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Modeling common carp under-ice movement using hierarchical Markov simulation

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ABSTRACT

Common carp is an invasive species in North American waters, disrupting ecological systems and replacing native species in water systems they enter. Mass removal by seining of this species from infected waters is a labor-intensive task that requires knowledge of their behavior and popular aggregation locations. It has been shown that carp tend to aggregate and slow down during winter months leaving them potentially vulnerable to seining. In 2010, Hennen used a fixed telemetry system to track carp movement during ice-cover periods and reported on their spatial distributions. Expanding on this work, we propose a model to describe the discrete movement of carp through a fixed telemetry system using a Bayesian Hierarchical Markov model.

1. Introduction

Common carp (*Cyprinus carpio*) (hereafter carp) have a circumpolar distribution following centuries of intentional and unintentional introductions outside their native range of the Black, Caspian, and Aral seas (Balon, 1995; Weber and Brown, 2009). In contrast to their highly valued recreational and consumer markets in Europe and Asia, carp are generally considered nuisance invasive species in North America and Australia where they can form dense populations and disrupt ecological functioning of aquatic ecosystems (Arlinghaus and Mehner, 2003; Weber and Brown, 2009; Bajer et al., 2009). Despite their widespread distribution, carp attain their greatest densities and have the most deleterious effects in large, relatively shallow, interconnected aquatic ecosystems found in midwestern North America and south-central Australia (Bajer and Sorensen, 2009; Bajer et al., 2009; Weber and Brown, 2009). At high densities, carp have been associated with: significant reductions in water quality; decreased rooted aquatic vegetation; and alterations in native fish, macroinvertebrate and zooplankton communities. The impact of carp presence primarily originates in their benthic feeding behaviors, which uproot vegetation and re-suspend nutrients from sediments into the water column (Chumchal et al., 2005; Bajer et al., 2009; Weber and Brown, 2009). Their presence shifts aquatic ecosystems from a clear water equilibrium state, characterized by extensive submerged aquatic vegetation growth, and limited suspended nutrients and phytoplankton biomass, to a turbid state, characterized by the opposite conditions (Scheffer et al., 1993; Weber and Brown, 2009).

Management strategies for overabundant carp populations are generally aimed at reducing abundance in an attempt to attain a clear water state (Scheffer et al., 1993; Weber and Brown, 2009; Bajer et al., 2011). However, improvements in an ecosystem may not be possible until more than 70% of the carp biomass is removed (Meijer et al., 1999; Weber and Brown, 2009). To limit the amount of time, money, and effort required for carp removal, fishery managers need to understand seasonal movement patterns to plan effective reduction strategies (Penne and Pierce, 2008; Weber and Brown, 2009; Bajer et al., 2011). Carp have demonstrated predictable seasonal movement patterns and aggregation during specific times of the year (Penne and Pierce, 2008; Bajer et al., 2011; Hennen and Brown, 2014). In northern latitude lakes, when water temperatures cool down in autumn and eventually ice cover occurs, adult carp form dense aggregations with limited activity (Johnsen and Hasler, 1977; Penne and Pierce, 2008; Bajer et al., 2011). Understanding the location(s), timing, and behavior of carp aggregations during periods of ice cover could prove essential for fisheries managers because carp would be vulnerable to large-scale removals (e.g., commercial seining) at this time (Johnsen and Hasler, 1977; Penne and Pierce, 2008; Bajer et al., 2011).

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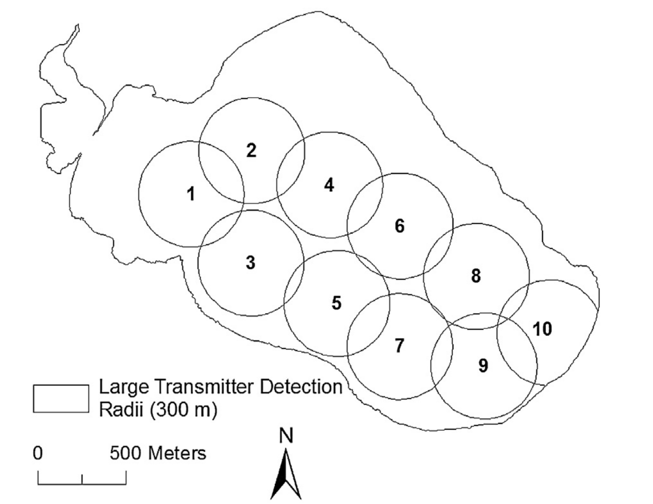

Fig. 1. Estimated detection radii of acoustic receivers in Brant Lake for small and large transmitters (Hennen, 2010).

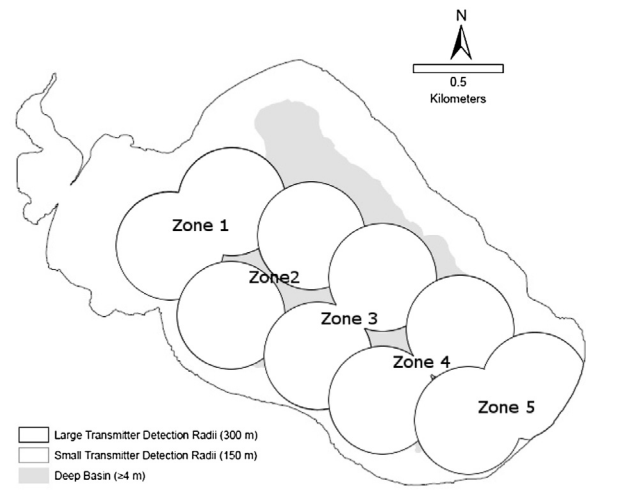

Fig. 2. Rezoned states.

Previous studies have used manual telemetry to evaluate spatial distributions of tagged carp under ice cover and the point data has been analyzed using various techniques including kernel utilization distributions (Penne and Pierce, 2008) and nearest neighbor analyses (Bajer et al., 2011). These analyses were successfully used to define aggregation timing and location(s) as well as pinpointing areas for carp removals (Penne and Pierce, 2008; Bajer et al., 2011). The operational requirements of manual telemetry render difficult the acquisition of carp movement over an extended period of time and during periods of ice coverage. On the contrary, autonomous telemetry receivers can be set out over a large area to collect carp movement over several months without human intervention.

Data collected from autonomous telemetry receivers requires alternative analyses. Specific point location cannot be associated with each tagged carp; rather, the detections are assigned to a general area defined by the detection radius of the receiver(s), as illustrated in Fig. 1. Furthermore, detection radii may vary and overlap, complicating the analysis.

Using descriptive data such as Hennen (2010), we can observe distinct trends in spatial distributions and movement patterns for tagged carp during the winter months (December–March), similar to other carp telemetry studies done in the Upper Midwestern region (Johnsen and Hasler, 1977; Penne and Pierce, 2008; Bajer et al., 2011). In Hennen (2010), carp aggregated in the western basin of Brant Lake and reduced activity occurred during the mid-winter period (i.e., December–February) of both years. This observation is significant for the management and control of abundant carp.

While the results presented in Hennen (2010) provides significant qualitative findings on the movement behavior of carp, the ability to predict the timing and location of under-ice carp aggregations is essential in developing successful removal programs. This paper proposes two longitudinal models that smoothes the raw data acquired by Hennen (2010) to quantify carp aggregations and predict school movements in order to potentially maximize the number of carp removed via under-ice seining. Both models use the complete data set (i.e., data from all acoustic receivers during the entire sampling period both years) collected by Hennen and Brown (2014) to examine the time (days) spent in each detection zone to determine carp spatial distributions and movement patterns (Fig. 2). The first model is equivalent to smoothing the longitudinal data by averaging it over a fixed period of time while the second model explicitly takes into account dependencies in the carp movement over time.

2. Materials and methods

The data used in this study was collected with an array of 10 fixed-location acoustic receivers deployed throughout the deep basin (depth = 3.5–4.5 m) area of Brant Lake, South Dakota. The receivers were used to continuously monitor tagged carp during winter periods of 2007–2008 and 2008–2009. We collected data from late-fall, prior to ice formation, to early spring following ice-off. The 2007–2008 observation period lasted from November 19, 2007 to May 5, 2008, a duration of 168 days; the 2008–2009 observation period lasted from November 12, 2008 to March 19, 2009, a duration of 128 days.

Twenty adult carp (586–807 mm; mean = 697 mm; 2800–7900 g; mean = 4623 g) were implanted with large acoustic transmitters in 2007. The estimated detection range by the acoustic receivers for the large transmitters (300 m) was greater than the range for small transmitters (150 m; Fig. 1).

The raw data is a function of continuous time. As a tagged carp swims through Brant Lake, its transmitter may have been detected by one or more acoustic receivers. Each receiver logged the detection of the carp at a regular time interval as long as the carp is within its detection radius. This results in an imbalanced dataset for a number of reasons: (1) a carp may produce a large number of consecutive entries for a particular acoustic receiver within a short period of time; (2) a small number of interlaced entries in multiple receivers are produced when a carp moves in and out of overlapping detection ranges; and, (3) no entries are recorded if a carp is out of range of all receivers.

To reduce the complexity of the modeling, we transformed the raw data to a function of discrete time measured in days. The data was conformed to describe which receiver(s) detected a tagged carp on a given day. To further reduce the complexity of the modeling, the acoustic receiver detection zones were reconfigured into five zones (Fig. 2) so that all receivers in the lake were used. The converted data represents the daily movement of carp as “multi-state” data entries which discretely describe the movement of a carp for any given day. There were four reasons for this approach:

1. The “NULL” zone was not defined in the raw dataset. Carp can leave the range of the receivers and they may not show up for multiple days, if ever again. The converted data represents the lack of acoustic detection in a given day as a NULL state. The NULL state is defined as a lack of detection by accoustic receivers during a time period of one day.