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Classification of Lentic Habitat for Sea Lamprey (*Petromyzon marinus*) Larvae Using a Remote Seabed Classification Device

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ABSTRACT: *Lentic populations of larval sea lampreys* (Petromyzon marinus) *are suspected of being a major source of recruitment to parasitic stocks in some areas of the Great Lakes, and methods are needed to estimate habitat and population sizes. A deepwater electroshocker has been used to quantitatively assess larval sea lamprey populations in deepwater areas, however a method has not been developed to efficiently identify the most promising locations to sample in this environment. A remote seabed classification device (RoxAnn™) was used to identify soft substrates in a lentic area where sea lamprey larvae have been found in Batchawana Bay (Ontario) in eastern Lake Superior, and related those substrate types to larval distribution and occurrence. Presence of larvae was significantly related to substrate type, distance from the stream mouth, and slope of the lake bottom. Remote seabed classification would be a useful tool in the Sea Lamprey Control Program to identify the most promising locations to conduct larval surveys in lentic areas.*

INDEX WORDS: *Substrate, lentic, sea lamprey, habitat, Thiessen polygon.*

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INTRODUCTION

A crucial element of the integrated approach to population management of sea lampreys (*Petromyzon marinus*) in the Great Lakes is to estimate the contribution to parasitic stocks from various sources. This requires quantitative assessments of larval sea lamprey populations and projections of the production of metamorphosing sea lampreys from both streams and lentic areas to support control allocation decisions for lampricide treatments.

A quantitative assessment protocol has been developed for larval surveys in streams, which uses a subjective classification of habitat quality to establish *a priori* strata for the sampling of larvae (Slade *et al.* 2003). Currently larval sea lamprey habitat in streams is classified into three different types: preferred (Type 1), acceptable (Type 2), and not acceptable (Type 3) (Slade *et al.* 2003). Type 1 habitat is characterized by soft substrate materials usually consisting of a mixture of sand and fine organic matter, often with some cover over the top such as detritus or twigs in areas of deposition. Type 2 habitat is characterized by substrates consisting of shifting sand with little if any organic matter and may also contain some gravel and cobble. Type 3 habitat consists of materials too hard for larvae to burrow including bedrock and hardpan clay. Although these habitat types are determined subjectively, the definitions used to separate habitat types are supported by more than 30 years of data that demonstrate habitat preference by larvae. In addition, agreement in habitat type determination is good among observers (Mullett and Bergstedt 2003).

Larval populations in lentic areas are suspected by sea lamprey control agents of contributing substantially to parasitic sea lamprey populations in some areas of the Great Lakes. This is especially true in Lake Superior where periodic floods scour the lower portions of rivers and flush sea lamprey larvae into the lake. Although information about growth and metamorphosis rates for larval sea lampreys in lentic areas is lacking, sea lamprey control agents consider the potential for production good, and their contribution to parasitic stocks should be investigated. Estimates of larval populations in portions of the St. Marys River, in what are essentially lentic areas, have been made using a deepwater electroshocker (Bergstedt and Genovese 1994), which is a quantitative sampling tool for deep areas. However, a method is lacking to locate and classify larval habitat in these deeper areas before sampling, as is currently done in shallower streams. The difficulty lies in the inability to quickly and directly observe substrates in deeper waters. Substrate samples have been gathered with a dredge or observed with video, but those activities can consume as much time as the larval sampling at deeper sites.

The RoxAnn™ seabed classification system (Chivers *et al.* 1990, Murphy *et al.* 1995) has been used successfully to remotely characterize lakebed surficial substrates (Greenstreet *et al.* 1997, Yin *et al.* 1998). This device classifies substrates using multiple echoes received by an echosounder transducer mounted to a survey vessel. The instrument develops two measurement indices (or acoustic parameters): the E1 index is based on the first echo which is a direct reflection of the acoustic signal from the substrate on the sea floor; the E2 index is based on the second echo which is the signal that has been reflected twice at the sea floor and once at the water surface before returning to the transducer. The E1 index is considered a measure of substrate roughness while the E2 index is a measure of surface hardness. These two indices are used in combination to identify surficial substrate material and have good potential for characterizing larval sea lamprey habitat in lentic areas.

Development of a remote-sensing method to rapidly classify large areas of lentic habitat for sea lamprey larvae into two or more classes would permit *a priori* design of more efficient surveys. The primary objective of this study was to determine the feasibility of the RoxAnn™ to classify available habitat in a sea lamprey-infested, lentic area of Lake Superior. The approach used to accomplish this objective had five steps; (1) collection of RoxAnn™ acoustic signatures over essentially homogenous substrate areas to serve as a "training" data set, (2) development of a substrate classification rule using discriminant function analysis from the training data set, (3) collection of RoxAnn™ acoustic data over a broader area of yet undetermined substrates, (4) collection of sea lamprey larval density data using a deepwater electrofisher over the same geographic area as where the RoxAnn™ data was collected, and (5) use of these data to determine whether substrate classification from RoxAnn™ data is useful in predicting the presence of sea lamprey larvae.

MATERIALS AND METHODS

Study Site

Batchawana Bay and Batchawana River (46°55′N, 84°31′W) are located in eastern Lake

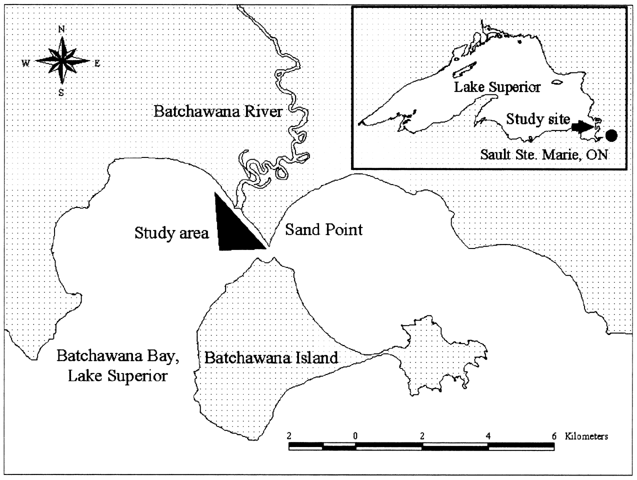

FIG. 1. Study site location in Batchawana Bay, Lake Superior, Ontario.

Superior about 50 km north of Sault Ste. Marie, Ontario (Fig. 1). About 1.6 km^2 of Batchawana Bay south of the river mouth was surveyed to classify substrates. The lake bottom is characterized by large areas of soft sediments composed mostly of sand with smaller amounts of silt and clay and intermittent areas of aquatic vegetation (primarily *Potomogeton* spp.). Water depths range from 0.3 to about 20 m. With the exception of Sand Point, where depths drop quickly to over 40 m, shallow water extends 200 to 500 m outward from shore. Farther from shore, the increase in depth becomes more gradual, and eventually ends in a flat plateau at about 15 m. The close proximity of Batchawana Island to Sand Point creates a strong water current that typically moves from west to east between these landforms.

Larval sea lampreys that originate from the Batchawana River infest this portion of the bay (Department of Fisheries and Oceans Canada, Sea Lamprey Control Centre, Sault Ste. Marie, Ontario, unpublished records). Density ranges from 2 to 5 larvae per m^2, and is considered high for a lentic environment compared to 0.3 per m^2 in East Bay and 0.05 larvae per m^2 in Ogontz Bay, Lake Michigan (Lee and Weise 1989). Past surveys for larval sea lampreys in Batchawana Bay clearly indicate a patchy distribution.

Instrumentation

A hydrographic quality echo-sounder (Innerspace Model 448, Innerspace Technology, Inc., Waldwick, NJ) coupled with a RoxAnn™ seabed classification device (RoxAnn™, Marine Micro Systems Ltd., Scotland) and a twelve channel real-time differentially corrected global positioning system (DGPS) was used to categorize surficial bottom substrate types, their depths, and spatial locations (Chivers *et al.* 1990, Murphy *et al.* 1995). The DGPS provided geographic positional accuracy within 1 m of true position. All equipment was installed on a 8-m motor boat. The echosounder transducer produced a single 8° beam at a frequency of 208 kHz. A laptop computer was used to serially connect all instruments, via a multi-port PCMCIA controller card (Comtrol Corporation, Minneapolis, MN), and to integrate substrate signal measures, real-time latitude and longitude positions, and water depth in ASCII data format. Hydrographic survey software (Hypack version 8.1, Coastal Oceanographics, Inc., Middlefield, CT) was used for data collection, establishing survey transects, and real-time electronic navigation while underway. Acoustic data were collected at the rate of 2 observations per second at speeds up to 22 km/hr. Geographical coordinates were collected in UTM (Universal Transverse Mercator) projection, Zone 16, and NAD 83 (North American Datum) datum.

Field Data

Although the survey area was the same for all data collections, the study consisted of two independent phases. First, acoustic sonar data were collected from both substrate-training fields and then from a broader area of unknown substrates, and second, a deepwater electrofishing survey for larval sea lampreys was conducted over that same broader area.

RoxAnn™ Training Data Collection

A supervised classification of substrate types was performed to fit unclassified E1 and E2 survey data to a ground-truthed model (Schlagintweit 1993, Campbell 1996). This method requires that acoustic reference or training files be collected from unique substrates to classify subsequently collected survey data.

On 21 July 1998 and 9 June 1999, 11 visually unique-looking substrate types consisting of varying gradations of softer sediments were located in Batchawana Bay. An underwater video camera was used to identify each substrate type as well as ensure the boat remained over that substrate during acoustic training data collection. Five acoustic training files were collected over each substrate type. Each file consisted of two observations recorded every second during the 60- to 120-second collection period (between about 120 and 240 observations per training file). For each substrate, the five training files were combined into one larger training file. Grab samples of each substrate type were collected using a petite Ponar dredge, visually inspected, and retained for later analysis. Substrate sediment grain analysis was subsequently conducted on those samples using standard hydrometric methods (Folk 1974). Sediments were weighed wet and dry, then fired to constant weight in an ashing oven to determine percentage organic content. Sediment grain size was determined using 2.00, 0.84, 0.50, 0.25, 0.125, 0.0625, and less than 0.0625-mm standard shaker sieves (coarsest to finest scale), and expressed using the Wentworth Scale, which categorizes substrates based on sediment size.

RoxAnn™ Broader Survey Data Collection

Acoustic sonar survey data were collected during 22–23 July 1998 along transects oriented north to south and spaced 20 m apart in a broader area of unknown bottom substrates. A total of 95 transects were sounded to yield data points spaced about every 1.6 m, a distance that was a result of the average underway boat speed. Survey data were processed and edited using standard techniques (Greenstreet *et al.* 1997). Suspect bathymetric or geographic coordinate data were identified by examination of adjacent data. If a bathymetric datum was consistent with a general pattern then it was retained; if it deviated by more than 20% compared to the preceding and following datum, it was removed. If a geographic coordinate was not contiguous with the preceding or following point, the data were likewise removed.

Discriminant function analysis (Sokal and Rohlf 1981) was used to predict substrate group membership for each observation. Classification rules were established using data from the ground-truthed substrate-training files. Lachenbruch's "holdout" procedure (Johnson and Wichern 1982) was used to produce a jackknifed classification matrix to evaluate the goodness of the classification. In this procedure, one observation is removed from the data, a discriminant function is developed from the remaining observations, and this function is used to classify the "holdout" observation. This process is repeated for each of the observations, and the resulting misclassification rate is a nearly unbiased estimate of the expected actual error rate.

Larval Sea Lamprey Density Survey

Density surveys for sea lamprey larvae were conducted from 6 June to 7 September 1998 using a deepwater electroshocker mounted on a modified pontoon boat. Sampling was conducted every 20 m on transects spaced 20 m apart in the broader survey area of Batchawana Bay. At each location operators visually inspected Ponar dredge grab samples, and from these observations made subjective assignments as to substrate composition and habitat suitability for larval sea lampreys, just as they would if the surveys were being routinely conducted instream. Four 0.61 m^2 plots were electroshocked (total area 2.44 m^2) at each location. The area chosen for electrofishing was larger than, and fully contained, the area believed to be historically infested by sea lamprey larvae in Batchawana Bay. Electrofishing was conducted toward shore to the point where shifting sand caused by wave action would prevent larvae from maintaining burrows, and in the deeper areas, to depths in the bay where larvae had never been captured. Larval catches and GPS coordinates in real-time were recorded at each electrofishing location.

Map Creation

The Thiessen polygon method for building vector-based coverages (Marriott 1991, Rukavina 1997) was used to map the data. This interpolation process creates one polygon for each point observation. Each polygon has the unique property that any location within a polygon is closer to the polygon's point than to the point of any other polygon (ESRI, Inc. 1991). Adjacent polygons of the same substrate category are then combined prior to converting the vector coverage to raster format (grids). Raster-based grids are preferred data products because they can be quantitatively queried and smoothed using various algorithms to explore relationships with other data. A cell size of 2×2 m was used in the grid formation process to minimize data loss because the Thiessen polygons initially created around each point approximated 2×20 m. The larger the cell size, the more likely a cell is influenced by neighboring polygons and may mask the correspondence of the cell to the original point information.

Relating Larval Presence to Substrates

Because the distribution of larval sea lamprey catches consists of a few samples with large catches and many samples with no larvae, the data were analyzed on the basis of larval presence rather than larval density. Predicting the probability of larval presence from habitat information would be effective in optimizing larval sea lamprey surveys. Logistic regression (Hosmer and Lemeshow 1989) was used to relate larval sea lamprey presence to substrate type. Water depth, bottom slope, and distance from river mouth were included as supplemental independent variables to substrate type because they might also influence the presence of larvae. Models were fit to predict the presence of larvae in the sample on substrate type alone,

$$p = \frac{1}{1 + e^{-\beta_{0i}}} \tag{1}$$

and with the additional independent variables,

$$p = \frac{1}{1 + e^{-(\beta_{0i} + \beta_1 dist + \beta_2 depth + \beta_3 slope)}} \tag{2}$$

where p is the probability of larval sea lamprey presence, the β are coefficients estimated by maximum likelihood, i represents substrate type, *dist* is the distance from the mouth of the river in meters, *depth* is the depth in meters, and *slope* is the angle of the lake bottom in degrees. The presence of larvae was also modeled for two and three classes of lentic habitat. For the model using two lentic habitat classes, substrate types were grouped into a high class and a low class based on larval presence in each substrate type. For the model using three lentic habitat classes, substrate types were grouped into a high class, a moderate class, and a low class based on larval presence in each substrate type.

The results of electrofishing were overlaid on the map of predicted substrates and each location was coded for the corresponding remotely-sensed substrate category. The electroshocking results were also overlaid on maps of the other physical factors (distance from the stream mouth and slope of the lake bottom) that might have influenced presence of sea lamprey larvae. Using the logistic regression, the probability of larval sea lamprey presence and associated confidence intervals were calculated.

RESULTS

Substrates

Eleven soft substrate types were categorized in the study area based on E1 and E2 acoustic signal profiles and sediment grain analysis (Table 1). Each substrate class was composed of several particle sizes, therefore the percentage particle size composition and level of organic content contained in each substrate type was used to quantitatively describe a unique substrate category. Descriptive keywords based on substrate appearance (Table 1) are used hereafter to refer to the substrates. The largest sediment grain size in the samples was at the 4-mm grade limit while many substrates were composed of finer materials about 0.0625 mm. Although the Wentworth Scale is repetitive for some of the substrates, the substrate grab samples exhibited gross differences in relative particle size composition as determined by touch and sight, percent organic matter, the presence of rooted macrophytes, or other key characteristics that made it easy to distinguish the samples as being unique during data collection. Some of the substrates contained large amounts of organic matter, while others virtually had none. No substrates composed of large particles such as rubble, boulder, or bedrock were observed in the survey area.

Acoustic survey data were collected along 95 transects. Data from two full transects and two partial transects were excluded due to uncertainty of positional accuracy. Several data points from other transects were either deleted or modified because depth measurements deviated more than 20% from the values of adjacent points. A total of 36,653 data points were submitted for classification to predict substrate composition from E1 and E2 data in the study area based on the discriminant function generated from ground truthed substrate-training file data (Table 2). Correct classification rates of the ground truthed data, ranged from 59% (sand with clay) to 100% (coarse sand and *Potomogeton* spp. in sand) with an overall correct classification rate of 88%. Seven of the 11 groups had classification rates of 90% or higher. The degree of separation is demonstrated in the confidence ellipsoids (Fig. 2) for bivariate means of E1 and E2 values for each substrate type. Those ellipsoids that overlap with other substrates will be misclassified more often than substrates with discrete ellipsoids.

The predicted substrate compositions were mostly sand/silt/clay conglomerate (30%), silt (22%), and silt with sand (14%). Clay with sand

TABLE 1. Wentworth classification, organic matter content, and percent composition by particle size for 11 substrates identified in Batchawana Bay, Lake Superior, Ontario.

			Percent composition[1] by particle size range (mm)						
Substrate	Wentworth classification	Percent organic content[2]	< 0.0625 (Coarse silt)	0.0625–0.124 (Very fine sand)	0.125–0.24 (Fine sand)	0.25-0.49 (Medium sand)	0.50-0.83 (Coarse sand)	0.84–1.99 (Very coarse sand)	2-4 Granules
1 Clay	Fine to very fine sand[3]	3.0	19	26	37	15	1	1	< 1
2 Clay with sand	Fine to very fine sand	4.4	30	36	31	2	< 1	< 1	< 1
3 Coarse sand	Medium sand	0.6	< 1	< 1	10	60	19	5	6
4 Fine sand	Fine sand	0.4	< 1	1	50	47	< 1	< 1	< 1
5 *Potomogeton* spp. with sand	Very fine sand to coarse silt	4.2	26	47	25	< 1	< 1	< 1	< 1
6 Sand with clay	Fine to very fine sand	2.5	26	35	35	3	< 1	< 1	< 1
7 Sand with vegetation	Very fine sand to coarse silt	4.6	28	37	27	6	1	< 1	< 1
8 Silt	Very fine sand	5.6	21	51	28	<1	< 1	< 1	< 1
9 Sand/silt/clay	Fine to very fine sand	1.3	11	24	47	14	2	1	1
10 Silt with sand	Fine to very fine sand	2.9	9	38	49	3	< 1	< 1	< 1
11 Very coarse sand	Coarse to medium sand	0.6	< 1	3	7	30	42	15	2

[1] As percent of total ash weight.
[2] As percent of total dry weight.
[3] The sample was mostly hardpan clay, and the ashed remainder was too hard to break apart for the sieves.

TABLE 2. Jackknifed classification matrix for 11 substrates classified from ground truthed training samples taken in Batchawana Bay, Lake Superior, Ontario. Correct classifications are in boldface. For example, substrate 2 (clay with sand) had 893 observations correctly classified and 38 observations incorrectly classified as substrate 4 (fine sand).

	Predicted substrate											
Substrate type	1	2	3	4	5	6	7	8	9	10	11	% Correctly Classified
1 Clay	**660**	0	0	0	0	0	0	2	0	1	31	95
2 Clay with sand	0	**893**	0	38	0	0	0	0	0	0	0	96
3 Coarse sand	0	0	**1,067**	0	0	0	0	0	3	0	0	100
4 Fine sand	0	0	0	**1,210**	0	9	0	0	0	0	0	99
5 *Potomogeton* spp. with sand	0	0	0	0	**942**	0	0	0	0	0	0	100
6 Sand with clay	0	0	0	39	0	**702**	2	0	124	0	0	80
7 Sand with vegetation	0	0	0	0	0	50	**801**	0	0	30	0	91
8 Silt	0	0	156	0	0	3	0	**684**	43	5	265	59
9 Sand/silt/clay	0	0	63	0	0	99	5	19	**948**	4	0	83
10 Silt with sand	0	0	0	2	0	37	135	8	3	**807**	0	81
11 Very coarse sand	0	0	0	0	0	0	0	40	0	1	**438**	91
Total	660	893	1,286	1,289	942	900	943	753	1,121	848	734	**88**

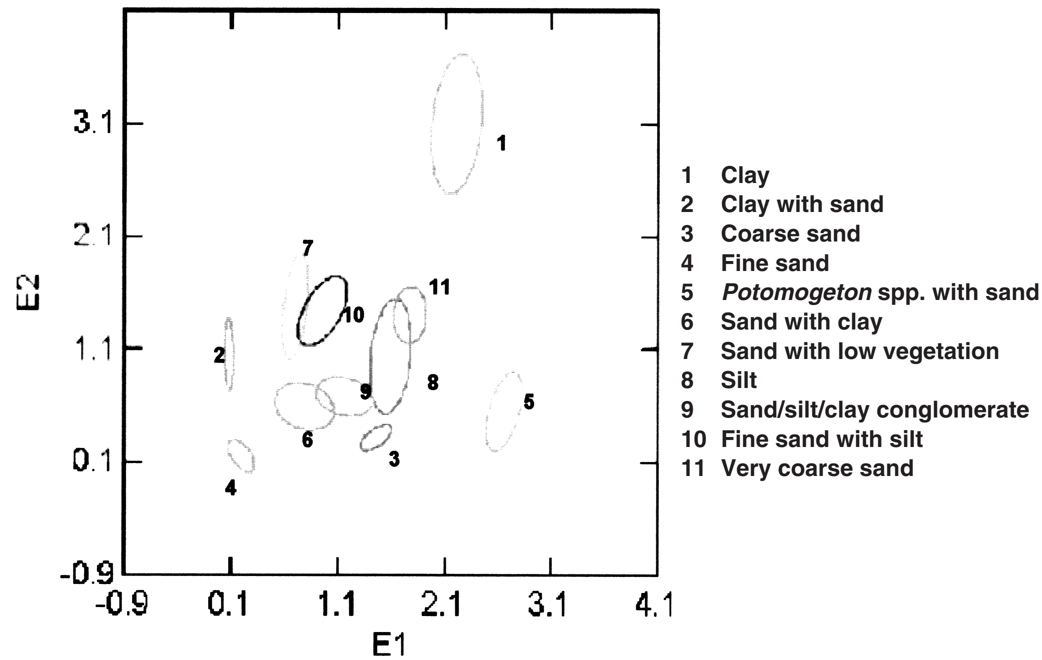

FIG. 2. Confidence ellipses (95%) for mean E1, E2 values of 11 different substrates calculated using discriminant function analysis.

(1%) and coarse sand (1.5%) were the least common substrates encountered (Fig.3). The raster-based map is divided into three zones that describe the survey area in the bay. In the central zone (A), directly offshore of the river mouth, there is a narrow strip of the substrate categories fine sand and sand with clay. Just adjacent but further from shore to the south and west lies a pocket of *Potomogeton* spp. in sand. To the south and east, a mosaic of silt and the sand/silt/clay conglomerate predominates the zone. This area of conglomerate forms the largest contiguous area of any substrate in the study area. In the eastern zone (B), a unique dome-shaped area (D) exists consisting of fine sand; sand with clay; and sand/silt/clay conglomerate. Further to the south, very coarse sand gives way to a distinct area of clay. The western zone (C) contains a large area of silt to the north and many abrupt changes to the south among three different sandy substrates: sand with clay; sand/silt/clay conglomerate; and silt with sand.

Bathymetry information indicates a steep drop-off to 16.5-m near Sand Point on the east margin of the study area. Areas near the northwest margin show a near equal distance among 1.6- to 10-m depth contours and a rather flat region in the center of the study area ranging between 3.3 to 4.5 m. This flat region is composed of a mosaic of silt and the sand/silt/clay conglomerate. The dome-shaped area previously noted lies on a flat at 3.3 m. Between shore and 1.1 m are shallow water areas where acoustic data were not collected because of the draft of the acoustic survey boat.

Larval Abundance

A total of 357 sites along 31 transects were electrofished and captured 349 sea lamprey larvae. The mean density for all sites was 0.978 larvae/m^2, uncorrected for gear efficiency. Only 104 sites (29%) yielded sea lamprey larvae, and non-zero catches ranged from 1 to 18 larvae per site. Seventeen shallow water sites were excluded from further analyses because the acoustic survey boat was unable to enter these depths. One additional site was excluded because the suction hose on the deep-water electroshocker could not reach bottom. At least one sample was taken in each substrate category, but most of the samples were taken from substrates of silt and sand/silt/clay conglomerate. Most sea lamprey larvae were caught in silt, and none were captured in clay (Fig. 4). The density of larvae was highest in sand with low vegetation and coarse sand, however, few larval sampling locations were in these substrate categories (Fig. 4).

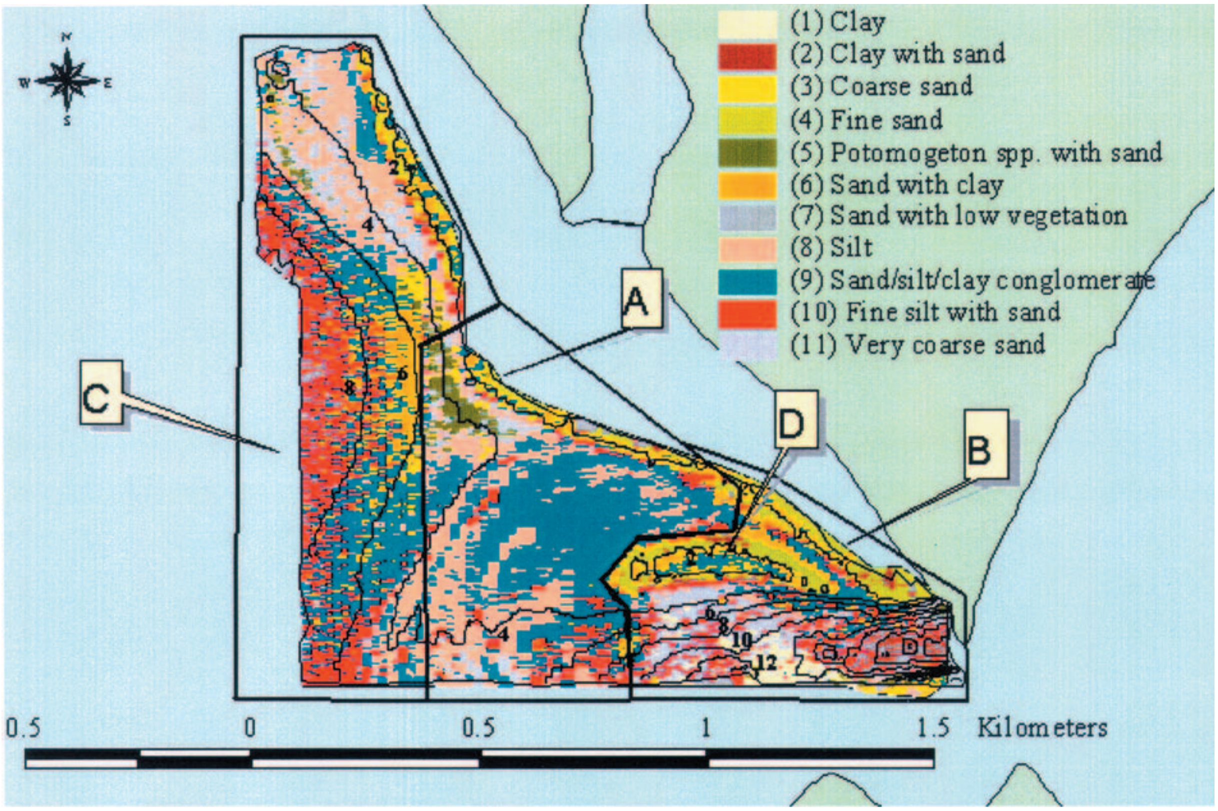

FIG. 3. Raster based grid using 2 × 2 meter cells created from Thiessen polygon vector coverage and two meter depth contours. Area A: central zone, B: eastern zone, C: western zone, and D: dome.

Most sea lamprey larvae were captured in a large area at depths of 1.6 to 3.3 m, offshore from the mouth of Batchawana River (Fig. 5). The mean density was similar across the range of observed depths, but most of the survey locations (86%) were in 1.6 to 3.6 m. Larval density decreased with distance from the mouth. No sea lamprey larvae were captured up-current from the river mouth to the northwest, but some were caught in down-current locations. This is likely the result from either the strong lake current or the effects of the prevailing westerly winds. Catches were typical of larval sea lamprey distributions: most locations were devoid of larvae and those locations with larvae had high densities.

Type 1 habitat in streams is considered preferred (optimal) for larvae. Most of the larvae captured in the bay were in areas classed by the electroshocker operators as Type 1 habitat (Fig. 5). Eighty-one percent of the larvae were captured in Type 1 habitat, which made up only 12% of the area. Silt, very coarse sand, and *Potomogeton* spp. in sand composed the majority of this area. These substrates all had similar particle size composition ranges and contained moderate to high levels of organic matter (Table 1).

Relating Larval Abundance to Substrates

Substrate type alone was found to have a significant effect on the presence of larvae ($\chi^2 = 27.572$, $p = 0.001$; Table 3, Fig. 6). Substrate types 1 and 2 were not found at any of the larval sampling sites and were excluded from further analysis. When combined with other covariates, the effect of substrate was still significant (Table 4). The covariates slope and distance from the mouth of the river were both significant in the model, but depth ($t = 0.172$, $p = 0.863$) was not significantly related to larval presence, and was removed from the model (Table 4).

Grouping combinations of substrate data into different classes may be important in describing lentic sea lamprey larval habitats that can be related to

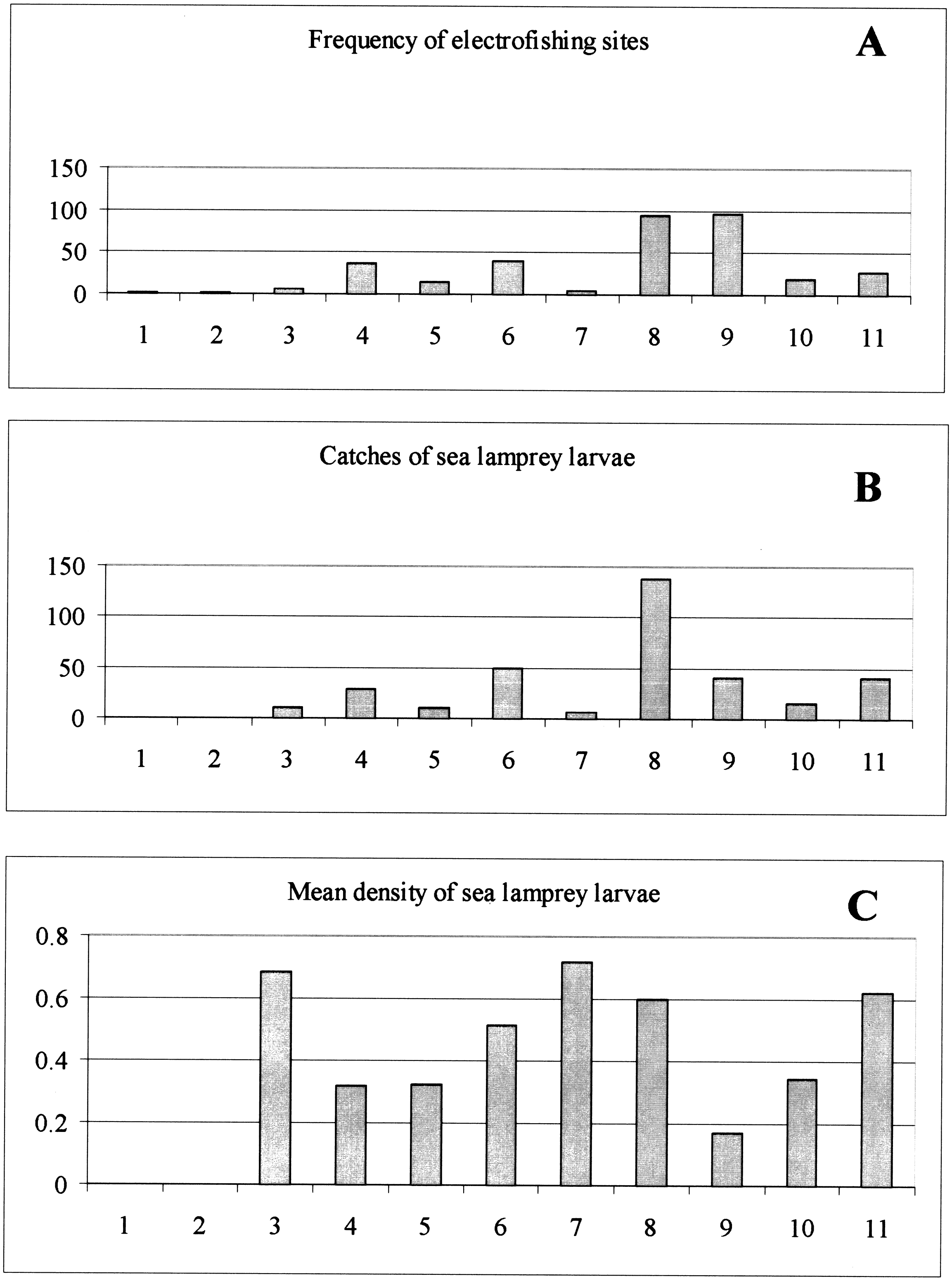

FIG. 4. Histograms of the number of deepwater electroshocker sites sampled (A), the total number of larval sea lampreys captured (B), and the mean larval density (no./m^2) (C) by substrate category at 357 locations in Batchawana Bay, Lake Superior, Ontario. Substrate 1: clay, 2: clay with sand, 3: coarse sand, 4: fine sand, 5: Potomogeton *spp. in sand, 6: sand with clay, 7: sand with low vegetation, 8: silt, 9: sand/silt/clay conglomerate, 10: fine silt with sand, and 11: very coarse sand.*

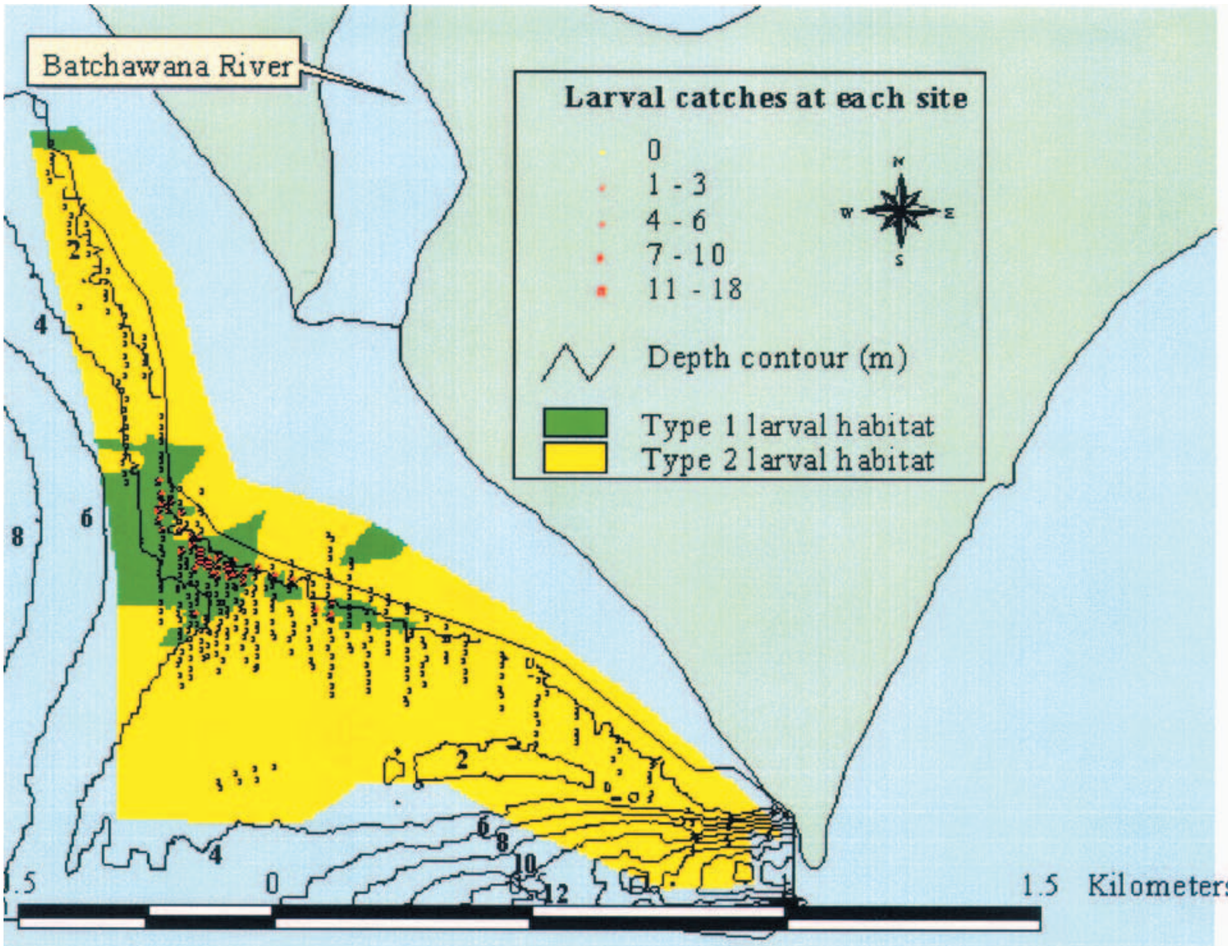

FIG. 5. Areas of type 1 and type 2 larval sea lamprey habitat classified by electroshocker operators in relation to the catches of larvae in Batchawana Bay, Lake Superior, Ontario.

larval presence much as it is done in streams. A logistic regression using two newly formed classes of lentic habitat to predict the presence of larvae was significant. The newly formed classes were grouped on the basis of determining that substrates *Potomogeton* spp. in sand, silt, and very coarse sand made up 75% of the area classified by the deepwater electrofishing team as Type 1 larval habitat. This habitat was located directly offshore of the river mouth where most of the sea lamprey larvae were captured. All other substrates outside this area were grouped in another class. The logistic regression of larval presence on this new habitat quality indicator was statistically significant (χ^2 = 14.846, $p < 0.0001$) and the calculated probabilities of larval presence for each group significantly differed, (the confidence intervals did not overlap (Fig. 7)).

Based on the results of the logistic regression with these two classes, an attempt was made to further improve the ability to predict presence of larvae by defining three classes instead of just two. Three classes of larval habitat [preferred (Type 1), acceptable (Type 2), and not acceptable (Type 3)] have been identified in assessments of shallower streams and may be appropriate in lentic situations as well. Therefore, three classes were formed using the same first grouping as before (highest probability of larval presence) and splitting the second class into two new groups: substrates sand with clay and sand/silt/clay conglomerate in the second class (moderate) and the remaining substrates in a third class (lowest). The logistic regression of larval presence on the three new classes of habitat quality was statistically significant (χ^2 = 16.679, $p <$ 0.0001), but the confidence intervals for the esti-

TABLE 3. Results of logistic regression of the presence of sea lamprey larvae modeled on substrate type. Substrates are in order from highest to lowest likelihood of capture for larval sea lampreys. (Substrate types 1 and 2 were not found at any of the larval sampling sites and were excluded from further analysis).

Substrate Type	Substrate keyword	Coefficient
3	Coarse sand	2.196
5	*Potomogeton* spp. with sand	0.874
11	Very coarse sand	0.363
8	Silt	0.064
6	Sand with clay	–0.348
7	Sand with low vegetation	–0.512
10	Fine sand with silt	–0.667
4	Fine sand	–0.702
9	Sand/silt/clay	–1.268

mated probabilities of larval presence for the three classes overlapped (Fig. 7).

DISCUSSION

Much information has been published on the ability of the RoxAnn™ to distinguish among several seabed materials ranging from hard to soft substrates, but little has been noted about its ability to

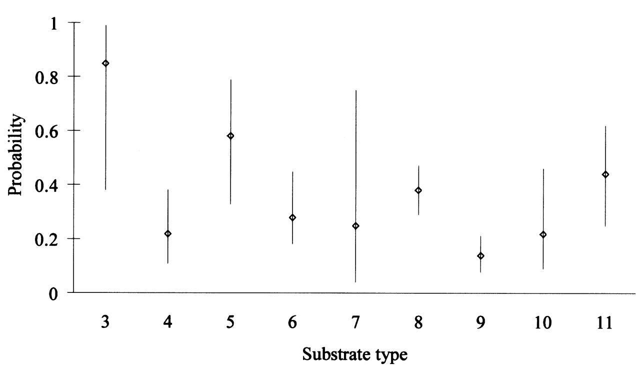

FIG. 6. Predicted probability of larval sea lamprey presence with 95% confidence limits. (Substrate types 1 and 2 were not found at any of the larval sampling sites and were excluded from further analysis. Substrate 3: coarse sand, 4: fine sand, 5: Potomogeton spp. in sand, 6: sand with clay, 7: sand with low vegetation, 8: silt, 9: sand/silt/clay conglomerate, 10: fine silt with sand, and 11: very coarse sand.)

TABLE 4. Results of multiple logistic regression of the presence of sea lamprey larvae modeled on substrate type, distance from the mouth of the river, and bottom slope.

Source	df	t	p-value
Substrate	8	18.055[1]	0.021
Distance	1	-4.045	< 0.001
Slope	1	3.554	< 0.001

[1]This statistic is χ^2 (chi square) because substrate type is a categorical variable and is solved for multiple levels simultaneously (SYSTAT™ ver. 8).

discriminate among multiple soft sediments. From naturally occurring softer sediments, 11 substrate types composed of very similar materials were located and visually categorized, and the RoxAnn™ verified their uniqueness in this supervised classification. Although these substrate types were not really discrete entities, there was sufficient separation in the RoxAnn™ acoustic profiles to provide useful breakpoints for these continuous substrate variables. While there was some degree of overlap in the E1 and E2 acoustic signal profiles for some substrates, this was not surprising due to the similarity of sediment particle materials and sizes. The presence and amount of organic matter in the substrates also influenced the output from the RoxAnn™ seabed classification device.

The distribution of substrate types in relation to depth and distance from shore is consistent with what is known about particle transport and deposition. Accordingly, observations made in this study compare favorably to the findings of Lee and Weise (1989), who demonstrated a composite relationship among depth, substrate particle size, and other physical factors in the Harmony Bay portion (eastern) of Batchawana Bay. In general, the presence of silt and clay particles was positively correlated with water depth, while the presence of sand was negatively correlated with water depth. In this study, most sandy substrates were found in waters shallower than 10 m and clay-like materials in waters deeper than 10 m (Fig. 3).

The larvae in this study were primarily found along the slope of the drop-off. Lee and Weise (1989) found large numbers of sea lamprey larvae off the mouth of the Chippewa River in eastern Batchawana Bay concentrated along the leading edge of the alluvial fan. This is where one would expect to find sea lamprey larvae when they escape from the river proper during flood conditions.

Results of the logistic regression indicate that lar-

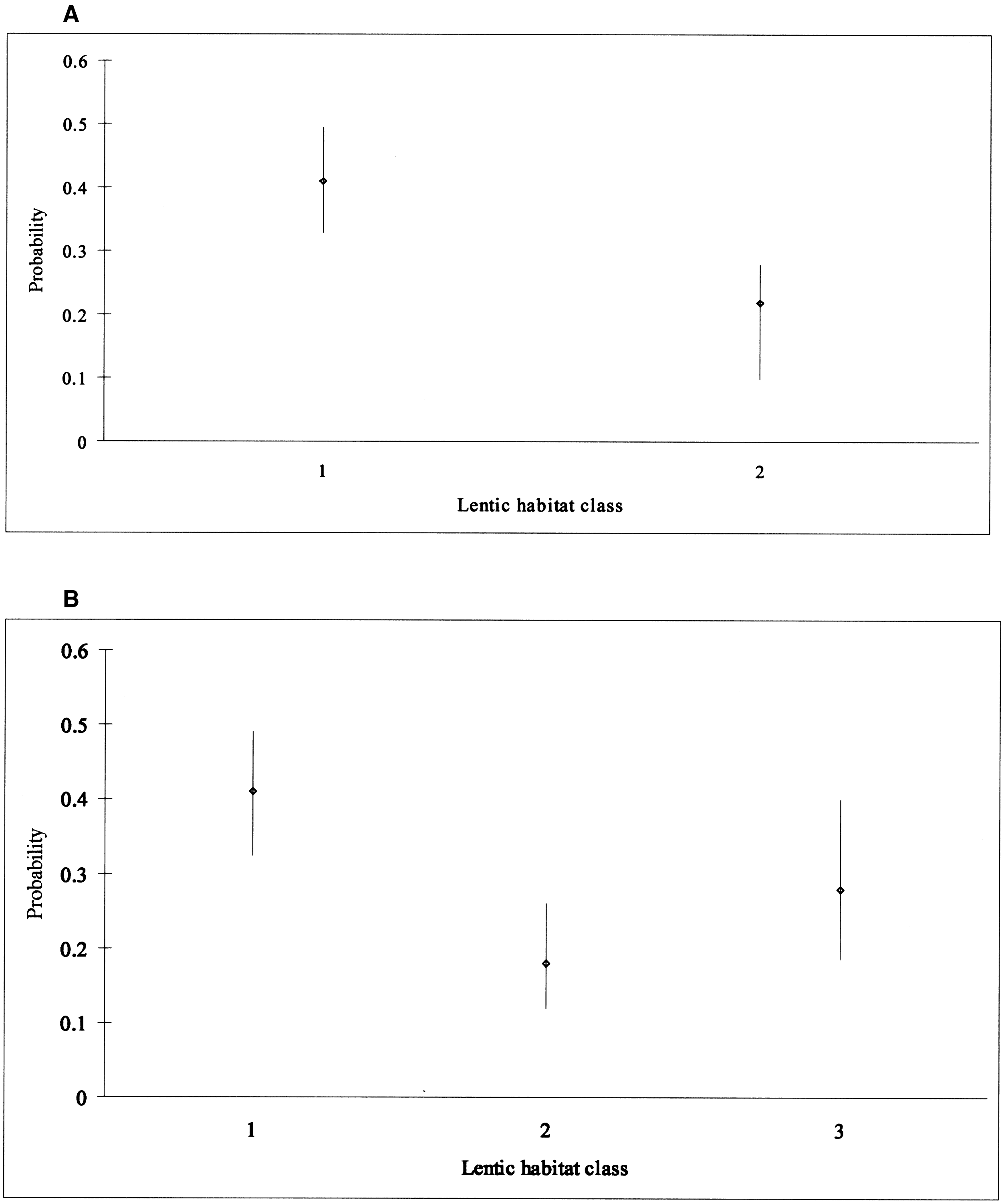

FIG. 7. Predicted probability of larval sea lamprey presence with 95% confidence limits based on (A) two and (B) three classes of lentic habitat. (A) Lentic habitat class 1 consisted of substrate numbers 5, 8, and 11 and habitat class 2 consisted of substrate numbers 3, 4, 6, 7, 9, and 10. (B) Lentic habitat class 1 consisted of substrate numbers 5, 8, and 11, habitat class 2 consisted of substrate numbers 6 and 9 and habitat group 3 consisted of 3,4,7, and 10. Substrate 3: coarse sand, 4: fine sand, 5: Potomogeton *spp. in sand, 6: sand with clay, 7: sand with low vegetation, 8: silt, 9: sand/silt/clay conglomerate, 10: fine silt with sand, and 11: very coarse sand.*

val presence was significantly related to substrate type. The relatively high probability of larval presence in coarse sand would typically indicate a sampling anomaly. Sea lamprey larvae are not usually found in mostly sandy substrates with low organic content. Sea lamprey larvae are usually most abundant in a combination of sand and other softer sediments with moderate to high amounts of organic material. Five of the six sites classified as coarse sand yielded sea lamprey larvae. The five positive sites, where the larvae were captured were surrounded by silt, whereas the negative site was not. The negative site was closer to the shoreline in shallower water, making it more likely to be influenced by wave action and thus unsuitable as potential larval habitat. Maybe more importantly, the substrate composition for the negative site was classed by the electroshocking team as only coarse sand with no softer secondary substrate materials. The positive sites contained at least some softer materials in a mixture with the coarse sand, despite all six sites being classed as coarse sand by RoxAnn™. Most of the larvae were captured in silt and the sand/silt/clay conglomerate, which corresponds to the same types of materials that compose Type 1 larval habitat in streams (Slade *et al.* 2003). Therefore, substrate composition is important regardless of habitat.

Anecdotal information suggests that lentic sea lamprey larvae accumulate along drop-offs near the mouths of streams when populations are found. In this study, sea lamprey catches were consistently higher along the drop-off where the slope was moderate with very few larvae captured when the slope was at either extreme (highest slope was Sand Point and the lowest slope was from the mouth of Batchawana River extending outward to the drop-off). Only two of 349 sea lamprey larvae were captured at depths greater than 5.2 m irrespective of substrate type. In their study of lentic larval lamprey habitat selection, Lee and Weise (1989) recovered very few marked larvae released in deeper waters of Batchawana Bay; a much larger number were recovered in shallower, high-gradient habitat and they interpreted this as a demonstration of active habitat selection by the sea lamprey larvae. They estimated a ten-fold decrease in density from the relatively shallow alluvial fan (1.5 m abruptly increasing to 11 m) outward 50 to 200 m into deeper water (up to 33 m). The physical aspects of their area of high gradient (the drop-off area) is quite similar to the area of moderate slope (the drop-off area) near Batchawana River with the exception that the drop-off near Chippewa River is somewhat more steep. Presumably, sea lampreys may be indirectly selecting for water velocity along the slope. In his review of larval sea lamprey habitat requirements in a lotic environment, Jones (1997) concluded that proper velocities are required in streams to deposit preferred substrate particle sizes for the establishment and maintenance of larval burrows. This also may explain why depth was not a significant determinant of larval presence in the logistic regression model. If larvae are selecting directly for particle size (and indirectly for water velocity), depth would only be important in the context that these other factors would be present. Because larvae are considered photophobic (Jones 1997), depth would be important in terms of light intensity and growth of macrophytes, including *Potomogeton* spp. Thus, the presence of a field of *Potomogeton* spp. just up-current from the largest concentration of larvae takes on special significance in that it may be an indicator of several factors coming together (habitat stability, substrate particle size, water velocity, and slope) to create optimal larval habitat. The actual values for distance from the river mouth should not be taken as absolute; each lentic situation would change from river to river. Although each situation would be different, the distance is important in establishing a range from river mouths where larvae could be expected to be present.

The results of the logistic regressions indicate that the identification of substrates by RoxAnn™ acoustic signal profiles in lentic areas can be used to define the relative likelihood of finding larvae, if a larval source stream is nearby. If a source is not present, then substrates will only indicate the potential of the lentic area to support larvae. Suitable substrates on moderate slopes within reasonable distances from the source stream will have a higher probability of yielding larval sea lampreys and can serve to focus larval sampling efforts. Given that the time required to make a RoxAnn™ survey is not great and the quality of information produced is high, RoxAnn™ would be a useful tool in the Sea Lamprey Control Program to identify the most promising locations in lentic areas to conduct larval density surveys.

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REFERENCES

Bergstedt, R.A. and Genovese, J.H. 1994. New techniques for sampling sea lamprey larvae in deepwater habitats. *N. Am. J. Fish. Mgmt.* 14:449–452.

Campbell, J.B. 1996. *Introduction to Remote Sensing, 2nd Edition.* New York: The Guilford Press.

Chivers, R.C., Emerson, N., and Burns, D.R. 1990. New acoustic processing for underway surveying. *The Hydrographic Journal* 56:9–17.

Environmental Systems Research Institute, Inc. 1991. *Arc/INFO ARC Command References.* ESRI.

Folk, R.L. 1974. *Petrology of sedimentary rocks.* Austin, Texas: Hemphill Publ. Co.

Greenstreet, S., Tuck, I. Grewar, G., Armstrong, E., Reed, D., and Wright, P. 1997. An assessment of the acoustic survey technique, RoxAnn™, as a means of mapping seabed habitat. *ICES J. Marine. Sci.* 53: 939–959.

Hosmer, D.W., Jr., and Lemeshow, S. 1989. *Applied logistic regression.* New York: Wiley and Sons.

Johnson, R.A., and Wichern, D.W. 1982. *Applied Multivariate Statistical Analysis.* Englewood Cliffs, New Jersey: Prentice-Hall.

Jones, N.E. 1997. The habitat of larval sea lamprey (*Petromyzon marinus*) in lotic environments: A review. B.S. thesis, University of Guelph, Guelph, Ontario.

Lee, D.S., and Weise, J.G. 1989. Habitat selection of lentic larval lampreys: preliminary analysis based on research with a manned submersible. *J. Great Lakes Res.* 15:156–163.

Marriott, F.H.C. 1991. *A dictionary of statistical terms.* New York: Longman Scientific and Technical.

Mullett, K.M., and Bergstedt, R.A. 2003. Agreement among observers in classifying larval sea lamprey (*Petromyzon marinus*) habitat. *J. Great Lakes Res.* 29 (Suppl. 1):183–189.

Murphy, L., Leary, T., and Williamson, A. 1995. Standardized seabed classification techniques. *Sea Technology* 7:15–19.

Rukavina, N. 1997. Substrate mapping in the Great Lakes nearshore zone with a RoxAnn™ acoustic seabed classification system. Can. Coastal Conf.

Schlagintweit, G. 1993. Real-time acoustic bottom classification for hydrography: a field evaluation of RoxAnn™. *Lighthouse (Spring Issue), Canadian Hydrographic Association* 47:9–14.

Slade, J.W., Adams, J.V., Christie, G.C., Cuddy, D.W., Fodale, M.F., Heinrich, J.W., Quinlan, H.R., Weise, J.G., Weisser, J.W., and Young, R.J. 2003. Techniques and methods for estimating abundance of larval and metamorphosed sea lampreys in Great Lakes tributaries, 1995 to 2002. *J. Great Lakes Res.* 29 (Suppl. 1):137–151.

Sokal, R.R., and Rohlf, F.J. 1981. *Biometry, 2nd Edition.* New York: W.H. Freeman and Company.

Yin K.X. Li, Bonde, J., Richards, C., and Cholwek, G. 1998. Lakebed classification using acoustic data. *Applied Mathematics and Computer Science* 8: 841–864.

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