High resolution habitat mapping to describe coastal denning habitat of a Canadian species at risk, Atlantic wolffish (Anarhichas lupus)
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Abstract

The Atlantic Wolffish (*Anarhichas lupus*) is listed by Canada’s Species at Risk Act as a species of special concern. Effective conservation strategies rely on accurate knowledge of habitat requirements, distribution, and vulnerabilities; however, current management plans cite lack of wolffish habitat data as a key limitation. For this study, coastal Atlantic Wolffish denning habitat was characterized and mapped with high resolution multibeam data and seafloor video in Conception Bay, Newfoundland. Four Atlantic Wolffish dens, used for feeding, spawning and egg-guarding, were surveyed and mapped. Based on the geomorphology and substrate of these dens, a supervised classification was applied to the multibeam bathymetry and backscatter data to identify other potential denning areas. Predicted denning habitat, limited by the occurrence of suitable rocky substrate, is most prevalent in shallow waters (<22m) distributed over 1.6km² (5.9%) of the study area. Shallow denning habitat is exposed to seasonal maximum temperatures that exceed the threshold for normal Atlantic Wolffish egg development, a potential vulnerability for nearshore wolffish. As management efforts progress, this information will guide research and prioritization of conservation areas.
Introduction

The Atlantic Wolffish is a large, slow growing, demersal fish found throughout the North Atlantic Ocean (Kulka et al. 2007; McCusker and Bentzen 2010). In Canadian waters, the range of Atlantic Wolffish extends from the Bay of Fundy to the Davis Strait (Kulka et al. 2007; DFO 2015). Wolffish are not commercially harvested in North America but are vulnerable to bycatch in 20 directed fisheries of Newfoundland and Labrador (Kulka et al. 2007). Following an estimated loss of 60% of the mature population within two generations (O’Dea & Haedrich 2003; Simpson et al. 2013), the Atlantic Wolffish was listed as a species of Special Concern under the Canadian Species at Risk Act (SARA) in 2003. Two other species of wolffish, the Spotted Wolffish (Anarhichas minor) and Northern Wolffish (Anarhichas denticulatus) are also listed under SARA as Threatened. Management of the species and habitat is a requirement for all species of Special Concern, and the identification of areas that are important to population recovery (i.e. nurseries, spawning areas and feeding grounds) is a key information gap for all three wolffish in Canadian waters (Kulka et al. 2007; Dutil et al. 2014). This paper presents recent efforts to characterize, predict, and delineate Atlantic Wolffish habitat in a coastal area known to be occupied year-round.

Trawl-based surveys in the waters of Newfoundland and Labrador frequently record Atlantic Wolffish at depths of 100-300m (Albikovskaya 1982), although they are known to occupy a much wider depth range. Atlantic Wolffish have been documented in trawls up to 918m depth (Kulka et al. 2007) and they are also often observed by SCUBA divers nearshore, as shallow as 5m (Pavlov and Novikov 1993; Simpson et al. 2015). In coastal areas, Atlantic Wolffish are associated with high-slope and high-rugosity boulder and bedrock habitats that form crevices and caves (Pavlov and Novikov 1993; Larocque et al. 2008). Kulka et al. (2004) suggested that reproduction of inshore resident wolffish is dependent on the presence of appropriate rocky substrate for denning. On the Labrador Shelf and Grand Banks of Newfoundland, Atlantic Wolffish have been found on a variety of substrates, including coarse sand, gravelly sand, and boulder and rocks (Kulka et al. 2004). Catch rates are highest on rock and sand with shell hash (Kulka et
al. 2004). Efforts to map broad scale habitats species in the Gulf of St Lawrence found Atlantic Wolffish most commonly occupy coarse sandy substrates and rocky outcrops (Dutil et al. 2014). It should be noted, however, that the spatial uncertainty related to trawl catch data may not facilitate accurate assessments of occupied substrates. Also, abundance may be under-estimated on preferred habitats, due to the challenge of conducting trawl surveys over rocky, uneven seafloor (Thorson et al. 2013; Fairchild et al. 2015).

Several authors have reported seasonal movements of Atlantic Wolffish, and have explained this migration as the separation of habitats for spawning (Jonsson 1982; Keats et al. 1985; Nelson and Ross 1992) and foraging (Fairchild et al. 2015). However, the timing, scale and prevalence of a seasonal migration are not clear, and may vary geographically. Tagging and telemetry studies of Atlantic Wolffish off Newfoundland suggest limited movement. In a mark-recapture study, most tagged wolffish were recaptured within 8 km of the release site after 5-7 years (Templeman 1984). Nearshore tagging and continuous detection with acoustic hydrophones found that most individuals remained within or returned to a 4-8 km home range over a two-year study period, however detection rates varied seasonally (Simpson et al. 2015). Traits such as long-term site fidelity, demersal life history, and substrate-dependent denning behaviour of Atlantic Wolffish support habitat characterization efforts based on seafloor bottom-type and geomorphology. Similar approaches have been used successfully to predict habitat suitability and distribution of demersal rockfish with similar life history characteristics (ex. Sebastes flavidus, S. rosaceus; Monk et al. 2010; Young et al. 2010).

While the substrate component of habitat remains relatively constant, Atlantic Wolffish distribution responds to shifts in oceanographic conditions (Bianucci et al. 2016). Due to the narrow preferred temperature range and reduced population size, the Committee on the Status of Endangered Wildlife in Canada recognizes Atlantic Wolffish as a species that is potentially vulnerable to the impacts of climate change (COSEWIC 2012). The expansion of oxygen-poor water masses in recent decades is a significant driver in the contraction of suitable wolffish habitat (Bianucci et al. 2016). Hypoxia becomes lethal for juvenile wolffish at about 20% saturation (Le François et al. 2001) and habitat is considered suboptimal.
for Atlantic Wolffish <65%, below which heart rate is reduced (Bianucci et al. 2016). Growth, fecundity and recruitment will likely suffer among Atlantic wolffish limited to hypoxic habitat (Simpson et al. 2013). Analysis of Atlantic Wolffish area of occupancy confirms the avoidance of severely hypoxic areas. Only 1% of high density Atlantic Wolffish trawl sets were caught in areas with dissolved oxygen below 35% saturation; the majority (69%) of high density catches were retrieved in areas of oxygen saturation over 55% (Simpson et al. 2013).

Temperature is also a significant driver of Atlantic Wolffish distribution, and as a result the species has been called a “temperature seeker” (Simpson et al. 2012) or “temperature keeper” (Kulka et al. 2007). In Newfoundland waters, Atlantic Wolffish are found between -1 and 10° C, and offshore trawl catch biomass peaks within the narrow 1-4° C range (Kulka et al. 2004). Dive surveys in the St. Lawrence estuary found that resident wolffish were vertically limited by the thermocline associated with the Gaspé current (Larocque et al. 2008) and research in the North Sea also indicates that distribution of wolffish is related to temperature (Liao and Lucas 2000). Temperature is particularly important to early life stages. Overall, Atlantic Wolffish hatch success was reduced when temperatures were above 7° C (Pavlov and Moksness 1994) and normal fin ray development did not occur in incubations of 9° C or warmer (Pavlov and Moksness 1995). Once hatched, however, larvae and fry may seek slightly warmer waters. Atlantic Wolfish larvae raised under controlled conditions by McCarthy et al. (1998) demonstrated highest specific growth rates at temperatures of 11-14° C, however survival was highest among fish raised at 8° C. Similar results were found for juvenile Atlantic wolffish between 9-12 months of age, with optimum temperatures for growth rate and efficiency between 9-11° C, but slightly higher survival at 8° C (McCarthy et al. 1998). For both juvenile and mature wolffish extreme warm temperatures result in reduced aerobic performance, impacting muscular activity, growth, and reproduction. Among mature Atlantic Wolffish in culture, conditions between 7-9° C produced optimal growth rate, and growth rate was shown to decline during seasonal warm periods (Moksness 1994). In Newfoundland nearshore waters, Atlantic Wolffish pair and spawn between August and October, the warmest months of the year.
(Keats et al. 1985) and newly hatched Atlantic Wolffish remain close to the hatching location during the larval phase (Templeman 1985). As ocean conditions change, optimal habitat will continue to shift, and may deteriorate or disappear completely in some areas. It is important to understand the vulnerability of both occupied and potential habitats to anthropogenic impacts, including fishing effort, coastal and offshore development, and climate change.

Current knowledge of wolfish distribution is limited by relatively sparse records of the species and poor understanding of their habitat (Dutil et al. 2014). In Conception Bay, dive surveys have recorded denning, pairing, feeding and egg guarding behaviours among Atlantic Wolffish at four den sites (Simpson et al. 2015); this area provides a valuable study site as a feeding ground, spawning area, and nursery. A better understanding of Atlantic Wolffish denning habitat may also support management of Spotted Wolffish (Anarhichas minor). Spotted Wolffish, recognized as a Threatened species under SARA, kept in laboratories have been shown to use shelters similar to Atlantic Wolffish (Lachance et al. 2010). This study examines the geomorphology, temperature profile and surrounding biological community associated with nearshore Atlantic Wolffish denning habitat for the first time in Newfoundland waters.

The main objectives are to characterize, delineate, and predict Atlantic Wolffish denning habitat in a coastal area known to be occupied year-round.

**Methods**

The study area includes the nearshore waters (<200 m depth) of the northeastern coast of Conception Bay, Newfoundland and Labrador, Eastern Canada (Figure 1). Of particular interest is a small area near the community of Bauline, where Atlantic Wolffish dens have been identified and monitored by SCUBA surveys and tagged wolfish movements have been tracked by an array of moored hydrophones (Simpson et al. 2015).

*Multibeam Echo Sounding (MBES)*
The 27km² study area was surveyed by the Canadian Hydrographic Service (CHS) between July 22 and July 29, 2013 (Figure 1). Seafloor acoustic data, including bathymetry and backscatter, were collected using a Kongsberg EM710 multibeam echo sounder. Bathymetric and backscatter data were processed by the CHS using the software CARIS HIPS-SIPS. Additional processing of the backscatter data was conducted by the Marine Geomatics Research Lab of Memorial University, using Fledermaus software to remove acquisition artefacts. All multibeam data were gridded into 1m² pixels and imported into ArcGIS 10.1 for analysis and mapping.

**Seafloor Video**

Ground-truthing of the study area was conducted in the summer and early fall of 2014 (June-October) through ship-based Deep Blue Pro drop video camera with video-embedded GPS overlay. Video surveys were conducted from two vessels throughout the study season: a 22ft Boston whaler (the DFO Newfoundland Seaskiff) and an 18ft rigid hull inflatable boat (RHIB) provided by Tangly Whales Ltd. Continuous position of the survey vessel during transects was recorded by a WAAS enabled Garmin eTrex-10 hand-held GPS with an estimated horizontal accuracy of <3m. This method avoids the use of high-cost underwater positioning equipment (ex. Ultra-Short Baseline systems), however it assumes the camera system remains directly below the vessel and therefore data collection is limited to very calm weather conditions, relatively shallow waters and small survey platforms. Forty-five depth-stratified, randomly distributed sample stations were identified and thirty were successfully sampled (Figure 1). High sea states prohibited survey efforts beyond Biscayan Cove in the northern portion of the study area. Timed video transects (four minutes, approximately 100m length) were recorded, beginning at each randomly generated sample point and travelling in the direction of the dominant current for the duration of the video. All visible organisms in the videos were identified to the lowest taxonomic level possible and counted for each site from continuous video. Substrate was recorded as percent cover for five prevalent bottom types (mud, gravel and mixed substrate, boulder/bedrock, coralline algae, and macroalgae-covered rock) in still frames extracted at 20 second intervals. Still-frame extraction was
automated through the VideoLAN Client (VLC) media player. A Micheli-Menten species accumulation curve was plotted to test for adequate sampling of biota.

Characterization of Benthic Habitats

An unsupervised classification of multibeam backscatter, bathymetry, slope, and curvature was carried out using the ArcGIS 10.1 iterative self-organizing (ISO) classification algorithm. This method provides a reproducible quantitative clustering of the multibeam data, without the influence of prior assumptions. Backscatter provides a proxy measure of sediment hardness, based on the strength (dB) of the returning echo. Bathymetry, which co-varies with light, pressure, and temperature, exerts a first order effect on species distribution. Geomorphometric variables (slope and curvature) were derived from bathymetry in ArcGIS 10.1 with the Benthic Terrain Modeler extension (Rinehart et al. 2004). Slope and curvature were selected for inclusion in the classification routine to capture biologically relevant terrain attributes without internal correlation (McArthur et al. 2010; Lecours et al. 2015).

Biological communities were identified using the PRIMER-E v.6 statistical software. Species counts were standardized for transect length and fourth-root transformed to prevent one or two very abundant species from dominating analysis of species composition similarity between sites. A Bray-Curtis similarity matrix was generated for the transformed data. Samples were grouped by underlying substrate type and tested for significant differences in species composition through non-metric multi-dimensional scaling (MDS), and analysis of similarity (ANOSIM). Biologically similar substrates were merged to represent community-level habitats. Accuracy of the resulting map was calculated through an error matrix comparing predicted habitat (based on unsupervised classification of multibeam substrate) and biological community (based observed species composition and abundance in the video data). Through this method, the full groundtruthing survey was available as an independent dataset for accuracy assessment of the multibeam-based habitat map. A similarity percentages (SIMPER) analysis was also conducted to identify the characteristic taxa of each habitat.
Atlantic Wolffish Habitat

Atlantic Wolffish were captured as bycatch in the local lobster fishery or targeted directly with modified crab pots deployed by DFO-NL. Acoustic transmitters (VEMCO V13 or V16) were surgically implanted in the abdominal cavity, providing a continuous and unique ping frequency for each fish (full methods described in Simpson et al. 2015). Acoustic telemetry data was recorded by 16 moored acoustic hydrophones in the study area between July 2011 and September 2012 (Simpson et al. 2015). Each hydrophone has an estimated detection range of 3.7km, allowing broad scale assessment of presence and movement behaviour. Unique ping records were used to plot the paths of individual fish, and to identify trends in seasonal detection rates.

Targeted SCUBA surveys were conducted over two days (August 5-6, 2014) to record 25m video transects at each den, travelling parallel to shore. All visible species were identified from the videos to the lowest taxon possible. The geomorphology of the confirmed den sites informed a supervised classification of multibeam data for the whole study area. Classification rules were generated for depth, backscatter value, slope, and distance to high slope, in order to identify areas similar to the wolffish dens. Areas that conformed to the den classification rules were plotted to generate a map of potential Atlantic Wolffish denning habitat within the study area. Temperature data from conductivity, temperature and depth (CTD) sensor casts and temperature loggers moored near the den sites throughout 2013 provided characterization of the oceanographic conditions (see Simpson et al. 2015 for full methods).

Recreational divers and citizen scientists were also invited to report sightings of Atlantic Wolffish through the Newfoundland Thornback Dive Club network. Reported wolffish sightings were mapped to demonstrate the prevalence of inshore wolffish habitat beyond the study area and to inform future survey efforts.

Results

Multibeam Substrate Classification
The unsupervised ISO classification identified six distinct substrate types based on differences in bathymetry, backscatter, slope and curvature (Figure 2). Class 1 is characterized by shallow depths and high backscatter response, which indicates hard, rocky substrate. Class 2 is similarly shallow and high backscatter, but is differentiated by high slope, which corresponds to steep rocky bottoms. Classes 3 and 4 include mid-range depths and backscatter values, which indicate mixed substrates. Class 5 is defined by deep water, low slope and low backscatter values, which indicates soft sediment; and Class 6 corresponds with deep water and mid-range backscatter response.

**Biological Communities**

The Michelis-Menten species accumulation curve for the drop-video transects reached asymptote after about 12 sample stations suggesting that sampling (N=30) was sufficient to identify characteristic taxa of the survey area across all identified substrate types. A total of 33 animal taxa were identified from the video, including seven fish: Atlantic cod (*Gadus morhua*), Atlantic halibut (*Hippoglossus hippoglossus*), winter flounder (*Pseudopleuronectes americanus*), rock gunnel (*Pholis gunnelus*), common cunner (*Tautogolabrus adspersus*), sculpin (*Myoxocephalus* sp.), and pout (*Zoarces* sp.). The vast majority of species identified were invertebrates, including toad crab (*Hyas areneus*), snow crab (*Chionoectes opilio*), green urchin (*Strongylocentrotus droebachiensis*), Arctic cookie star (*Ceramaster arcticus*), brittle star (*Ophiopholis aculeata*), basket star (*Gorgonocephalus articus*), frilled anemone (*Metridium senile*), Northern red anemone (*Urticina felina*), and strawberry soft corals (*Gersemia rubiformis*).

Analysis of Similarity (ANOSIM) and Similarity Percentages (SIMPER) tests conducted on pairwise combinations of the substrate classes identified three statistically distinct biological assemblages across the six substrate classes: (a) urchin-dominated (substrate classes 1 and 2), (b) brittle star-dominated (substrate classes 3, 4, and 6), and (c) deep habitats characterized by the presence of snow crabs and Arctic cookie stars (substrate class 5). These three communities were visualized in a non-metric multi-
dimensional scaling plot (Figure 3). Full results of the ANOSIM and SIMPER analyses are included as supplementary materials (Table S1).

Characterization of Benthic Habitats

The three distinct biological communities and their corresponding substrate types are mapped in Figure 5. Substrate classes 1 and 2 were combined into a single habitat class, representing shallow boulder and bedrock habitats, including occasional patches of cobble, gravel, coarse sand and mussel hash between boulders. These communities are characterized by high density of green urchins and blue mussels (Mytilus sp.). Encrusting coralline algae (Lithothamnion arcticus and other Melobesioidae sp.) cover most rocky substrate in this habitat, with some patches of macroalgae including sea colander (Agarum sp.) and Northern sea fern (Ptilota serrata). Substrate classes 3, 4, and 6 were combined, representing muddy cobble and muddy gravel habitats. These communities are characterized by the presence of brittle stars (Ophiopolis aculeata), and anemones (Urticina and Stomphia sp.). Substrate 5 represents muddy habitat occupied by snow crab and Arctic cookie stars, with pelagic arrow worms (Sagittidae sp.) frequently observed above bottom.

The areas identified as ‘boulder/bedrock’ habitat (6.99 km²) were restricted to shallow depths, where coastal bedrock does not gather silt and where coralline algae receives sufficient sunlight (depth < 50m). The ‘muddy cobble and gravel’ habitat was found to be the most prevalent habitat in the study area (16.34 km²) across the greatest depth range (50-150m). The ‘mud’ habitat (3.74 km²) was found in deep (>125m), low slope areas, though small patches of this habitat were predicted to occur in depressions sheltered by high slope bedrock and boulder features in the northern extent of the study area.

Table 1 presents the error matrix generated to evaluate the accuracy of the habitat map. Producer’s accuracy refers to the likelihood that a pixel in habitat X will be correctly classified as Class X. User accuracy refers to the likelihood that a pixel in classified as X truly represents habitat X. For example, bedrock/boulder habitats have a producer’s accuracy of 100%, indicating that all sites ground-truthed as
bedrock/boulder were correctly identified in the classification routine. However, the user’s accuracy for this substrate (classes 1 and 2) is 81.8%, because two sites that were classified as bedrock/boulder were ground-truthed as muddy cobble/boulder. Mud and bedrock/boulder habitats were correctly identified by the unsupervised classification in all cases. The mixed muddy gravel and cobble habitats were misclassified in 15% of ground-truthed sites; two muddy gravel and cobble sites were misidentified by the ISO unsupervised classification procedure as bedrock/boulder. The accuracy across all habitat types was 93.3% (28 of 30 stations correctly classified).

Table 1. Error matrix for unsupervised substrate classification predictions of observed biological communities

Atlantic Wolffish Denning Habitat

Four Atlantic Wolffish dens located in 15-17m depth were documented and monitored annually by Simpson et al. (2015) near Bauline in the Conception Bay study area. No wolffish were observed during drop-video transects or SCUBA surveys in 2014. The wolffish dens are located in areas where boulder or bedrock features form crevices or caves with a high slope angle at their entrance (Figure 4). Multibeam data near the dens show high slope as well as a high backscatter response (> -15 dB). The slope at the recorded location of each den was found to fall between 30-60°.

Supervised classification of the multibeam data, based on the slope and backscatter of the four surveyed wolffish dens of Bauline, identified 1.6km² of potential denning habitat for Atlantic Wolffish, distributed unevenly along the coast, covering 5.9% of the study area (Figure 5). Surveyed dens, and the majority of predicted denning habitat, occur within the boulder/bedrock habitat, which provides hard substrate, high slope features and complex seafloor geomorphology. The area of Bauline, where the DFO-surveyed dens
are found, represents a small portion of the predicted denning habitat. The northern extent of the study area, beyond Biscayan Cove, was predicted to have the greatest area, and most continuous patches of denning habitat (Figure 5).

All four known dens occur below the summer thermocline, which was recorded at 10m depth in July 2014, and where they are exposed to relatively cold temperatures (0-8°C) for most of the year. However, the recorded thermocline moved past the den depth to approximately 35m depth by October 2014, exposing the dens to surface temperatures. Continuous thermographs moored at 20m depth near the surveyed dens showed variable temperatures occasionally reaching highs of 12-15°C in the later summer and early fall of 2013. In addition to the surveyed dens, approximately 30% of all potential denning habitat is found above the fall thermocline (Figure 6).

Acoustic tags were implanted in 44 Atlantic Wolffish in the study area by DFO-NL between 2010-2013. Size of the tagged fish ranged from 55 – 90cm (mean length = 70.7cm). Thirty-nine of the tagged Atlantic Wolffish were recorded by moored hydrophones, and of these 32 were recorded in more than one detection event during the July 2011- June 2012 recording period (Figure 7). Most Atlantic Wolffish (71%) remained within the range of one hydrophone (3.7km detection radius) for months at a time and only 5% carried out long distance movements beyond the study area (Simpson et al. 2015). The spatial resolution of this data provided useful information on the presence and movement of Atlantic Wolffish throughout the year; however it could not be applied to fine scale occupation of substrate or habitat types.

Presence was relatively consistent in the study area, and behaviour of most wolffish was sedentary. However, detection rate (% of released tags that were detected, calculate monthly) varied over time (Figure 8). In general, more of the tagged Atlantic Wolffish were present in the summer and early fall, between June and October when pairing and spawning is expected to occur (Kulka et al. 2004; Simpson et al. 2015). In the summer of 2012, however, fewer tagged fish were recorded in July, August, and September 2012, at a time when mean monthly sea surface temperatures exceeded 15°C, well above the
reported optimal thermal range of adult wolffish in the field (1-4 °C; Kulka et al. 2004) and under laboratory conditions (7-9° C; Moksness 1994).

Prevalence of inshore Atlantic Wolfish habitat in Newfoundland

Recreational divers of the Newfoundland Thornbacks Dive Club reported wolffish dens at thirteen locations, including Newfoundland west and south coasts and the Avalon Peninsula. Figure 9 shows the reported locations in addition to those previously reported by Kulka (2004). Seven of these sites represent areas where Atlantic wolffish have been consistently found by different divers over the course of 3 or more years, as far back as the 1970s in the case of Gadd’s Point, Bonne Bay.

Discussion

Nearshore habitats (bedrock/boulder, muddy cobble/gravel, and mud) in Conception Bay were mapped with high overall accuracy (93%) based on unsupervised classification of high resolution multibeam data. Misclassification occurred only between the bedrock/boulder habitat and the muddy gravel/cobble habitat; these classification errors appear to be related to the fuzzy boundary between similar habitats, not due to spatial inaccuracy. The results of this study indicate that distribution of denning habitat for Atlantic wolffish is substrate dependent, and that potential denning habitat is unevenly distributed throughout the study area. The muddy habitats do not provide features for dens, and support very low prey density. According to multibeam analysis, some areas of the muddy gravel and cobble provide high seafloor complexity and may provide denning habitat. The vast majority of potential denning habitat, and the four confirmed dens analyzed for this paper, are found within the shallow boulder and bedrock habitat. No wolffish were observed during drop-video transects or SCUBA surveys in 2014 in Conception Bay, however this may be due to the timing of the survey or limitations of wolffish detection, as fish may be concealed deep within dens and/or avoiding contact with divers. Two of the four dens were, however, found to be occupied by pout (Zoarces sp.), a potential wolffish competitor. The characterization and
prediction of denning habitat distribution for this study is limited by the small sample size of confirmed
dens (N=4), however the findings presented here are generally consistent with, and add new high
resolution data to, previous research on denning habitat of Atlantic Wolffish (Pavlov and Novikov 1993;
Kulka et al. 2004; Laroque et al. 2008).

The Atlantic Wolffish denning habitat surveyed for this study provides high densities of prey species,
including green urchin, blue mussel, and rock crab. In coastal areas, green urchin appears to be the most
important prey item, up to 75% of overall diet by weight (Keats et al. 1986). Previous SCUBA surveys in
this area have recorded evidence of feeding debris at den openings, confirming that the inshore habitat is
used for foraging in addition to providing important habitat for reproduction and early life stages
(Simpson et al. 2015). It should be noted that dens are not the only habitat used by Atlantic Wolffish; for
example, seasonal foraging aggregations have been documented in areas unsuitable for denning (Fairchild
et al. 2015). Hagen and Mann (1992) hypothesize that “undisturbed” populations of Atlantic Wolffish and
American Lobster (*Homarus americanus*) may have helped control sea urchin population booms, and
supported development of complex macro algal habitats which serve as nursery areas for many fish
species. The disappearance of highly productive kelp beds due to urchin herbivory in Nova Scotia waters
in the 1970s has been linked to the reduction of sea urchin predators including Atlantic Wolffish (Keats et
al.1986; Steneck et al. 2004). At sufficient abundance, Atlantic Wolffish and similar predators may
deliver conservation benefits through the increased biomass and diversity associated with complex
macroalgal habitat in place of urchin barrens (Keats et al. 1987; Scheibling 1996; Hereu et al. 2005).

The low-fecundity Atlantic Wolffish relies on extended parental care (Keats et al. 1985), large egg size
(6mm), and internal fertilization (Johannessen et al. 1993; Pavlov 1994) to increase reproductive success
(Kulka et al. 2007). Post-hatch larvae appear to remain near the den, which serves as an early nursery
(Templeman 1985). The conditions in Conception Bay may already place Atlantic Wolffish at the upper
limit of their thermal tolerance, particularly in the late summer/early fall (August-October) when
temperatures are the highest and the fish are expected to be spawning (Keats et al., 1985). The warm
temperature extremes recorded in September and October (>12°C) exceed the healthy development
threshold for Atlantic Wolffish eggs, and may reduce aerobic performance in adults (Moksness 1994;
Pörtner and Knust 2007). At the shallow depths where dens are identified in Conception Bay (<20m),
temperature is highly variable. As atmospheric and ocean temperatures continue increase, there may arise
a temporal mismatch between habitat suitability and Atlantic Wolffish reproduction. Acoustic telemetry
data confirmed wolffish presence in the area throughout the year, with highest presence and most activity
in the summer and fall (Simpson et al. 2015), which agrees with recreational diver reports that wolffish
are found in the summer and fall. However, in 2012, when mean monthly sea surface temperatures
peaked in late summer, presence of tagged wolffish in the area declined, which may indicate a
behavioural response to the warm temperatures (Figure 8).

Previous Atlantic Wolffish monitoring efforts conducted by DFO-NL focused on the Bauline dens. This
study has shown that Bauline represents a small fraction of potential denning habitat in the study area
(Figure 5), and throughout Newfoundland (Figure 9). Reports from recreational divers in particular, have
indicated that inshore Atlantic Wolffish denning habitat is more prevalent than previous records
suggested. Dive surveys reported by Kulka et al. (2004) list Atlantic Wolffish den sites in three areas:
Bonne Bay, Portugal Cove and Bay Bulls. Reports provided by members of a local dive club have added
12 additional wolffish den sites to this list, including new areas in Conception Bay, Trinity Bay, and the
south and east coasts of Newfoundland. The distribution of these reports is limited to areas where road
and wharf access allow diving. It is likely that much more of the Newfoundland coast is used by denning
and spawning Atlantic Wolffish. Although this study focuses on inshore habitats, wolffish denning habitat
may not be limited to shallow coastal areas. Characterization of Atlantic Wolffish habitat offshore, such
as in the Gulf of St. Lawrence, were associated with coarse sediments and high relief rocky outcrops
(Dutil et al. 2014), which is consistent with the surveyed and predicted denning habitat in this study. The
resolution of bathymetric data in most offshore areas (e.g. 100km² grid applied by Dutil et al. 2014),
however, does not allow the identification of fine scale denning structures as shown in this study. There is
limited evidence that spawning may also occur offshore; Atlantic Wolffish eggs have been recorded in trawl sets at 130m on LaHave Bank, Nova Scotia (Powles 1967). Two Atlantic Wolffish adults, a clutch of eggs and newly hatched larvae, were also retrieved from Green Bank, Newfoundland, at 158m in April 2014 (CFER, unpublished data).

Due to the decrease in fishing effort in Newfoundland waters since the early 1990s, and live-release of most Atlantic Wolffish that are inadvertently caught by commercial fisheries, human-induced mortality rates have declined in recent years (Simpson et al. 2013; Grant and Hiscock 2013). However, the species remains at very low levels compared to pre-collapse abundance (DFO 2015), and the impact of by-catch pressure on reproductive success remains a concern (Grant and Hiscock 2013). Availability of suitable denning habitat is crucial to recovery of Atlantic Wolffish populations. Denning habitat, as characterized by this study, is defined by the occurrence of discontinuous rocky features, and cannot be identified by depth range and oceanographic variables alone. Mapping of potential denning habitat based on substrate types indicates that only 1.6 km$^2$ (5.9%) of the 27km$^2$ surveyed in this study provides suitable denning habitat for Atlantic Wolffish. Potential denning habitat identified by this study extends as deep as 165m, with a mean depth of 60m. Still, the den-forming bedrock and boulder features are most prevalent and most continuous between 7-40m, within the range influenced by highly variable and warming surface temperatures. For the Atlantic Wolffish, which exhibit a low-fecundity/slow-growth life history and low abundance (Kulka et al. 2007), the additional physiological cost of occupying a warming habitat may reduce the effect of conservation measures such as by-catch reduction and ultimately slow or halt population recovery (Pörtner and Knust, 2007; Rutterford et al. 2015).

Conclusions

Nearshore habitats mapped in this study appear to contain very important potential denning areas for Atlantic Wolffish, providing foraging, spawning, and nursery areas for early life stages. Substrate-dependent dens appear to be required for nearshore reproduction of Atlantic Wolffish, and it is therefore...
important to achieve a better understanding of the distribution and vulnerabilities of this habitat. The research presented here has shown that high-resolution multibeam data provides a powerful surrogate for characterizing nearshore habitats with high accuracy, and these data can be applied as a useful tool for the identification of potential Atlantic Wolffish denning habitat. Potential denning habitat mapped by this study was distributed unevenly, and made up less than 6% of the study area.

Although the decline of Atlantic Wolffish abundance in Canadian waters has slowed, and perhaps stopped (DFO 2015), by-catch and habitat degradation remain important considerations as managers plan for population recovery. The impacts of warming waters, and other threats such as expanding hypoxic areas and habitat disruption by fishing gear present significant challenges, and assessment of distribution-wide habitat vulnerabilities are often limited by lack of sufficient data. Continued efforts to identify and to better understand habitats of threatened or depleted fish species such as Atlantic Wolffish, particularly the distribution of denning, spawning and other critical habitats, are crucial to successful management and conservation.

References


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of terrain attributes and GIS software for meaningful analysis. In Jasiewicz, J., Zwolinski, Z.,


Table 1. Error matrix for unsupervised substrate classification predictions of observed biological communities

<table>
<thead>
<tr>
<th>Ground-truthed habitats</th>
<th>1, 2</th>
<th>3, 4, 6</th>
<th>5</th>
<th>Total sites</th>
<th>Producer accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock/boulder</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>100</td>
</tr>
<tr>
<td>Muddy gravel/cobble</td>
<td>2</td>
<td>11</td>
<td>0</td>
<td>13</td>
<td>84.6</td>
</tr>
<tr>
<td>Mud/silt</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>11</td>
<td>8</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>User Accuracy</td>
<td>81.8</td>
<td>100</td>
<td>100</td>
<td></td>
<td><strong>93.3</strong></td>
</tr>
</tbody>
</table>
Figure 1. Study area in Conception Bay, Newfoundland, Eastern Canada including CHS multibeam bathymetry, DFO-NL moored hydrophones, and distribution of benthic video transect sites.
Figure 2. Unsupervised substrate classification. Insets show (A) an area beyond Biscayan Cove with all six classes represented; (B) bathymetry; (C) backscatter; (D) slope; and (E) curvature.
Figure 3. Non-metric multi-dimensional scaling plot of species abundance and composition similarity within video transects conducted on six acoustically derived substrate classes.
Figure 4. Atlantic Wolffish and multibeam derived slope (displayed with hillshade effect). Photos of Atlantic Wolffish dens contributed by (A) Samantha Trueman, (B) Trevor Maddigan, and (C) Neil Burgess.
Figure 5. Benthic habitat types, Atlantic Wolffish dens and supervised classification of potential denning habitat in Conception Bay, NL.
Figure 6. Depth distribution of pixels classified as potential denning habitat (% of total predicted area).
Figure 7. Presence of tagged Atlantic Wolffish within the Conception Bay study area, as recorded by moored hydrophones. Filled red points indicate new tagging events and detection within the same month; empty red points indicate a tagging event without a hydrophone detection record in the same month; black points show subsequent detection events.
Figure 8. The number of Atlantic Wolffish detected monthly by hydrophones within the Conception Bay study area July 2011-June 2013. DFO-NL tagging events are displayed in dark blue and monthly mean sea surface temperature in red (NOAA 2014).
Figure 9. Atlantic Wolffish den sites reported by members of the Thornback’s Dive Club or listed by previous Atlantic Wolffish dive surveys (Kulka et al. 2004).