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Using the Judas technique to locate and remove wintertime aggregations of invasive common carp

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Abstract Radio- and acoustic telemetry in three Midwestern lakes demonstrated that common carp, *Cyprinus carpio* L., aggregate as water temperatures descend below 10 °C. Particularly dense aggregations formed at temperatures < 5 °C, and once located, these aggregations could be removed with an efficiency of up to 94% using seine nets. Carp aggregated just below the surface of the ice (approximately 1.5 m) and rarely descended to warmer waters, which extended down to 10 m. Although aggregations consistently formed close to shore, their locations could not be explained by temperature or dissolved oxygen. The aggregations also moved frequently, making radio-tagged fish invaluable to locate them. Coldwater aggregations of carp may reflect a type of shoaling behaviour and can be exploited with the aid of radio-tagged (Judas) fish to control this invasive fish effectively. Similar approaches might be developed for other gregarious invasive fishes.

KEYWORDS: acoustic telemetry, invasive species, mark–recapture, nearest neighbour, radiotelemetry, winter seining.

Introduction

Control of long-lived invasive species requires a removal component (Simberloff *et al*. 2005). This task is particularly challenging for fish that live in large volumes of water and are not easily located. However, selective removal approaches might be developed for species that aggregate if they could be effectively located. Biologists working with invasive goats, pigs and birds have solved the problem of locating their aggregations using the Judas technique (Taylor & Katahira 1988; Woolnough *et al*. 2006; Cruz *et al*. 2009; McCann & Garcelon 2009). In this technique, a few individuals are captured, radio-tagged and then followed as they relocate (and inadvertently betray) the groups in which they normally live and which can then be targeted and removed. Many fish aggregate or shoal (Pitcher & Parrish 1993), suggesting that they too might be controlled using the Judas technique. Common carp, *Cyprinus carpio* L., one of world's most invasive fish (Sorensen & Bajer 2011), forms aggregations during winter (Johnsen & Hasler 1977; Penne & Pierce 2008), and while few details are available about this behaviour, it appears to be a good model for developing Judas techniques for invasive fish that exhibit shoaling behaviours.

The common carp (hereafter carp) is a large, long-lived cyprinid native to parts of Eastern Europe and Western Asia that has been introduced worldwide during the last 150 years (Balon 1995). In many regions, especially North America and Australia, the carp is invasive and super-abundant (Bajer *et al*. 2009; Weber & Brown 2009; Bajer & Sorensen 2010). It is presently managed using whole-lake poisoning (Schrage & Downing 2004) and water drawdowns (Shields 1958; Koehn 2003), which are expensive and ecologically damaging. Although carp live in small, dispersed groups during the summer (Penne & Pierce 2008; Bajer *et al*. 2010), they have been reported to form large aggregations in ice-covered lakes of the North American Midwest and Eastern Europe (Johnsen & Hasler 1977; Osipova 1979; Penne & Pierce 2008). Historically, commercial fishermen have exploited this behaviour but their success has not been quantified. Also, although observations from ice-covered aquaculture ponds suggest that carp may be selecting relatively deep and warm refuges (Bauer & Schlott 2004, 2006), there have been no systematic studies of under-ice behaviour of free-ranging carp inhabiting larger, more natural systems.

In this study, radio and acoustic telemetry was used to evaluate the winter aggregation behaviour of

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common carp in three Midwestern lake systems, where carp population abundances were estimated using mark and recapture methods. The depths and temperatures selected by the carp were recorded using pressure-sensitive tags, while dissolved oxygen concentrations and temperatures measured throughout each lake were used to determine whether or not carp selected for specific areas. Finally, aggregations were targeted with seine nets using the locations of radio-tagged Judas fish to determine how effective this combination of techniques might be for removing this invasive species.

Materials and methods

The distribution of carp was studied in three lakes in south-central Minnesota USA. Two of these lakes, Lake Riley (area = 120 ha, max. depth = 14 m) and Lucy (area = 36 ha, max. depth = 6 m), are located within the same chain of lakes (44°50′08″N, 93°31′18″W); however, artificial and natural barriers block the movement of carp between them. The third lake, Lake Gervais (area = 95 ha, max. depth = 12 m), is located in another chain of lakes approximately 40 km to the east (45°01′13″N, 93°04′16″W). This lake is connected with two shallow basins, Lake Kohlman (area = 30 ha, max. depth = 3 m) and Lake Keller (area = 29 ha, max. depth = 3 m), which collectively form a relatively large and complex system. All study lakes are covered with approximately 30 cm of ice cover from December to March of each year.

Proceeding in a step-wise manner, the investigations began in the autumn of 2008 in Lake Riley in which a group of carp (Judas fish) was implanted with radio transmitters and tracked throughout the winter to determine whether or not the fish aggregated and therefore could be selectively captured using a seine net. A few Judas carp (n = 2) were also implanted with pressure-sensitive transmitters to determine depths at which they aggregated. This study of aggregation behaviour continued for an additional year during which captured and radio-tagged Judas carp were rereleased into lakes Lucy and Gervais as well. Distributions of Judas carp during the second year were monitored in all study lakes, and their winter aggregations were once again targeted with the seine. Population sizes and capture efficiencies were estimated throughout the study using mark and recapture analyses. During the second winter, temperature and dissolved oxygen profiles were measured in random locations within and outside areas in which carp aggregated to test whether they were selecting for warmer or more oxygen-rich areas in each lake. In addition, in the largest and more complex Lake Gervais, a group of carp was implanted with temperature- and depth-sensitive acoustic transmitters to determine habitats selected by carp under the ice. More detailed description of the data collected in each lake is presented below, followed by an analytical section that describes procedures common to all lakes.

Experiments in Lake Riley commenced in November 2008 by capturing 13 adult common carp (410–760 mm TL) using an electrofishing boat and implanting them with radio transmitters (F1850; Advanced Telemetry Systems; Isanti, Minnesota, USA) following established procedures (Penne & Pierce 2008; Bajer & Sorensen 2010). Two additional carp were implanted with archival radio transmitters (also Advanced Telemetry Systems), which recorded the depth of these fish at 5-min intervals. All carp survived the surgery and were located approximately every 3 weeks thereafter by following their radio signals until they were strong and unidirectional (an accuracy of 15 m determined in control trails). Their UTM coordinates (NAD 83) were recorded with a GPS unit (Garmin eTrex Vista). Once carp were determined to be aggregating (see statistics section), they were targeted with a 500-m seine net (3.5-cm square mesh size; 15 m deep). Seine netting followed procedures employed by local commercial fishermen and began by cutting a 5 × 5 m opening in the ice through which the net was deployed into the lake. A series of holes were drilled in a V-shaped pattern surrounding the aggregation, and ropes were stretched under the ice between them using remote-controlled submersibles. These ropes were used to pull both sides of the net with power winches. The net was then landed through a 5 × 5 m opening cut near shore so fish could be easily handled. Captured carp were counted, and two-thirds of them were removed from the lake (the objective of a parallel study that evaluated the effects of carp biomass on water quality), while the remaining carp were released after approximately 50% of them had been tagged with a numbered T-bar tag (TBF-1; Hallprint, Hindmarsh Valley, South Australia) inserted under the dorsal fin (Table 1).

Radio telemetry resumed in the summer in Lake Riley and continued throughout the next autumn and winter, when carp aggregations were once again located. Five dissolved oxygen and temperature profiles (YSI® 85; 0.5-m vertical resolution) were collected within and outside the aggregation using random point selection function in ArcMap (v9.3.1; Esri, Redlands, CA, USA) to test for differences. The area in which carp aggregated was then targeted with the seine net as before, but this time all carp were examined for T-bar

Table 1. The number of carp captured in different seine nettings and the percent of each lake's carp population that they represented along with population estimates (n and 95% CI) calculated from the number of carp that were marked (M) and subsequently examined for marks (C) and recaptured (R) in each lake

Lake	Date	Captured	% population	n	95% CI	M	C	R
Riley	19/1/09	4440	68	6499*	6177–6821	600	2303	388
Riley	3/3/10	2303	65	3559†	–	–	–	–
Gervais	14/1/10	3537	52	6745	4953–8537	1035	292	44
Lucy	24/1/10	642	94	685	601–769	642	15	14

*Estimate includes 2940 carp that were removed from the lake on 19 January 2010.
†Estimate was derived by subtracting 2940 carp that were removed from the lake on 19 January 2009 from the population of 6499 carp.

tags and fin clips and removed from the lake. Temperatures in the lake were monitored throughout the entire study by collecting bi-monthly vertical profiles.

Experiments in Lake Lucy began in September 2009 by implanting ten carp (400–700 mm TL) with radio transmitters. All survived the surgery. These fish were located monthly through January, and water temperatures were monitored with a similar frequency. Once the carp were found to be aggregating, five temperature and dissolved oxygen profiles were measured at randomly selected locations within and outside the aggregation. Then, the aggregation was targeted using seine nets (as in Lake Riley), and all carp were counted, measured, marked with T-bar tags and released. To estimate population size and capture efficiency, three 1-h electrofishing surveys were conducted the following summer and recapture rates determined.

Experiments in the Gervais system of lakes commenced in May 2009 by implanting 38 carp with radio transmitters (10 in Gervais, 10 in Kohlman and 18 in Keller). Within the first 2 months, two of the carp shed their tags or perished in Lake Gervais and six carp from Lake Keller emigrated downstream. One carp in Lake Kohlman was never found. The remaining fish were located approximately every 2 weeks throughout the next spring. In October 2009, an additional ten carp were captured in Lake Gervais and implanted with acoustic tags (V13 coded transmitter; Vemco, Halifax, NS, Canada) that transmitted their temperature and depth (accuracy ± 0.1 °C and ± 0.2 m) every 90 s. This information was automatically recorded by three receivers (VR2W, Vemco; approximately 150-m detection range) placed in different areas of the lake. Ten temperature and dissolved oxygen profiles were measured at randomly selected locations within and outside carp aggregations to define the available and used habitats. Winter aggregations were then targeted using seine netting. Approximately one-third of the captured carp were marked with numbered T-bar tags and released while others were released without marking (Table 1). As in Lake Lucy, the population was estimated by collecting several hundred carp from the entire system using an electric fishing boat during the following summer and determining recapture rates (Table 1).

For statistical analysis, locations of carp were plotted on bathymetric maps using ArcMap. The tendency of carp to aggregate was quantified by calculating nearest neighbour distances (NNDs; mean distance to five nearest neighbours; Penne & Pierce 2008) using Hawth's Tools (Beyer 2004). The NNDs were plotted against seasonal changes in water temperature in each study lake to discern seasonal patterns and determine when tightest aggregations occurred. Ultimately, data from all lakes were combined, and a single regression relationship between water temperature and NND was developed in SAS (v9.2; Carry. NC, USA). Statistical comparisons (Students' two-tailed t-test, using SAS) of mean temperature and dissolved oxygen concentrations within and outside carp aggregations were undertaken for the upper 2 m of the water column only (because carp rarely descended to greater depths). Petersen's equations (Krebs 1999) were used to estimate the mean and 95% CI of carp population in each lake from the number of individuals that were marked and released (M), examined for marks (C) and recaptured (R):

$$N = \left[\frac{(M+1)(C+1)}{R+1}\right];$$

$$95\%\ \mathrm{CI} = 1.96\sqrt{\frac{(M+1)(C+1)(M-R)(C-R)}{(R+1)^2(R+2)}}.$$

Results

Although radio-tagged carp in Lake Riley were dispersed relatively widely throughout the summer and autumn, they formed tight aggregations during both winters (Figs 1 & 2). During the first winter, carp started aggregating in mid-December, and by

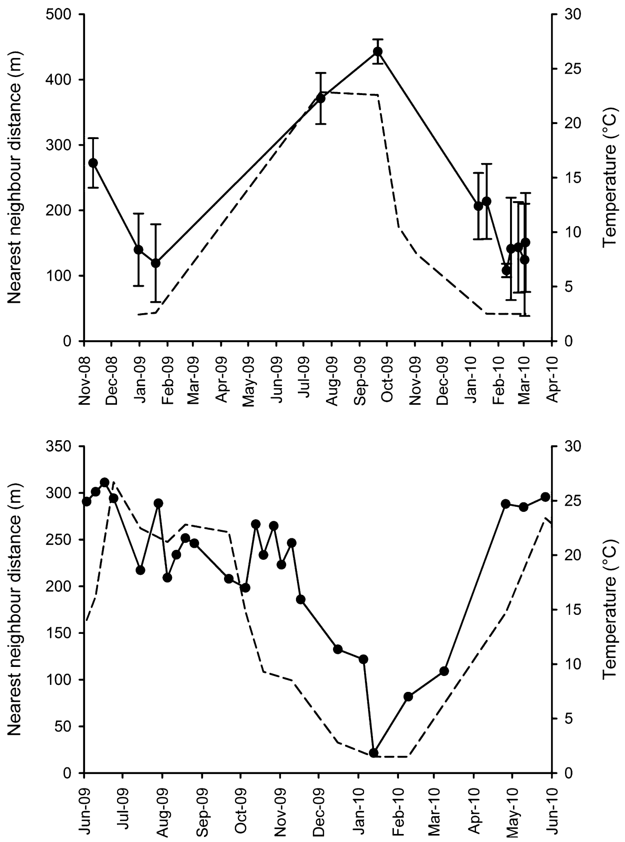

Figure 1. Top: Mean nearest neighbour distances (solid line) of radio-tagged carp in Lake Riley and mean water temperature in the lake (broken line). Bottom: the same relationship for carp in the Lake Gervais system of lakes.

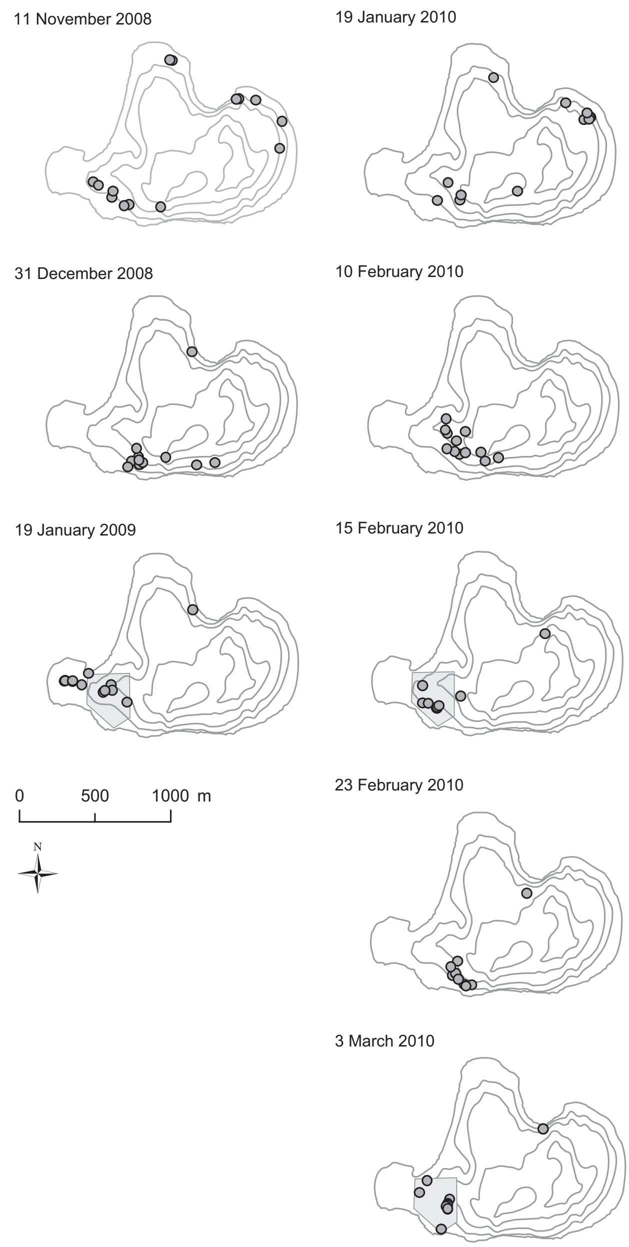

Figure 2. Locations of radio-tagged carp (circles) in Lake Riley during the winter of 2008–2009 (left) and 2009–2010 (right). Aggregations documented on 19 January 2009, 15 February 2010 and 3 March 2010 were targeted with a seine net. Shaded polygon represents the area seined. Bathymetric contours represent 3-m depth increments.

mid-January, all but one radio-tagged carp formed a dense aggregation in SW area of the lake with NND of approximately 100 m (Figs 1 & 2). The centre of aggregation was 100 m offshore, and the fish were found over an area that was relatively shallow (1–6 m) and had a gradually sloping bottom (Fig. 2). Seine netting was conducted, and a total of 4440 carp were captured (440–800 mm TL; 2940 carp were removed from the lake while the rest was released). As was later estimated, this catch comprised approximately 68% of the entire population (of the 600 carp that were marked and released, 388 were recaptured next winter among 2303 carp; Table 1). One of the two fish that carried archival transmitters was also captured, and archived data showed that between 31 December and 19 January, when the carp were aggregating, this individual spent most of the time approximately 1.5 m below the ice even though oxygenated and warmer waters extended to a depth of 10 m in adjacent areas of the lake (Fig. 3). During the winter of 2009–2010, two loose aggregations were noted in January, but a tight aggregation did not occur until mid-February (Fig. 2). On 15 February 2010, all but one radio-tagged carp were once again located in the SW area of the lake (Fig. 2). This time, the fish remained slightly further offshore (mean = 125 m) and over a slightly deeper area (3–9 m). There were no differences between water temperatures (P = 0.09) and dissolved oxygen (P = 0.82) inside vs outside the aggregation area. An

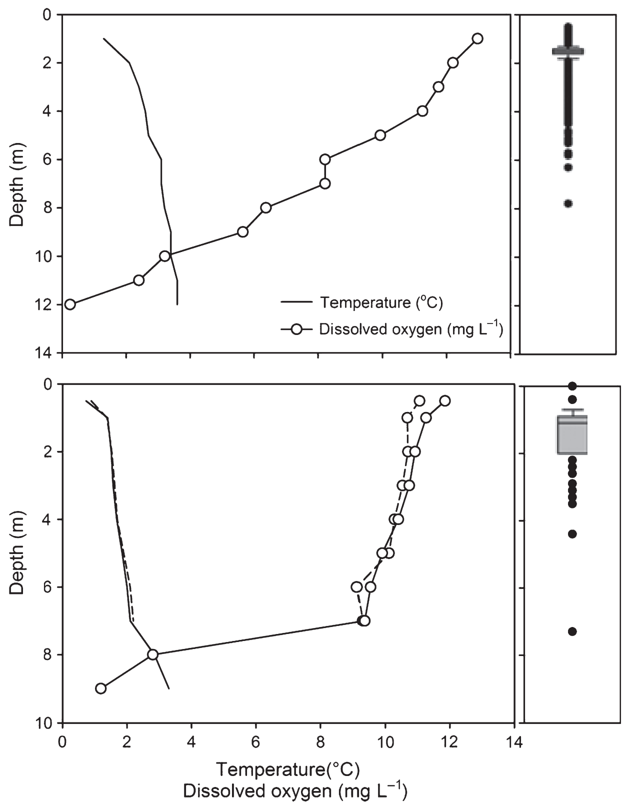

Figure 3. Top: Mean depth profiles of temperature and dissolved oxygen (DO) in Lake Riley in January 2009 (left panel) vs the depth selected by the carp implanted with pressure-sensitive radio transmitter during the same month (box and whisker plot to the right). Bottom: Mean depth profiles of temperature and dissolved oxygen measured within (broken lines) and outside (solid lines) the aggregation of carp in Lake Gervais in January 2010 vs the depths selected during the same period by carp carrying depth-sensitive acoustic transmitters (box whisker plot to the right).

attempt to net this aggregation was complicated by equipment problems (submersible malfunction), which substantially delayed the process, and only 376 carp were captured (radio-tracking showed that carp were able to swim around the net before it was closed). The aggregation reformed in approximately the same area in early March (Fig. 2), and this time 2303 carp were captured, which comprised of approximately 65% of the population (Table 1).

Radio-tagged carp in Lake Lucy were relatively evenly dispersed along the shoreline in the summer and fall of 2009 (NND = 146 m, SD = 28 m), but by January they were aggregated tightly in the SW area of the lake (NND = 29 m; SD = 3.9 m) (Fig. 4). This area was approximately 3 m deep and 140 m off the nearest shore and did not differ from other areas of the lake in terms of water temperature (P = 0.34) and dissolved oxygen (P = 0.26), which was relatively high (>7 mg L^{-1}). This aggregation was seine netted on 24 January, and 694 carp were captured (size range 300–777 mm TL), including all radio-tagged fish. Recapture rates determined during the following summer, which included 14 marked fish among 15 collected, suggested that this catch represented 94% of the population (Table 1).

Radio-tagged carp in the Gervais system of lakes were relatively dispersed in the summer and autumn, and most of them were found in shallow waters of lakes Kohlman and Keller. This pattern persisted until mid-December 2009 when NNDs declined to <130 m, and the carp were gradually leaving the two shallow lakes and aggregating in the deeper Lake Gervais (Figs 1 & 5). By early January, all carp had moved to Lake Gervais and formed two tight aggregations, both of which were located 50–60 m offshore and occurred in areas in which the depth increased from approximately 3 to 6 m (Fig. 5). Although the areas in which carp aggregated had similar temperatures as other locations in the lake (P = 0.19), they had slightly lower oxygen concentrations (P = 0.01; Fig. 3). Data from acoustic tags showed that the carp stayed relatively close to the surface of the ice (median depth = 1.07 m) and experienced relatively cold temperatures despite warmer and oxygenated waters extending down to 8 m in areas located further offshore (Fig. 3). The larger of these two aggregations was targeted with the seine net on 14 January, and a total of 3537 carp were captured (size range 340–978 mm TL). Recapture rates documented during the following summer (44 marked fish among 292 examined) suggested that this catch represented 52% of the entire population of 6745 carp that inhabited this three-lake system (Table 1). Following their release, the carp re-aggregated in the western area of the lake in February. In March, approximately 50% of the fish moved to the south-eastern area of the lake, and by late April, the carp had dispersed into the two adjacent shallow lakes (Fig. 5).

When the results from all study lakes were combined, a strong relationship was found between mean water temperature and carp NNDs (Fig. 6). This relationship explained over 60% of the overall variance in carp NNDs and showed that carp exhibited a tendency to aggregate once water temperatures declined below 10 °C, with particularly strong aggregations occurring <5 °C. The bycatch (of non-target native species) was $<10\%$ of the total carp biomass.

Discussion

This study demonstrated that common carp inhabiting Midwestern lakes form tight winter-time aggregations

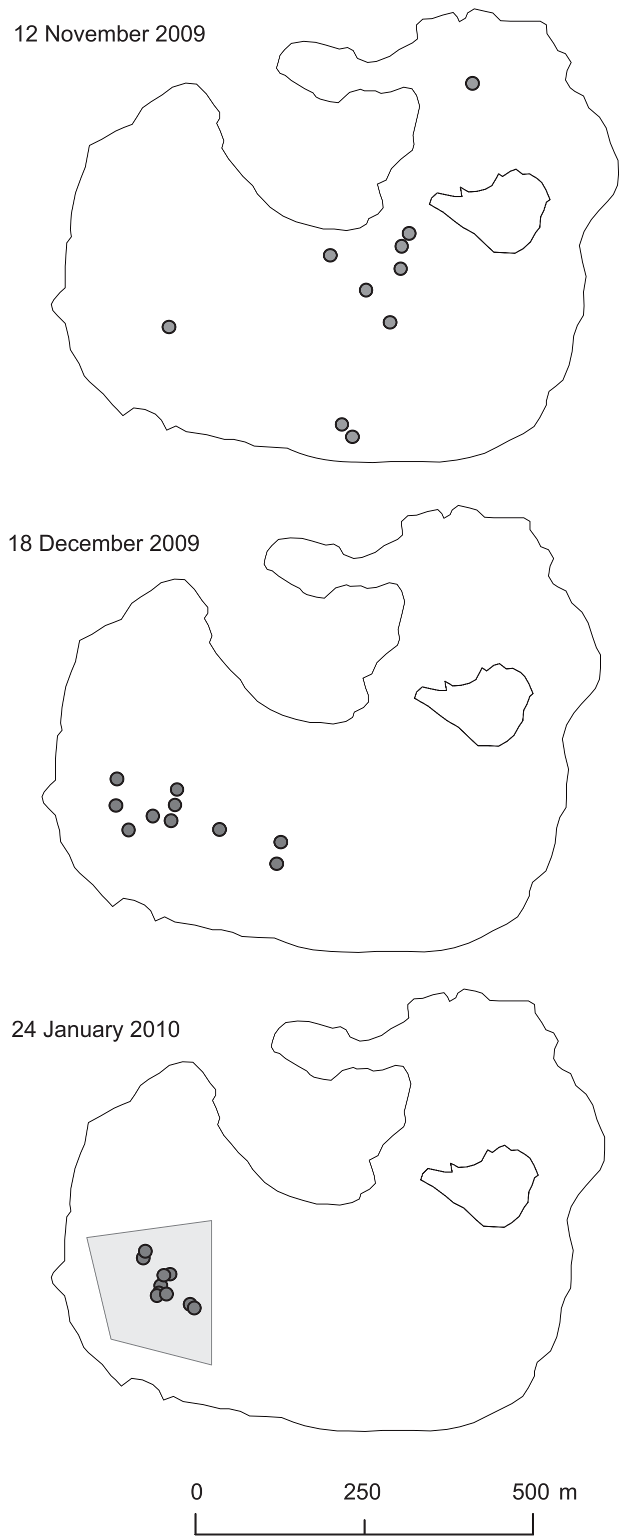

Figure 4. The distribution of radio-tagged carp in Lake Lucy in the winter of 2009–2010. The shaded polygon indicates the area seined.

that can be precisely tracked and removed using small numbers of radio-tagged Judas fish. Conventional commercial seining guided by Judas fish achieved high removal rates (52–94%), suggesting that the Judas technique could be very useful in carp control. It is especially intriguing that carp will move between lakes and aggregate at single locations, implying that entire systems of lakes might be controlled by targeting small focal areas. Although the experiments were conducted in relatively small lakes, similar approaches might also be used in large ecosystems where aggregations have also been demonstrated (Johnsen & Hasler 1977; Penne & Pierce 2008). This technique might also be useful in regions that do not experience ice cover because aggregations appear to correlate with declining temperature and not necessarily with ice formation.

Aggregations appear to represent a type of carp shoaling behaviour rather than strong attraction to specific areas or habitats. Shoals moved within each lake (especially in Lake Gervais) and did not occur in areas with measurable differences in temperature or dissolved oxygen. However, the fact that carp aggregated in the south-western area of Lake Riley during both years suggests that they may be cueing on less-conspicuous habitat features that were not evaluated. Further, all aggregations occurred relatively close (50–150 m) to shoreline vegetation, where water depths increased from approximately 1 to 6 m. This scenario matches sites of winter-time aggregations reported by Johnsen and Hasler (1977). Both this study and the study by Johnsen and Hasler (1977) indicated that deeper, open water sites were consistently avoided, but this does not appear to be the case in shallow systems in which deeper areas were preferred (Penne & Pierce 2008).

Carp appear to aggregate when water temperatures decline < 10 °C, with particularly tight aggregations occurring below 5 °C. Contrary to expectations, there was no evidence that carp selected warmer, deeper waters, but instead tended to stay approximately 1 m below the ice experiencing relatively cold temperatures. This behaviour was not caused by dissolved oxygen deficiencies, which occurred only at depths exceeding 8–10 m. The tendency to aggregate as temperature decreases below 10 °C, at which point carp appear to stop foraging (Bauer & Schlott 2004), suggests a shift from foraging to a predator defence strategy. Although carp are large and have few fish predators, they are subject to winter predation by otters and possibly also seals in their native range (Adamek *et al*. 2003; Kortan *et al*. 2007). Thus, shoaling near the surface of the ice may represent an example of 'many eyes' visual

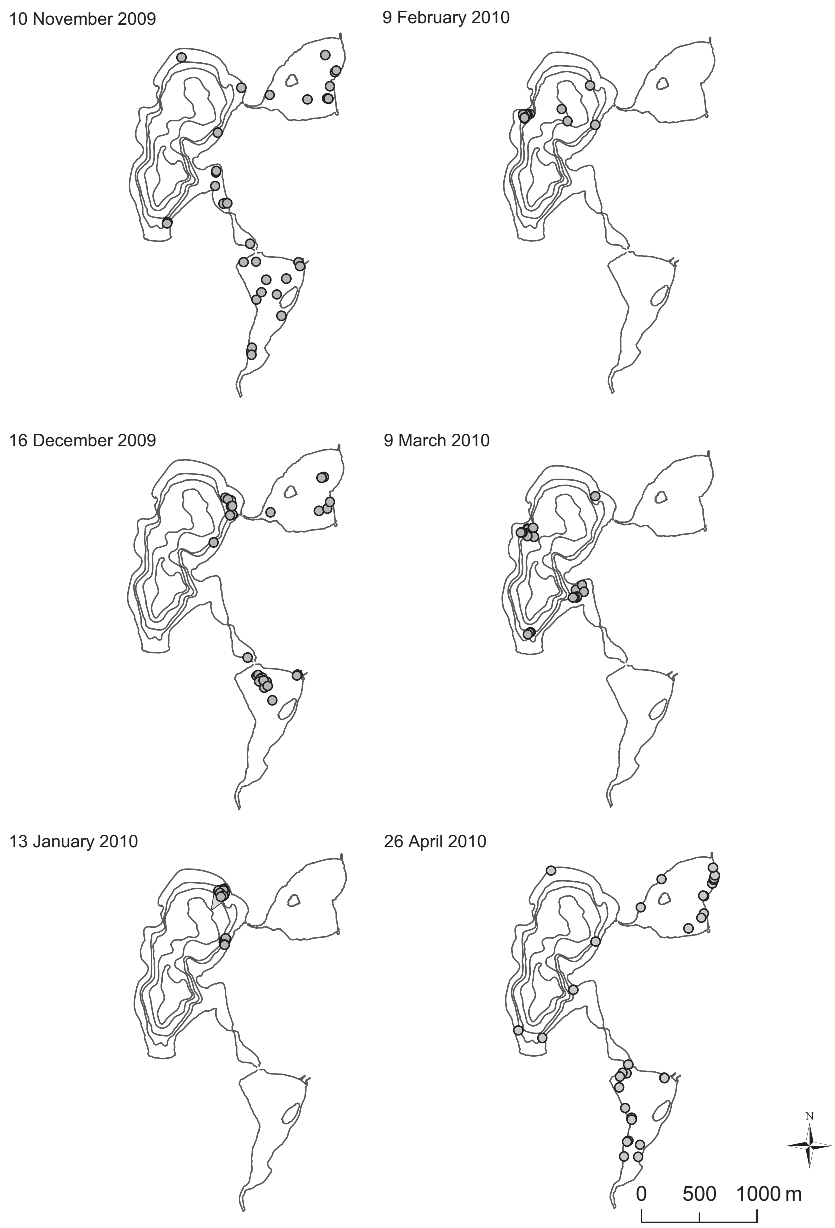

Figure 5. Locations of radio-tagged carp in Lake Gervais (the westernmost lake) and the two adjacent shallow basins: Lake Kohlman (upper right) and Keller (lower right) from November 2009 to April 2010. The larger of the two aggregations found on 13 January 2010 was targeted with a seine net. The shaded polygon indicates the area seined. Bathymetric contours represent 3-m depth increments.

defence mechanism against fast-moving predators (Pitcher & Parisch 1993). This hypothesis is partially supported by rapidly attenuating light conditions at depths > 2 m in the study lakes. Similar light-mediated shoaling behaviours have been shown for coregonids (Gjelland *et al.* 2009). This hypothesis warrants further study.

Because carp do not aggregate over areas that we can predict with confidence, and then move between locations during the course of the winter, Judas fish are needed to target them effectively for removal. Being able to locate these aggregations precisely is critical to seine netting success, as even large nets can only cover a small fraction of most lakes (mean seined area was approximately 8 ha) and seining can only be conducted in areas that are free of obstacles. Further, carp are very sensitive to sound and can easily avoid nets if targeting is imprecise and/or noisy, as was the case of the second haul in Lake Riley. To reduce this risk, preparatory work (drilling pilot holes, using submers-

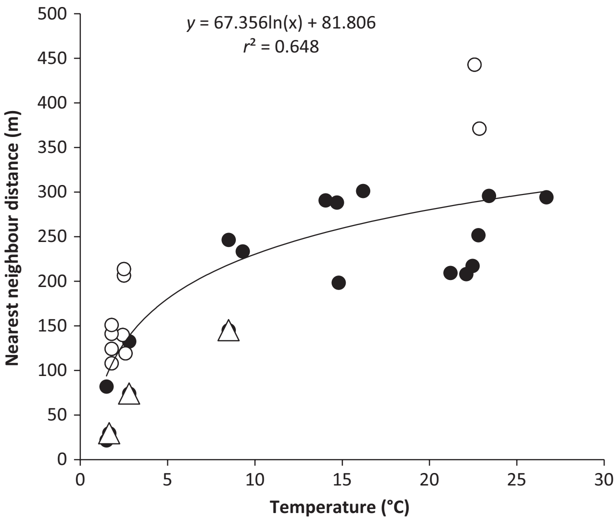

Figure 6. Relationship between nearest neighbour distance and water temperature in lakes Riley (open circles), Gervais (filled circles) and Lucy (triangles). A logarithmic relationship was fitted to data combined across lakes ($P < 0.05$).

ibles to stretch ropes under the ice) can be performed 1 day in advance and the locations of carp can then be verified before the net is deployed. Finally, targeting aggregations of carp using the Judas technique may not only improve capture efficiencies of carp, but also reduce the bycatch of native fish (see Results).

The Judas technique has previously been used successfully to remove invasive mammals and birds from islands (Simberloff *et al.* 2005). Recent reports also suggest that Judas male carp can be used to locate and target aggregations of pre-spawning female carp (Inland Fisheries Service, Tasmania 2009). Judas techniques may be useful for other species. For example, spawning aggregations of lake trout *Salvelinus namaycush* (Walbaum) (Warner *et al.* 2009) might be located and targeted using Judas fish to control these invasive fish in western lakes (Ruzycki *et al.* 2003). Similar techniques might be also explored for the Asian carp *Hypophthalmichthys* sp., which also appear to shoal (D. Chapman, US Geological Survey, personal communication). The Judas technique could be further enhanced by exploiting cognitive abilities of fish by enticing and training them to aggregate in locations suitable for capture using targetable cues such as food or pheromones (Sorensen & Stacey 2004; Bajer *et al.* 2010).

Acknowledgments

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