Estuaries Vol. 26, No. 3, p. 720–730 June 2003

Habitat Use and Movement of the Mummichog (*Fundulus heteroclitus*) in a Restored Salt Marsh

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ABSTRACT: The mummichog, *Fundulus heteroclitus*, is one of the most abundant macrofaunal components of salt marsh ecosystems along the east coast of the United States. During April–November 1998, we determined the habitat use and movement patterns of young-of-the-year (YOY) and adult mummichogs in a restored marsh, formerly a salt hay farm, and an adjacent creek in order to expand our understanding of the ecology of the species and evaluate the success of the restoration. Four major fish habitat types (large first-order natural creek, second-order created creek, linear drainage ditch, and marsh surface) were identified within the study site. Patterns of relative abundance and mark and recapture using coded wire tags were used to determine the habitat use, tidal movements, home range, and site fidelity of the species within these habitat types. A total of 14,784 fish, ranging from 20–100 mm SL, were captured with wire mesh traps and tagged, and 1,521 (10.3%) fish were recaptured. A variety of gears were used to attempt to recapture fish across all habitat types, including wire mesh traps, push nets, and otter trawls. Based on abundance and recaptures of tagged fish, the YOY and adults primarily used the shallow subtidal and intertidal areas of the created creek, the intertidal drainage ditches, and the marsh surface of the restored marsh but not the larger, first-order natural creek. At low tide, large numbers were found in the subtidal areas of the created creek; these then moved onto the marsh surface on the flooding tide. Elevation, and thus hydroperiod, appeared to influence the microscale use of the marsh surface. We estimated the home range of adults and large YOY (20–100 mm SL) to be 15 ha at high tide, which was much larger than previously quantified. There was strong site fidelity to the created creek at low tide. The habitat use and movement patterns of the mummichog appeared similar to that reported for natural marshes. Coupled with the results of other studies on the feeding, growth, and production of this species in this restored marsh, the species appeared to have responded well to the restoration.

Introduction

Faunal movement is a fundamental but often poorly understood ecological process, which is essential to understanding any ecosystem (Turchin 1998). Movement also reflects habitat use and habitat quality (Pyke 1983), and may be used to detect problems with habitat quality that may not be detectable using other ecological attributes (Winker et al. 1995). Such movements are clearly important in assessing the quality of estuarine fish habitat (Able 1999) and may be central to effective evaluation of marsh restoration.

The mummichog, *Fundulus heteroclitus,* is the most abundant resident fish in most of the salt marshes on the east coast of the United States, and, as a result, is a key ecological component (Teal 1962; Nixon and Oviatt 1973; Valiela et al. 1977; Kneib 1986; Talbot et al. 1986) because these fish use marshes as foraging, spawning, and possibly refuge habitats (Weisberg and Lotrich 1982; McIvor and Odum 1988; Kneib and Wagner 1994; Able and Fahay 1998; Able and Hagan 2000, 2003). Mummichogs make daily tidal migrations between the intertidal marsh surface and adjacent channel and pond habitats (Butner and Brattstrom 1960; Weisberg and Lotrich 1982) and, as a result, are hypothesized to play an important role in the export of marsh production to the open estuary (Kneib 1997). Despite these movements, they are thought to have a highly restricted summer home range of only 36 m (Lotrich 1975).

This study is an attempt to establish the habitat use, tidal movements, and home range of adult and large young-of-the-year (YOY) mummichogs in a restored salt marsh. With mitigation and restoration playing central roles in the no net loss policy of wetlands conservation of the U.S., there has been an increase in the acreage and number of restoration efforts undertaken in salt marshes (Zedler 1996, 2001; Zedler and Lindig-Cisneros 2000). The restoration effort we have been studying entailed the return of a former salt hay farm to tidal influence as part of a large-scale restoration effort covering approximately 4,000 ha in Delaware Bay (Weinstein et al. 1997). It is essential to understand mummichog habitat use and movement patterns and to establish how salt marsh res-

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toration affects these patterns, but to our knowledge there has been no previous attempt to do so.

Previous studies have indicated four main habitat types in the same restored salt marsh (large first-order natural creeks, second-order created creeks, drainage ditches, and marsh surface; Able et al. 2000). By comparing the relative abundance of mummichogs in these habitats we determined if any of the habitat types were being used preferentially. We determined if adult and large YOY mummichogs were making daily tidal migrations between the marsh surface and the adjacent created creeks and drainage ditches by comparing the relative abundance and recapture rate in these habitat types at low and high tide. We estimated the home range and site fidelity of the mummichogs with tag and recapture techniques using coded wire tags. As there have been no previous published attempts to use coded wire tags on mummichogs that we are aware of, we evaluated the tag retention and tag detection rates and the effect of coded wire tags on the behavior, growth, and survival of mummichogs, both in the laboratory and in the field.

Restoration Effort and Study Site

The marsh restoration was undertaken by Public Service Enterprise Group as part of a large-scale project, affecting approximately 4,000 ha in Delaware Bay (Weinstein et al. 1997). Part of the effort (1,780 ha) involved restoring natural tidal flows to previously diked salt hay farms (Dennis Township) located in the mesohaline portion of lower Delaware Bay, New Jersey (39°11.143′N, 79°54.927′W). Prior to restoration, tidal inundation of the salt hay farms was prevented by perimeter dikes, allowing for dry conditions that were conducive to the farming of salt hay, *Spartina patens,* a naturally occurring high marsh plant (Sebold 1992). The lack of tidal inundation had also resulted in subsidence or the lack of accretion of the marsh surface resulting in an elevation ranging from mean tide level to mean high water as occurs elsewhere (Roman et al. 1984). Restoration of the site started in January 1996 and was completed in August 1996. It consisted of returning normal tidal flow through a series of excavated creek channels and pre-existing drainage ditches to create a flood-drain system with a hydroperiod amenable to the revegetation of the site with smooth cordgrass, *Spartina alterniflora,* a naturally occurring low marsh plant (Weinstein et al. 1997). By the end of the summer of 1998, the marsh surface vegetation had become dominated by tall form *S. alterniflora* (Public Service Electric & Gas Co. 1999a).

This study was conducted in a portion of the West Creek watershed (a natural creek that drains into Delaware Bay and borders the restored salt marsh) and the watershed of Creek 3 (a created creek within the restored marsh; Fig. 1). Tidal exchange between Creek 3 and West Creek occurred primarily through the mouth of Creek 3 because Stipson's Island Road and a series of earthen dikes bordering the upland portion of the marsh are above the spring high tide level. West Creek is a large subtidal creek with a mean width of approximately 30 m and a maximum depth of approximately 3 m at mean low tide. Similar to other created creeks in the restoration effort, Creek 3 had a mean width of approximately 10 m and a combined length of approximately 600 m, including both main branches. The Creek 3 watershed had both subtidal and intertidal areas, with a maximum depth of approximately 1 m at mean low tide. The mouth of Creek 3 had a pronounced sill, approximately 10 cm in depth at mean low tide. Exchange of water between Creek 3 and West Creek was relatively limited at low tide. Two pre-existing drainage ditches from the former salt hay farm, 300 and 200 m in length, completely drained into Creek 3

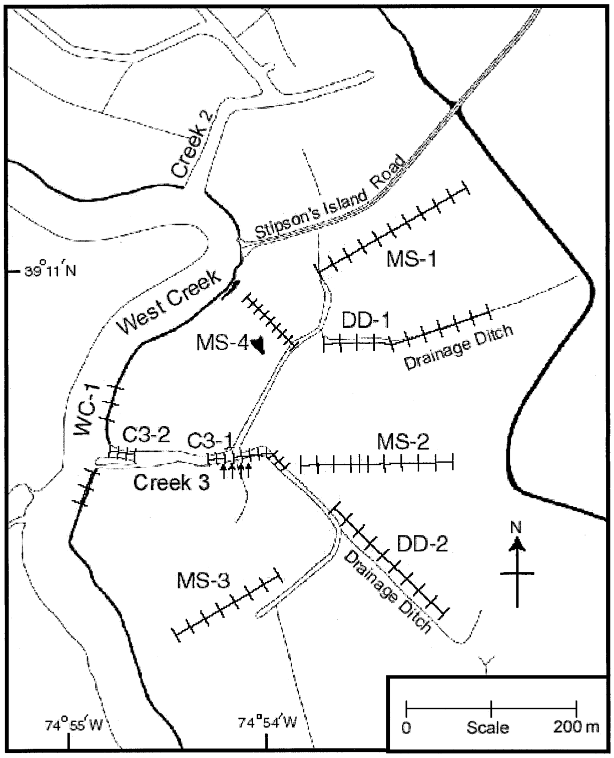

Fig. 1. Location of trapping transects in West Creek (WC-1), Creek 3 (C3-1, C3-2), drainage ditches (DD-1, DD-2), and on the marsh surface (MS-1 to MS-4) within the Dennis Township marsh restoration site. Exact position of each trapping station (each station having 3 traps) is indicated by the perpendicular lines on each transect line. Arrows indicate locations of release stations in Creek 3.

TABLE 1. Comparison of catch per unit effort (CPUE) between the large, subtidal West Creek and small, intertidal Creek 3 for wire mesh traps, otter trawls, and push nets, using ANOVA. n = number of samples. Significant differences are indicated by * ($p < 0.05$) and ** ($p < 0.01$).

Gear	Location	CPUE (mean ± SE)	n	F value	Pr > F
Traps	West Creek	0.10 (0.04)	45	8.37	0.0040**
	Creek 3	13.2 (1.47)	425		
Otter trawls	West Creek	0.00 (0.00)	40	4.47	0.0369*
	Creek 3	1.80 (0.63)	72		
Push nest	West Creek	0.53 (0.27)	36	1.21	0.2729
	Creek 3	60.6 (38.2)	73		

at low tide (Fig. 1). Small, shallow (< 3 cm in depth) pockets of water could be found on the marsh surface after the tide had receded. Small rivulets (< 20 cm deep), which formed naturally on the marsh surface after restoration, drained the marsh surface into Creek 3. The study area had a semidiurnal tidal range of approximately 2 m (as recorded by a YSI 600xlm datalogger located at the mouth of Creek 3, October 1998–May 1999).

Materials and Methods

Evaluation of Tagging Technique

Coded wire tags (1.1 mm long × 0.28 mm diameter, Northwest Marine Technology Inc.) were used to tag large YOY and adult mummichogs. Before use in the field, a laboratory experiment determined the rates of tag retention, and the effects of tagging on mortality, growth, and behavior. The efficiency of tag detection was also estimated under controlled conditions. One hundred and eighty fish in three size classes, small (35–40 mm SL), medium (45–50 mm SL), and large (> 60 mm SL), were collected from the study site and divided into 6 experimental groups by size class and treatment (control versus tagged). Each experimental group (treatment by size class) of 30 fish were further divided and placed in three 38 L flow-through aquaria, each containing 10 fish, with conditions ambient to Great Bay, New Jersey (water temperature ranging 20–28°C, salinity ranging 29–30‰). After a 2-wk acclimation period, treatment fish were tagged on the left side of the dorsal musculature with a handheld coded wire tag injector (Northwest Marine Technology Inc.). The efficiency of tag detection was estimated by 10 repeated blind tests in which an operator separated several tagged fish from approximately 100 untagged fish.

Mortality of tagged and untagged fish was checked visually every day. Once a week, fish were removed from the tanks and measured (mm SL). At the same time, tagged fish were also checked for tag retention by passing a handheld wand detector (Northwest Marine Technology Inc.) over the fish. During the experiment, fish were fed daily with 25% of their approximate dry body weight in equal amounts of frozen brine shrimp and standard fish food flakes. Survival percentages were arcsine transformed before analysis to conform to normality and homoscedasticity assumptions (Sokal and Rohlf 1995). Analysis of variance (ANOVA) with repeated measures (RM ANOVA) was used to detect differences between treatment and control groups. All statistical analyses were performed using the SAS System v. 6.12 (SAS Institute Inc.).

In the field, the distribution of the sizes at release for recaptured fish was compared with the overall size distribution of all tagged and released fish, using the non-parametric Kolmogorov-Smirnov two-sample test. If there was no size selective mortality of tagged and released individuals in the field, the distributions of sizes at release for both recaptured fish and all the tagged and released fish should be similar.

Sampling, Tagging, and Recapturing Techniques

Mummichogs were sampled with a variety of techniques (Table 1) in order to determine habitat use and maximize recapture of tagged fish. Most mummichogs were collected at nine trapping transects in the four habitat types within the restored marsh (Fig. 1). One transect was located in West Creek (WC-1), two were in the subtidal portion of Creek 3 (C3-1, C3-2), two were in drainage ditches (DD-1, DD-2), and four were located on the marsh surface (MS-1, MS-2, MS-3, MS-4). Each transect consisted of a line of fixed stations with three unbaited wire mesh traps (Cuba Specialty Manufacturing, 3 mm mesh) deployed within 2 m of each station. The wire mesh traps were oriented with their openings parallel to the flow of water. Stations were placed 20 m apart in 6 transects (WC-1, DD-1, DD-2, MS-1, MS-2, and MS-3) and 10 m apart at 3 transects (C3-1, C3-2, and MS-4). The stations of transects C3-1, C3-2, and MS-4 were placed 10 m apart because we wanted to improve our spatial resolution in those areas, especially Creek 3. Transect lengths ranged 30–200 m. Transect lengths around the mouth of Creek 3 (C3-2 and WC-1) were relatively short because these transects were intended to detect movement between Creek 3 and West Creek. Transects on the marsh surface extended from the banks of Creek 3 to the mean high water mark on the marsh surface and varied in length because of variations of the high water mark at different transects.

The traps on the marsh surface were set when the marsh surface began to flood and were retrieved when it was drained (2.25–3.5 h). These traps were pushed into depressions until their openings were level with the marsh surface. The traps in the drainage ditches were set when the ditch began to flood and were retrieved at slack high tide (4.5–5 h). The traps in Creek 3 were set approximately 1.5 h before slack low tide and retrieved 1.5 h after the tide had turned; the process was repeated for slack high tide (3 h for each tide). The traps in West Creek were set at the end of the day and retrieved at the same time on the next day (24 h).

Five tag-and-recapture experiments were conducted from May to October 1998. Each monthly experiment consisted of a tagging period (2 d), when mummichogs were collected, tagged, and released, and a recapture period (4 d), when mummichogs were sampled and checked for tags. Wire mesh traps were used to collect mummichogs (20–100 mm SL) at four stations along transect C3-1 (Fig. 1). Collected fish were first checked for prior tags, measured (mm SL), then tagged and released at the same station where they were caught (Fig. 1). Individuals showing signs of distress or abnormal behavior were removed and not released.

During each monthly recapture period, mummichogs were sampled from all trapping transects and checked for tags with a handheld wand detector. Transects in Creek 3 were sampled twice (once at low tide and once at high tide) while all the other transects were only sampled once during each monthly recapture period. All recaptures were preserved in 95% ethanol. In the laboratory, the standard length of each preserved recaptured fish was recorded and converted to length of a live individual (preserved SL mm = 0.948, live SL mm − 1.275, $r^2 = 0.978$, $n = 61$, Teo 1999). The tags were removed by dissection, cleaned with bleach, and decoded (Unwin et al. 1997). Once recaptures were identified, the standard length at release, release station, and release date were determined from tagging records. The catch per unit effort (CPUE; fish $\text{trap}^{-1}\ \text{h}^{-1}$) and recaptures per unit effort (RPUE; recaptures $\text{trap}^{-1}\ \text{h}^{-1}$) were determined for all transects. Individuals were classified as YOY or adults by comparison with monthly length-frequency distributions (Teo 1999).

Habitat use and movements were determined by comparing the CPUE and RPUE of each habitat type. The use of CPUE from wire mesh traps as an estimate of abundance can be influenced by the duration of deployment (Kneib and Craig 2001). While the use of wire mesh traps is not ideal, there are limited alternatives for capturing mummichogs across these habitat types in a cost-effective and timely manner. The data from Kneib and Craig (2001) suggest that trap deployments greater than 1 h, as in this study, are a conservative measure of abundance and tend to reduce the apparent differences in the CPUEs between locations. Large differences in the CPUE (using trapping durations longer than 1 h) likely indicate real differences in abundance between locations. Raw abundance data was analyzed in a similar fashion as the CPUE data and resulted in similar patterns of abundance between locations (Teo and Able unpublished data). As a result, as this study was only concerned with very broad patterns of relative abundance, it is our opinion that using CPUE was adequate for this study. For statistical analysis, CPUEs and RPUEs were log transformed by $\log_e (x+1)$ to control heteroscedasticity and conform to normality assumptions (Sokal and Rohfl 1995). The CPUE and RPUE of each habitat type at low tide and high tide were compared using ANOVA with the Tukey-Kramer Studentized range test. The CPUE and RPUE of each transect on the marsh surface at high tide was also compared using ANOVA with the Tukey-Kramer Studentized range test.

Data collected by other concurrent studies, using a variety of gears (Table 1) in the same study area were also used to determine distribution by habitat. General faunal surveys using otter trawls (2 min tows, 4.8 m otter trawl, 6 mm mesh codend, Able et al. 2000) and push nets (2 min tows, 1.2 m^2, 3 mm mesh, Public Service Electric & Gas Co. 1999b) were conducted in West Creek and Creek 3. Otter trawls were conducted only during high tide while push net surveys were conducted at low and high tides. For statistical analysis, CPUEs were log transformed by $\log_e (x+1)$ to control heteroscedasticity and conform to normality assumptions (Sokal and Rohfl 1995). The CPUE (fish tow^{-1}) of mummichogs in West Creek and Creek 3 were compared using ANOVA with the Tukey-Kramer Studentized range test. Mummichogs that were caught in a study in adjacent Creek 2 (Chitty 1999) were also checked for the presence of coded wire tags.

HOME RANGE AND SITE FIDELITY

Home range of tagged individuals moving onto the marsh surface at high tide was estimated by constructing a minimum convex polygon and determining its area (Worton 1987). Home range of mummichogs has been previously quantified along

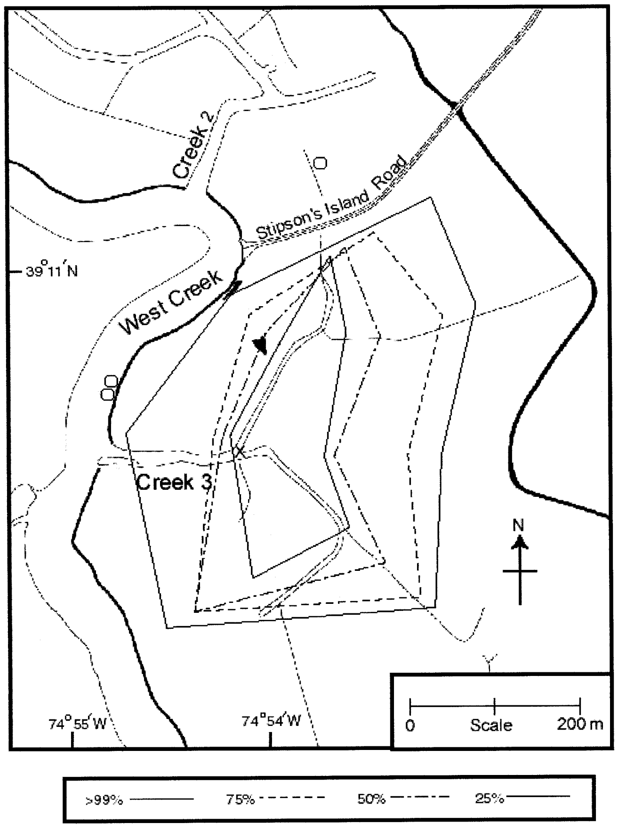

Fig. 2. Home range of mummichogs depicted as polygons based on the cumulative recapture of tagged fish. Polygons represent > 99%, 75%, 50%, and 25% cumulative percentages of recapture for each transect, respectively; using the mean release point (indicated by X) in Creek 3 as the reference point. Three recaptures occurred outside the polygonal home range and are indicated by open circles. In the Creek 2 watershed, one fish was recaptured by another study.

the length of a creek (Lotrich 1975). It was important to quantify the amount of marsh surface that the mummichogs use as the home range because the species is dependent on the marsh surface for food, refuge, and reproduction (Weisberg and Lotrich 1982). We calculated the cumulative percentages of recaptures along each transect, starting with the station nearest Creek 3. For each transect, the stations where the cumulative 25%, 50%, 75%, and 99% of recaptures occurred were then joined together, resulting in four polygons (Fig. 2). The 99% polygon was then used to determine the area of the home range. The ratios of the areas of the four polygons were used to determine the evenness of recaptures over the home range.

We suspected that after mummichogs retreated from the marsh surface as a result of the ebbing tide, they may have been exhibiting site fidelity in their low tide refuge. We determined the effect of the length of time between tagging and recapture (period at liberty) and the distance from release stations on the number of recaptures at transect C3-1. Only mummichogs recaptured at that station during low tide and more than 1 d at liberty were used for this analysis because the mummichogs were released at this transect and most of the recaptures during low tide were made at this transect (Teo 1999). Each recaptured individual was classified according to the distance between the points of recapture and release, and its period at liberty (2–30, 31–60, 61–90, 91–120, and 121–150 d). The transect C3-1 was 100 m in length and one of the release stations was in the middle of the transect. The maximum distance between release and recapture within C3-1 for that release station would therefore be 50 m. In order to compare the site fidelity of all four release stations, any recapture greater than 50 m was not used.

We corrected the mean number of recaptures by the number of releases for the period at liberty. There were two possible permutations for a period at liberty of 91–120 d to occur (i.e., released in May and recaptured in September or released in June and recaptured in October), while there was only one possible permutation for a period at liberty of 121–159 d (i.e., released in May and recaptured in October). The number of recaptures for a period at liberty of 91–120 d was divided by the total number of releases made in May and June, while the corresponding number for 121–159 days was divided by the number of releases in May only.

Environmental Parameters

Selected physical and chemical parameters were measured at the start and end of each sampling effort to determine if these influenced the habitat use and movements of mummichogs. Surface water temperature, salinity, and dissolved oxygen were measured using a handheld (salinity, temperature, and dissolved oxygen; YSI Model 85) meter. Hydroperiod of each marsh surface transect was estimated by recording the amount of time each transect was flooded. The physical and chemical characteristics of each transect were then compared using ANOVA with the Tukey-Kramer Studentized range test.

Results

Evaluation of Tagging Technique

The laboratory and field evaluations suggested that coded wire tagging was an appropriate technique for marking large YOY and adult mummichogs. There was no obvious influence on the swimming ability of tagged fish and no abnormal behavior was observed. In the laboratory, overall tag retention was 98.9%, with only one fish losing

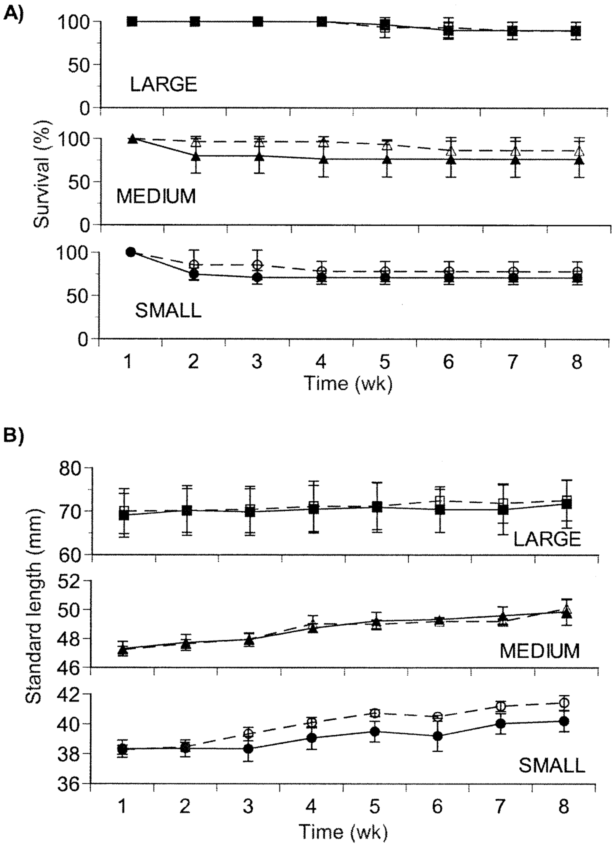

Fig. 3. Survival (A) and growth (B) of tagged (closed symbols) and control (open symbols) fish in 3 size classes: large (> 60 mm SL), medium (45–50 mm SL), and small (35–40 mm SL) over 8 wk (mean ± SD). There were 3 tanks for each experimental group (size class × treatment), with each tank containing 10 fish at the start of the experiment. Survival percentages were arcsine transformed before analysis, using RM ANOVA. Significant differences between the growth of small tagged versus small control fish are indicated by * ($p < 0.05$).

its tag. The survival of large tagged fish was similar (RM ANOVA, $F_5 < 0.01$, $p = 0.949$) to large control fish (Fig. 3). Small (RM ANOVA, $F_5 = 1.52$, $p = 0.285$) and medium (RM ANOVA, $F_5 = 0.77$, $p = 0.429$) tagged fish had a lower survival rate than similarly sized control fish in the first few weeks but these differences were not statistically significant. Growth was similar between large (RM ANOVA, $F_5 = 0.04$, $p = 0.852$) and medium (RM ANOVA, $F_5 = 0.10$, $p = 0.772$) tagged fish versus control fish (Fig. 3). Small tagged fish were approximately 1 mm smaller (RM ANOVA, $F_5 = 11.35$, $p = 0.028$) than small control fish at the end of the 8-wk experiment. Tag detection efficiency was 100% over 10 trials in controlled conditions.

In the field, the tagging method appeared to be relatively successful in determining the habitat use and movement patterns of large YOY and adult mummichogs. The size distribution at release of recaptured individuals appeared to be slightly larger than the overall size distribution at release of all tagged and released individuals (Fig. 4) but this difference was not statistically significant (Kolmogorov-Smirnov two-sample test, $Z = 1.336$, $p = 0.056$). This suggests that there could be some size-selective mortality of smaller tagged fish but the importance of this size-selective mortality is equivocal. Out of the 14,784 adults and YOY tagged and released (Fig. 4), 1,521 individuals were recaptured, resulting in a relatively high recapture percentage of 10.3%. Although habitat use and movements of mummichogs in this restored marsh were studied May–October 1998, tagging and recapture continued through June 1999 as part of a larger study (Teo 1999). Tagged fish were consistently recaptured throughout the year (May 1998–June 1999), with one recapture occurring one year after release.

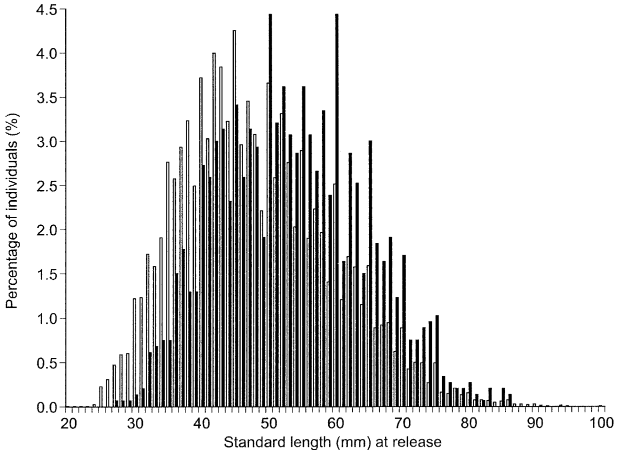

Fig. 4. Distributions of standard lengths (mm) at release, of all tagged (open columns, 14,784 individuals), and recaptured (closed columns, 1,521 individuals) mummichogs. There were no significant difference between the two size distributions (Kolmogorov-Smirnov two-sample test, $Z = 1.336$, $p = 0.056$).

HABITAT USE

The restored watershed of Creek 3 appeared to be the primary habitat for large YOY and adult mummichogs. Mummichogs were much more abundant in Creek 3 than West Creek (Table 1) for all gears (wire mesh traps, otter trawls, and push nets). Within this watershed, the species appeared to be using the subtidal portions of Creek 3 most consistently but also used the drainage ditches and the marsh surface (Fig. 5). Habitat use varied with tidal stage, i.e., the mummichogs used the created creek at low tide and moved onto the marsh surface at high tide. Mummichogs were relatively abundant in Creek 3 at low tide but became significantly lower in abundance (ANOVA with Tu-

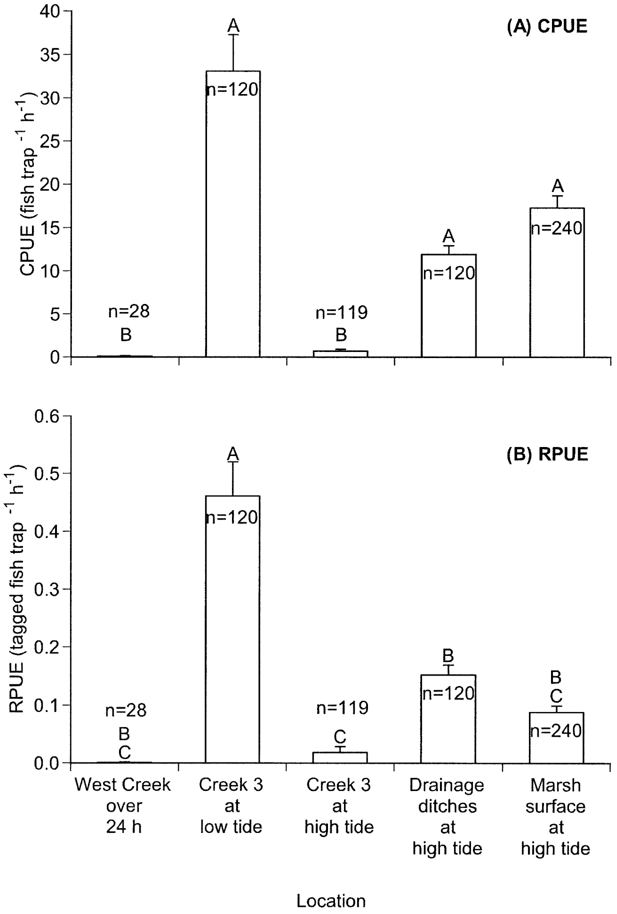

Fig. 5. Comparison of (A) catch per unit effort (CPUE), and (B) recaptures per unit effort (RPUE) between West Creek, Creek 3 at low and high tide, drainage ditches, and the marsh surface (mean ± SE, n = sample size for that habitat). Different letters indicate significant ($p < 0.05$) groupings using the Tukey-Kramer Studentized range test. All CPUEs and RPUEs were transformed by $\log_e (x+1)$ for statistical analysis and back-transformed for graphing.

TABLE 2. Comparison of catch per unit effort (CPUE) and recaptures per unit effort (RPUE) between the marsh surface transects (see Fig. 1 for MS-1, MS-2, MS-3, MS-4) in the restored marsh, at high tide. All CPUEs and RPUEs were transformed by $\log_e (x + 1)$ for statistical analysis. Different letters indicate significantly different ($p < 0.05$) groupings using the Tukey-Kramer Studentized range test. There were no significant ($p > 0.05$) differences between the CPUEs of the four transects but there were significant ($p < 0.05$) differences in their RPUEs.

Transect	n	CPUE (mean ± SE)	RPUE (mean ± SE)
MS-1	66	16.63 (2.86)^{a}	0.085 (0.019)^{a}
MS-2	60	15.79 (1.82)^{a}	0.091 (0.017)^{a}
MS-3	60	16.38 (2.62)^{a}	0.019 (0.009)^{b}
MS-4	54	20.72 (3.84)^{a}	0.167 (0.034)^{c}

key-Kramer Studentized range test, $p < 0.001$, df = 622) at high tide (Fig. 5). The pattern of RPUE appeared similar to that of CPUE, with the RPUE of Creek 3 significantly higher (ANOVA with Tukey-Kramer Studentized range test, $p < 0.001$, df = 622) during low tide as compared to high tide. Although the RPUE of the marsh surface appeared to be higher than that of West Creek and Creek 3, these differences were not statistically significant (ANOVA with Tukey-Kramer Studentized range test, $p > 0.05$, df = 622). Contrary to the trend in the subtidal portions of Creek 3, the marsh surface and drainage ditches had relatively high CPUEs at high tide (Fig. 5). Individuals from the created creek were not moving onto the marsh surface at one particular transect (MS-3) as much as the other three marsh surface transects (Table 2). While the relative abundance on the four marsh surface transects were similar (ANOVA with Tukey-Kramer Studentized range test, $p > 0.05$, df = 240), there were significant (ANOVA with Tukey-Kramer Studentized range test, $p < 0.05$, df = 240) differences in the RPUE (Table 2). The RPUE of transect MS-3 was much lower than the other transects. While the salinity (18.5 ± 0.6‰, mean ± SE, ANOVA, $F_{21} = 0.01$, $p = 0.912$), temperature (26.2 ± 1.6°C, mean ± SE, ANOVA, $F_{21} = 0.07$, $p = 0.795$), and dissolved oxygen content (6.32 ± 0.7 mg l^{-1}, mean ± SE, ANOVA, $F_{17} = 0.07$, $p = 0.798$) of the four marsh surface transects were similar, the hydroperiod of MS-3 (115 ± 15.3 min, mean ± SE) was significantly (ANOVA, $F_{24} = 13.69$, $p = 0.001$) shorter than the other three marsh surface transects (191.7 ± 10.8 min, mean ± SE).

HOME RANGE AND SITE FIDELITY

Based on > 99% of recaptures (1,518 fish), the population studied had a relatively large home range of approximately 15 ha (Fig. 2) but also exhibited strong site fidelity to the subtidal portion of the created creek. The recaptures were generally evenly spread over the marsh surface, with 25% (380 ind), 50% (760 ind), and 75% (1,141 ind) of recaptures covering 3.1, 5.8, and 9.6 ha, respectively.

When the mummichogs moved back into the created creek at low tide, site fidelity appeared to be relatively strong. The mean number of recaptures was highest at the release station and generally became lower as the distance between release and recapture increased (Fig. 6). This pattern was seen even after more than 120 d at liberty, but this pattern was less evident over longer periods of time. Although the peak of recaptures occurred at the release station, the mummichogs exhibited movement throughout the subtidal areas of Creek 3 with recaptures occurring at all stations of transects C3-1 and C3-2.

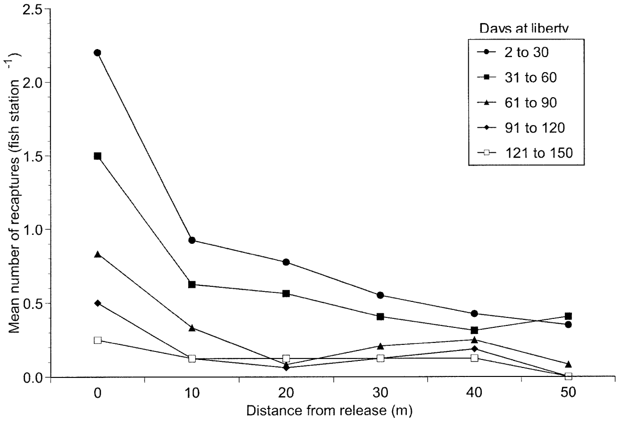

Fig. 6. Mean number of recaptures in Creek 3 during low tide, at 0 to 50 m from release site, for 5 different periods between release and recapture.

Discussion

Evaluation of Tagging Technique

In both laboratory trials and field experiments, coded wire tagging of mummichogs appeared to be an appropriate technique for adult and large YOY mummichogs because tag loss and growth were generally similar to untagged fish. The slightly lower recapture rate of small YOY mummichogs may have been due to size selective natural mortality (Valiela et al. 1977). The very high (100%) detection of tagged fish under controlled conditions was similar to that previously reported in other species (Mattson et al. 1990) and indicated that false negatives were not a problem. Several false positives were discovered when these alleged recaptures were dissected to recover the tag. Small pieces of metal were ingested by these individuals or embedded into their muscle, setting off the tag detector in the field. False positives were not included in any analysis and did not affect any results.

Habitat Use

The habitat use patterns of large YOY and adult mummichogs in the restored marsh at Dennis Township appeared to be comparable to that in natural marshes. During low tide in natural marshes, adult and large YOY mummichogs prefer to use the subtidal areas of small creeks as low tide refuges, rather than the large subtidal creeks draining them (Bozeman and Dean 1980; Talbot and Able 1984; Rozas et al. 1988; Kneib and Wagner 1994; Halpin 1997). Within our study site, the adult and large YOY mummichogs also prefer to use the subtidal portions of the small created creek (Creek 3) as low tide refuges, rather than the large subtidal natural creek draining it (West Creek).

The mummichogs in the restored marsh also appeared to be moving onto and using the marsh surface in phase with the tide, similar to mummichogs in natural marshes. At low tide, a large portion of the mummichog population that was located in the subtidal areas of the created creek, moved onto the marsh surface at high tide and back to the creek on the ebbing tide. This pattern is similar to the tidal movements previously described in natural marshes (Butner and Brattstrom 1960; Kneib and Wagner 1994) and is probably due to the mummichog using the marsh surface for food, reproduction, and possibly refuge (Weisberg and Lotrich 1982; Able and Hata 1984; McIvor and Odum 1988; Kneib 1997). The similar patterns of CPUE and RPUE show that the differences in the relative abundance between the various habitat types were primarily due to the movement of mummichogs.

Habitat preferences and predator avoidance may have, in part or in combination, influenced the movements and habitat use of the mummichogs. The species may have been preferentially attracted to the habitats within the created creek watershed because of high food availability. Related studies in the same creek watershed have indicated that food availability is similar to that of a reference marsh for both small YOY mummichogs (Smith et al. 2000) and other YOY fishes that use a variety of benthic prey (Nemerson 2001). The presence of predators in the deeper, natural West Creek may have caused the mummichogs to stay within the shallow areas in Creek 3 and use it as a refuge. Mummichogs formed a common component (9% by dry weight) of the diet of striped bass, *Morone saxatilis,* in the West Creek watershed, and acoustic tagging showed these predators to be primarily located in the large natural creeks, around the mouths of created creeks, during low tide (Tupper and Able 2000). A pronounced sill at the mouth of the created creek that was exposed at spring low tides may have acted as a barrier against large predators coming into the creek at low tide when mummichogs were abundant. Another predator, the Atlantic croaker, *Micropogonias undulatus,* may have also influenced the tidal movements of the mummichog. From June to August 1998, approximately 31% of the YOY Atlantic croaker stomach samples examined had mummichogs in their guts at low tide (Nemerson 2001). Mummichogs formed the largest proportion (43% by dry weight) of the gut contents of the Atlantic croaker collected at low tide, while they generally formed a much smaller portion (8% by dry weight; Nemerson 2001) at high tide. This predation at low tide suggests that the Atlantic croakers were taking advantage of these low tide concentrations of mummichogs in the created creeks. At high tide, the movement of the mummichogs onto the marsh surface may have reduced their susceptibility to such predation.

Elevation and hydroperiod have a strong influence on the nekton use of salt marshes (Rozas 1995) and were probably influencing the marsh surface use by mummichogs in this restored marsh. Most of the adults and larger YOY that were abundant in the subtidal portions of the created creek did not appear to be using the marsh surface at MS-3 as much as the other marsh surface transects. The marsh surface was heavily used by smaller YOY fish in the late summer and autumn when these fish were abundant, and this was especially apparent at transect MS-3. In September 1998, a larger proportion of the fish trapped on transect MS-3 (39%) appeared to be smaller than 30 mm SL, as compared to MS-4 (2%) and MS-2 (6%; Teo 1999). This pattern of use of the marsh system by small YOY is also apparent in natural marshes (Talbot and Able 1984; Smith 1995; Kneib 1997; Able and Hagan 2000, 2003) and in this restored marsh (Smith et al. 2000). The shorter hydroperiod at transect MS-3 may be reducing the time and area that was accessible to large fish from Creek 3 and reducing predation pressure on the small YOY fish.

One of the presumed natural functions of a marsh is the export of marsh production to coastal regions, with the mummichog being considered an important link in the export chain (Teal 1962; Deegan 1993; Kneib and Wagner 1994; Kneib 1997). The species is thought to feed on the marsh surface and subsequently be preyed upon by larger predators that then move further down the trophic relay (Kneib 1997). The twice-daily tidal movements of the mummichogs feeding on this restored marsh surface (Smith et al. 2000) and the predation by striped bass and Atlantic croaker indicate that this is probably happening in this restored marsh. The export of marsh production from this restored marsh is probably occurring, at least for the mummichog.

HOME RANGE AND SITE FIDELITY

It has been suggested that the home range of an animal be described as an area rather than a linear distance (Worton 1987), and this is the first time an areal home range has been determined for the mummichog. The home range of the mummichogs in this restored marsh appears to be substantially larger than previously found in natural creeks. The summer home range of the species was previously quantified for another Delaware Bay marsh as 36 m, making it one of the most localized of fishes (Lotrich 1975). Although the difference in the way home range is described (linear versus area) makes comparison with this study difficult, the home range area of 15 ha found in this restored marsh is clearly much larger than 36 m. There have been several other accounts of tidal movements (Chidester 1920; Butner and Brattstrom 1960; Kneib and Wagner 1994) showing that mummichogs move along intertidal drainages and onto the marsh surface. Since these drainages are commonly longer than 36 m, the movements of mummichogs in the marshes from the Lotrich (1975) study were probably also much larger than 36 m. The lower elevation of the marsh surface, which is typical of former salt hay farms (Weinstein et al. 1997) due to dewatering and oxidation of the sediments, probably caused deeper water to be on the marsh surface for a longer period of time, which may have resulted in more extensive movements on each tidal cycle.

Closer examination of this and Lotrich's (1975) much-cited study, however, suggests that the apparent differences in home ranges are probably due to the different methods used. We sampled on the marsh surface whereas Lotrich (1975) only sampled along the marsh edge. If we reinterpret the results of Lotrich (1975) as strong site fidelity rather than a limited home range, both of these studies show that mummichogs exhibit strong site fidelity in the subtidal portions of a creek at low tide. This would suggest that the movements of the mummichogs in this restored marsh are comparable with those in a natural marsh.

In summary, the habitat use and movement patterns of mummichogs in this restored marsh appear similar to natural marshes. This suggests that, with respect to the mummichog, the habitat quality of the restored marsh is probably comparable to that of a natural marsh. Similar to some natural populations, the mummichogs in this restored marsh appeared to be moving onto and using the marsh surface in phase with the tide, while at the same time exhibiting strong site fidelity in the subtidal portion of the created creek at low tide. Reproduction of the species was apparently occurring because large numbers of small YOY were feeding on the restored marsh surface (Smith et al. 2000), which resulted in good growth and production (Teo and Able 2003). These results, coupled with the export of marsh production through predators like striped bass and Atlantic croaker (Tupper and Able 2000; Nemerson 2001), indicate that this former salt hay farm has responded positively to this restoration effort.

ACKNOWLEDGMENTS

We would like to thank the Public Service Enterprise Group's Estuary Enhancement Program and the Rutgers University's Institute of Marine and Coastal Sciences (IMCS) for funding this study as well as the numerous people from the Rutgers University Marine Field Station who assisted us in the field and the laboratory, especially J. Chitty, J. Graham, R. Aguilar, and R. Bush. We would also like to thank two anonymous reviewers for suggestions that improved the manuscript. This paper is IMCS Contribution No. 2003-10.

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Received for consideration, August 21, 2001
Revised, May 28, 2002
Accepted for publication, July 16, 2002