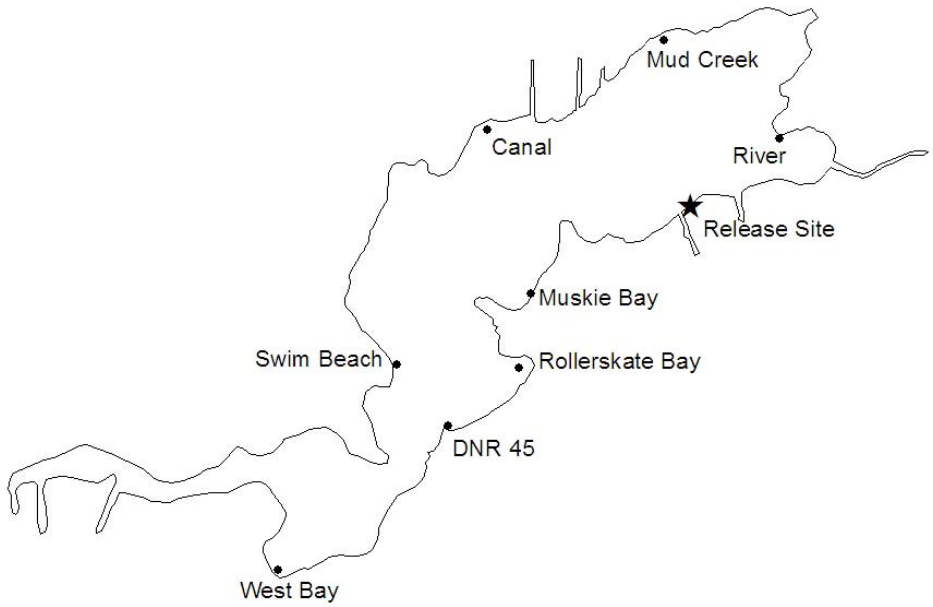

Figure 2. Netting and muskellunge capture locations in 2004 and 2005. Fish were tagged and released at the Michigan DNR boat launch (indicated by a star).

This study used muskellunge under 127 cm in length, the minimum length for harvest, to prevent anglers from taking tagged fish. Prior to and after surgery, fish were held in holding pens in the lake. Before surgery, muskellunge were anesthetized in tricane methane sulfonate (MS-222) until they could not maintain equilibrium in water (Strand 1986). The fish were then transported to the surgery table, and the skin around the incision was cleaned with isopropyl alcohol to remove dirt and mucus. All surgical instruments and the transmitter were sterilized with iodine. A 2-3 cm mid-ventral incision was made with a scalpel posterior to the pelvic girdle, and an ultrasonic transmitter (Sonotronics Inc., Tucson, AZ model CT-82-2, 63x16mm, 8.0 g in H_2O) was inserted. The incision was closed with 2-3 absorbable sutures (coated monocryl, 2/0 cutting CP-1 needle) (Crossman 1977, Strand 1986). Oxytetracycline (10mg/kg body weight) (Crossman 1977) was injected into the incision to prevent infection. All captured muskellunge were also implanted with a passive integrated transponder (PIT) tag. All fish were returned to the lake following egg take and surgical procedures.

Telemetry and Data Collection

Muskellunge were tracked from a boat equipped with a unidirectional hydrophone (Sonotronics model DH-4) connected to a receiver (Sonotronics models USR-96 and USR-5W). Fish were located when the signal was equally loud in all directions. Every time a fish was located, GPS coordinates were recorded so that the location could be later plotted on a map of the lake. At each fish location, water temperature (°C) and dissolved oxygen ($mg \cdot L^{-1}$) measurements were taken at the surface and bottom of the lake, depth (m) was recorded, and a Secchi disk transparency reading (m) was recorded. Secchi disk readings provide insight on water clarity, which can play an important role in muskellunge biology, as muskellunge locate potential prey through sight (New et al. 2001). Water temperature and dissolved oxygen were measured using an YSI 650 data sonde, Secchi depth was measured by lowering a Secchi disk into the water until the markings on the disk were no longer visible, and water depth was measured through the use of a hand held (SONAR) depth finder.

Muskellunge locations were transferred from GPS unit to computer using DNRGarmin 4.4.1 (Minnesota Department of Natural Resources, 2001). Locations were converted into shapefiles using ArcGIS 9.0 (ESRI 2006). Home-ranges were calculated using Animal Movement Analyst 2.0 (Hooge and Eichenlaub 1997), an extension program for ArcView 3.3 (ESRI 2006). Smoothing factors for Kernel home-range analysis were left as default (automatically calculated by the program using least-squares cross validation) within the home-range calculation program.

To provide habitat samples for comparison to fish selected sites, the lake was divided into 15 approximately equal sections ($\bar{x} = 0.11\ km^2$, range = $0.09 – 0.15\ km^2$). Six samples were haphazardly collected twice monthly in June, July, and August 2005 in each section. GPS coordinates, water temperature, dissolved oxygen, depth, and Secchi depth were recorded at each site. These sites were selected in the lab using ArcGIS 9.0 to prevent bias against habitat types in the field (inadvertently selecting and sampling one habitat type more often than other habitat types).

Muskellunge are broadcast spawners, and female fish spread their eggs across the lake bottom during spawning. To determine if the lake contained suitable spawning substrate, samples were collected with an Eckman dredge at 90 random sites between

August and November 2005. Approximately one liter of substrate was collected, homogenized, and frozen. In the laboratory, samples were thawed, homogenized, and sub-sampled to a volume of 50 mL. The substrate was then passed through a series of sieves using the wet sieve technique outlined by Johnson (1989). The sieve mesh sizes were 2 mm, 500 µm, 250 µm, 125 µm, and 63 µm (Wentworth scale, Table 1). Water containing very fine particles that passed through the 63 µm sieve was also collected. The sieves and containers holding very fine particles were dried to a constant mass and weighed to determine percent composition of substrate by particle size.

Table 1: Substrate particle size and diameter, modified from Wentworth (1922).

Substrate Classification	Diameter
Silt and Clay	< 63 µm
Very Fine Sand	124 µm – 63 µm
Fine Sand	249 µm – 125 µm
Sand	499 µm – 250 µm
Fine Gravel	2 mm – 500 µm
Gravel	> 2 mm

Vegetation beds were delineated twice a month in June, July and August, 2005, with GPS to map changes in location, size, and shape. ArcGIS was then used to plot the bed boundaries on a map of the lake. Vegetation was sampled with a hook every 200 meters along the perimeter of the lake (70 locations per month); plants collected were identified to lowest possible taxa and returned to the lake. Emergent species near the lakeshore were also identified and recorded. Dock locations were also marked with GPS and plotted on ArcGIS to determine if there was an association between muskellunge locations and dock locations.

To determine the abundance muskellunge prey within the lake, forage fish were sampled twice a month in June, July, and August, 2005. Four fyke nets were set for 12 hours overnight. The fyke nets were comprised of a standard 1.2 x 1.8 m frame, with a 1.2 m deep throat. The mesh size was 5.0 cm on half of the nets (large mesh) and 2.5 cm on the remaining nets (small mesh). Fish captured during sampling were identified, measured (nearest mm), and released near the capture site. Fish that could not be identified in the field were euthanized and preserved according to American Fisheries Society recommendations (Kelsch and Shields 1996) and returned to the laboratory where they were identified (IACUC approval # 05-08).

Data Analysis

Muskellunge data points from GPS were plotted with ArcGIS. Distances from each fish's capture site to each location site were measured in 50 meter increments using the buffer and measuring tools in ArcView. The proportion of locations (of total locations) in each 50 meter increment was calculated and proportions were transformed using an arcsine transformation (arcsine $\sqrt{y}$). The transformed proportions were then compared to the distance increments using a general linear model analysis of variance (ANOVA) (Proc GLM, SAS Institute Inc. 2006).

Animal Movement Analyst Extension (AMAE) (Hooge and Eichenlaub 1997) for ArcGIS was used to calculate home-range estimates, such as minimum convex polygon (MCP) (Odum and Kuenzler 1955, Winter 1977) and kernel (Worton 1989) estimators. For an animal to occupy a home-range, it must first exhibit site fidelity (Spencer et al. 1990). To accommodate this, site fidelity was determined for each fish using the site fidelity analysis tools incorporated in AMAE before home-ranges were calculated. The site fidelity test consists of a Monte Carlo random walk test in which the observed movement pattern is compared to a user selected number (in this case 1000) of randomly generated paths. If the observed movement path was more constrained than 95% of the random walks, the fish exhibited site fidelity. Fish that did not exhibit site fidelity were not included in home-range analysis.

One of the most commonly used home-range estimators is the minimum convex polygon (MCP), which is the smallest possible convex polygon that encompasses all known locations of an animal (Hayne 1949). MCPs are popular because they are easy to conceptualize and do not rely on the data having an underlying statistical distribution (Row and Blouin-Demers 2006). Unfortunately, MCPs often include large areas that are never used by an animal and ignore patterns of selection within a home-range (Taulman and Seaman 2000).

Kernel estimators have become popular in recent years as advances in GPS and GIS technology have allowed researchers to more accurately determine animal locations. Kernel techniques are the most useful and consistent technique used for examining intensity of home-range use and therefore habitat selection within the home-range. Kernel estimators are non-parametric techniques that estimate the likelihood of finding an animal at any given point within the home-range. Like MCP techniques, Kernel home-ranges may include areas that the animal never occupies. A major drawback of Kernel techniques is that they rely on user input smoothing factors. These smoothing factors are the most important and difficult aspect of using Kernel techniques.

A problem encountered when comparing home-range size is that different estimator techniques have differing degrees of sensitivity to sample size. Kernel estimators are less sensitive (require fewer data points) than MCP techniques (Kenward 2001). Even when the same technique is used, home-range estimates can vary due to different procedural details, time intervals, and objectives of the study. These factors make it difficult to compare home-range sizes between studies (Miller and Menzel 1986b).

Differences in male and female home-range sizes were examined with a Mann-Whitney Wilcoxon test (Proc NPAR1WAY, SAS Institute Inc. 2006). A correlation test was used to test for associations between fish length, weight, age, and the number of fish locations and home-range size (Proc CORR, SAS Institute Inc. 2006). A multiple response permutation procedure (MRPP) test (Blossom Statistical Software 2006) was used to determine if there was a spatial difference between male and female home-ranges (Cade and Hoffman 1993). The MRPP test compares the spatial distribution of two or more groups of observed locations to all possible permutations within and between the groups.

A logistic regression analysis (Proc CATMOD, SAS Institute Inc. 2006) was conducted to model habitat preference (vegetated or open water) based on surface temperatures and dissolved oxygen concentrations. This allowed the comparison of categorical data (habitat type) to continuous data (temperature or oxygen concentration). A repeated measure multiple analysis of variance (MANOVA) (Proc GLM, SAS Institute Inc. 2006) tested for differences in temperature and dissolved oxygen between known muskellunge sites and the "non-muskellunge" sites. A general linear model ANOVA

(Proc GLM, SAS Institute Inc. 2006) was used to determine if there was a difference in habitat parameters (temperature, dissolved oxygen, Secchi visibility) between the 15 lake sections, between two habitat types (open and vegetated), and inshore (water depth < 3 m) and offshore (water depth > 3 m) habitats. Muskellunge habitat use was evaluated using compositional analysis by comparing the proportions of locations within the three habitat types (open water, vegetation, docks).

Habitat use was defined as the proportion of locations in each habitat type with respect to the relative availability of each habitat type within the lake. Habitat selection was determined by compositional analysis, which compares log-transformed use and availability data to the likelihood ratio statistic (Aebischer et al. 1993). Many habitat selection studies fail in that they are unable to correctly identify the sample unit (usually the animal, not the location), are hindered by the non-independence of habitat proportions, cannot identify differential use patterns by groups of animals, and the available habitat is arbitrarily defined (Aebischer et al. 1993). Compositional analysis has advantages over other habitat selection statistical tests (Pendleton et al. 1998) as it addresses these concerns.

Substrate analysis was conducted by using an ANOVA (Proc GLM, SAS Institute Inc. 2006) to determine if there was a difference in substrate particle size proportion between the 15 sections and to determine if there was a difference in particle size proportions between inshore (water depth < 3 m) and offshore (water depth > 3 m) sites. A general linear model ANOVA (Proc GLM, SAS Institute Inc. 2006) test was used to analyze total number of prey fish captured. Prey capture was analyzed on several levels, including differences in species counts, differences due to surrounding habitat (open or vegetated), differences in the mesh size of the net, and temporal (month to month) differences. Interactions between all of these variables were also investigated.

CHAPTER IV

RESULTS

Twenty-two muskellunge were captured and implanted with ultrasonic transmitters (Table 2). Muskellunge were located at 513 locations within the lake ($\bar{x}$ = 24 per fish, SE = 7.24, range = 16-38) (Table 2). A single transmitter ceased functioning within one week of implantation and was excluded from analysis. Several transmitters that were implanted in 2004 failed during the summer of 2005. These fish were not included in the analysis of 2005 results. No fish mortality occurred during the duration of the study, and there was no evidence of lost ultrasonic tags. The implantation of transmitters caused no evident adverse effects, as determined by superficial examination of 11 fish recaptured in subsequent MDNR surveys. All recaptured fish exhibited healed incisions and increases in length and weight during the study (Kregg Smith, MDNR, personal communication).

Fish dispersed throughout the lake within 1-2 days after tagging and release, moving to shallow, vegetated areas near shore. Fish remained in shallow areas throughout most of the summer but did move to deeper offshore habitats as surface temperatures increased ($P < 0.0001$). Fish mainly exhibited movements parallel to the lake shore, remaining within the littoral zone, but were also observed moving across deeper parts of the lake basin before returning to shoreline habitats (Appendix A, B).

Fish did not exhibit fidelity for initial capture sites. Location distances ranged from 50 meters to 2550 meters from the capture site, with the median distance at 700 meters. As the distance from location to capture site increased beyond

Table 2: Fish captured and tagged in 2004 and 2005. Transmitter code indicates the transmitter beep sequence by which each fish was uniquely identified. Twenty-two fish were tagged over the two year study, nine in April of 2004 and thirteen in April of 2005. Eleven fish of each sex were tagged. Mean length (cm) and weight (kg) were 94.57 ± 15.24 and 6.03 ± 2.95 respectively. All fish at time of capture were sexually mature and between the ages of 3 and 11 years old. Capture location indicates the MDNR net location in which the fish was captured (See Figure 2). Mean number of locations per fish (excluding fish 3336) was 23.4 ± 8.5. Fish tagged in 2004 were tracked until November 2005 or until the tags expired. Fish tagged in 2005 were tracked until the end of the study in November 2005. Total days tracked excludes November 2004 through April 2005 (as fish were not tracked during this time period).

Transmitter Code	Sex	Length (cm)	Weight (kg)	Age (years)	Capture Location	Year Tagged	Number of Locations	Period Tracked	Total Days
3334	M	70.36	2.15	5	Rollerskate Bay	2004	37	15-Apr-2004 to 3-Nov-2005	385
3336[a]	M	87.38	4.20	5	Canal	2004	2	15-Apr-2004 to 21-Apr-2004	6
3345	M	91.69	5.74	7	Canal	2004	16	13-Apr-2004 to 28-Apr-2005	224
3347	M	92.71	4.56	5	Rollerskate Bay	2004	35	15-Apr-2004 to 3-Nov-2005	411
3354	M	90.93	5.1	7	Rollerskate Bay	2004	38	15-Apr-2004 to 3-Nov-2005	411
3356	F	99.06	6.71	7	Canal	2004	35	13-Apr-2004 to 3-Nov-2005	413
3365	F	98.04	6.6	5	Rollerskate Bay	2004	30	15-Apr-2004 to 3-Nov-2005	411
3367	M	69.09	1.97	3	Canal	2004	23	15-Apr-2004 to 7-June-2005	258
3374	M	65.02	1.75	3	Mud Creek	2004	33	15-Apr-2004 to 3-Nov-2005	385
3376	M	78.99	3.15	4	Canal	2005	19	9-Apr-2005 to 3-Nov-2005	208
444	F	120.14	12.04	11	Mud Creek	2005	19	9-Apr-2005 to 3-Nov-2005	208
445	F	103.38	7.57	8	DNR 45	2005	16	9-Apr-2005 to 3-Nov-2005	208
446	F	105.66	8.53	6	DNR 45	2005	18	11-Apr-2005 to 20-Oct-2005	192
447	F	101.70	6.28	8	Swim Beach	2005	20	9-Apr-2005 to 3-Nov-2005	208
448	M	76.71	2.29	4	Rollerskate Bay	2005	26	9-Apr-2005 to 3-Nov-2005	208
449	F	105.41	7.96	6	Muskie Bay	2005	20	9-Apr-2005 to 20-Oct-2005	194
4410	M	88.14	2.97	5	Mud Creek	2005	21	9-Apr-2005 to 20-Oct-2005	194
4411	F	106.93	9.14	10	DNR 45	2005	24	11-Apr-2005 to 3-Nov-2005	206
4412	F	102.11	8.28	8	Canal	2005	22	11-Apr-2005 to 3-Nov-2005	206
4413	F	113.28	9.64	11	DNR 45	2005	20	9-Apr-2005 to 3-Nov-2005	208
4414	M	97.54	5.78	11	Muskie Bay	2005	24	11-Apr-2005 to 3-Nov-2005	206
4415	F	116.21	10.18	11	Mud Creek	2005	17	9-Apr-2005 to 20-Oct-2005	194

[a] Fish excluded from analysis due to transmitter failure.

700 meters, the proportion of locations decreased ($P < 0.0001$, Figure 3). Three of the nine fish tagged in 2004 were recaptured in 2005. None of these fish was recaptured in the same location in 2005. Eight fish were recaptured in egg take efforts in 2006; however, the netting effort was conducted by MDNR, and records were not kept regarding the capture locations of tagged fish.

The mean distance between locations was 452 meters (SE = 110, range = 288-607) (Table 3). Grand mean distance per day was 36.8 meters (SE = 12, range = 26.1-63.1). These data are slightly misleading, as the sampling design prohibited tracking of fish every day during the study. Fish were only tracked from April to November, and any long range movements outside this time frame (i.e., spawning movements taking place before April) may have been missed.

There was no proportional difference in muskellunge use among the 15 lake sections (P = 0.68). Consequently, it was impossible to determine if fish selected habitat characteristics in specific sections. Of the 513 muskellunge locations, one was observed outside of the main lake basin. Fish number 4413, a female (TL = 113 cm), was observed in the main channel of the Thornapple River approximately 1.7 km downstream from the western lake basin. This location was observed late in the year (November 2005), and it is unknown whether or not the fish returned to the lake (Figure 4). Three of eight fish occupied home-ranges in 2004, and eight of twenty fish occupied home-ranges in 2005. No fish occupied home-ranges in both 2004 and 2005, so it was impossible to determine changes in home-range size and location between years.

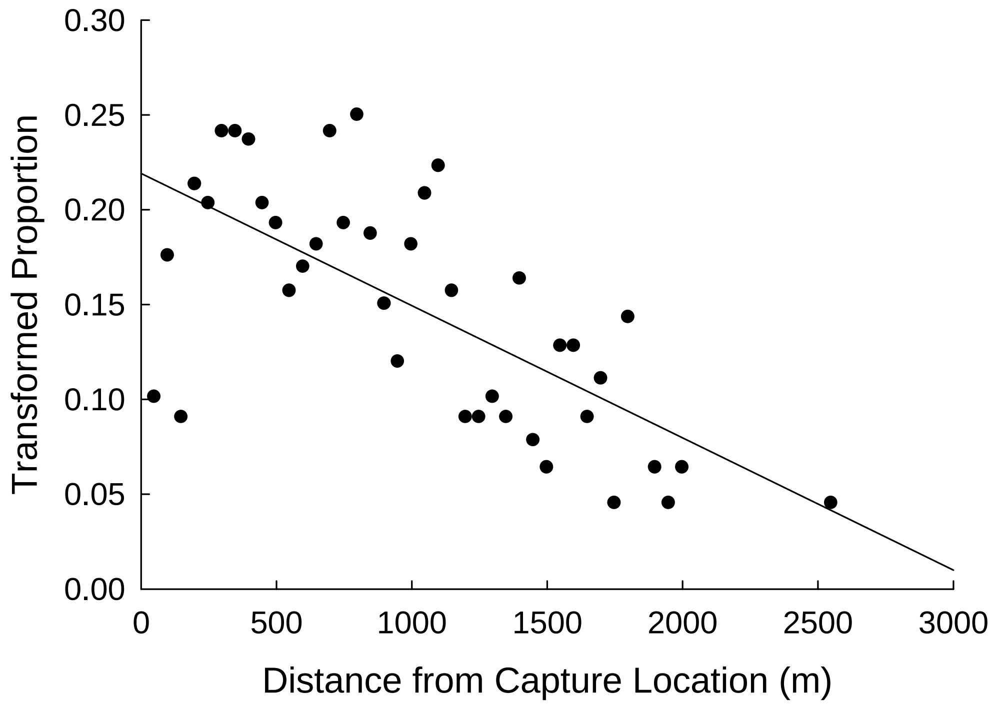

Figure 3. Location distance from original fish capture sites. All locations of each fish were used in analysis, proportions were calculated by determining the proportion of fish locations (out of the total number of locations for that fish) that were located within each 50 m distance increment from the original capture site. Proportions were transformed using the transformation arcsine √proportion. Fish did not exhibit fidelity for their capture site, as median location distance was 700 m (a relatively long distance in Thornapple Lake). After this 700 m threshold, the proportion of locations decreased as distance from capture site increased (*P*< 0.0001).

Table 3: Movement data for Thornapple Lake muskellunge. Mean distance traveled ± SE (meters), total distance between all locations (meters), and the mean distance moved per day (meters) for each fish are displayed. Grand mean distance between locations was 452.0 meters ± 110.0 meters, mean total distance traveled was 11133.8 meters ± 4588.6 meters, and grand mean distance per day was 36.8 meters ± 12.0 meters. Fish 3336 was excluded due to transmitter failure.

	Distance Traveled		
Fish Transmitter Code	Mean Distance Between Locations (m) ± SE	Total Distance (m)	Mean Distance Per Day (m)
3334	450.4 ± 419.4	16215.5	42.1
3345	448.6 ± 389.6	6728.8	30.0
3347	560.7 ± 362.0	19062.5	46.4
3354	504.7 ± 376.4	19179.2	46.7
3356	586.0 ± 407.6	21094.9	51.1
3365	489.6 ± 337.8	14199.5	34.5
3367	599.0 ± 453.0	13776.6	53.4
3374	419.8 ± 262.3	13853.3	36.0
3376	288.6 ± 305.2	5484.0	26.4
444	323.1 ± 373.4	6138.8	29.5
445	607.1 ± 606.0	9714.0	46.7
446	451.2 ± 377.5	8121.2	42.3
447	305.5 ± 397.8	6110.6	29.4
448	395.7 ± 245.4	10287.5	49.5
449	369.2 ± 466.4	6276.5	32.4
4410	454.6 ± 501.4	9546.3	49.2
4411	437.5 ± 445.8	10500.7	51.0
4412	591.1 ± 356.3	13004.4	63.1
4413	603.5 ± 1002.3	12069.1	58.0
4414	307.8 ± 258.8	7386.2	35.9
4415	297.7 ± 222.3	5061.2	26.1

Figure 4. Muskellunge locations in 2004 and 2005. A total of 513 locations were recorded over the two year study. Fish were primarily located in shallow littoral habitats, but were also observed in deep, open water areas. Only one location was observed outside of the main lake basin.

Of these 11 fish, five male and six female fish occupied home-ranges over the two year period. Male and female fish occupied home-ranges in different areas of the lake (P > 0.0001), with male home-ranges occurring most frequently in the central lake basin and female fish most often in the eastern lake basin near the Thornapple River and Mud Creek inlets. Male and female fish occupied home-ranges that were similar in area (Table 4) (MCP: $P = 0.25$; Kernel 50%: $P = 0.72$). There were no relationships between home-range area and age ($P = 0.39$), length ($P = 0.33$), weight ($P = 0.28$), or number of contacts ($P = 0.13$) for MCP home-range areas. For 50% kernel home-ranges, there was no correlation between home-range area and length ($P = 0.08$), weight ($P = 0.13$), or the number of contacts ($P = 0.43$). A negative correlation existed between fish age and 50% kernel home-range area ($P = 0.03$), where home-range area decreased as fish age increased (Figure 5).

Habitat sampling revealed that surface water temperature in Thornapple Lake ranged from 18 ºC to 30 ºC, and bottom water temperature ranged from 11 ºC to 28 ºC (Figure 6) from June to August. Surface dissolved oxygen concentrations ranged from 9 $mg \cdot L^{-1}$ to 18 $mg \cdot L^{-1}$, and bottom dissolved oxygen concentrations ranged from 0.5 $mg \cdot L^{-1}$ to 14 $mg \cdot L^{-1}$ (Figure 7) within the same time period. Secchi visibility varied between 0.3 and 1.5 meters (Figure 8) during the summer. All environmental variables changed significantly through time (Table 5). Bottom temperature (Figure 9) and bottom dissolved oxygen (Figure 10) were significantly higher at inshore sites compared to offshore sites (bottom inshore temperature $\bar{x} = 24.18$, °C SE = 2.47; bottom offshore temperature $\bar{x} = 16.24$, SE = 3.56 °C, $P < 0.0001$; bottom inshore dissolved oxygen $\bar{x} = 10.05$, SE = 3.11 $mg \cdot L^{-1}$; bottom offshore dissolved oxygen $\bar{x} = 3.17$, SE = 2.09 $mg \cdot L^{-1}$,

$P < 0.0001$). Secchi visibility was higher in open habitats (Figure 11) (Secchi vegetated $\bar{x} = 0.89$, SE = 0.26 m; Secchi open $\bar{x} = 1.41$, SE = 0.83 m, $P = 0.03$), while bottom dissolved oxygen was higher in vegetated habitats (Figure 12) (bottom open dissolved oxygen $\bar{x} = 6.51$, SE = 4.41 $mg \cdot L^{-1}$, bottom vegetated dissolved oxygen $\bar{x} = 12.27$, SE = 2.30 $mg \cdot L^{-1}$, $P = 0.01$). All other relationships between environmental variables and habitat or depth were not significant.

Table 4: MCP and Kernel 50% home-range areas (ha) for different muskellunge in Thornapple Lake in 2004 and 2005. See Table 2 for fish capture locations and biological data. No fish occupied home-ranges in successive years. Only fish that exhibited site fidelity are included. Mean MCP and Kernel 50% home-range sizes in 2004 and 2005 were 40.3 ± 14.1 ha and 12.5 ± 7.3 ha, respectively. Male and female fish occupied home-ranges of similar sizes for both home-range calculation methods (MCP: P = 0.25; Kernel 50%: P = 0.72)

	Home-range		
Transmitter Code	Year Occupied	MCP Area (ha)	Kernel 50% Area (ha)
3347	2004	44.99	11.66
3356	2004	43.48	9.72
3367	2004	17.83	9.86
3374	2005	41.29	22.73
444	2005	44.70	4.18
446	2005	29.16	23.06
447	2005	15.67	9.22
448	2005	46.55	12.88
4412	2005	66.19	15.07
4414	2005	18.17	7.58
4415	2005	27.40	5.63

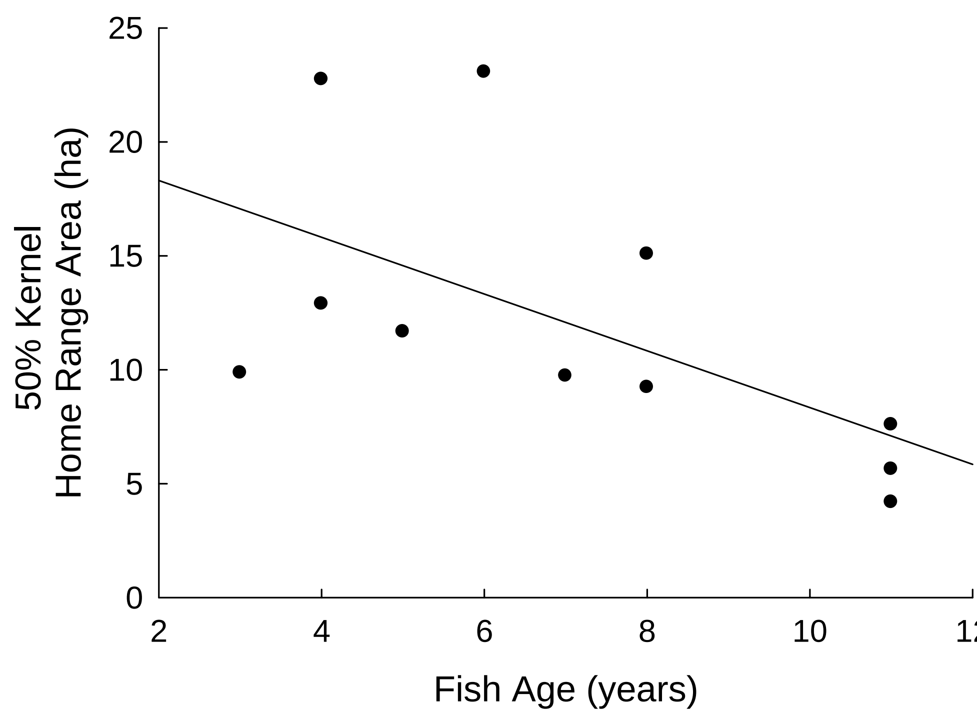

Figure 5. Relationship between muskellunge age (years) and 50% kernel home-range area (ha). As fish age increased, home-range area decreased (P = 0.03).

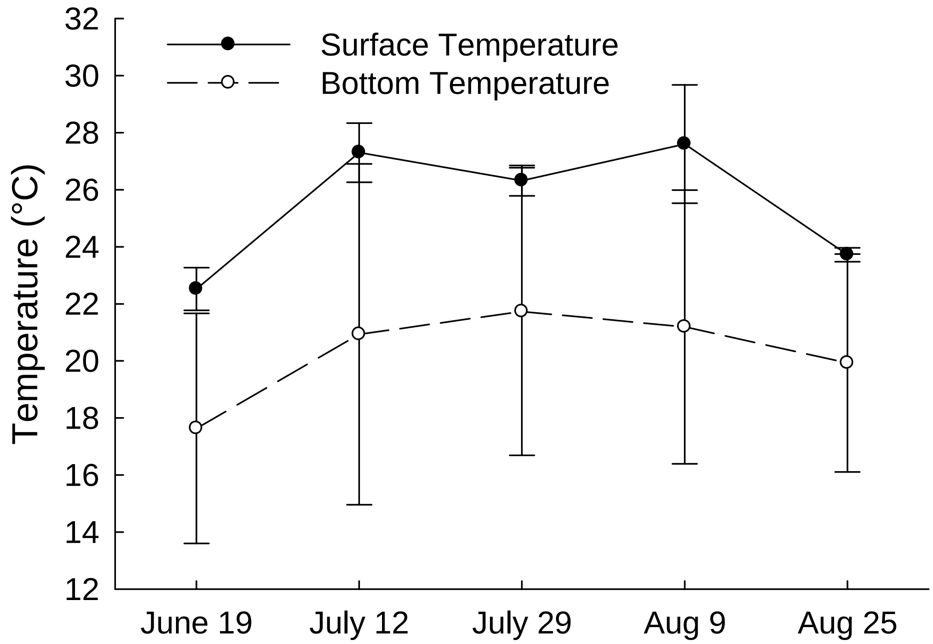

Figure 6. Mean (± SE) surface and bottom water temperature (ºC) in Thornapple Lake in 2005. Surface temperatures ranged from 18-30 ºC, bottom temperatures from 11-28 ºC.

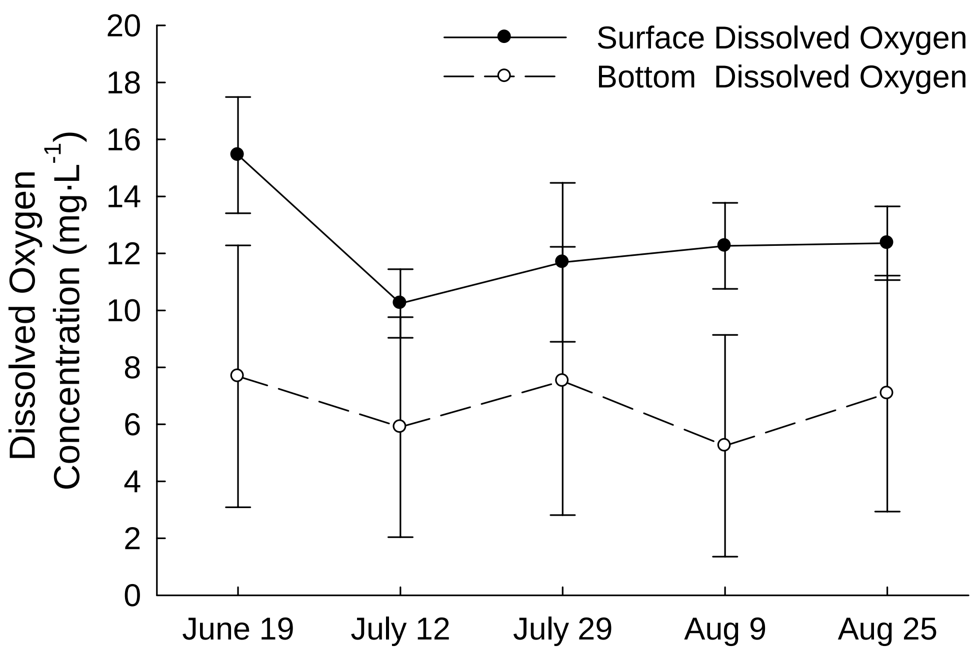

Figure 7. Mean (± SE) surface and bottom dissolved oxygen (mg·L^{-1}) concentrations in Thornapple Lake in 2005. Surface dissolved oxygen ranged from 9-18 mg·L^{-1}, bottom dissolved oxygen concentrations from 0.5-14 mg·L^{-1}.

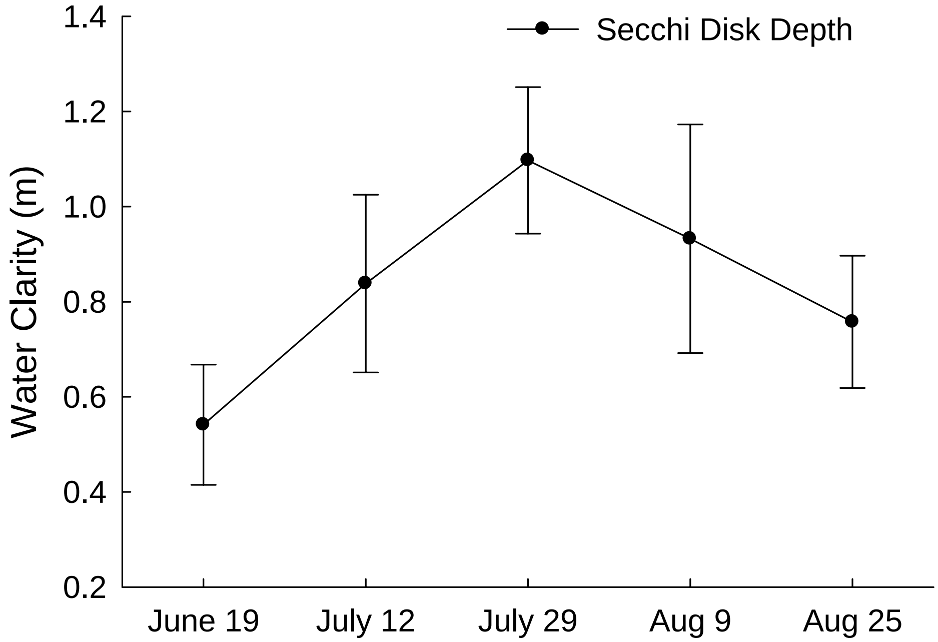

Figure 8. Mean (± SE) Secchi visibility (m) in Thornapple Lake in 2005. Visibility ranged from 0.3-1.5 m.

Table 5: Summary of analysis of variance testing the effects of time (week of the year), depth (inshore or offshore), and habitat (open water or vegetated) on environmental variables (temperature, dissolved oxygen and Secchi visibility). Bottom temperature and dissolved oxygen were higher in inshore habitats, and bottom dissolved oxygen and Secchi visibility were highest in vegetated habitats. Asterisks (*) indicate significant effects.

Habitat Variable	Source of Variation	df	F	*P*
Surface Temperature	Week	1	40.31	< 0.0001*
	Depth	1	0.34	0.56
	Habitat	1	0.22	0.64
	Overall Model	3	13.62	< 0.0001*
Bottom Temperature	Week	1	43.26	< 0.0001*
	Depth	1	855.28	< 0.0001*
	Habitat	1	1.14	0.29
	Overall Model	3	299.89	< 0.0001*
Surface Dissolved Oxygen	Week	1	58.77	< 0.0001*
	Depth	1	0.56	0.46
	Habitat	1	0.00	0.98
	Overall Model	3	19.78	< 0.0001*
Bottom Dissolved Oxygen	Week	1	7.95	0.005*
	Depth	1	787.96	< 0.0001*
	Habitat	1	6.10	0.01*
	Overall Model	3	267.34	< 0.0001*
Secchi Depth	Week	1	79.33	< 0.0001*
	Depth	1	2.58	0.11
	Habitat	1	4.92	0.03*
	Overall Model	3	28.94	< 0.0001*

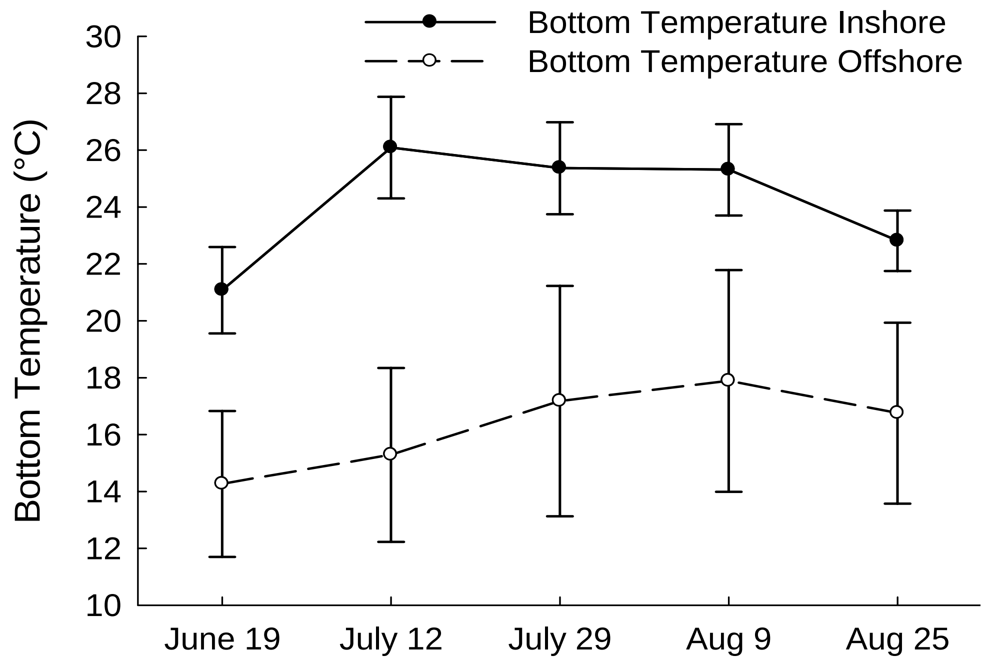

Figure 9. Mean (± SE) bottom inshore (depth < 3 m) and offshore (depth > 3 m) temperatures (ºC) in Thornapple Lake in 2005. Bottom inshore temperatures were significantly higher than bottom offshore temperatures ($P < 0.0001$).

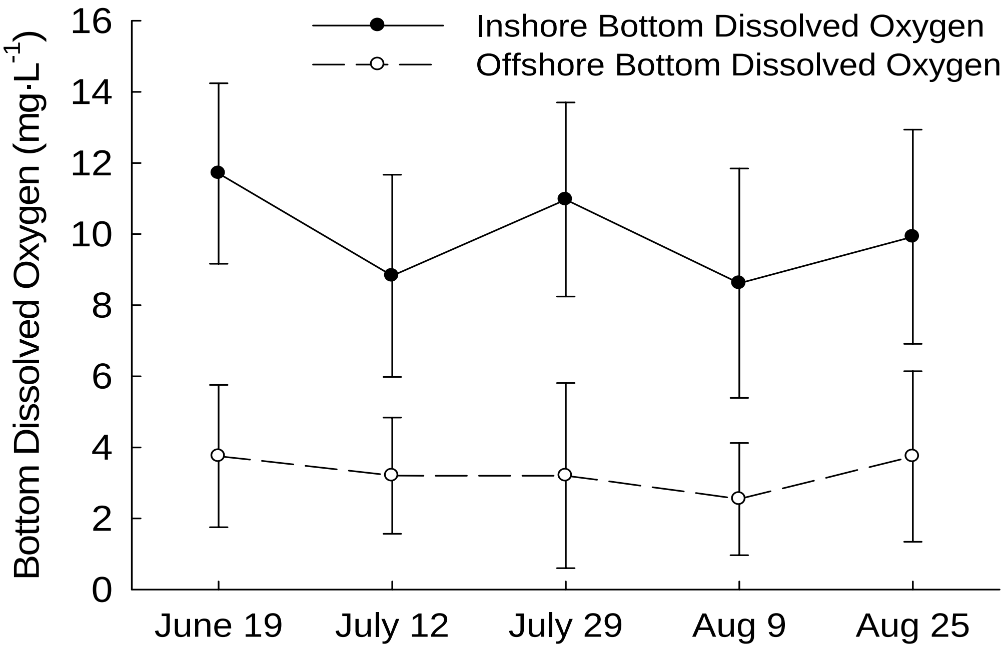

Figure 10. Mean (± SE) bottom inshore (depth < 3 m) and offshore (depth > 3 m) dissolved oxygen concentrations ($mg \cdot L^{-1}$) in Thornapple Lake in 2005. Bottom inshore dissolved oxygen was significantly higher than bottom offshore dissolved oxygen ($P < 0.0001$).

Numerous species of aquatic macrophytes were found in Thornapple Lake. Curly leafed pond weed (*Potamogeton crispus*) dominated the littoral zone from May through late July. Other species present included northern and Eurasian watermilfoil (*Myriophyllum* spp.), coontail (*Ceratophyllum demersum*), cattails (*Typha* spp.), bulrushes (*Scirpus* spp.), pickerelweed (*Pontederia cordata*) and duckweed (*Lemna* spp.) (Table 6).

The area of vegetated habitat available to muskellunge changed through the summer, with the most vegetated habitat available in early August (Table 7). The decrease in vegetated habitat between July and August coincided with a die-off of curly leafed pondweed, which was eventually replaced by coontail and milfoil. Open water was the most available habitat type, followed by vegetation, with dock habitats the least available. Composition analysis determined muskellunge preferentially selected vegetated habitat over dock and open water habitats (P = 0.001). Fish also showed a slight inclination towards dock type habitats over open water habitats, although this difference was not significant (P = 0.13).

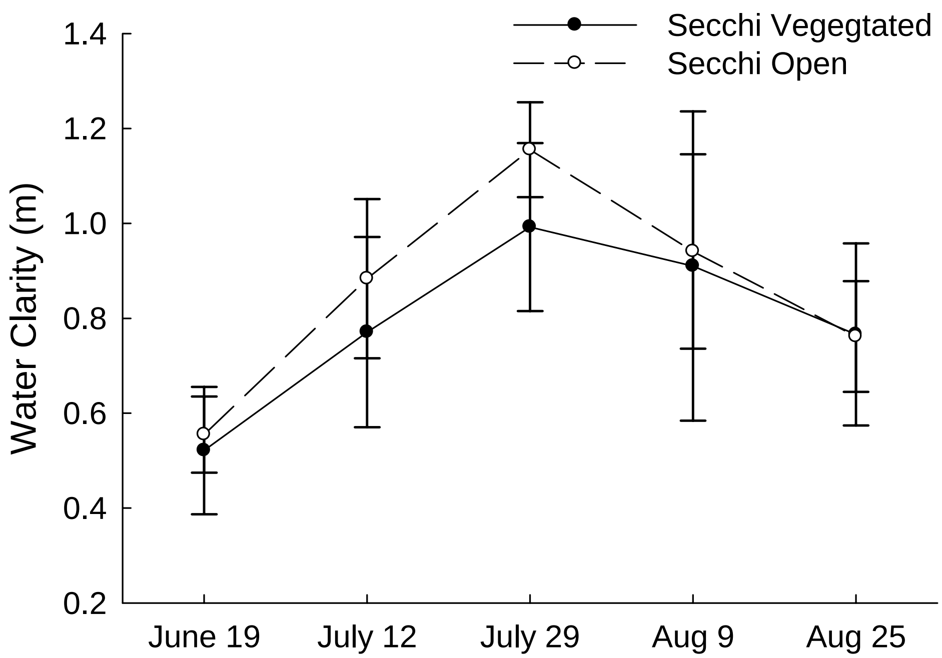

Figure 11. Mean (± SE) Secchi visibility (m) in open and vegetated habitat types in Thornapple Lake in 2005. Visibility was significantly higher in open water habitats (P = 0.03).

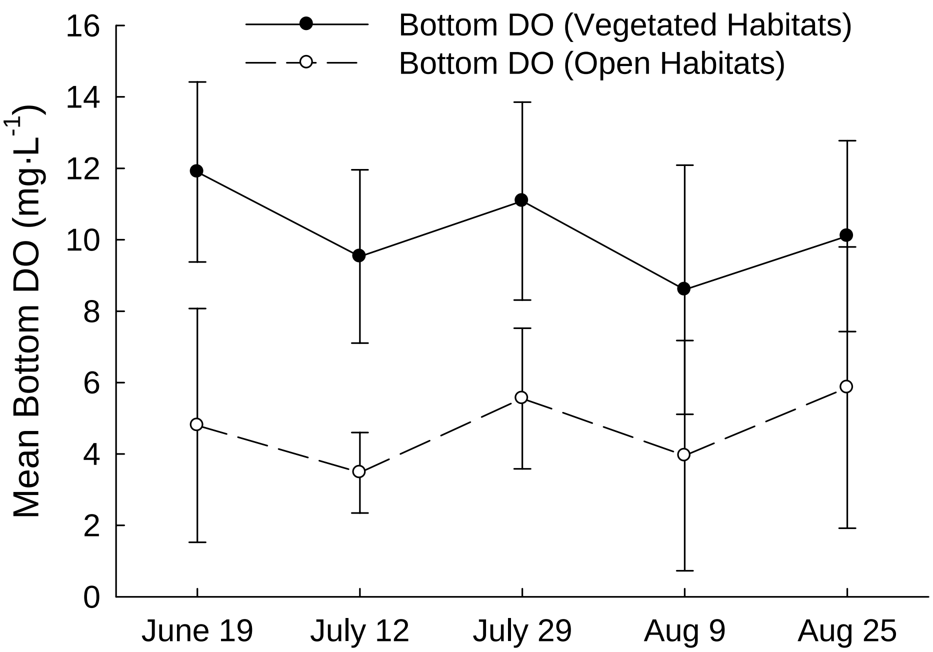

Figure 12. Mean (± SE) bottom dissolved oxygen (DO) ($mg \cdot L^{-1}$) concentrations in open and vegetated habitats in Thornapple Lake in 2005. Dissolved oxygen concentrations were significantly higher in vegetated habitats ($P = 0.01$).

Table 6: Aquatic macrophyte species collected from Thornapple Lake in 2005. Indicated are dates of highest abundance, and the abundance (proportion of sites in which the species was found) that the species reached during this time period.

Species	Dates (2005)	Abundance
Potamogeton crispus	May 20 – July 28	0.86
Other *Potamogeton* spp.	May 20 – Oct 02	0.23
Ceratophyllum demersum	June 20 – Oct 02	0.81
Myriophyllum spp.	June 20 – Oct 02	0.89
Pontederia cordata	July 12 – Sept 02	0.42
Lemna spp.	May 20 – Oct 02	0.62
Nymphaea spp.	June 12 – Oct 02	0.35
Nuphar spp.	June 12 – Oct 02	0.39
Typha spp.	May 20 – Nov 05	0.21
Scirpus spp.	May 20 – Nov 05	0.24

Table 7: Available habitat area for the three habitat types measured in Thornapple Lake from May to August 2005. Although docks were present through the entire summer, dock area was only measured once in mid June.

Date	Area of Vegetated Habitat (ha)	Area of Open Habitat (ha)	Area of Dock Habitat (ha)
20 May, 2005	34.34	131.38	-
16 June, 2005	34.52	131.20	2.22
12 July, 2005	35.05	130.68	-
28 July, 2005	30.01	135.71	-
6 August, 2005	35.22	130.50	-
19 August, 2005	31.58	134.14	-

Analysis of substrate samples taken from Thornapple Lake showed no differences in percent composition (gravel $P = 0.14$, fine gravel $P = 0.28$, sand $P = 0.94$, fine sand $P = 0.89$, very fine sand $P = 0.33$, silt/clay $P = 0.98$) of sediment particle sizes among the 15 sections. However, there was a significant difference between inshore and offshore samples for all particle sizes (gravel $P = 0.01$, fine gravel $P < 0.0001$, sand $P < 0.0001$, fine sand $P < 0.0001$, very fine sand $P = 0.01$, silt/clay $P < 0.0001$) (Figure 13). Offshore sites were primarily composed of silt and very fine organic matter. Sediment composition from inshore sites varied depending on the land use patterns of the surrounding land. Samples from inshore sites near docks, boat launches, and river inlets were primarily composed of gravel and sand.

Prey availability within the lake varied temporally and spatially. Abundant muskellunge forage was captured within the lake, including a wide range of fish lengths that should support muskellunge at all life stages (Bozek et al. 1999) (Table 9, 11). Bluegill (*Lepomis macrochirus*) and black crappie (*Pomoxis nigromaculatus*) were present in all net samples and were caught more frequently than other fish. Yellow bullhead (*Ameiurus natalis*) and golden shiners (*Notemigonus crysoleucas*) were most abundant in June. More fish were caught in smaller mesh nets (Tables 8, 9, 10), which were capable of capturing young-of-the-year bluegill, crappie and largemouth bass (*Micropterus salmoides*). Greater redhorse suckers (*Moxostoma valenciennesi*) were most abundant in open habitats. There were no other differences in fish abundance between the two habitat types.

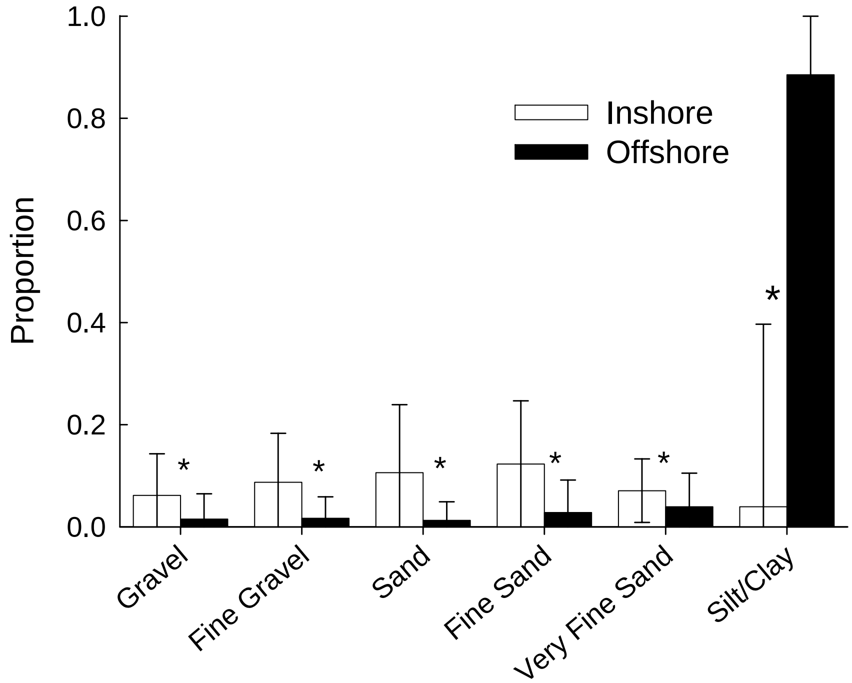

Figure 13. Proportion (± SE) of sediment composition collected from Thornapple Lake in 2005. There was a significant difference in composition between inshore and offshore sites for all particle sizes (asterisks indicate $P < 0.05$). Gravel, fine gravel, sand, fine sand, and very fine sand were all found in higher proportions in inshore sites. Silt and clay particle sizes were most common in samples from offshore sites.

Table 8: Summary of analysis of variance testing the effects of month (June, July or August 2005), habitat (open water or vegetated), net mesh size (large or small), and the month x mesh size interaction. More total fish were caught in small mesh than large mesh, yellow bullhead were caught most often in June in small mesh nets, largemouth bass were most common in small mesh nets, golden shiners were most common in June in small mesh nets, and greater redhorse were caught more often in open habitats. Asterisks (*) indicate significant effects.

Group or Species	Source of Variation	df	F	*P*
Total Fish	Month	2	2.05	0.15
	Habitat	1	1.09	0.31
	Mesh size	1	7.15	0.01 *
	Month x mesh	2	2.07	0.15
	Overall Model	6	2.75	0.03 *
Yellow Bullhead	Month	2	3.06	0.06
	Habitat	1	2.73	0.11
	Mesh size	1	5.91	0.02 *
	Month x mesh	2	9.31	0.01 *
	Overall Model	6	5.56	0.01 *
Largemouth Bass	Month	2	2.67	0.09
	Habitat	1	3.39	0.08
	Mesh size	1	4.99	0.03 *
	Month x mesh	2	1.54	0.23
	Overall Model	6	2.80	0.03 *
Golden Shiner	Month	2	9.11	0.001 *
	Habitat	1	0.47	0.50
	Mesh size	1	4.87	0.03 *
	Month x mesh	2	4.65	0.02 *
	Overall Model	6	4.13	0.01 *
Greater Redhorse	Month	2	2.71	0.09
	Habitat	1	7.43	0.01 *
	Mesh size	1	0.70	0.41
	Month x mesh	2	1.23	0.31
	Overall Model	6	2.67	0.04 *

Table 9: Scientific and common names for all fish species captured during fyke netting. Number captured and mean length (mm) ± SE for June, July, and August 2005. A dash (--) indicates that no individuals of that species were captured in that month. Smaller bluegill, black crappie, yellow perch, and largemouth bass were captured in August 2005 in small mesh nets once young-of-the-year fish recruited to a size in which they became susceptible to the sampling gear.

		Number Captured			Mean length (mm) ± SE		
Common Name	Scientific Name	June	July	August	June	July	August
Bluegill	*Lepomis macrochirus*	370	585	1830	145.3 ± 23.0	144.5 ± 23.9	70.4 ± 32.3
Black Crappie	*Pomoxis nigromaculatus*	74	144	243	185.6 ± 22.3	188.1 ± 40.9	105.4 ± 66.0
Rock Bass	*Ambloplites rupestris*	12	5	11	151.1 ± 29.4	154.8 ± 24.2	140.0 ± 40.1
Pumpkinseed	*Lepomis gibbosus*	16	60	36	161.3 ± 11.6	134.9 ± 32.3	135.6 ± 30.0
Green Sunfish	*Lepomis cyanellus*	1	3	4	142	158.7 ± 18.6	114.8 ± 32.3
Warmouth	*Lepomis gulosus*	6	7	10	168.0 ± 15.0	182.3 ± 16.5	151.5 ± 34.0
Largemouth Bass	*Micropterus salmoides*	2	2	71	301.0 ± 69.3	133.0 ± 10.0	80.8 ± 15.7
Yellow Perch	*Perca flavescens*	41	20	144	180.2 ± 14.3	166.8 ± 29.8	91.1 ± 35.5
Walleye	*Sander vitreus*	--	3	2	--	616.7 ± 56.9	580.5 ± 55.9
Longnose Gar	*Lepisosteus osseus*	2	2	--	566.0 ± 48.1	681.0 ± 41.0	--
Bowfin	*Amia calva*	--	--	2	--	--	656.5 ± 75.7
Channel Catfish	*Ictalurus punctatus*	--	--	1	--	--	491
Brown Bullhead	*Ameiurus nebulosus*	2	--	--	260.5 ± 54.5	--	--
Yellow Bullhead	*Ameiurus natalis*	9	1	--	237.0 ± 63.8	300	--
Northern Pike	*Esox lucius*	5	--	1	475.0 ± 193.3	--	710
Common Carp	*Cyprinus carpio*	1	--	--	710	--	--
Golden Shiner	*Notemigonus chrysoleucas*	4	--	--	166.8 ± 60.1	--	--
White Sucker	*Catostomus commersoni*	--	2	--	--	557.5 ± 46.0	--
Shorthead Redhorse	*Moxostoma macrolepidotum*	1	--	--	361	--	--
Golden Redhorse	*Moxostoma erythrurum*	2	4	3	474.5 ± 19.1	445.3 ± 194.4	616.7 ± 15.0
Greater Redhorse	*Moxostoma valenciennesi*	--	3	--	--	531 ± 167.2	--

Table 10: The species and number of fish captured in vegetated or open habitats and in large or small mesh nets in June, July, and August 2005. More total fish were captured in small mesh nets once young-of-the-year fish recruited to a size in which they became susceptible to our sampling gear. Greater redhorse were captured most often in open habitats, while golden shiners, largemouth bass, and yellow bullhead were captured most often in small mesh nets.

	Number of Fish Captured			
Fish Species or Group	Vegetated Habitat	Open Habitat	Large Mesh	Small Mesh
Bluegill	1601	1183	554	2230
Black Crappie	390	72	153	309
Rock Bass	16	12	12	16
Pumpkinseed	96	19	35	80
Green Sunfish	6	3	2	7
Warmouth	17	6	4	19
Largemouth Bass	27	49	3	73
Yellow Perch	164	40	42	162
Walleye	5	0	3	2
Longnose Gar	2	2	4	0
Bowfin	2	0	2	0
Channel Catfish	0	1	0	1
Brown Bullhead	1	1	1	1
Yellow Bullhead	10	0	1	9
Northern Pike	2	5	7	0
Common Carp	1	0	1	0
Golden Shiner	4	0	1	3
White Sucker	0	2	2	0
Shorthead Redhorse	0	1	1	0
Golden Redhorse	10	1	7	4
Greater Redhorse	0	2	2	0
Total Fish	2354	1399	837	2916

Table 11: Proportion of catch by number and by weight for fish sampling efforts in June, July and August 2005. A dash (--) indicates that no individuals of that species were captured that month. Total proportion by number and weight includes data from all three months pooled together. Weight was calculated through the use of length-weight relationships published in Schneider (2000).

	June		July		August		Total	
Common Name	Proportion by Number	Proportion by Weight	Proportion by Number	Proportion by Weight	Proportion by Number	Proportion by Weight	Proportion by Number	Proportion by Weight
Bluegill	0.68	0.45	0.70	0.44	0.78	0.32	0.74	0.41
Black Crappie	0.14	0.14	0.17	0.20	0.10	0.16	0.12	0.17
Rock Bass	0.02	0.02	0.01	0.01	0.00	0.01	0.01	0.01
Pumpkinseed	0.03	0.03	0.07	0.05	0.02	0.04	0.03	0.04
Green Sunfish	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Warmouth	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Largemouth Bass	0.00	0.02	0.00	0.00	0.03	0.01	0.02	0.01
Yellow Perch	0.07	0.04	0.02	0.01	0.06	0.03	0.05	0.03
Walleye	--	--	0.00	0.08	0.00	0.18	0.00	0.09
Longnose Gar	0.00	0.02	0.00	0.02	--	--	0.00	0.01
Bowfin	--	--	--	--	0.00	0.09	0.00	0.03
Channel Catfish	--	--	--	--	0.00	0.02	0.00	0.01
Brown Bullhead	0.00	0.01	--	--	--	--	0.00	0.00
Yellow Bullhead	0.02	0.04	0.00	0.00	--	--	0.00	0.01
Northern Pike	0.01	0.09	--	--	0.00	0.04	0.00	0.04
Common Carp	0.00	0.09	--	--	--	--	0.00	0.02
Golden Shiner	0.01	0.01	--	--	--	--	0.00	0.00
White Sucker	--	--	0.00	0.05	--	--	0.00	0.02
Shortnose Redhorse	0.00	0.01	--	--	--	---	0.00	0.00
Golden Redhorse	0.00	0.04	0.00	0.06	0.00	0.10	0.00	0.07
Greater Redhorse	--	--	0.00	0.06	--	--	0.00	0.03

CHAPTER V

DISCUSSION

Fish tagged in other muskellunge telemetry studies (Miller and Menzel 1986a, Miller and Menzel 1986b, Strand 1986, Younk et al. 1996) and in this study exhibited no tagging mortality. Tagged fish exhibited growth that was similar to untagged Thornapple Lake muskellunge, which has also been reported in previous studies in other systems (Miller and Menzel 1986a). Normal growth results for tagged fish suggest that the tagging process had little effect on fish feeding behavior and prey capture efficiency. By the same logic, if tagged fish had prey capture efficiencies similar to non-tagged fish, the tagging process likely had little effect on fish habitat selection, as tagged fish and non-tagged fish should inhabit equally optimal habitats.

As in other studies (Miller and Menzel 1986a), fish dispersed throughout the lake after tagging and fish were most often located greater than 700 meters from their capture location. All tagged fish were stocked in the lake and should not exhibit spawning site fidelities, which is further reflected by the fact that none of the fish that were tagged in 2004 returned to their capture locations in the following year. Previous studies have demonstrated homing behavior in both naturally reproducing and stocked muskellunge populations (Crossman 1977, Miller and Menzel 1986b). Due to the large size of the lake systems in these studies, the authors typically considered a fish to be "homing" if it returned to an area within 1000 meters of its capture location or previous home-range. Because Thornapple Lake is much smaller system, 1000 meters is a relatively long distance in the lake. It is especially difficult to compare multiple studies when there are vast differences in system size and no consensus on the minimum distance (or in this case a relative distance) required before an animal can be considered to be "homing".

Muskellunge have been observed moving out of a lentic environment and into lotic habitats. In Crossman (1977), a fish was captured and released in the lake, but proceeded to move into a connecting stream where it remained for the summer. Observations in the current study were similar in the fact that the fish was captured and released into the lake. However, in the current study, the fish did not move out of the lake until late in the field season (November 2005), and only one location was observed outside the study area. Prior to moving out of the lake, the fish exhibited a very erratic movement pattern in which it would occupy a very small area (within a circular area with a diameter of 10-20 meters) and then unexpectedly move long distances (greater than 1 km) before again resuming the sedentary behavior. This pattern was repeated several times through the summer of 2005.

Most muskellunge remained within Thornapple Lake during this study, and only one fish was located outside the main lake basin. Similar trends have been observed by Dombeck (1979), Miller and Menzel (1986a, 1986b), and Strand (1986). These observations imply that adult fish typically do not move out of the lake system and that adult emigration is not likely the cause of muskellunge dispersion to downstream locations.

Home-ranges were determined for 11 of 22 (50%) fish over both study seasons. In contrast, Crossman (1977), Dombeck (1979), Minor and Crossman (1979), and Miller and Menzel (1986b) found all fish to occupy home-ranges (Table 12). In these studies, the authors designated a center for the home-range and then proceeded to arbitrarily and subjectively include (or reject) fish locations to define the home-range area (Miller and Menzel 1986b). Few details are reported regarding the exact methodology used. In defense of these authors, these studies were published before the advent of GIS tools and GPS methods that allowed fast and accurate calculation of site fidelity and home-ranges. It should also be noted that a published test for site fidelity was not present in the literature until after the publication of these papers (Spencer et al. 1990). If these studies were re-examined using current methodologies, the authors may find that not all tagged fish exhibit site fidelity and therefore did not occupy home-ranges. The inclusion of all fish (without justification) in home-range determination will likewise affect further analyses.

The effects of site fidelity analysis can be seen in the mean home-range size found for fish in this study. In the current study, mean home-range sizes were substantially smaller than those previously reported (Dombeck 1979, Miller and Menzel 1986b, Strand 1986) and were proportionally larger (Table 12). This can be attributed to the random walk site fidelity test (Hooge et al. 2001). When site fidelity is calculated, wide-ranging fish do not exhibit site fidelity. Wide-ranging fish are excluded from the home-range mean, resulting in a smaller mean home-range size. If the authors of the previous studies (Crossman 1977, Minor and Crossman 1978, Dombeck 1979, Miller and Menzel 1986b) were to re-examine their data with this in mind, they may find that wide-ranging fish did not exhibit site fidelity and should be excluded from home-range mean values. The removal of "false" home-ranges from reported mean values will alter the results.

Table 12: Mean home-range area (ha) (± SE), surface area of the lake (ha), the number of fish occupying home-ranges, the home-range calculation method used in current study and previous studies, and the proportion of the study area for each mean home-range.

Study	Mean Home-range (ha)	Lake Area (ha)	Number of Fish	Method	Proportion of Study Area
Minor And Crossman 1979	0.32 ± 0.05	35	14	Grid square	0.01
Strand 1986	2713 ± 1959	45134	12	MCP	0.06
Dombeck 1979 (Moose L.)	10.7 ± 9.2	676	11	Grid square	0.02
Dombeck 1979 (Black L.)	1.5 ± .7	52	7	Grid square	0.03
Miller and Menzel 1986	63.0 ± 9.6	1540	9	Grid square	0.04
Miller and Menzel 1986	146 ± 120	1540	9	MCP	0.09
Current Study	39 ± 13.2	165	11	MCP	0.24
Current Study	18.8 ± 14.1	165	11	Kernel 50%	0.11

Previous studies (Minor and Crossman 1979) have demonstrated relationships exist between home-range size and the number of contacts, fish age, length, and weight for MCP home-ranges, and between fish length, weight, and the number of contacts for 50% kernel home-ranges. In contrast, this study describes one negative relationship between fish age and area of the 50% kernel home-range (as fish age increased, home-range area decreased), which is contradictory to the findings of Minor and Crossman (1979) who found that home-range area increases as fish length increased. Fish ages were not determined in the Minor and Crossman (1979) study, so it is impossible to determine if there would have been a relationship between fish age and home-range area. Comparisons are further complicated in that the methods used to determine home-range in the Minor and Crossman (1979) study are outdated (grid square method) and not comparable to probabilistic (kernel) home-range estimators.

Current site fidelity tests may not be appropriate for this study system. The random walk Monte-Carlo site fidelity test works by using observed movement distances with a random direction of travel in between each movement segment. In this study, the random movement paths were also constrained so that the generated path did not exit the lake at the boundary between the lake and shore. This created a problem, as Thornapple Lake is much longer east to west than it is north to south. Muskellunge in the lake are able to move long distances in the east-west direction, but not in the north-south direction. When the observed movement distances were then repeated at a randomized direction of travel, the test program was unable to complete the analysis, as an error would occur whenever a movement path encountered the lake boundary. This made it impossible to finish site fidelity testing for a number of fish, and these fish were considered to not occupy home-ranges. In larger systems, the random movement paths may be less likely to encounter lake boundaries, which could result in less error during analysis.

Surface temperature and dissolved oxygen concentrations changed as the summer progressed. Surface temperatures were higher than bottom temperatures, and in both cases, the mean lake temperature steadily increased from April through September before steadily decreasing. Inshore bottom temperatures were higher than offshore bottom temperatures. Inshore sites were in shallower water that was closer to the lake's surface and able to warm up faster than deeper sites. The temperature range within the lake was within the temperature tolerance range of muskellunge (Cook and Soloman 1987) and should not affect the population.

While dissolved oxygen concentrations were higher at the lake surface than the lake bottom, there were no predictable trends in mean surface dissolved oxygen concentration as the season progressed from May through August. The lack of a predictable trend is not surprising, as surface dissolved oxygen concentrations fluctuate based on numerous factors including the amount of algae and macrophytes present (Cross and Summerfelt 1987). Bottom dissolved oxygen concentrations remained stable and exhibited little fluctuation through the summer. Bottom dissolved oxygen concentrations at inshore sites were significantly higher than bottom dissolved oxygen concentrations at offshore sites. Again, this was not surprising as the inshore sites were more likely to be vegetated and accessible by algae, which would cause increased oxygen concentrations due to the production of oxygen through photosynthesis. Anoxic conditions did occur at the sediment-water interface, but these conditions should not affect muskellunge, as they are a pelagic lie-in-wait predator. Muskellunge are not adapted for life at the bottom of the lake and therefore will not encounter these anoxic conditions. Oxygen concentrations at the surface were found to be within the tolerance range of muskellunge (Cook and Soloman 1987) and should not be a factor in the muskellunge population declines in the lake.

Secchi visibility fluctuated unpredictably throughout the summer. Water clarity depends on numerous factors, including the amount of precipitation (Summerfelt 1971) in the watershed surrounding a river or lake. The relatively high Secchi readings in July were recorded after a rainstorm, which flushed suspended sediments downstream and cleared the water column. There was no difference in Secchi visibility between inshore and offshore sites, although visibility in inshore sites was typically lower than in offshore sites. This could be explained by the presence of aquatic macrophytes in inshore habitats, which could prevent water from flowing through the lake and flushing out the suspended sediments in the inshore sites. Water clarity was below the recommended water clarity level for muskellunge (Cook and Soloman 1987) for most of the summer, which could theoretically cause reduced prey capture efficiencies, as muskellunge search for prey based primarily on sight (New et al. 2001). Fish with reduced capture efficiencies may experience a decrease in growth and eventually death (Inskip and Magnuson 1986). This scenario is unlikely to be causing a decline in the muskellunge population in the lake, as muskellunge growth within the lake is comparable to trophy muskellunge lakes in Wisconsin (Kregg Smith, MDNR, personal communication). Additionally, muskellunge growth in Thornapple Lake is higher than the Michigan growth average (Kregg Smith, MDNR personal communication).

Muskellunge prefer vegetated habitats (Crossman 1977, Dombeck 1979, Miller and Menzel 1986a, Strand 1986), in Thornapple Lake, the amount of vegetated habitat available to muskellunge fluctuated through the summer. Vegetated habitat was least available in late July, which corresponded to the decline in curly leafed pond weed at the end of its growing season. The subsequent increase in vegetation in August was due to an increase in coontail and milfoil species, which occupied the areas left vacant by the decline of curly leafed pond weed.

Muskellunge used vegetated habitat in a greater proportion than available in the environment and preferentially selected vegetated habitat over open water habitats. Dock habitats were selected secondarily after vegetated habitats, but there was no significant difference in selection between dock and open water habitats.

Vegetation as a choice of cover offers many trade-offs in the form of costs and benefits to different fish species. Predator behavior and predation rate vary depending on the type of vegetation, density, and the species of predator and prey (Savino and Stein 1989). Changes in predator growth and condition have also been related to changes in vegetation density, abundance, and structure complexity (Colle and Shireman 1980). Predators differ in their foraging behavior, efficiency, and choice of prey in vegetated habitats. Largemouth bass are less efficient predators in vegetated habitats. When foraging in complex vegetated habitats, they choose prey that are less likely to escape (Nyberg 1971). Other predators (northern pike) prefer to forage in vegetated habitats regardless of a possible reduction in capture success. Northern pike use vegetation as cover and stalk prey, only to attack prey once they are nearby (Hobson 1979). The observed selection of vegetated habitats by muskellunge in this study likely reflects a predatory strategy similar to that of northern pike. Indeed, both species are closely related, have similar body shapes that facilitate movement through structure, and have cryptic coloration that helps them hide within vegetation.

As the majority of vegetated habitat in the lake was composed of non-native species, there is a possibility that muskellunge populations may be affected in the future if landowners around Thornapple Lake begin a macrophyte control project. Because the fish select vegetated habitats, a decline in vegetated habitat will concentrate muskellunge populations and eventually force some fish to inhabit sub-optimal habitats. Any future macrophyte control project should be designed such that it has minor effects on fish stocks, and attempts to mitigate these effects should also be investigated (e.g., the re-introduction of native aquatic macrophytes).

Lakeshore development has potential to affect fish communities. Coarse woody debris and aquatic macrophytes (common structures in littoral nearshore habitats) provide substrates for the growth of periphyton (Vadeboncoeur and Lodge 2000), provide habitat for macroinvertebrates (Bowen et al. 1995), and positively affect growth rates and abundance of some littoral fish species such as bluegill and largemouth bass (Schindler et al. 2000). Age-0 fish use macrophytes and coarse woody debris as nursery habitat and benefit from the interstitial spaces and increased macroinvertebrate density that has been associated with coarse woody debris (Bowen et al. 1995). In Wisconsin lakes, the removal of coarse woody debris caused a diet shift and a decline in size specific growth rate in largemouth bass, as well as a decline in forage fish abundance (Sass et al. 2006). Small areas of lakeshore development, however, may benefit fish and other aquatic organisms by diversifying habitat. Largemouth bass, muskellunge, and northern pike, common predators in the littoral zone, are most effective at capturing prey in vegetated habitats that are diverse and have many interstitial spaces (Savino and Stein 1989, Anderson 1984). Extensive and uniform lakeshore development is detrimental to these same species (Jennings et al. 1999).

Though muskellunge preferentially selected vegetated habitats, fish were observed in deeper offshore habitats. Analysis showed that these offshore movements were associated with increased surface temperature. Fish likely moved into these offshore habitats to avoid high surface temperatures. As fish are ectothermic, they must regulate their body temperatures by changing their location within the water column. Muskellunge in this study vacated warm littoral habitats to cooler offshore habitats in an effort to escape temperatures above their optimal temperature range (25 °C, Dombeck 1979).

Spring muskellunge movements are characterized by long movements (up to 27 km) into shallow spawning areas where the fish will remain for 1-2 weeks (Younk et al. 1996). Males move into the spawning areas first and remain there longer than females (Younk et al. 1996). As fish were captured and implanted with transmitters after they had made these movements into spawning areas, this pattern was not observed in this study.

Fall movements are characterized by “excursions” outside of the summer home-range, possibly due to increased feeding during gonadal development (Dombeck 1979). These excursions may explain the long downstream movement of female fish 4413 in November. In late fall, muskellunge move to deep water thermal refuges where they overwinter (Younk et al. 1996). During winter, fish become sedentary and movements are short and unpredictable (Younk et al. 1996).

Water temperature has been suggested as a significant factor affecting muskellunge movement and home-range size. Winter home-ranges are smaller than summer home-ranges because of reduced fish activity (Dombeck 1979). Minimum activity (reduced home-range size) is observed during the winter (water temperature 0-2 °C) (Dombeck 1979). Maximum activity occurs between 10-15 °C but does not decrease until water temperature reaches above 25 °C (Dombeck 1979).

Substrate analysis revealed that there was no difference in sediment composition between the 15 sections in the lake, which may be explained by the flow of the Thornapple River through the lake. As the river flows through the lake, sediments are carried and dispersed evenly. There was, however, a significant difference in particle sizes between inshore and offshore sites. Large particles (gravel, sand) were more common in inshore sites and small particles (silt, clay) were found in offshore sites. Sediment particles washed into the lake by wave action settle out of the water column by weight. The largest particles fall out of the water column near the shore while smaller, lighter particles are carried to deeper parts of the lake. Sediment collected from inshore habitats (muskellunge spawning habitats) was composed primarily of sand or decaying vegetation. This type of substrate is inappropriate for muskellunge spawning sites as sand facilitates fungal infection of the eggs and decaying vegetation increases the biological oxygen demand, resulting in anoxic conditions at the substrate-water interface (Dombeck et al. 1984).

Fish assemblages in Thornapple Lake were comparable to fish assemblages in other small Midwestern lakes (Hatzenbeler et al. 2000, Pierce et al. 2001). Few soft rayed fishes (cyprinids, catostomids), preferred muskellunge prey items, were captured (Bozek et al. 1999). Yellow perch (*Perca flavescens*) are important muskellunge food source (Bozek et al. 1999) and were captured in small numbers. This, however, is unlikely to be limiting the muskellunge population in the lake. Because muskellunge in Thornapple Lake exhibit trophy growth potential that exceeds the mean muskellunge growth for other Michigan lakes, they must be able to locate and capture enough prey to maintain a high growth potential. The observed fish assemblage was dominated by centrarchids, which are more susceptible to fyke nets than other species as these fish are adapted to moving around and through objects that provide cover (such as vegetation or the lead of a net). It is likely that the choice of net type, netting locations, or netting technique contributed to the observed fish assemblage.

The muskellunge population decline within Thornapple Lake may be caused in part by poor survival of stocked fish. Post-stocking survival of juvenile muskellunge is typically variable and may range from 0% to over 95% (Hanson et al. 1986). The survival of stocked fish is determined by the number and density of potential predators, as well as potential environmental factors such as temperature shock (Mather and Wahl 1989). Temperature shock may occur whenever there is a rapid change in ambient temperature, such as when fish are moved from the hatchery transport truck to the lake. The potential effects of temperature shock can be mitigated by careful monitoring of lake temperature and stocking date. Predation on stocked fish is difficult to control. Juvenile muskellunge are typically raised in large open ponds that do not contain predators, and fish are less likely to be able to recognize potential predators and may lack the escape response necessary to survive (Wahl and Stein 1989). Thornapple Lake supports a large population of potential predators of juvenile muskellunge (northern pike, largemouth bass, and muskellunge), all of which could thwart MDNR stocking efforts. Furthermore, the lack of natural reproduction would result in an eventual depression of the spawning population.

Juvenile fish may also move outside of the lake and into the connecting river systems. Previous research by the MDNR in Lake Belleville has confirmed that juvenile muskellunge moved downstream to reside in river impoundments after they were stocked in the lake system (Gary Towns, MDNR, personal communication). Genetic testing confirmed that the fish captured in these impoundments were stocked in Lake Belleville and were not the result of natural reproduction. It is possible that juvenile fish moved downstream in an attempt to escape predation pressure or to decrease the effects of competition (Gary Towns, MDNR, personal communication). Similar to Lake Belleville, the Thornapple River is impounded downstream of Thornapple Lake, which could provide suitable habitat for juvenile muskellunge. If these fish do not return to Thornapple Lake to spawn, it could result in declines of the adult spawning stock in the lake.

Thornapple Lake is capable of producing large trophy length muskellunge, and the state record muskellunge was captured in Thornapple Lake in 2000 (Kregg Smith, MDNR, personal communication). Since the capture of this fish, the lake has experienced an increase in angler pressure (Kregg Smith, MDNR, personal communication). Muskellunge are susceptible to delayed mortality, in which an apparently healthy fish may die hours or days after it has been released by an angler (Beggs et al. 1980). Delayed mortality is typically associated with physiological stress (Beggs et al. 1980) or physical damage to gills or internal organs (Gasbarino 1986). As the lake is experiencing increased angler pressure, increased mortality (harvest mortality or delayed mortality) may be causing a decline in the muskellunge population.

Competition from other piscivorous fish species may also affect the muskellunge population in the lake. Largemouth bass, walleye (*Sander vitreus*), and northern pike are all present in the lake in large numbers and may compete with muskellunge for resources (Harrison and Hadley 1978). Competition between northern pike and muskellunge has been previously documented (Harrison and Hadley 1978), and northern pike may be competitively superior to muskellunge (Harrison and Hadley 1978). These factors could also contribute to muskellunge population declines within the lake.

Assumptions

All habitat selection studies assume that the animals selected for the study are selected at random (Alldredge et al. 1998). This assumption is necessary if the goal of the project is to extrapolate data collected from a few individuals to the entire population. Technically, this assumption was not met in the current study, as we did not implant transmitters into fish that were greater than 127 cm long. However, only one fish over this length was captured during the study, and it is likely that few individuals in the lake exceed 127 cm in length. This study also only used mature, spawning adults, as these fish were most susceptible to the capture gear.

Animal locations must also be independent of each other and not spatially or temporally correlated (Swihart and Slade 1997). This can easily be violated if locations are close together in time. However, if locations are collected too far apart, a researcher may miss observing locations in habitat types that are visited infrequently and occur in relatively small patches but are nevertheless important. These assumptions were met by relocating fish every three days during the field season and once per week during spring and autumn.

Habitat selection by an animal must also be independent of the habitat selection by other animals (Alldredge et al. 1998). This assumption may be violated if the species of interest is gregarious or territorial (Alldredge et al. 1998) as the behavior of one individual may affect habitat selection of another animal. This assumption was likely met in this study as muskellunge are not gregarious or territorial. However, it is possible that another species (humans, northern pike, walleye, and largemouth bass) present in the system did affect habitat use (through predation or competition) by the tagged muskellunge.

Animals must also have the same access to all habitat types, from which they will select the best habitat in which to forage or reside (Alldredge et al. 1998). Presumably, this assumption was met, as there are no barriers to fish movement within the lake. Habitat availability is assumed to be constant, known, and correctly identified through the entirety of the study (Nams 1989, Schooley 1994). These assumptions were all met for determining the amount of vegetated and open habitats, as this study used highly accurate GPS techniques to map and determine habitat areas. Habitat availability was compared from month to month and determined to be relatively constant. Dock habitat types were not available in equal abundances through the course of the study, as land owners install and remove docks at different times within the year (docks are removed during the winter to protect them from ice damage). Most docks were installed by June 10 and removed by October 15 in both years.

Finally, all animals are assumed to be equally detectable (Alldredge et al. 1998). This assumption was met by attempting to locate all individuals during each tracking session. However, the pulse generated by ultrasonic transmitters quickly diminishes when moving through thick macrophyte vegetation. It is possible that fish that were located within, behind a curtain of macrophytes, or within a river channel in thick cover and were unable to be located until they moved to the edge of the vegetated cover and could then be detected. If a fish could not be located after two passes through the lake, tracking was ended for the day.

Management Implications

The fish implanted with transmitters in this study were not observed moving out of the lake and into adjacent river systems. At this time, a change in the fishing regulations (to limit angler harvest) in the Thornapple River is unlikely to increase the spawning population in the lake. However, due to the popularity of the lake as a trophy fishery, it is recommended that the 127 cm minimum length limit remain in effect on the lake to prevent angler harvest.

Lack of appropriate spawning substrate and nursery habitat in the shallow littoral zone is likely contributing to the reproductive failure of fish in the lake (Dombeck et al. 1984, Dombeck 1986, Dombeck et al. 1986, Strand 1986, Cook and Soloman 1987, Zorn et al. 1998). Rehabilitation of these areas is costly and requires the support of landowners in order to be successful. Though this action may eventually lead to natural muskellunge reproduction, the high-risk nature of the project and constant required maintenance would make an undertaking too costly to consider at the time. The lake should continue to be stocked at the current rate of four individuals per acre every other year to support the spawning population necessary to provide eggs and sperm to the state muskellunge rearing program. It is also recommended that a project be conducted in the near future to determine if juvenile fish are leaving the system after they are stocked into the lake.

The current aquatic flora present in the lake is primarily composed of exotic species (curly leafed pondweed, Eurasian watermilfoil) that can form dense mats, which are undesirable for recreational boating and swimming on the lake (Valley and Bremigan 2002). As muskellunge select these areas in the spring and fall, the removal of these habitat types could cause a decline in the population in the future, especially if the MDNR or landowners around Thornapple Lake decide to begin an aquatic plant control program.

In 2005, viral hemorrhagic septicemia (VHS) was discovered in Lake St. Clair, Michigan. The disease is capable of infecting and killing many fish species, including muskellunge, and is believed to have been unintentionally spread to the Great Lakes through ballast water discharge from ships. VHS can also be spread by moving infected fish from one system to another (e.g., baitfish) (Kregg Smith, personal communication). The disease has since spread to Lakes Huron and Erie, as well as several inland lakes throughout Michigan (Kregg Smith, personal communication). If VHS becomes established in Thornapple Lake, a new source lake for muskellunge brood stock will need to be selected by the MDNR, to prevent the introduction of VHS into the MDNR hatchery system.

Conclusions

The muskellunge population decline in Thornapple Lake is not due to emigration of adult fish from the study area. Only one fish out of the 22 that were observed moved into the Thornapple River, and as this occurred late in the field season (November). This may be related to seasonal muskellunge movement observed in other studies (Dombeck 1979).

Muskellunge selected vegetated habitat in Thornapple Lake, consistent with previous findings (Minor and Crossman 1978, Miller and Menzel 1986a). This is important to consider, as further development of the lake for human recreation will likely result in the clearing or control of aquatic vegetation, which could result in declines in the muskellunge population in the future. None of the other variables that were investigated appears to be causing the population decline in the lake, as prey was plentiful and environmental variables (temperature, dissolved oxygen, and water clarity) were within muskellunge tolerance limits.

It is likely that inappropriate spawning and nursery areas are contributing to the lack of natural reproduction and recruitment of juveniles to adult stocks. The lack of natural reproduction will require the MDNR to continue stocking fish into the system to ensure that the adult population does not decline further.

It is also possible that the juvenile fish that are stocked into the lake experienced high post-stocking mortality in the past. This could result in poor recruitment of one or more year classes to the spawning stock (resulting in a depression in the muskellunge population). It is also very likely that the juvenile fish could be moving downstream to become resident fish in the Thornapple River or in the impoundment downstream of the lake. These fish could be moving downstream to escape predation or competition pressures in the lake.

Further research needs to be conducted on the juvenile fish that are stocked into the lake. Many techniques (genetic analysis of fish recaptured downstream, mark-recapture) could be used to evaluate movement of juvenile fish downstream. I also recommend that the MDNR begin marking all fish that are stocked into the lake. Currently, fish are added with no distinguishing marks. The presumed lack of natural reproduction is determined by the lack of fish from "non-stocking" years when the fish are aged as adults. The addition of an easily recognizable and permanent mark would facilitate resolution of the hypothesis that natural reproduction and recruitment are failing in the lake (as naturally reproduced fish will not bear the mark). I feel that these actions would be the next logical steps to understanding the population dynamics of the muskellunge within the lake.

APPENDICES

APPENDIX A

MOVEMENT PATHS OF TRANSMITTER TAGGED FISH IN THORNAPPLE LAKE IN 2004.

Figure 14. Movement of fish 3334 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

Figure 15. Movement of fish 3345 in Thornapple Lake in 2004. The black line represents the fish’s observed movement path.

Figure 16. Movement of fish 3347 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

Figure 17. Movement of fish 3354 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

Figure 18. Movement of fish 3356 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

Figure 19. Movement of fish 3365 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

Figure 20. Movement of fish 3367 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

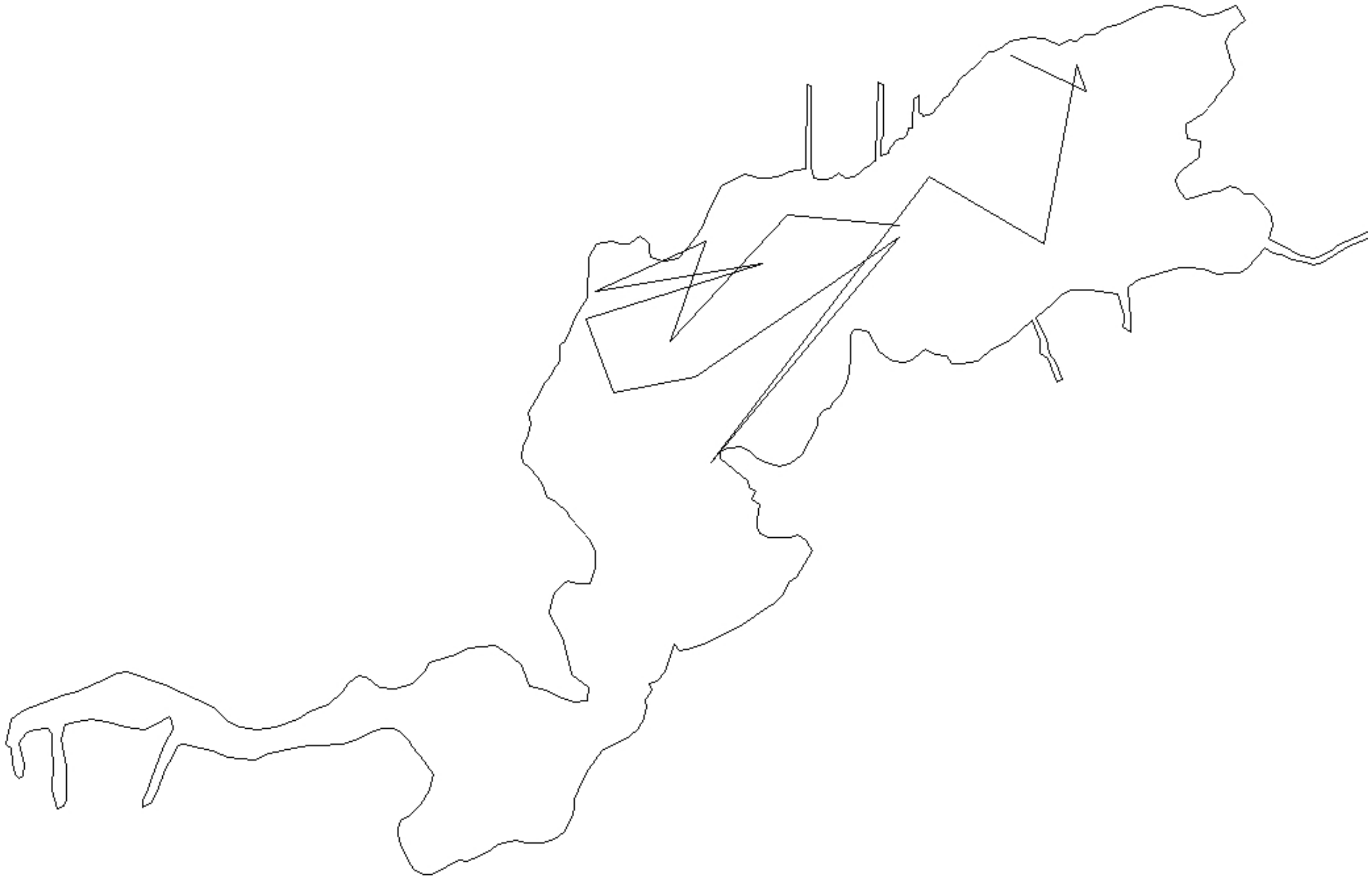

Figure 21. Movement of fish 3374 in Thornapple Lake in 2004. The black line represents the fish's observed movement path.

APPENDIX B

MOVEMENT PATHS OF TRANSMITTER TAGGED FISH IN THORNAPPLE LAKE IN 2005.

Figure 22. Movement of fish 3334 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 23. Movement of fish 3347 in Thornapple Lake in 2005. The black line represents the fish’s observed movement path.

Figure 24. Movement of fish 3354 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 25. Movement of fish 3356 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 26. Movement of fish 3365 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

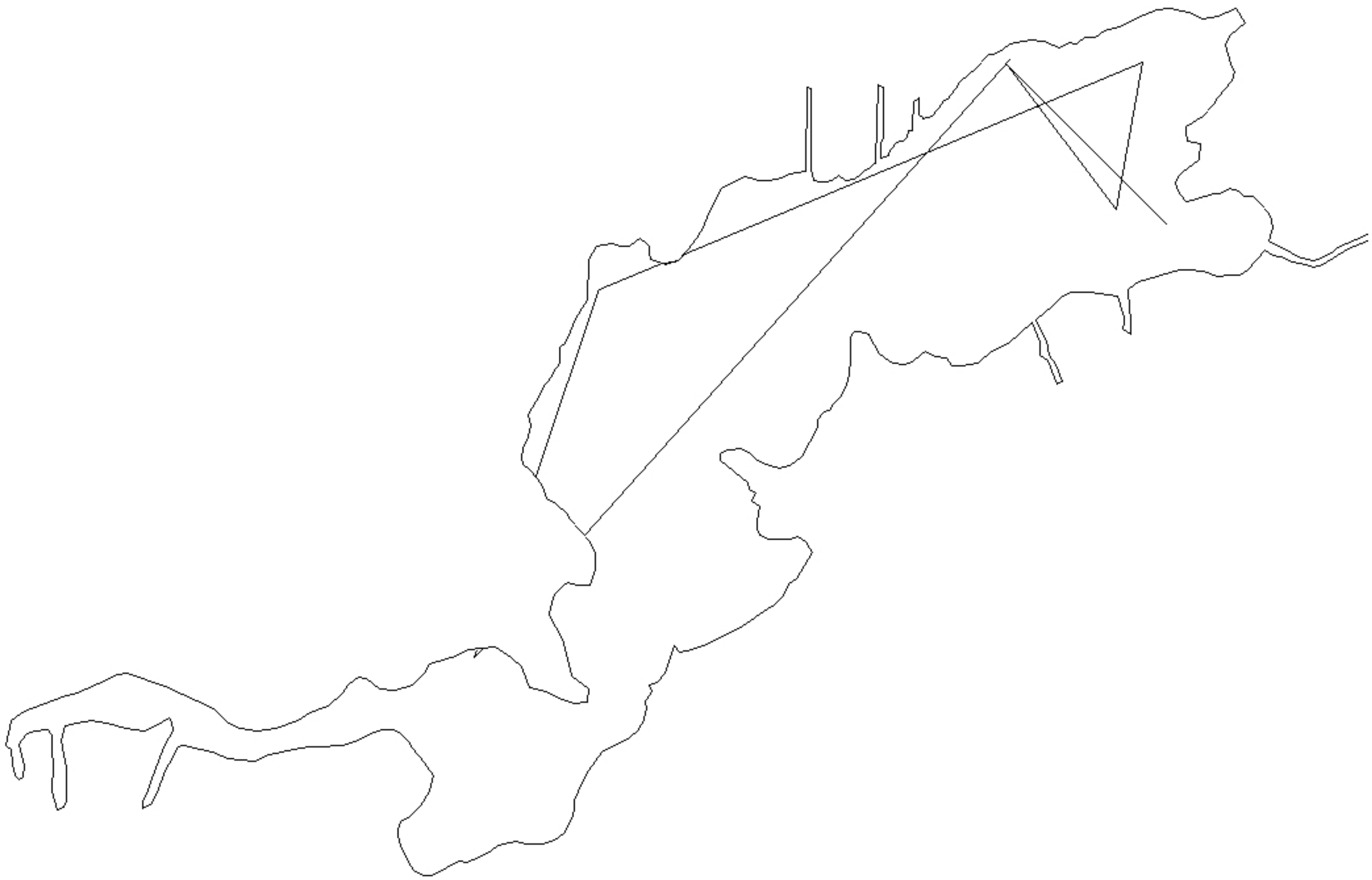

Figure 27. Movement of fish 3367 in Thornapple Lake in 2005. The black line represents the fish’s observed movement path.

Figure 28. Movement of fish 3374 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 29. Movement of fish 3376 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 30. Movement of fish 444 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 31. Movement of fish 445 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 32. Movement of fish 446 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

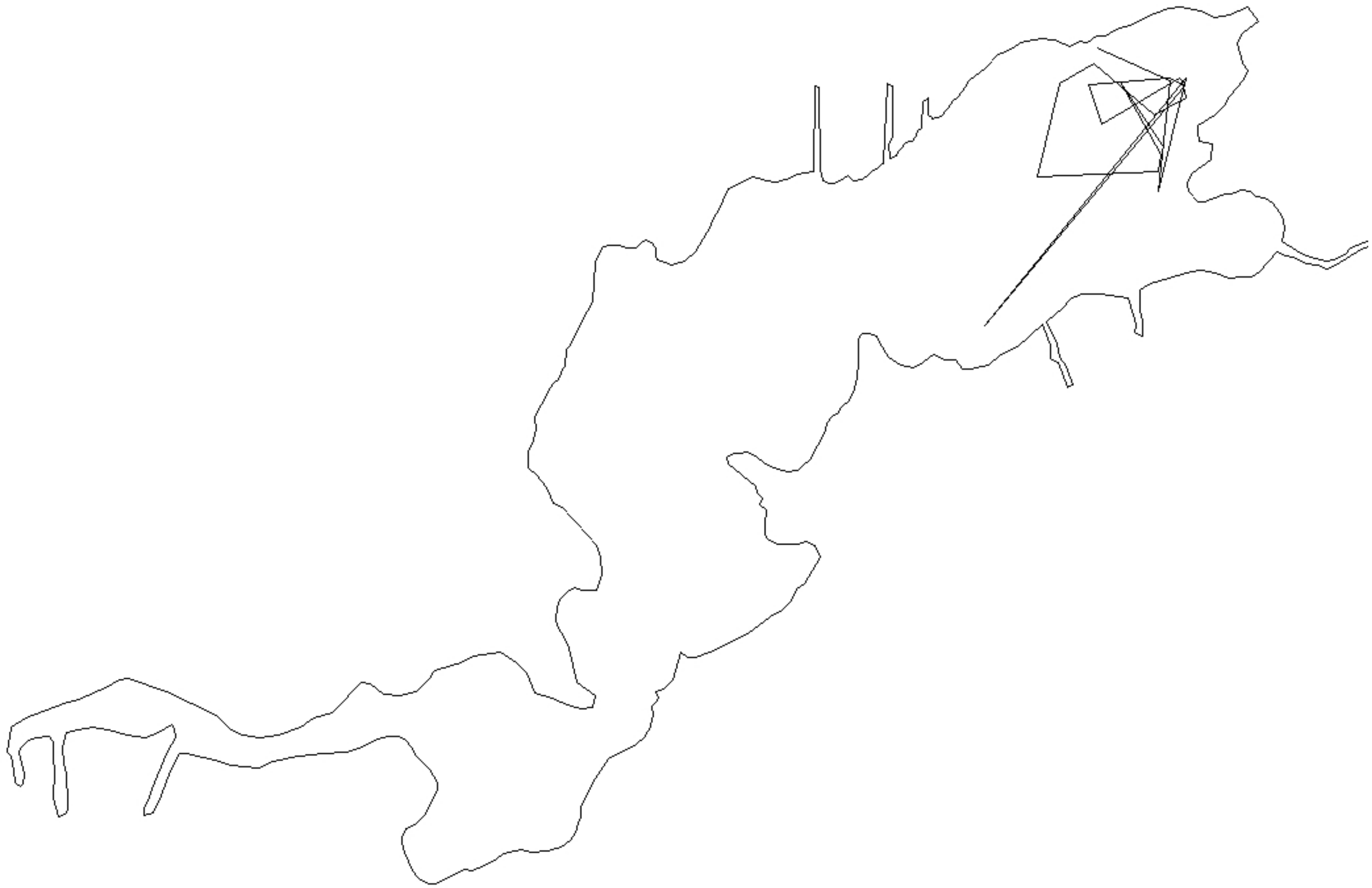

Figure 33. Movement of fish 447 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 34. Movement of fish 448 in Thornapple Lake in 2005. The black line represents the fish’s observed movement path.

Figure 35. Movement of fish 449 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 36. Movement of fish 4410 in Thornapple Lake in 2005. The black line represents the fish’s observed movement path.

Figure 37. Movement of fish 4411 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 38. Movement of fish 4412 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 39. Movement of fish 4413 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

Figure 40. Movement of fish 4414 in Thornapple Lake in 2005. The black line represents the fish’s observed movement path.

Figure 41. Movement of fish 4415 in Thornapple Lake in 2005. The black line represents the fish's observed movement path.

APPENDIX C

HOME-RANGES OF TRANSMITTER TAGGED FISH IN THORNAPPLE LAKE IN 2004.

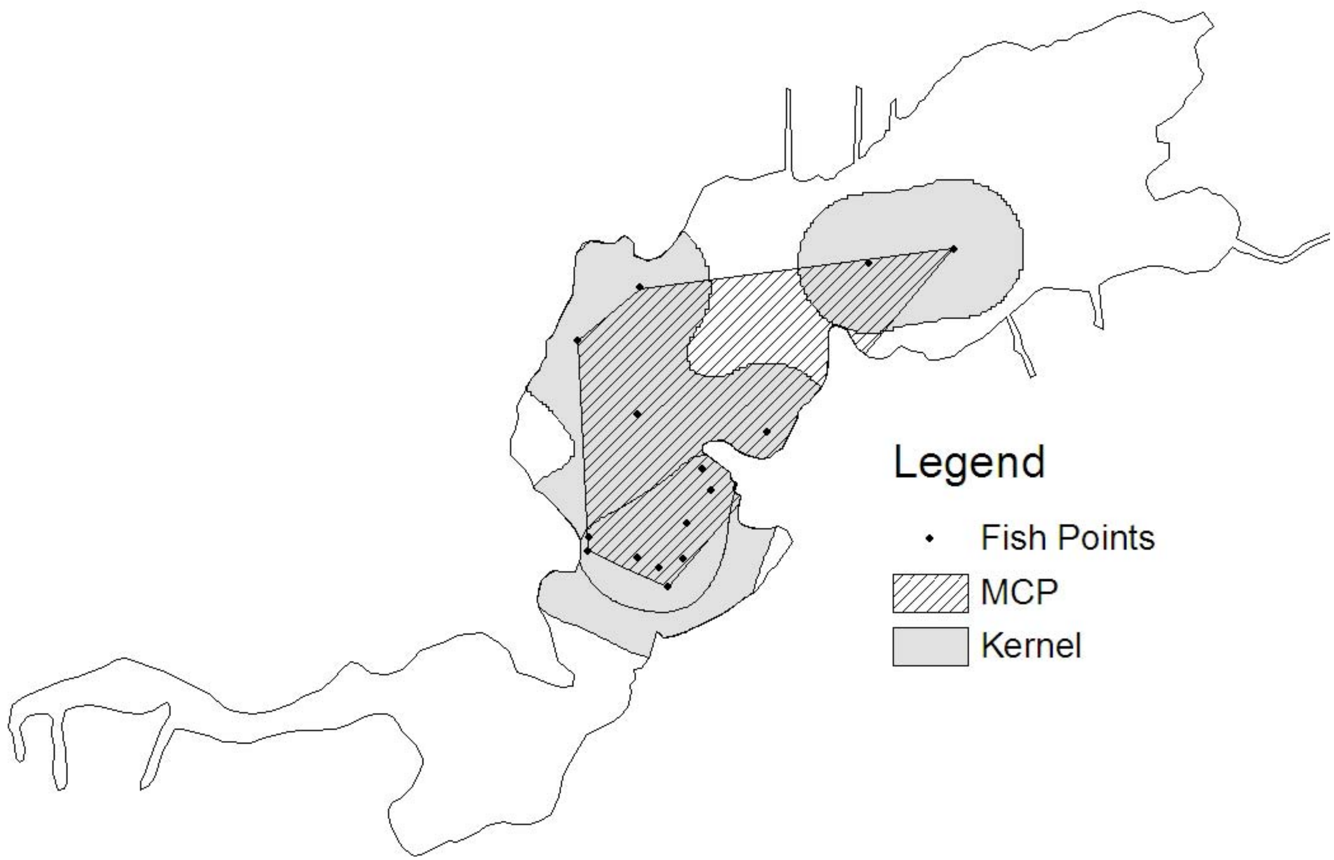

Figure 42. Fish locations, MCP, and kernel home-ranges of fish 3347 in 2004. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

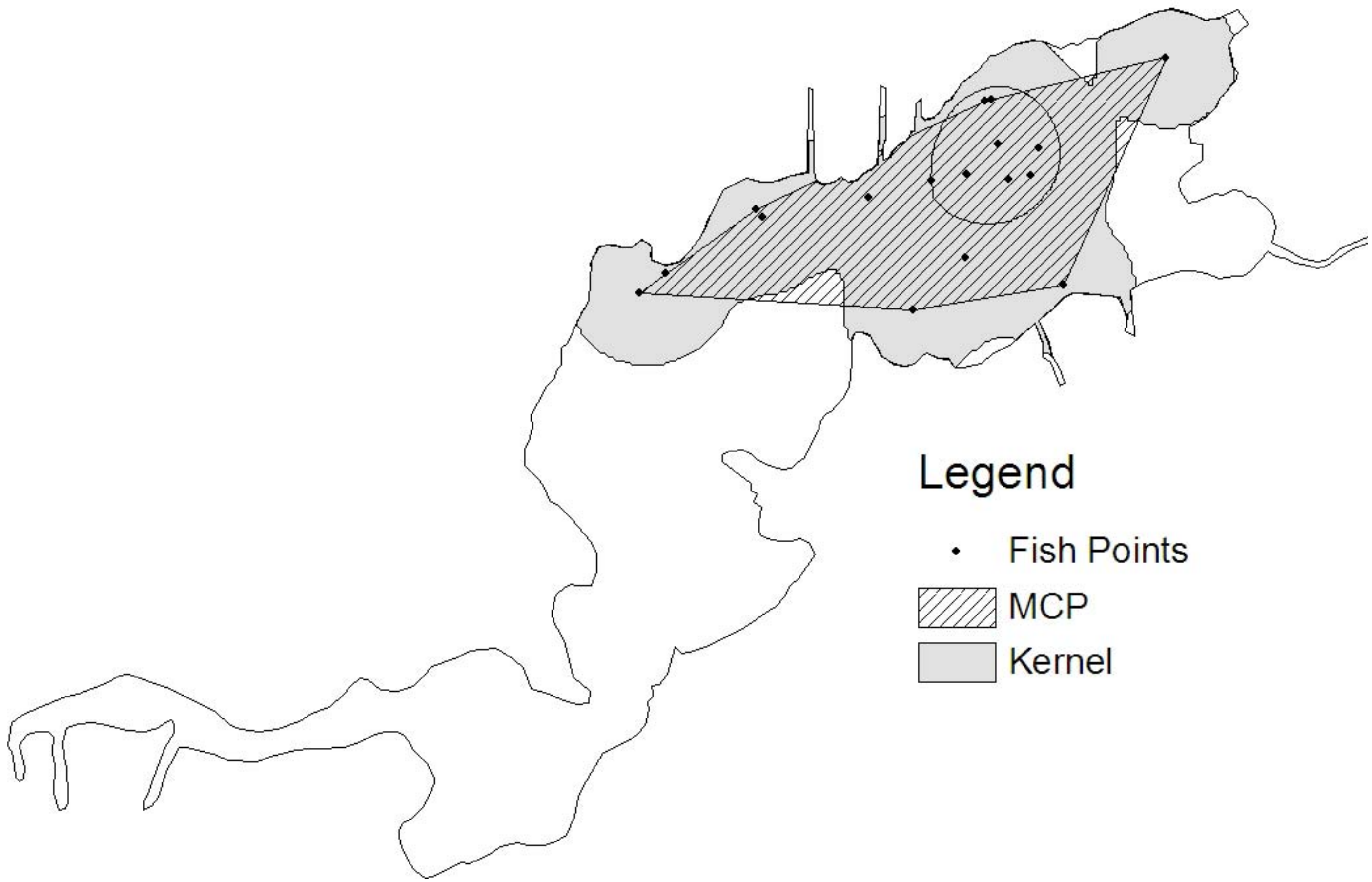

Figure 43. Fish locations, MCP, and kernel home-ranges of fish 3356 in 2004. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

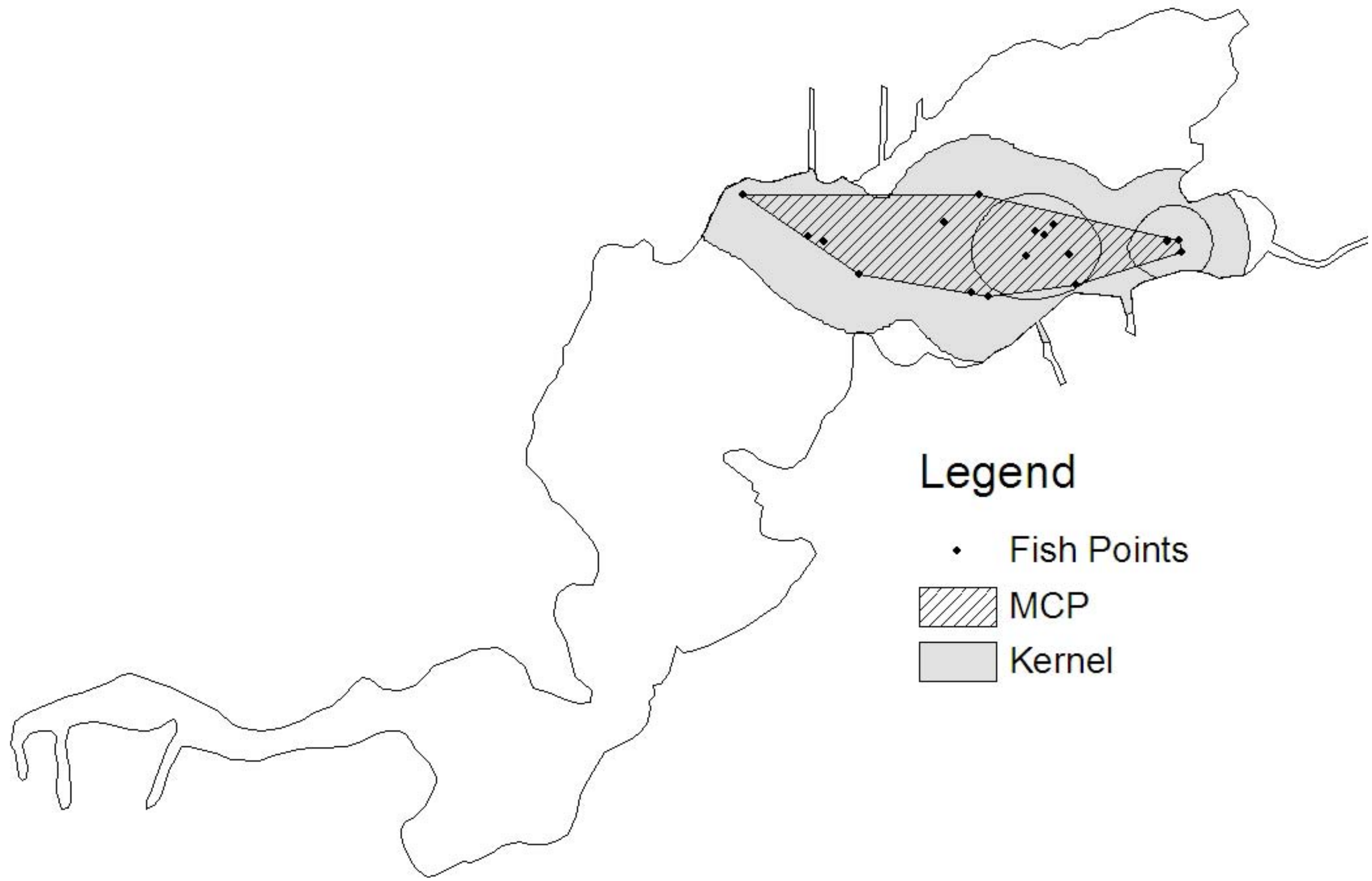

Figure 44. Fish locations, MCP, and kernel home-ranges of fish 3367 in 2004. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygons within the 95% kernel home-range.

APPENDIX D

HOME-RANGES OF TRANSMITTER TAGGED FISH IN THORNAPPLE LAKE IN 2005.

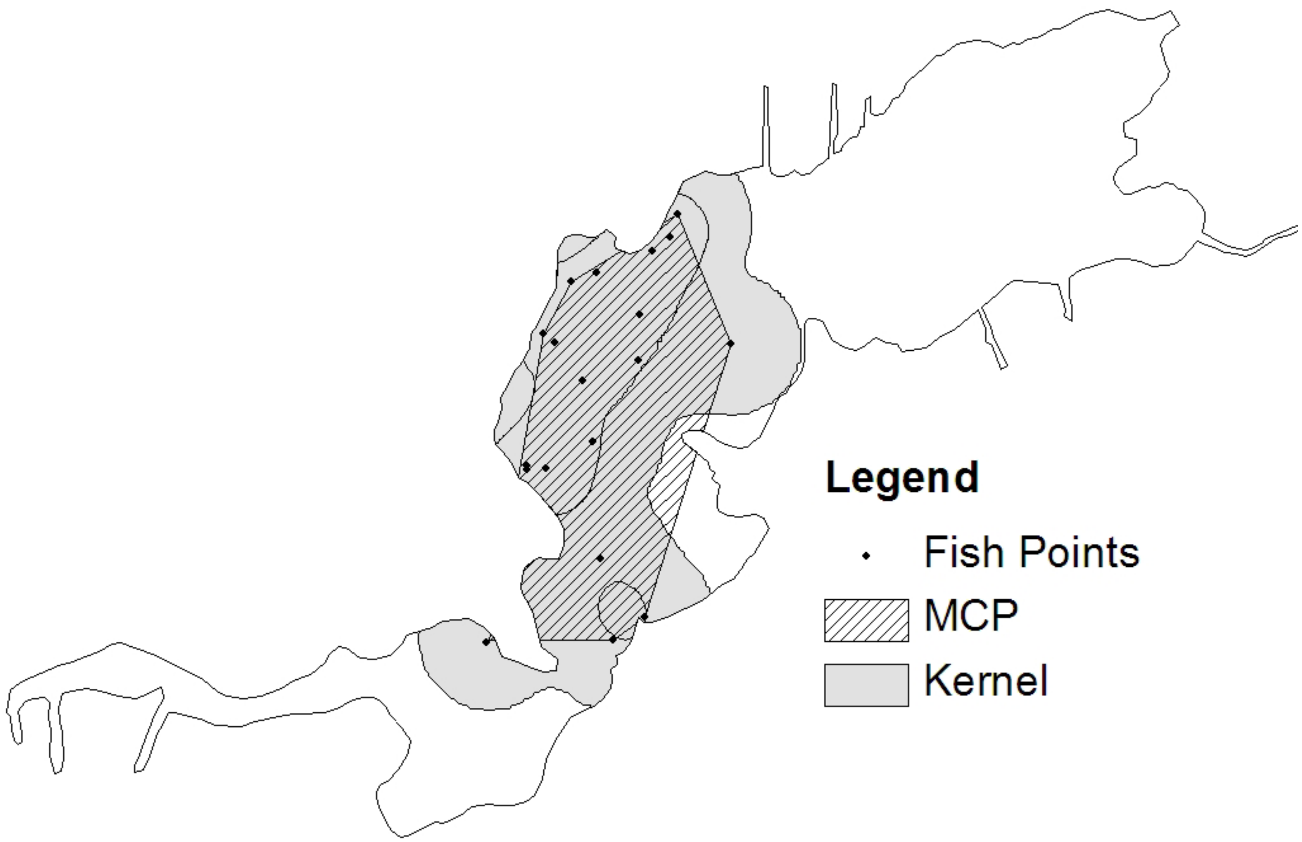

Figure 45. Fish locations, MCP, and kernel home-ranges of fish 3374 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygons within the 95% kernel home-range.

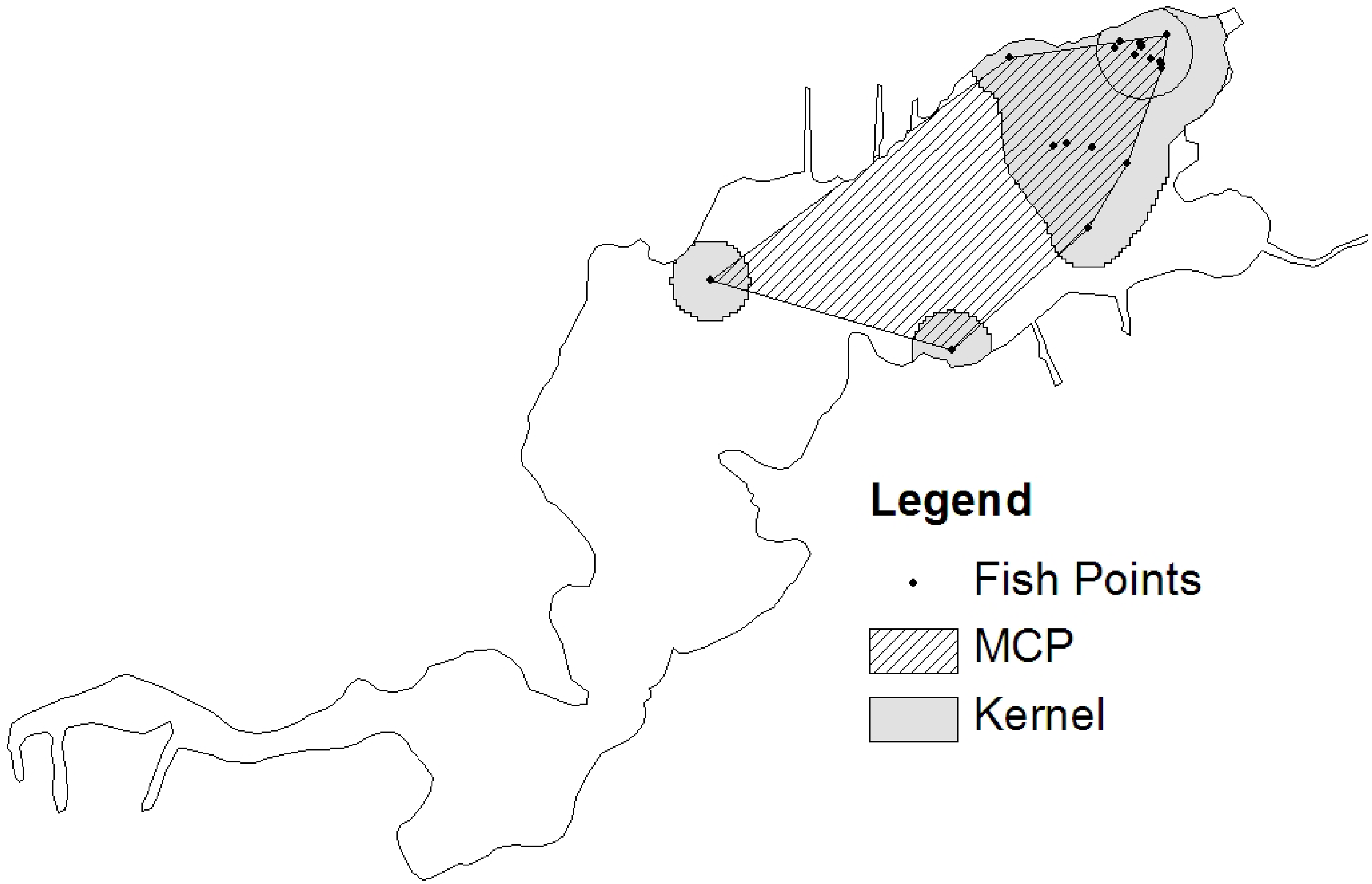

Figure 46. Fish locations, MCP, and kernel home-ranges of fish 444 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

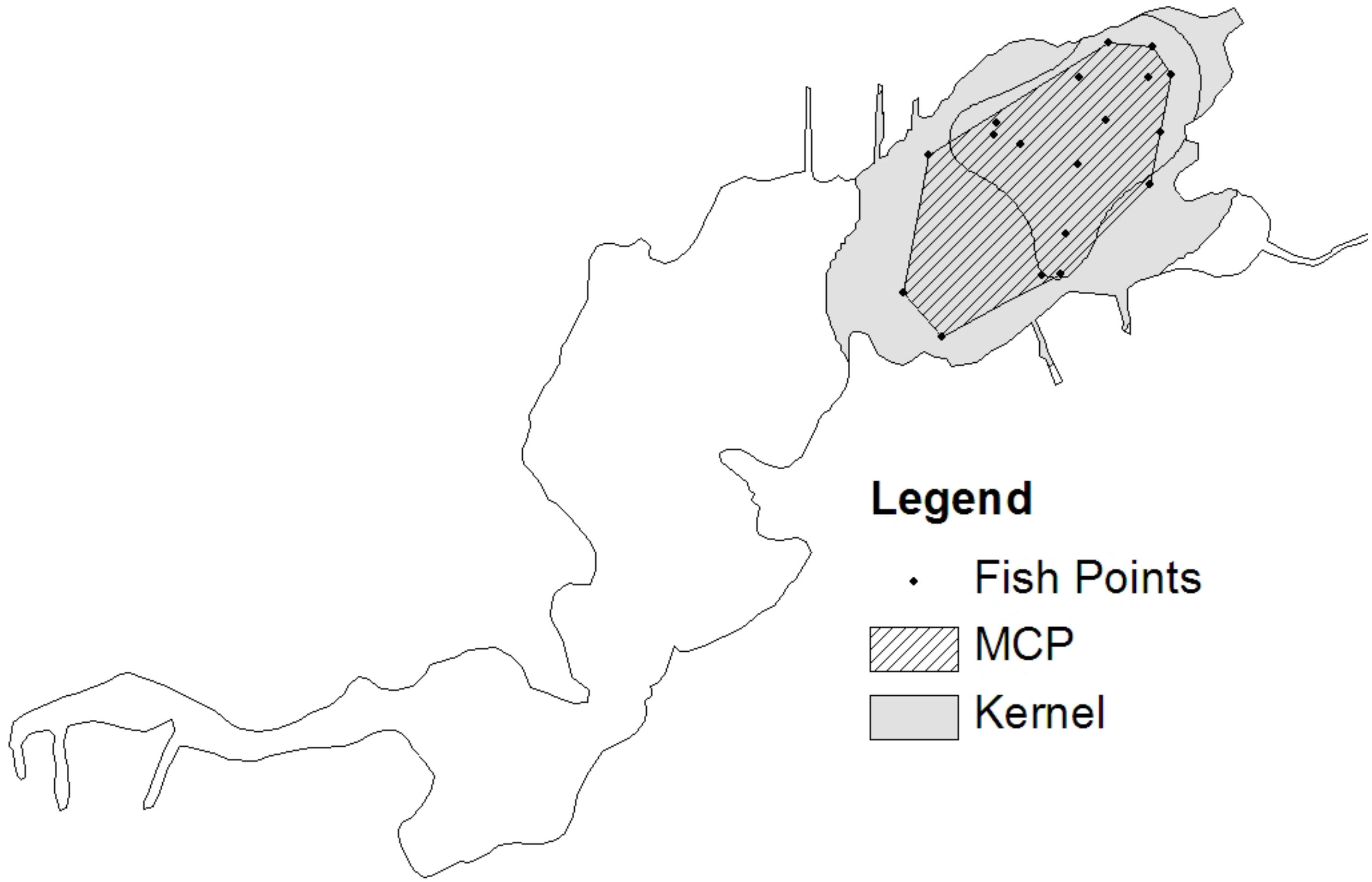

Figure 47. Fish locations, MCP, and kernel home-ranges of fish 446 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

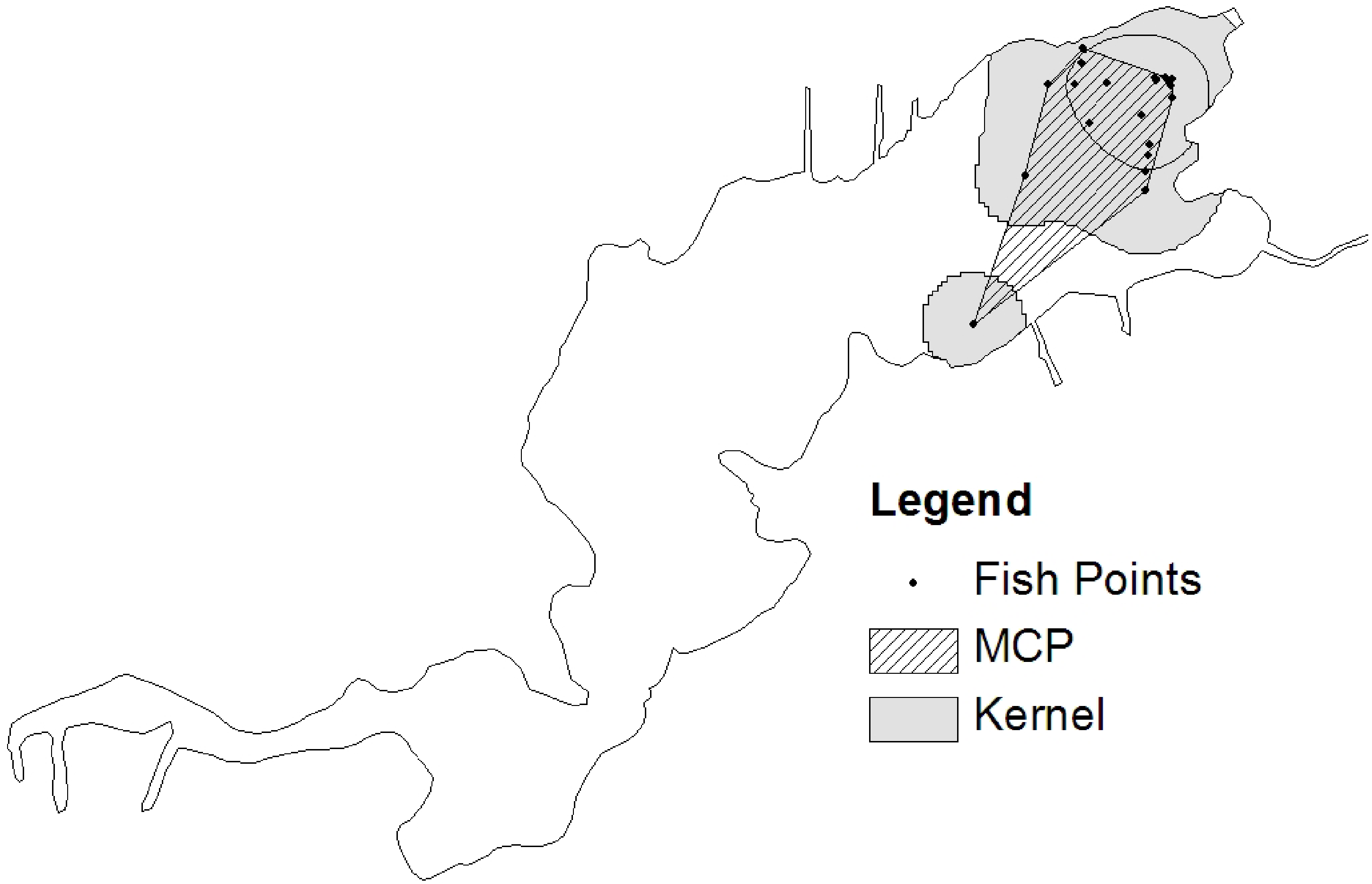

Figure 48. Fish locations, MCP, and kernel home-ranges of fish 447 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

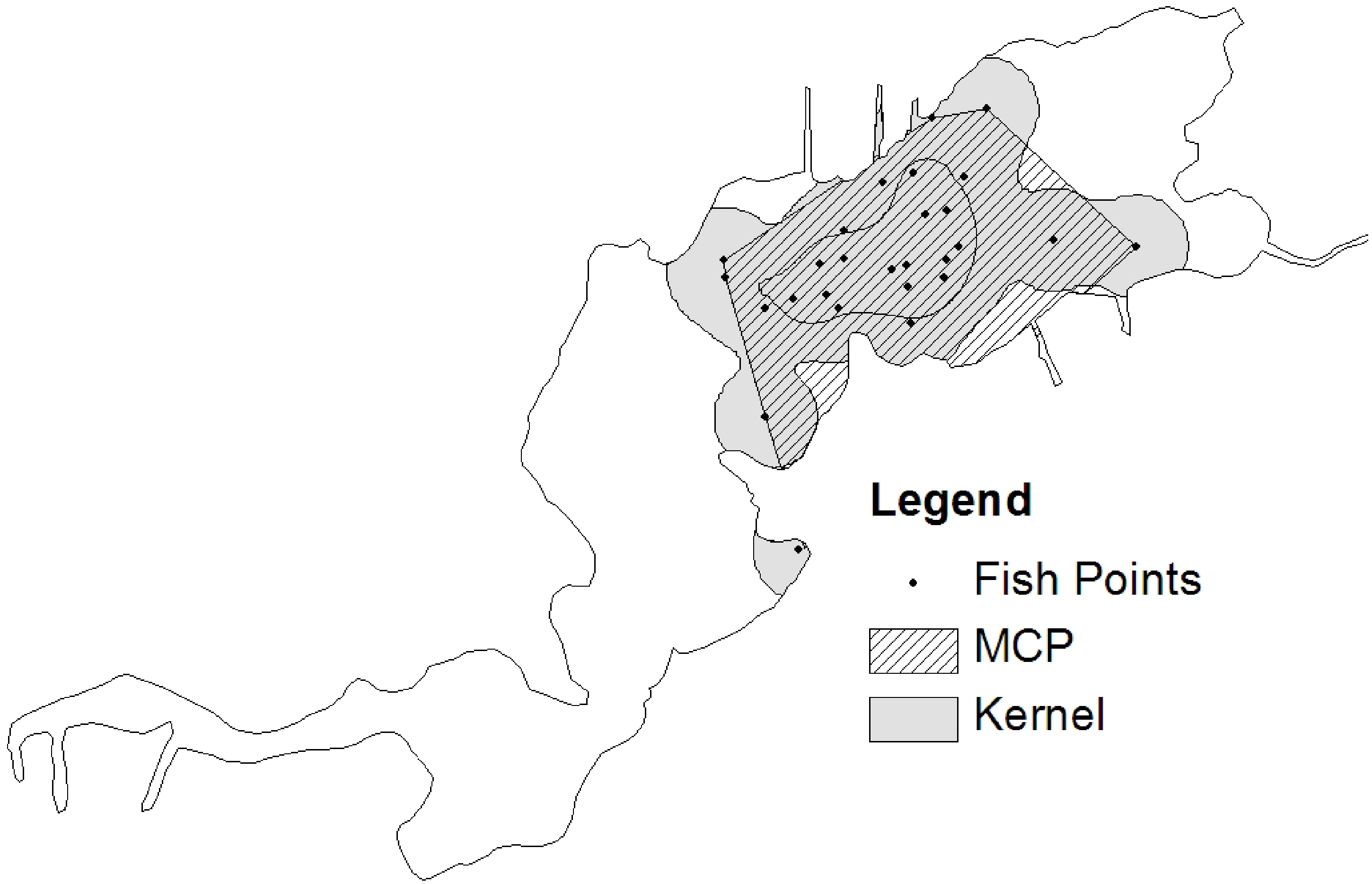

Figure 49. Fish locations, MCP, and kernel home-ranges of fish 448 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

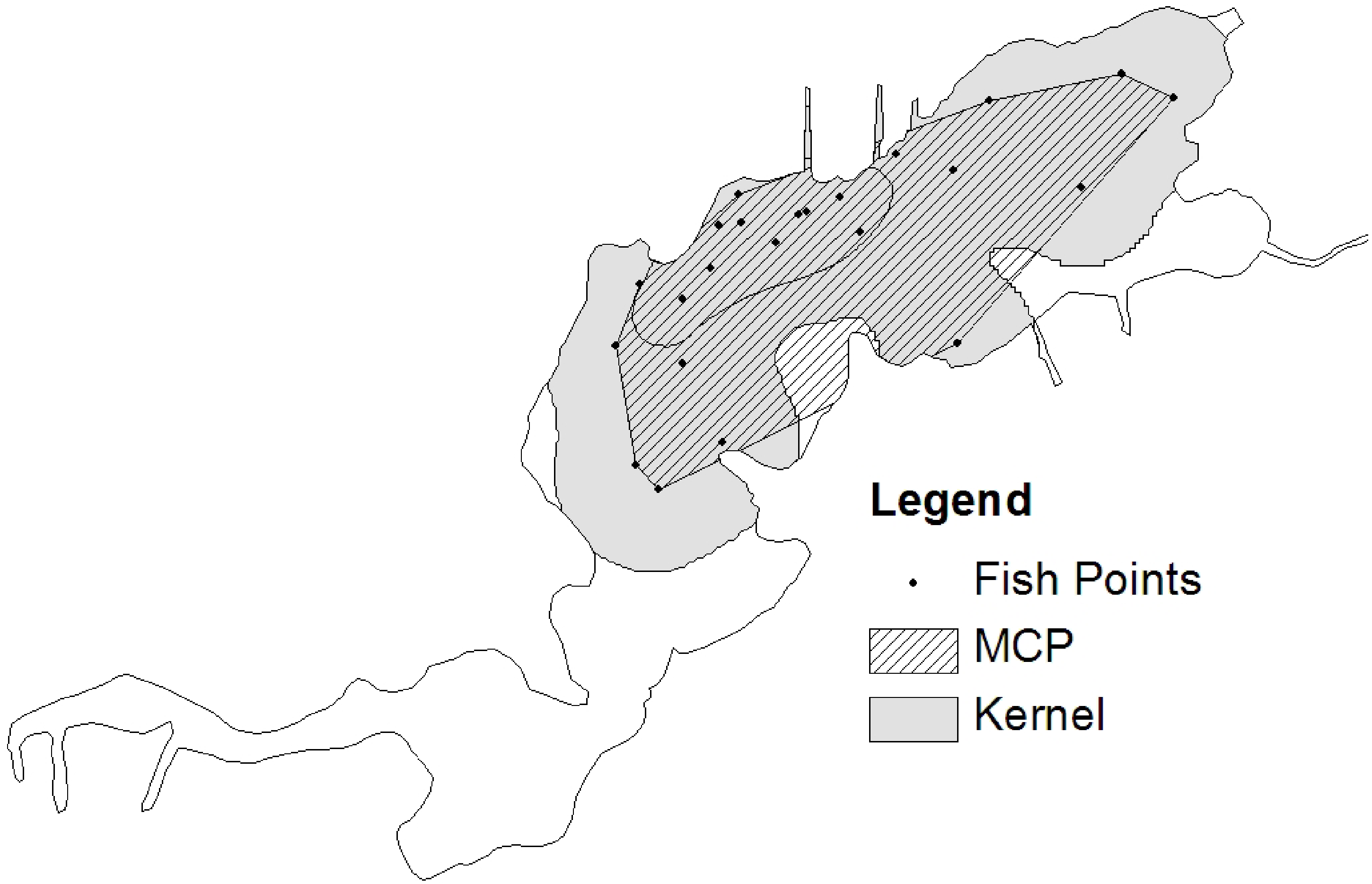

Figure 50. Fish locations, MCP, and kernel home-ranges of fish 4412 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

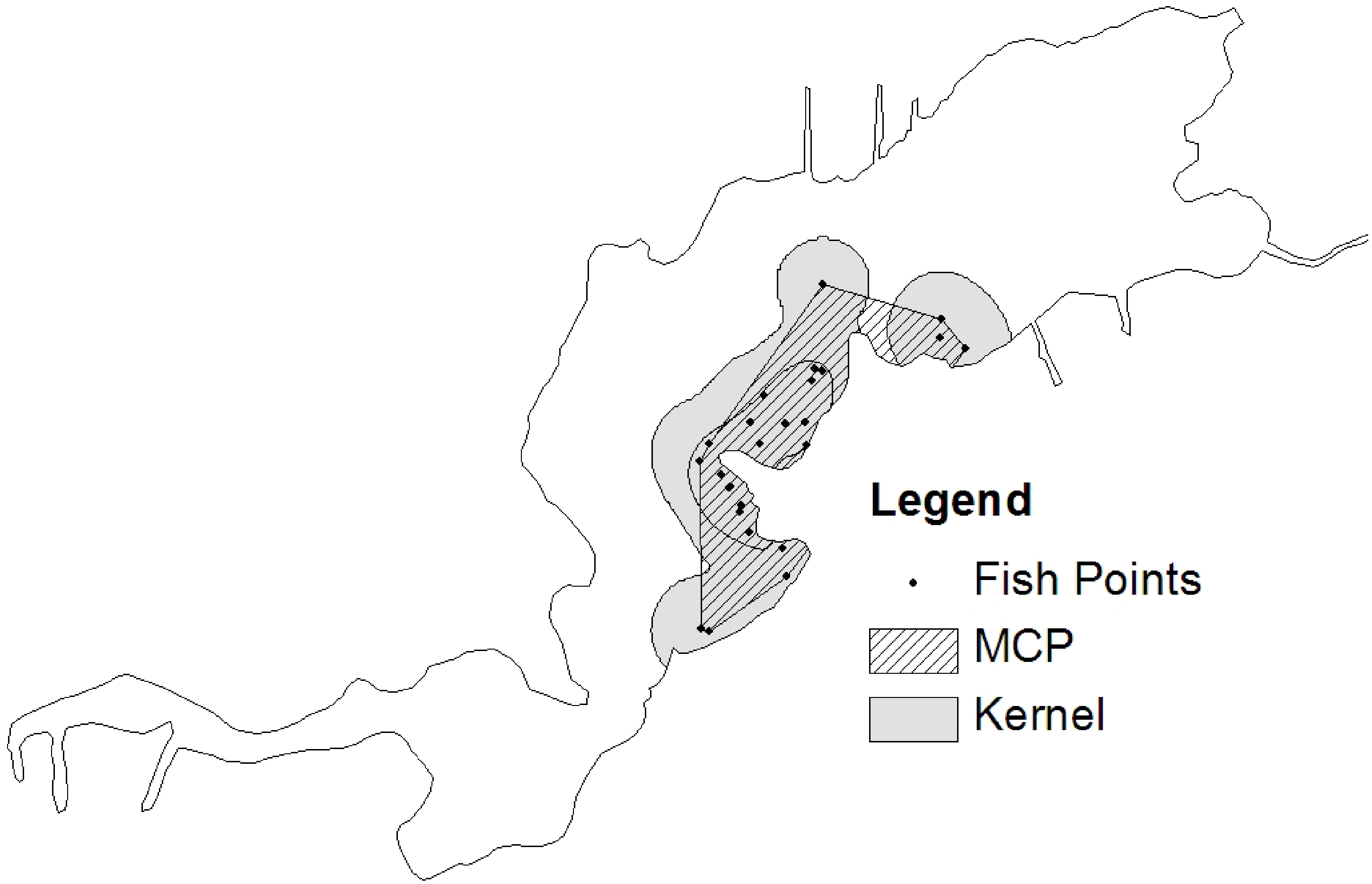

Figure 51. Fish locations, MCP, and kernel home-ranges of fish 4414 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

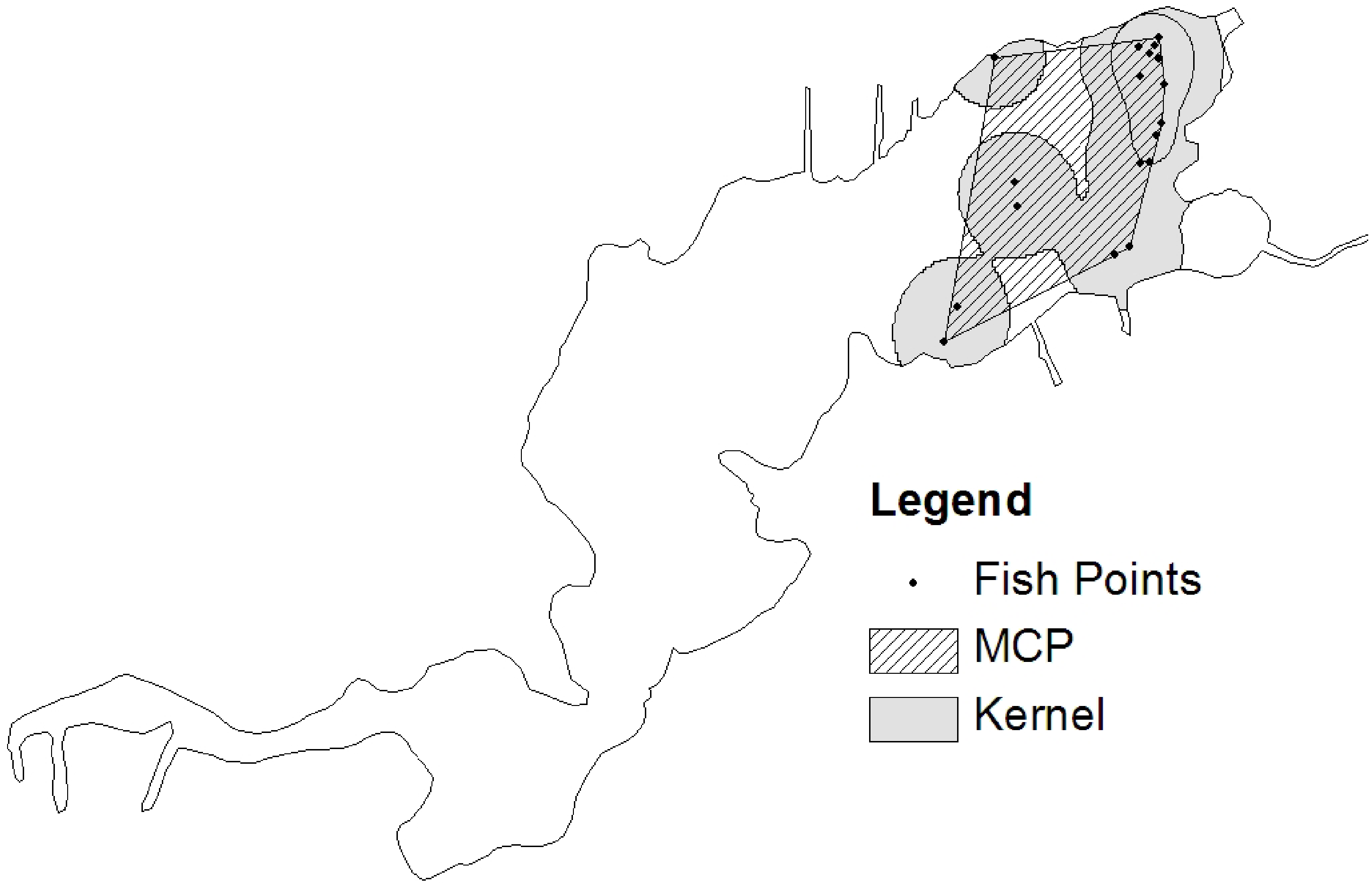

Figure 52. Fish locations, MCP, and kernel home-ranges of fish 4415 in 2005. The black points indicate fish locations, the diagonal hatched polygon represents the MCP home-range, and the grey filled polygon represents the kernel home-range. The outer most perimeter of the kernel home-range encompasses the 95% home-range; the 50% home-range (or core area of activity) is represented by the smaller polygon within the 95% kernel home-range.

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