



## Research Paper

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# Specimens of opportunity provide vital information for research and conservation regarding elusive whale species

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## Summary

Elusive species are challenging to study and conserve because basic elements of their biology may be unknown. Specimens of opportunity provide a means of collecting information on these species and may be critical for elusive species' conservation. We used snowball sampling to identify Sowerby's beaked whale (*Mesoplodon bidens*) specimens in museums and research institutions. Snowball sampling proved highly effective: we located 180 specimens from 24 institutions in North America and Europe, 62 of which were not listed in online collections databases, resulting in the largest collated dataset for this species. Analysis of these data resulted in several new findings for this species, including significant morphological variation between specimens from different collection regions, suggesting the presence of previously unidentified population structuring in this species. These data provide critical information regarding this species and demonstrate the effectiveness of specimens of opportunity for elusive species research and conservation. We recommend other researchers consider snowball sampling when designing research projects utilizing specimens of opportunity. Our results demonstrate the usefulness of snowball sampling and specimens of opportunity to elusive species research and conservation, and the methods of our study can be readily adapted for other species.

## Introduction

Conservation of elusive species is challenging because often there are large gaps in knowledge regarding these species' biology and ecology (Cunningham & Lindenmayer 2005, McKelvey et al. 2008). As a result, the conservation needs of elusive species may be unknown; thus, such species may not receive adequate protection and management. Researchers face many challenges in trying to fill the knowledge gaps associated with elusive species because traditional field research methods, such as mark recapture or satellite tagging, may be ineffective, particularly if the species is rare, difficult to capture, has a large range, or actively avoids researchers (Kalton & Anderson 1986, Green & Young 1993, McDonald 2004, Meek et al. 2014). Further, these traditional research methods require considerable time and financial resources to implement effectively. Conservation science, however, is a crisis discipline that often requires practitioners to implement management procedures for rare, endangered or data deficient species long before they are confident in the sufficiency of their data (Soulé 1985, Soulé 1986). Methodologies that allow rapid acquisition of reliable data thence are critical to such conservation efforts.

For many rare or elusive species, specimens of opportunity may be the most effective way to fill these knowledge gaps, and for some species they may be the only source of reliable knowledge (Robbirt et al. 2011, Roberts et al. 2016). Specimens of opportunity, such as salvaged carcasses and museum specimens, have proved essential in identifying new species, clarifying a species' range and population structure, and in retrospective analyses of biodiversity (Newbold 2010, Holmes et al. 2016, Baus et al. 2019, Coombs et al. 2019, Schwartz et al. 2020). As many museums and research institutions face financial pressure to justify maintenance and upkeep of research collections, it is increasingly important to highlight the value of these collections to wildlife and conservation studies.

Beaked whales (family Ziphiidae) are some of the most elusive and poorly understood mammals. Comprising at least 23 species, this diverse group of whales accounts for >25% of extant whale and dolphin species, and most information on their biology has come from specimens of opportunity (Dalebout et al. 2004, Mead 2007, Mead 2009). Beaked whales are difficult to locate at sea due to a variety of factors: they often occur in smaller groups than many other whale and dolphin species, are gray in coloration with a streamlined fusiform body shape lacking a prominent dorsal fin, and may actively avoid research vessels (MacLeod et al. 2005, Ellis & Mead 2017). They are thought to prefer deeper, pelagic habitats, which when coupled with their

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general lack of aerial displays, can render it nearly impossible to locate and study them in situ. When they are located, it is challenging to identify most species, and many at-sea sightings can only be reliably classified to the genus level, with possibly a suggestion of the species. For these reasons, specimens of opportunity may provide the most reliable means of collecting species-specific information for many beaked whales.

Specimens of opportunity have proven critical to increasing knowledge and understanding of beaked whale diversity, morphology and biology. Genetic analyses of museum specimens identified four new species of beaked whales in the last 20 years, and three species of beaked whales – *Mesoplodon bowdoini*, *M. traversii* and *M. hotaula* – are known only from morphological and genetic analyses of stranded specimens (Dalebout et al. 2002, van Helden et al. 2002, Dalebout et al. 2014, Morin et al. 2017, Yamada et al. 2019). Phylogenies have been generated using specimens of opportunity, resolving questions of relatedness among certain species (Dalebout et al. 2008, Einfeldt et al. 2019b); comparative anatomy of beach-cast carcasses has helped to identify species-specific morphological differences (Mead 2007, Lambert et al. 2011, March et al. 2016); and necropsies have shed light on beaked whale parasites and diseases, sexual maturity and gestation times (Besharse 1971, Auriollesgamboa 1992, Macleod & Herman 2004, Landrau-Giovannetti et al. 2020).

The Sowerby's beaked whale (*M. bidens*) was the first mesoplodont beaked whale to be described (Sowerby 1804), yet little has been learned about its biology or behaviour in more than 200 years. This species strands relatively frequently compared to other beaked whales, and most of what is known about Sowerby's beaked whales has come from specimens of opportunity. In 1804, James Sowerby described the Sowerby's beaked whale from a single male specimen that stranded in the Moray Firth, Scotland, naming it '*bidens*' because of the presence of only two teeth, both in the lower jaw (Sowerby 1804). This species is thought to exclusively inhabit the North Atlantic, ranging from Norway to the Canary Islands in the east and from Newfoundland to the northeast of the USA, although specimens have been collected as far south in the USA as Florida and Georgia (Dix et al. 1986, Bonde & Oshea 1989, Lien et al. 1990, Carlstrom et al. 1997, Martin et al. 2011). Strandings often are a single animal or a mother-calf pair, and when observed at sea they typically occur in groups of  $\leq 10$  animals. In 2011, attempts were made to tag Sowerby's beaked whales in the Azores, a location where they are regularly sighted, especially during the summer. A single animal was successfully tagged, but the animal immediately dislodged the tag (Visser 2012). Recently, a few acoustic recordings have been made of Sowerby's beaked whales, laying the groundwork for passive acoustic monitoring for the presence of this species (Cholewiak et al. 2013, Stanistreet et al. 2016, Stanistreet et al. 2017, Clarke et al. 2019). There are no data regarding this species' abundance or movement behaviour anywhere in its range.

Males and females are sexually dimorphic, with males displaying a single pair of tusks in the middle of the lower jaw; smaller versions of these teeth are present in females, but they do not erupt (Macleod & Herman 2004). Tooth placement is a distinguishing feature among beaked whales and is the best diagnostic tool for differentiating Sowerby's beaked whales from other mesoplodont beaked whales in the North Atlantic. The exact purpose of these tusks is unknown but based on the extensive scarring pattern observed on males it is assumed they are important in sexual displays and competitions, where males scratch or rake each other with their tusks. Most other morphological characteristics have not been well defined in this species; however, Mead (2007) identified differences in stomach anatomy among beaked whales, and found that Sowerby's beaked whales have

a derived stomach anatomy most similar to two other North Atlantic species, *M. europaeus* and *M. mirus*. Published body and fluke measurements are available for a few individuals (e.g., Bonde & Oshea 1989, Bose et al. 1990, Martin et al. 2011). There are no data regarding most aspects of this species' reproductive biology, including age of sexual maturity in either males or females, gestation time, or how long calves remain with their mothers.

Little genetic information is available for this species. Mitochondrial and nuclear analyses suggest the Sowerby's beaked whale may be the most basal member of the genus (Einfeldt et al. 2019b, MCGowen et al. 2019). Regionally distinct and overlapping mitochondrial haplotypes were identified in east and west Atlantic specimens ( $n = 7$  and  $7$ , respectively); however, the results of this analysis were never published (COSEWIC 2006). No studies have investigated population structure or genetic diversity in Sowerby's beaked whales.

Numerous Sowerby's beaked whale specimens are preserved in museum and research institutions, yet no studies have compiled data regarding these specimens. In this study we: (1) detail our sampling method and discuss how it can be applied to other studies; and (2) characterize the specimens we located and provide new data on this species that can be used to inform conservation efforts.

## Methods

### Locating specimens of opportunity

We used a common social science technique called snowball sampling to identify museums or research institutions with Sowerby's beaked whale specimens (Goodman 1961, Wright & Stein 2005). In this method, a set of informants is identified from a larger population; these individuals then are asked to refer others to participate in the study. In 2015, we queried three online repositories of biological specimen information: GBIF (2020), VertNet (2020), and the Smithsonian National Museum of Natural History (NMNH) mammal collection database (2020). We identified 42 Sowerby's beaked whale specimens in three museum collections: the NMNH ( $n = 14$ ), National Museums Scotland (NMS) ( $n = 15$ ), and the Natural History Museum, London (NHM) ( $n = 13$ ). We began sampling in 2016 at the NMNH and during this trip met a curator from the University Museum of Bergen, Norway, who confirmed the presence of Sowerby's beaked whales in that museum's collection, despite their not being listed in an online database, and invited us to sample them. This trip then led to recommendations of other collections to contact, and each subsequent visit to a museum or research institution led to additional suggestions of collections to visit.

### Data collection and evaluation

We collected data from specimens originating in both the east and west Atlantic, here defined as the specimen's original collection location being on either side of the 35<sup>th</sup> meridian west. For each specimen, we recorded sex, age class, collection location and the condition of the specimen (Supplementary Table 1). For some specimens, portions of this information were missing, particularly sex and age class. We evaluated tooth size, overall specimen size, and degree of skeletal suture fusion to infer sex and age class in some specimens; however, in many this was not possible, and we recorded this information as 'unknown'. Where possible, we used the same soft 72 cm tape measure to measure seven skull and mandibular elements: total skull length (TSL); braincase width (BCW); proximal beak width (PBW); beak length (BL); total

mandibular length (TML); mandibular skull to symphysis length (MSSL); and mandibular symphysis to distal length (MSDL) (Fig. 1) (Smithsonian Open Access 2020). We collected measurements from 62% of specimens ( $n = 112$ ); however, some of these skulls and mandibles were incomplete and we could only collect certain of these measurements (Supplementary Table 1). For specimens we did not measure, the skulls and mandibles were not collected or preserved, were on display and thus inaccessible, or were broken or disassembled.

We used descriptive statistics to quantify the seven skull and mandibular measurements (Table 1). Next, we performed factorial analysis of covariance (ANCOVA) to determine whether there were differences in measurement values by specimen sex or collection region using total body length as a control variable. Total body length and at least one skull or mandibular measurement were available for 44 specimens. We explored regional patterns with stepwise quadratic discriminant analysis to identify which measurements contributed most to observed variation. We then evaluated tooth eruption location, measured as MSDL, to total body length in 34 specimens, and the ratio of total mandibular length that is comprised of the MSDL in 87 specimens because tooth eruption location is the primary means of distinguishing morphologically similar beaked whales. Thus, quantifying these relationships may provide a method for estimating age class and serve as an efficient species identification tool. We considered  $p$ -values  $\leq 0.05$  significant where relevant. Analyses were performed using R (R Core Team 2018) with RStudio (RStudio Team 2016) and JMP Pro 15.2.1 (SAS 2019).

## Results

### Specimen sampling

We ultimately located and collected data on 180 specimens from 24 museums and stranding programmes in North America and Europe (Supplementary Table 1). We identified an additional 11 potential Sowerby's beaked whale specimens from three museums but were unable to obtain access to these specimens and could not confirm their identification. Thus, we did not include them in this study. We expect there are additional collections with samples that we did not identify. We concluded our sampling in 2019 and know that a few additional specimens identified as Sowerby's beaked whales have been recovered and added to museum and research collections since, but we have not seen these specimens.

### Specimen collection location

Original specimen collection location information was available for 97% of specimens ( $n = 174$ ) (Fig. 2). Of these, 45 were collected in the west Atlantic and 129 in the east Atlantic. In the west Atlantic, 21 specimens were bycaught in the former swordfish (*Xiphias gladius*) pelagic drift gillnet fishery of the western North Atlantic (Wenzel et al. 2013) and 24 were beach cast carcasses. In the east Atlantic, 7 specimens were recovered during dredging operations in the North Sea, and 122 specimens were beach cast carcasses. This group also contained the type specimen, originally collected in 1800 (Sowerby 1804). For some of the historical specimens collected in the early 1800s, the original records list collection method as 'caught'; however, there are no records suggesting that Sowerby's beaked whales were intentionally hunted. We think this could mean bycaught in fishing nets, be an alternative term for stranded, or in some cases, the animal may have already been sick and close to shore and was opportunistically hunted.

### Age and sex of specimens

Specimen sex was either recorded when the specimen was originally collected or we were able to determine sex through a combination of specimen size and tooth morphology in 71% of specimens ( $n = 128$ ) (Fig. 3a, Supplementary Table 1). Of these, 69 were female and 59 male. Female specimens were predominantly adults ( $n = 49$ ), but a sizable minority ( $n = 14$ ) were sub-adults and included juveniles ( $n = 2$ ). Male specimens were also predominantly adult ( $n = 45$ ) but included calves ( $n = 1$ ) and juveniles ( $n = 4$ ) in addition to sub-adults ( $n = 7$ ). For both sexes there was a small subset of specimens for which we could not determine age class (females = 4; males = 2). Sex could not be determined for 52 specimens; this group was primarily sub-adults ( $n = 21$ ) and juveniles and calves ( $n = 10$ ), but also included 6 adult specimens and 15 specimens of unknown age. Both of these groups were comprised of specimens with missing or damaged skulls and mandibles, so we could not collect measurements or evaluate suture fusion.

### Skull and mandible measurements

ANCOVA demonstrated three skull and mandibular elements (TSL, TML and MDSL) were significantly different between specimens collected in the east and west Atlantic (Table 2). ANCOVA also indicated that three measurements were significantly different by sex class (i.e., male, female, unknown). Post hoc analysis with Student's  $t$ -tests, however, established that male and female specimens were not significantly different for any measurement; instead, observed differences were driven by individuals of unknown sex, which were predominantly sub-adults and juveniles. Stepwise quadratic discriminant analysis demonstrated that 100% of specimens could be assigned to their collection region based on MSDL, total body length and BCW ( $n = 26$ ).

Tooth eruption location was strongly positively correlated with total body length ( $R^2 = 0.76$ ; Fig. 3b). As body length increased, the distance between the tooth eruption location and the distal end of the mandible increased (i.e., MSDL; see Fig. 1). We found significant positive correlations between the percent ratio of TML that is comprised of MSDL, and TML for female, male and unknown sex specimens ( $R^2 = 0.59, 0.61$  and  $0.62$ , respectively; Fig. 3c). As TML increased, the percent ratio of that length that is MSDL also increased. For juvenile and calf specimens, TML was  $<45$  cm, and the mean percent ratio of MSDL to TML was 22.5% (SD = 2.2%). In sub-adult and adult animals TML was  $>44$  cm and the mean percent ratio of MSDL to TML increased to 31.2% (SD = 4.0%).

## Discussion

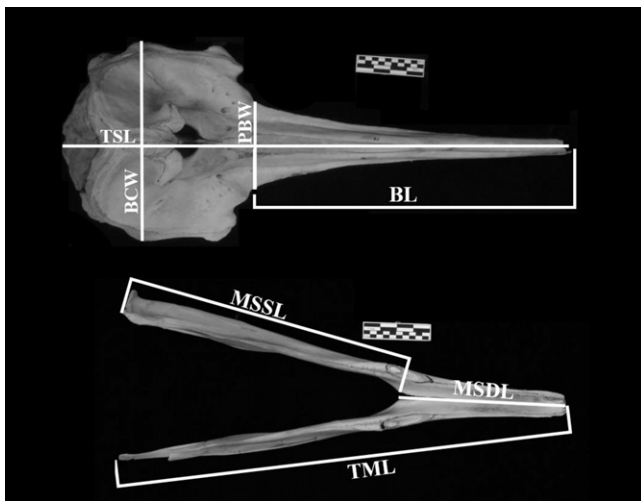
### Sampling efficacy

Snowball sampling (Goodman 1961, Wright & Stein 2005) proved highly successful at rapidly locating museums with specimens that we otherwise would not have identified. Although some museums maintain their own online collections database, the number of museums we would have had to individually search to identify specimens would have been time prohibitive. Additionally, many museums do not have online searchable databases, and we would have had to personally contact each of these museums to inquire about specimens. To complicate matters further, some museums do not provide contact details for curators, and only provide a general inquiry form that can be submitted to customer relations. By employing snowball sampling, we were able to tap into the curator

**Table 1.** Median, minimum, and maximum measurement values for 7 skull and mandibular elements of Sowerby's beaked whale (*Mesoplodon bidens*) specimens housed in museum or research institutions. We took measurements from 112 specimens; however, not all specimens had all elements present.

Measurements (cm)		Sex and age classes									
		Female <sup>a</sup>			Male <sup>a</sup>			Unknown			
		Adult	Sub-adult	Juvenile	Adult	Sub-adult	Juvenile	Adult	Sub-adult	Juvenile	Calf/neonate
Total skull length (TSL)	n	26	8	1	24	6	2	1	5	4	1
	median	75.7	64.9	47.6	72.3	57.8	47.0	67.6	60.7	46.1	30.3
	min	55.9	46.2	47.6	59.4	48.1	46.4	67.6	56.2	40.4	30.3
	max	83.6	73.2	47.6	82.8	71.7	47.5	67.6	63.8	51.7	30.3
Braincase width (BCW)	n	31	13	1	28	7	3	3	7	4	1
	median	29.8	25.7	20.3	30.3	25.4	20.9	29.1	24.2	21.5	12.4
	min	27.3	22.2	20.3	27.6	23.2	20.3	28.1	22.1	19.9	12.4
	max	33.1	27.2	20.3	34.1	26.9	23.1	34.9	27.4	22.8	12.4
Proximal beak width (PBW)	n	32	14	1	29	7	3	2	7	4	1
	median	13.9	11.7	9.9	13.2	11.6	9.8	12.2	11.8	9.8	5.6
	min	11.7	9.1	9.9	11.8	10.7	8.9	11.3	10.1	8.1	5.6
	max	15.5	13.3	9.9	14.9	12.4	10.3	13.1	11.9	12.6	5.6
Beak length (BW)	n	27	8	1	26	6	2	1	6	4	1
	median	48.5	39.4	27.4	45.8	32.5	25.3	36.5	37.6	26.3	17.3
	min	28.3	29.1	27.4	29.4	23.9	24.4	36.5	33.1	25.3	17.3
	max	58.0	46.6	27.4	55.3	43.8	26.0	36.5	40.6	29.2	17.3
Total mandibular length (TML)	n	31	8	1	25	5	3	1	10	5	2
	median	68.2	55.6	42.9	64.4	49.6	43.2	59.7	53.2	44.1	24.0
	min	48.5	44.8	42.9	44.3	49.3	40.0	59.7	48.4	34.9	23.5
	max	73.8	63.0	42.9	74.9	62.6	44.1	59.7	61.2	44.5	24.5
Mandibular skull to symphysis length (MSSL)	n	32	9	1	26	6	3	1	11	5	2
	median	44.5	38.6	34.1	44.7	37.2	30.9	43.6	37.3	31.4	19.2
	min	32.4	32.2	34.1	23.2	35.3	30.9	43.6	36.1	25.8	18.6
	max	50.4	426.0	34.1	51.1	45.2	34.9	43.6	45.2	34.1	19.8
Mandibular symphysis to distal end length (MSDL)	n	31	9	1	27	5	3	1	10	5	2
	median	23.9	17.1	8.8	20.9	14.2	9.1	16.1	14.7	10.2	4.8
	min	11.8	10.1	8.8	12.2	12.3	8.3	16.1	8.3	9.1	4.7
	max	27.2	26.3	8.8	38.9	17.4	10.2	16.1	18.3	10.4	4.9

<sup>a</sup>No calf/neonate specimens with measurements could be identified as male or female, so we have not included columns for these age classes.



**Fig. 1.** Skull and mandibular measurements of Sowerby's beaked whales (*Mesoplodon bidens*). TSL = Total Skull Length; BCW = Braincase Width; PBW = Proximal Beak Width; BL = Beak Length; TML = Total Mandibular Length; MSSL = Mandibular Skull to Symphysis Length; MSDL = Mandibular Symphysis to Distal Length. Photographed specimen is USNM 572008, courtesy of Smithsonian Open Access. Scale bar is 10 cm (short boxes are 1 cm and long boxes are 1 in).

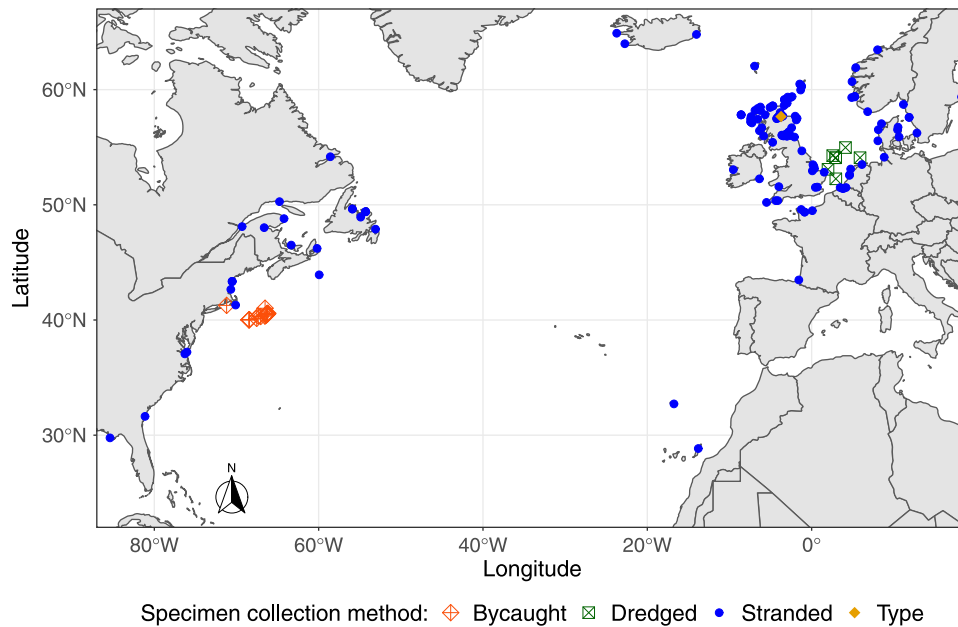
network and learn about samples that we otherwise would have missed. Had we not used this method we probably would have missed 62 samples from 11 museums and research institutions. These were primarily smaller, regional museums that may not

be able to invest time and funds into collection digitization. However, samples from these institutions often are accompanied by detail-rich records that provide critically important context, and active efforts to identify these institutions and include them in studies should be made.

At many institutions, we identified and/or located additional specimens in the collection, including at the three original museums we identified through online databases. This included one additional specimen at the NMNH, 39 at the NMS, and nine at the NHM. In one example of identifying additional specimens when visiting the collection, we were invited to give a lecture to museum staff and visitors; after the lecture we were approached by a curator who had been given a Sowerby's beaked whale mandible by a beachcomber several years earlier. Collection data and coordinates for the specimen had been recorded by the beachcomber on scratch paper, and both had been stored away by the receiving curator. Our visit reminded the curator of the specimen, staff members recovered it from storage, and the specimen was accessioned during our visit and made available for sampling.

**Specimen demographics**

Male and female specimens were represented roughly equally in our study; however, there was a sizeable number of specimens for which sex could not be determined. Most of these were juveniles or calves in which teeth would not have erupted, making it nearly impossible to determine sex if the sex organs were absent when the specimen was collected. Genetic analysis should be used to determine sex of these specimens, which may provide further



**Fig. 2.** Original collection location and method for 174 Sowerby's beaked whale (*Mesoplodon bidens*) specimens housed in museums or research institutions; 45 specimens were collected in the west Atlantic and 129 specimens were collected in the east Atlantic. Specimens in the west Atlantic were either incidental bycatch (orange diamonds) or stranded (blue circles); in the east Atlantic specimens were stranded (including the type specimen, indicated with a gold diamond) or recovered in dredging operations (green squares).

data regarding sex-specific stranding patterns. Additionally, Einfeldt et al. (2019a) identified XXY aneuploidy in three North Atlantic beaked whale specimens (two *Hyperoodon ampullatus* and one *M. mirus*); these specimens displayed a mixture of male and female sexual characteristics, suggesting that in a minority of beaked whale specimens external sexual morphology may not be a reliable indicator of sex, and therefore sex-specific behaviour, necessitating sex identification by genetic analysis.

Specimens were collected more often in the east Atlantic than west; this could be due to oceanic currents carrying specimens away from versus towards shore, respectively. In the west Atlantic, the Gulf Stream may be carrying distressed and dead animals away from shore, resulting in a smaller number of strandings. Conversely, in the east Atlantic the North Atlantic Drift Current may carry distressed or dead animals towards shore and explain the high proportion of stranding in the British Isles, particularly Scotland. Additionally, MacLeod et al. (2005) argued that the North Sea may be acting as a shallow trap for pelagic and deep diving beaked whales, confusing them and resulting in a large number of deaths and strandings on the surrounding shoreline.

The high proportion of strandings in the east versus the west Atlantic has resulted in a few previous studies and reports suggesting that Sowerby's beaked whales may be less common in the west Atlantic than east (e.g., MacLeod et al. 2005, COSEWIC 2019). However, nearly half of the west Atlantic specimens in our study were bycaught in the former swordfish drift gillnet fishery. That such a high number of specimens were bycaught in a relatively small area over a short period suggests that this may be an important habitat for west Atlantic members of this species, and supports the idea that Sowerby's beaked whales may be similarly abundant in the west Atlantic as east, but become beach cast less often. This knowledge is critical to those tasked with conserving this species across its range.

Our dataset includes four extralimital strandings of Sowerby's beaked whales in the west Atlantic (Fig. 2, Supplementary Table 1). These specimens stranded in the US states of Florida, Georgia and Virginia. Previous extralimital strandings in the east Atlantic, such as in the Canary Islands, prompted reconsideration of the species accepted range in that region (Martin et al. 2011). These four

strandings in the west Atlantic, in addition to photographs of animals strongly resembling Sowerby's beaked whales stranding in Brazil and the Caribbean, warrant further investigation by conservation scientists and reconsideration of the accepted range for Sowerby's beaked whales in the west Atlantic (Simões-Lopes & Ximenez 1993, NMNH 2020).

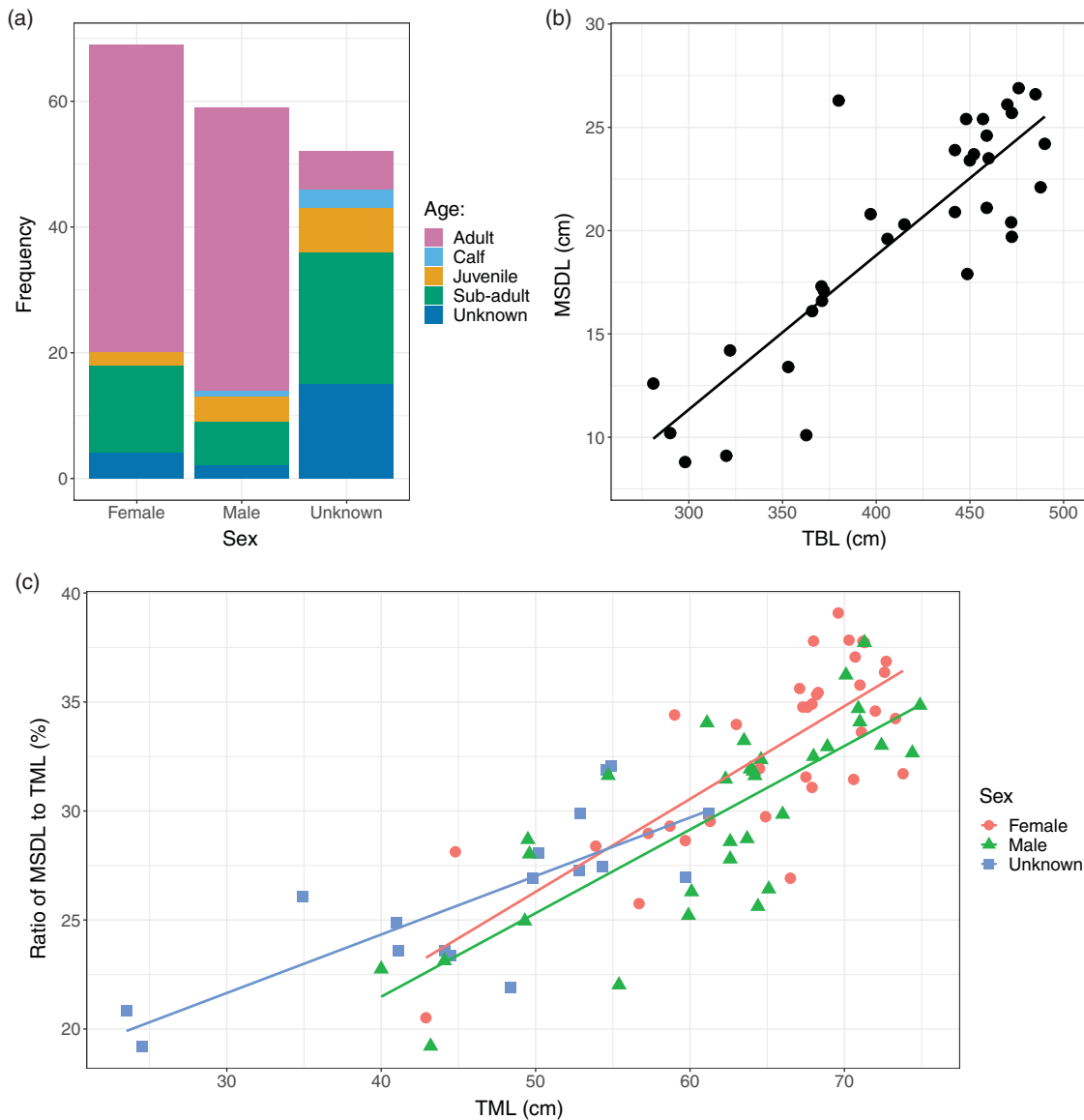
### Specimen morphology

Prior to our study, few data were available on Sowerby's beaked whale skull and mandibular measurements and morphology beyond simple characteristics, such as tooth eruption location. By collecting and collating skull and mandibular measurements, in addition to total body length and body weight data for a small subset of specimens (Supplementary Table 1), we generated a robust data set that can be used by population ecologists and conservation scientists to better investigate morphological variation among Sowerby's beaked whales. In particular, the ratio of MSDL to TML may prove highly useful in assigning specimens to an age class and improving our understanding of Sowerby's beaked whale growth and development. Similarly, the relationship between tooth eruption location and body length will serve as an efficient means of distinguishing among stranded beaked whale species, aiding cetacean stranding and recovery programmes, and decreasing the chance a specimen will be misclassified.

Despite tooth morphology acting as a sexually dimorphic characteristic and a previous study identifying sexually dimorphic variation in the mandibular elements associated with tooth eruption (e.g., length of the alveolus), we found no mandibular or skull measurements that were sex specific or indicated sexual dimorphism (MacLeod and Herman 2004). This was somewhat surprising because male tusks are larger than female teeth and erupt from the mandible, and we expected some sex-specific variation in mandibular measurements to accommodate male tusks. The trend we observed in increasing percent ratio of MSDL to TML in both males and females, similarly observed by MacLeod and Herman (2004) in 18 east Atlantic Sowerby's beaked whale specimens, may help to explain this from an evolutionary perspective. In

**Table 2.** Factorial analysis of covariance for 7 skull and mandibular elements, controlled by total body length, of Sowerby's beaked whale (*Mesoplodon bidens*) specimens housed in museum or research institutions. Superscript letters for Student's *t*-test indicate group assignment; groups with different letters are significantly different ( $p \leq 0.05$ ).

Measurements (cm)	n	Sex		Student's <i>t</i> -test			Region	
		F Ratio	P	Female	Male	Unknown	F Ratio	P
Total skull length (TSL)	31	3.173	0.059	69.986 <sup>A</sup>	69.946 <sup>A</sup>	57.558 <sup>B</sup>	9.100	0.006
Braincase width (BCW)	42	3.624	0.037	27.775 <sup>A</sup>	27.771 <sup>A</sup>	25.300 <sup>B</sup>	3.031	0.090
Proximal beak width (PBW)	43	2.247	0.120	12.803 <sup>A</sup>	12.745 <sup>AB</sup>	11.610 <sup>B</sup>	0.862	0.359
Beak length (BL)	32	0.805	0.457	43.886 <sup>A</sup>	42.783 <sup>A</sup>	38.023 <sup>A</sup>	2.804	0.106
Total mandibular length (TML)	34	5.066	0.013	62.022 <sup>A</sup>	61.789 <sup>A</sup>	54.386 <sup>B</sup>	7.382	0.011
Mandibular skull to symphysis length (MSSL)	38	3.593	0.039	41.700 <sup>A</sup>	41.434 <sup>A</sup>	37.526 <sup>B</sup>	0.001	0.983
Mandibular symphysis to distal end length (MSDL)	34	1.691	0.202	20.943 <sup>A</sup>	20.054 <sup>A</sup>	18.073 <sup>A</sup>	19.923	<0.001



**Fig. 3.** Analysis of 180 Sowerby's beaked whale (*Mesoplodon bidens*) specimens housed in museums and research institutions. Panel a: sex and age class frequencies for all specimens. Panel b: tooth eruption location, measured as mandibular symphysis to distal length (i.e., MSDL; see Fig. 1) to total body length (TBL) for 34 specimens ( $y = -11.02 + 0.075x$ ,  $R^2 = 0.76$ ,  $p < 0.001$ ). Panel c: percent ratio of mandibular symphysis to distal end length (MSDL) to total mandibular length (TML) plotted by total mandibular length for 35 female ( $y = 4.99 + 0.426x$ ,  $R^2 = 0.59$ ,  $p < 0.001$ ), 32 male ( $y = 6.14 + 0.383x$ ,  $R^2 = 0.61$ ,  $p < 0.001$ ), and 20 unknown sex ( $y = 13.61 + 0.268x$ ,  $R^2 = 0.62$ ,  $p < 0.001$ ) specimens (total = 87).

1953, Fraser (1974) used radiographs to identify vestigial teeth in the mandible of a male sub-adult Sowerby's beaked whale; we also observed vestigial teeth in a juvenile specimen of unknown sex in the course of this study. Basal-beaked whales in the family Ziphiidae are thought to have retained full dentition until the mid-Miocene, so perhaps MSDL continued to grow in basal ziphiids to accommodate those teeth, and modern MSDL growth in both males and females is an evolutionary holdover (Lambert et al. 2015). Advancing genetic analysis techniques may provide a way to identify functional genes related to mandibular growth, providing more information on this interesting pattern.

We recorded significant differences in three skull and mandibular measurement variables (TSL, TML and MSDL) between east and west Atlantic specimens (Table 2). This suggests that east and west Atlantic Sowerby's beaked whales are comprised of  $\geq 2$  distinct populations with differing skull and mandibular morphology, which is directly relevant to conservation of this species. However, because east Atlantic specimens were more highly represented in our dataset, it is possible these differences may be artifacts of unequal sampling. Previous mitochondrial analysis of 14 specimens produced both regionally distinct and regionally overlapping mitochondrial haplotypes (COSEWIC 2006). To better explore population structure in Sowerby's beaked whales, population ecologists and conservation scientists should conduct both whole genome analysis and stable isotope analysis for the specimens we located. Whole genome analysis will provide more data regarding population structure and genetic relatedness in this species, while stable isotope analysis will provide insight into foraging behaviour and habitat use variation among populations.

## Conclusions

Specimens of opportunity are vital resources for biological and conservation studies, and snowball sampling proved an efficacious means of identifying these specimens in this study. By compiling data on 180 disperse Sowerby's beaked whale specimens of opportunity, we: (1) identified significant differences in three median skull and mandible measurements between specimens collected in the east and west Atlantic, which suggests this species may be comprised of  $\geq 2$  distinct populations; (2) provided the first quantified skull and mandibular measurements for a sizeable group of this species; (3) demonstrated the relationship between tooth eruption location and body length, which can be employed to quickly identify stranded Sowerby's beaked whales specimens; (4) identified an interesting trend in mandibular growth patterns; and (5) provided a spatial distribution of Sowerby's beaked whale specimen collection locations, which may support expanding the species' accepted range in the west Atlantic. These data will aid future research into this species' population structure, distribution and behaviour, and directly contribute to the identification of threats to, and conservation plans for, this species.

We encourage researchers to utilize specimens of opportunity in their study design, and to employ snowball sampling to locate these samples in museum and research institutions. Employing these methods in our study quickly led to considerable reliable data on an array of factors addressing the pressing time issue detailed by Soulé (1985) for conservation research and application. Thus, the biological collections in museum and research institutions are invaluable to ecological and conservation research. However, as museums face shrinking budgets, the digitization of collection records may have to be put on hold, necessitating alternative means of locating specimens of opportunity. Our results demonstrate the

usefulness of snowball sampling and specimens of opportunity to elusive species research and conservation, and the methods of our study can be readily adapted for other species.

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