SC/32/PS16

The Historical Status and Reduction of the Western Arctic Bowhead Whale (*Balaena mysticetus*) Population by the Pelagic Whaling Industry, 1848–1914

JOHN R. BOCKSTOCE[1] AND DANIEL B. BOTKIN[2]

[1] *New Bedford Whaling Museum, New Bedford, Massachusetts 02740*
[2] *University of California, Santa Barbara, California 93106*

ABSTRACT

From 1848, when the western Arctic whaling grounds were discovered, to 1914, when the whaling industry had collapsed, the bowhead whales of the Bering, Chukchi, and Beaufort Seas were systematically hunted by whaling vessels of several nations. This report attempts to determine the impact of the pelagic whaling industry upon the western Arctic bowhead whale. Data have been drawn from the logbooks and journals of the whaling industry representing 19% of all known whaling cruises made to those waters during the period. From these records we estimate that 18,650 whales were killed and 16,600 were taken by the pelagic whaling industry, an average of about 280 whales killed and 250 whales taken per year. DeLury estimates of the bowhead whale population for 1847 (the year before the beginning of exploitation by the whaling industry) suggest that the population numbered approximately 30,000, and was no less than 20,000 and no more than 40,000. The population appears to have been depleted rapidly: one-third of the total number of kills during the entire period of commercial whaling occurred in the first decade, and two-thirds of them in the first two decades. The ships' records also suggest that the species was rapidly eliminated from major parts of its range.

INTRODUCTION

Today the bowhead whale (*Balaena mysticetus*) population of the Bering, Chukchi, and Beaufort Seas (the western Arctic population) is at the center of a controversy about the effect of the Alaskan Eskimo hunt on its numbers (see Bockstoce, 1980). Although many observers believe the population was greatly reduced by pelagic whaling and has not recovered significantly from the low level at which it probably stood in 1915, hitherto no thorough attempt has been made to estimate the number of bowheads that existed prior to the commencement of commercial hunting or to determine the impact that the pelagic industry had on the population. This report presents the results of the first comprehensive and systematic attempt to answer these questions and is based on the best available data: the daily entries in the logbooks and journals of the whaling industry.

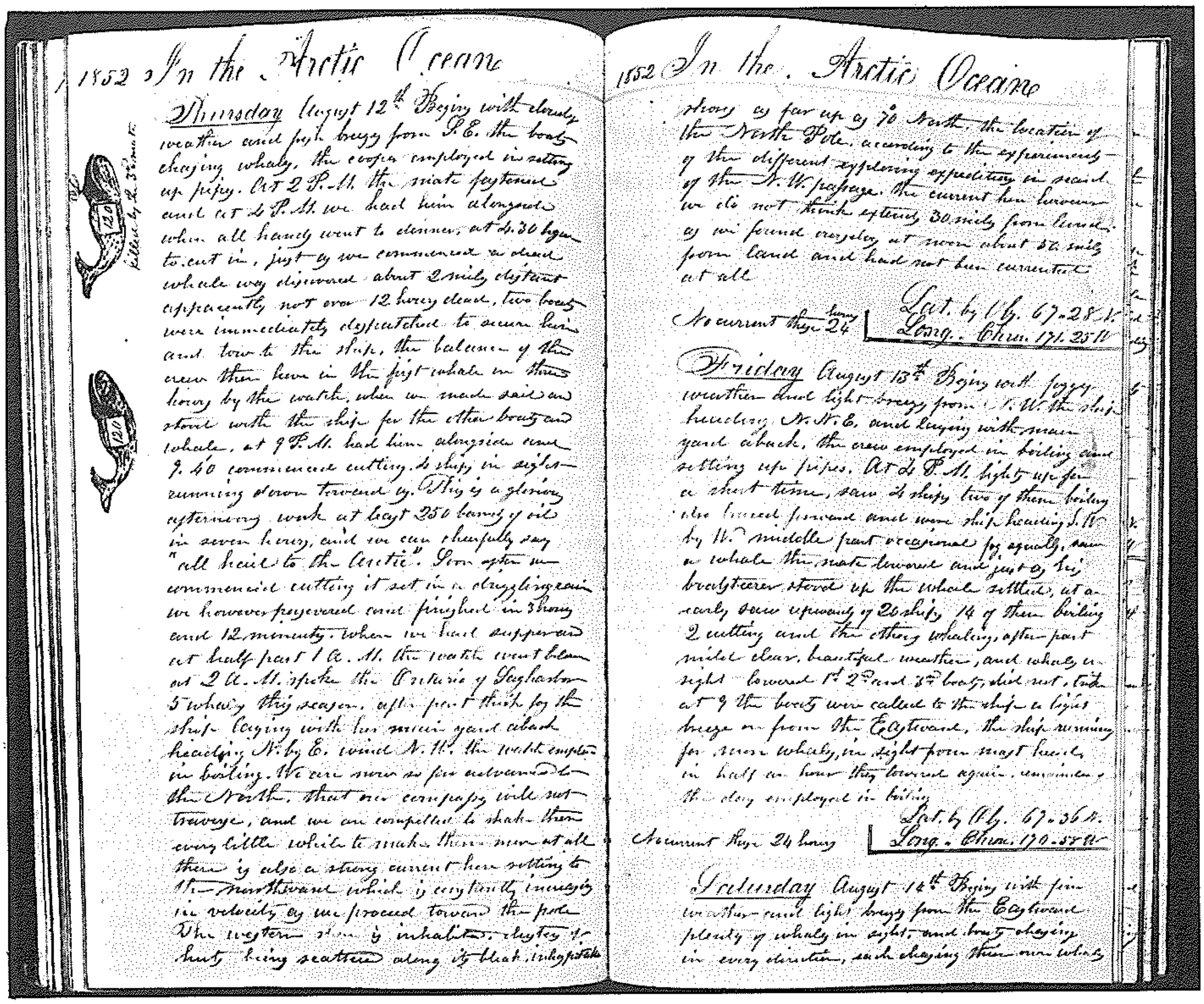
Although a few bowheads may have been taken between 1843 and 1847, these whales were not deliberately sought in the Bering Sea until 1848. In that year Captain Thomas Roys sailed into seas unknown to whalemen and discovered the great whaling grounds near Bering Strait where the bowheads, oil-rich, baleen-laden, and docile, were found in numbers. Roys quickly filled his ship and returned to Honolulu to broadcast his success. Word of these new whaling grounds spread quickly, and in the following year more than forty vessels sailed north and enjoyed equally successful cruises. In succeeding years the news of the 1849 season increasingly lured other vessels, and in 1852 more than 200 whaleships operated in the Bering Strait region.

The whalers quickly established a routine that they would vary only slightly for the next sixty years. Leaving New England in the autumn and rounding Cape Horn in the southern summer, they outfitted at Hawaiian ports or San Francisco, sailing for the Arctic in late March to reach the pack ice of the central Bering Sea a month later. Informal accounts suggest that they took a few whales as they worked their way north toward Bering Strait through the melting floes, but by early June most of the whales had passed them and gone deep into the safety of the ice on the migration to their summer feeding grounds in the Arctic Ocean. As the fishery progressed into its second decade the whalemen generally would not see their quarry again until late July when the ice allowed the ships to approach the north coast of Alaska and intersect the whales traveling from the Beaufort Sea to their autumn feeding grounds near Herald Island in the Chukchi Sea. The ships often cruised near Herald Island until the violent weather and encroaching ice of early October drove them back to ports in the Pacific Ocean.

The whalemen usually repeated these summer voyages once or twice more before returning to their home ports. Some alternated their summer hunts among cruises to the Arctic, the Okhotsk Sea, or the Gulf of Alaska, depending on where the best catches were being made; nevertheless, they rarely visited more than one of these areas per year.

The intensity of the hunting in the early years of the fishery quickly reduced the bowhead population (and it is possible that the whales themselves responded to the threat by fleeing the hunting areas), for the catches of 1853 and 1854 were poor enough in comparison with previous years that the fleet virtually abandoned the Bering Strait region in 1855, 1856, and 1857, and turned its attention to the bowheads of the Okhotsk Sea. It too was soon overhunted, and the whalemen returned to Bering Strait in 1858 to cruise there regularly for the following half century.

In the spring, once the ships reached 54° N, or, in the later years of the fishery, 57° or 58° N, the whalemen began to watch for bowheads; for the next five or six months they generally kept themselves in constant readiness to lower their boats. When they saw whales, if the seas were not too rough or the ice too dense, four or five boats usually went after them. If the men were lucky, a boat got close enough to strike a whale with a harpoon. The whale would then run, towing the line and boat after it, eventually becoming sufficiently exhausted so that it


1852 In the Arctic Ocean

Thursday August 12th Begins with cloudy weather and fresh breezes from S.E. the boats chasing whales, the cooper employed in setting up pipes. At 2 P.M. the mate fastened and at 4 P.M. we had him alongside when all hands went to dinner, at 4.30 began to cut in, just as we commenced a dead whale was discovered about 2 miles distant apparently not over 12 hours dead, two boats were immediately dispatched to secure him and tow to the ship, the balance of the crew then here in the first whale in three hours by the watch, when we made sail and stood with the ship for the other boats and whale, at 9 P.M. had him alongside and 9.40 commenced cutting. 4 ships in sight running down toward us. This is a glorious afternoon work at least 250 barrels of oil in seven hours, and we can cheerfully say "all hail to the Arctic". Soon after we commenced cutting it set in a drizzling rain we however persevered and finished in 3 hours and 12 minutes. When we had supper and at half past 1 A.M. the watch went below at 2 A.M. spoke the Ontario of Sag Harbor 5 whales this season. after part thick fog the ship laying with her main yard aback heading N. by E. wind N.W. the watch employed in boiling. We are now so far advanced to the North that our compasses will not traverse, and we are compelled to shake them every little while to make them move at all there is also a strong current here setting to the Northward which is constantly increasing in velocity as we proceed toward the pole The western shore is inhabited, clusters of huts being scattered along its beach, [illegible]

120

120

1852 In the Arctic Ocean

shore as far up as 70 North the location of the North Pole, according to the experiments of the different exploring expeditions in search of the N.W. passage. the current here however we do not think extends 30 miles from land as we found by [illegible] at noon about 50 miles from land and had not been current at all

No current this 24 hours | Lat. by Obs. 67.28 N. | Long. Chron. 171.25 W.

Friday August 13th Begins with foggy weather and light breezes from S.W. the ship heading N.N.E. and laying with main yard aback, the crew employed in boiling and setting up pipes. At 4 P.M. lighted up for a short time, saw 4 ships two of them boiling also braced forward and were ship heading S.W. by W. middle part occasional fog squalls, saw a whale the mate lowered and just as his boatsteerer stood up the whale settled, at an early saw upwards of 20 ships, 14 of them boiling 2 cutting and the others whaling, after part middle clear, beautiful weather, and whales in sight lowered 1st 2nd and 3rd boats, did not strike at 9 the boats were called to the ship a light breeze on from the Eastward, the ship running for more whales, in sight from mast head in half an hour they lowered again. [illegible] the day employed in boiling

No current this 24 hours | Lat. by Obs. 67.36 N. | Long. Chron. 170.58 W.

Saturday August 14th Begins with fine weather and light breezes from the Eastward plenty of whales in sight and boats chasing in every direction, each chasing their own whales

Fig. 1. Entries in journal of *Montreal*'s 1852 cruise (courtesy of the New Bedford Whaling Museum).

could be killed with a lance. But frequently whales escaped into the ice, towing lines and gear. In response to these losses the whalemen, after 1860, increasingly used darting guns (which were fixed to the harpoon shaft and fired a small bomb into the whale at the moment of striking) and shoulder guns (heavy brass smooth bores that fired a similar bomb from a distance and thus generally replaced the lance).

Once the whale was dead, or if a dead whale was found, the carcass was towed to the ship, where the crew took the baleen aboard and stripped off and 'tryed out' (rendered into oil) the blubber. As a rough average, a moderate-sized bowhead yielded 100 barrels of oil (a barrel was 31½ US gallons) and 1,500 pounds of baleen.

Information of this sort was recorded daily (Fig. 1) by the whalemen in their logbooks and journals (a logbook was an official ship's record; a journal, a private document). Usually recorded was information on the ship's position, wind velocity and direction, sea state, visibility, and ice cover. Similarly, if whales were encountered, the whalemen usually noted the species, number seen, and whether the boats chased, struck and lost, captured or found dead a whale. If the whale was processed, its oil and baleen yield were often recorded as well.

By 1866 the hunting pressure had put the bowhead population in steep decline, and to offset poor catches the whalemen began taking walrus (*Odobenus rosmarus*) and gray whales (*Eschrichtius robustus*) in the 'middle season' between their spring and autumn encounters with bowheads. A decline in oil prices soon ended this; by 1880 oil prices were so low that profits could only be made by taking baleen, the great flexible plates that hang from a bowhead's upper jaw and are used to filter food from the water. As the price of oil sank, forced down by petroleum products, the price of baleen began to rise dramatically, driven by the call of the fashion industry for, among its other uses, 'whalebone' corset stays and skirt hoops (Fig. 2).

In 1880 the western Arctic remained the major profitable whaling ground for the American fleet, and the rising price of baleen stimulated the development of steam-auxiliary whaling vessels. These immediately proved successful in pursuing the whales to the least accessible corners of the Arctic Ocean. In 1889 steamers reached the bowheads' summer feeding grounds off the MacKenzie River delta in Canada's Northwest Territories, and from then until 1914 the focus of the industry was concentrated largely on those waters. Changes in fashion and the introduction of flexible spring steel as a

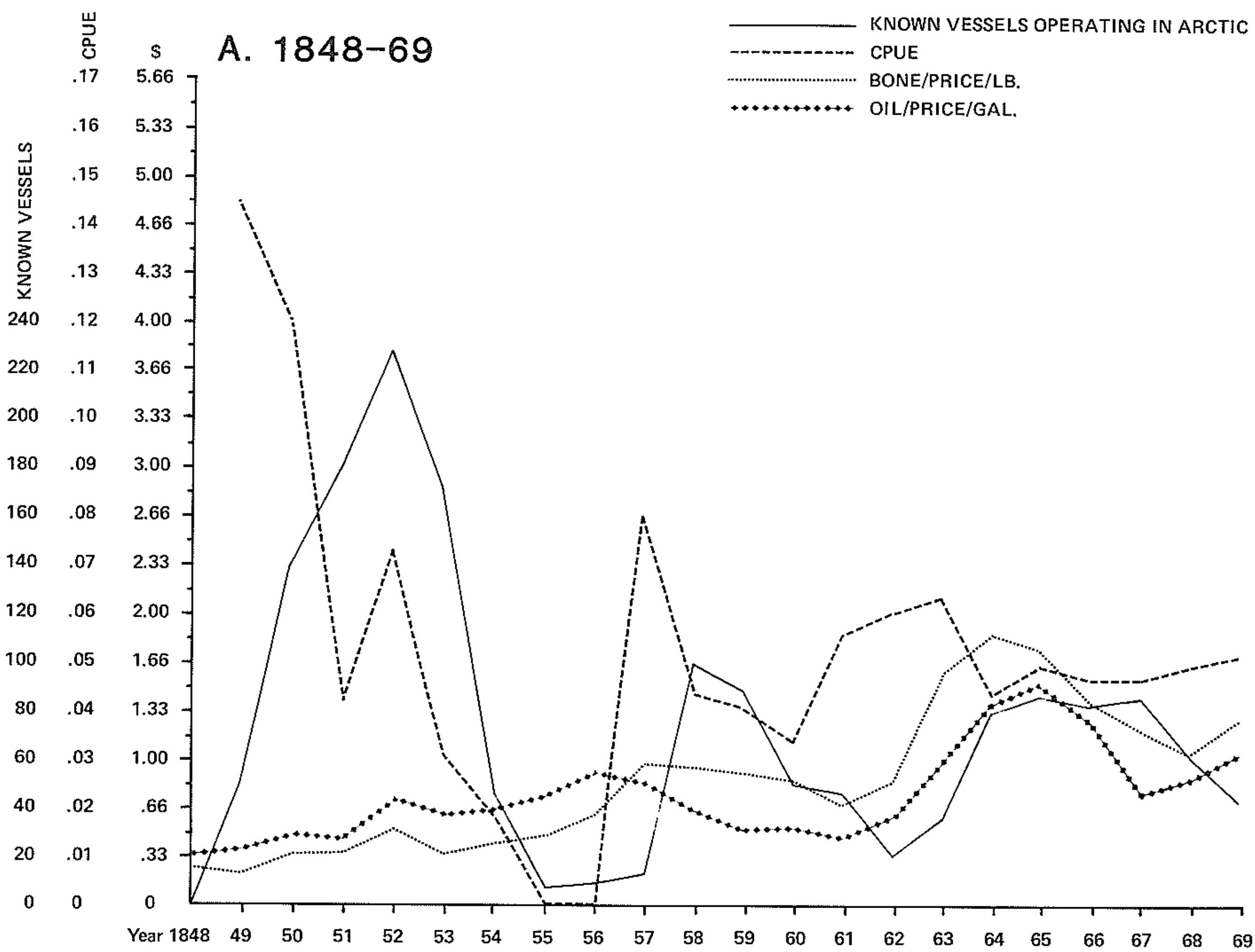


Fig. 2. Yearly variation in vessel numbers, catch per unit effort (CPUE) and product prices.

cheap substitute for baleen caused the market to collapse in 1908, dragging the industry with it. After 1914, although a few vessels cleared port as whaleships, they were in fact primarily on fur trading and freighting voyages, and only a few whales were taken by ships thereafter.

RESOURCES AND METHODS

Although the fundamental resource for this investigation was the information in the daily entries in whaling logbooks and journals, it was necessary to carry out several preliminary procedures before the extraction of the data could begin.

First, we had to identify all vessels that hunted bowheads in the Bering, Chukchi and Beaufort Seas to determine, among other things, both the size of the fleet in each year, and, of course, the names of those vessels for which logbooks or journals might have survived. The basic source for this phase of the study was the *Whalemen's Shipping List and Merchants' Transcript* (Fig. 3). Published in New Bedford from 1843 to 1914, it contains the most comprehensive documentation of the American whaling industry; its weekly issues posted the latest information on all American whaling vessels throughout the world. The *Shipping List* was of particular use to this project because whaling vessels usually touched at a major port to refit, to take on fresh provisions, and to report their cargoes immediately before and after their half-year Arctic cruise; thus, their Arctic catch can usually be determined (expressed in barrels of oil and pounds of baleen) by subtracting the cumulative cargo listed in the spring from that listed in the autumn. Once in the Arctic, ships passing one another frequently reported their 'season's catch' (usually expressed in the number of whales they had taken); this information, carried by ships leaving the Arctic, would also find its way to the pages of the *Shipping List*.

To organize these data we constructed a ledger sheet (Fig. 4) listing the following information from left to right: column 1, the vessel's name, rig, captain, and home port; columns 2 through 4, successive seasonal reports; column 5, the post-season report; column 6, the pre-season report. This information was gathered for each year and subdivided by home port.

The data from the *Shipping List* were augmented and corrected by adding information from other newspapers (principally from Honolulu's *Friend* and the *Pacific Commercial Advertiser* and several San Francisco papers) as well as from scattered data in more than 500 printed books, magazine articles, manuscripts, and government documents. This body of data was then spot-checked for accuracy against information compiled in the 19th century by Dennis Wood, a New Bedford insurance broker. These resources allowed us to expand our purview beyond the American whaling industry to

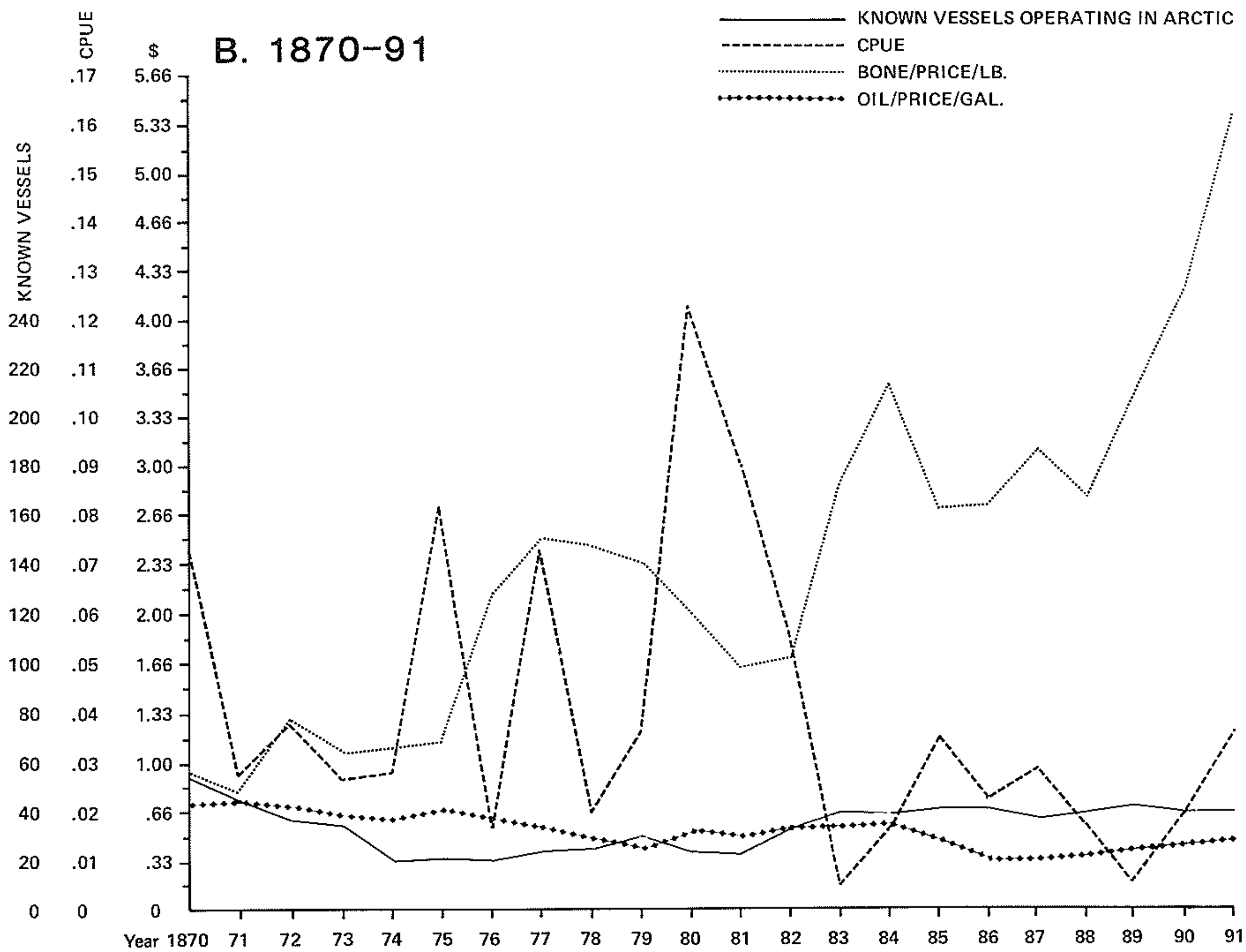


Fig. 2 (*cont.*)

include vessels of the other nations operating in the western Arctic: Hawaii, Germany, France, and Great Britain (Australia).

Later, as we carried out the data extraction, reports in the logbooks and journals of other ships seen on the whaling grounds were checked against the tables and inserted if the information was important. In all, more than 25,000 reports were processed, giving us a record of more than 2,700 annual cruises. Significantly, as the extraction phase wore on, fewer and fewer unreported ships were found to add to our list; in fact the decline was so remarkable that during the extraction of data from the last hundred or so documents no previously unreported vessels were identified. Thus we believe that, if our list of whaling vessels operating in the western Arctic is not now complete, we have certainly identified more than 99% of them.

A note should be made about the sources that we intentionally did not consult. A number of compendia of data about whaling voyages exist, but an examination of each revealed serious deficiencies for our needs. Although Hegarty's (1959) and Starbuck's (1964) important works were based on the information in the *Shipping List*, these authors included only the cumulative results of the entire whaling voyage and hence are of little value for determining the annual bowhead catch; furthermore there are some omissions and errors in each. Townsend (1935) devoted a section of his report to the bowhead whales of the North Pacific, but he segregated them neither geographically nor chronologically; consequently bowheads from the Okhotsk Sea and the western Arctic are listed together under the total number taken on an entire whaling voyage, not for each season. In addition, a spot-check of his data has revealed that occasionally gray whales and right whales were counted as bowheads and that some bowhead captures were overlooked. Although Clark (1887) listed seasonal reports for voyages to the western Arctic from 1868 to 1884, he omitted some vessels known to have operated there and included others that did not; his figures for each vessel's seasonal products frequently included walrus oil, gray whale oil, right whale oil and baleen, or bowhead baleen that was obtained in trade from the natives. Estimates of the bowhead kill that are based on these sources should be treated with skepticism.

Once our list of whaling vessels was well underway, we were able to turn to the published check-lists of the approximately 4,000 whaling logbooks and journals that are held in public collections in the United States, Canada and Australia. (A survey of whaling manuscripts held in other countries revealed no documents useful for our purposes.) Among those we found records for nearly 800 seasonal Arctic cruises; nevertheless it is regrettable that less than 550 were suitable, that is, containing a complete record for the entire seasonal cruise and being sufficiently legible and detailed for our needs. Of those that were

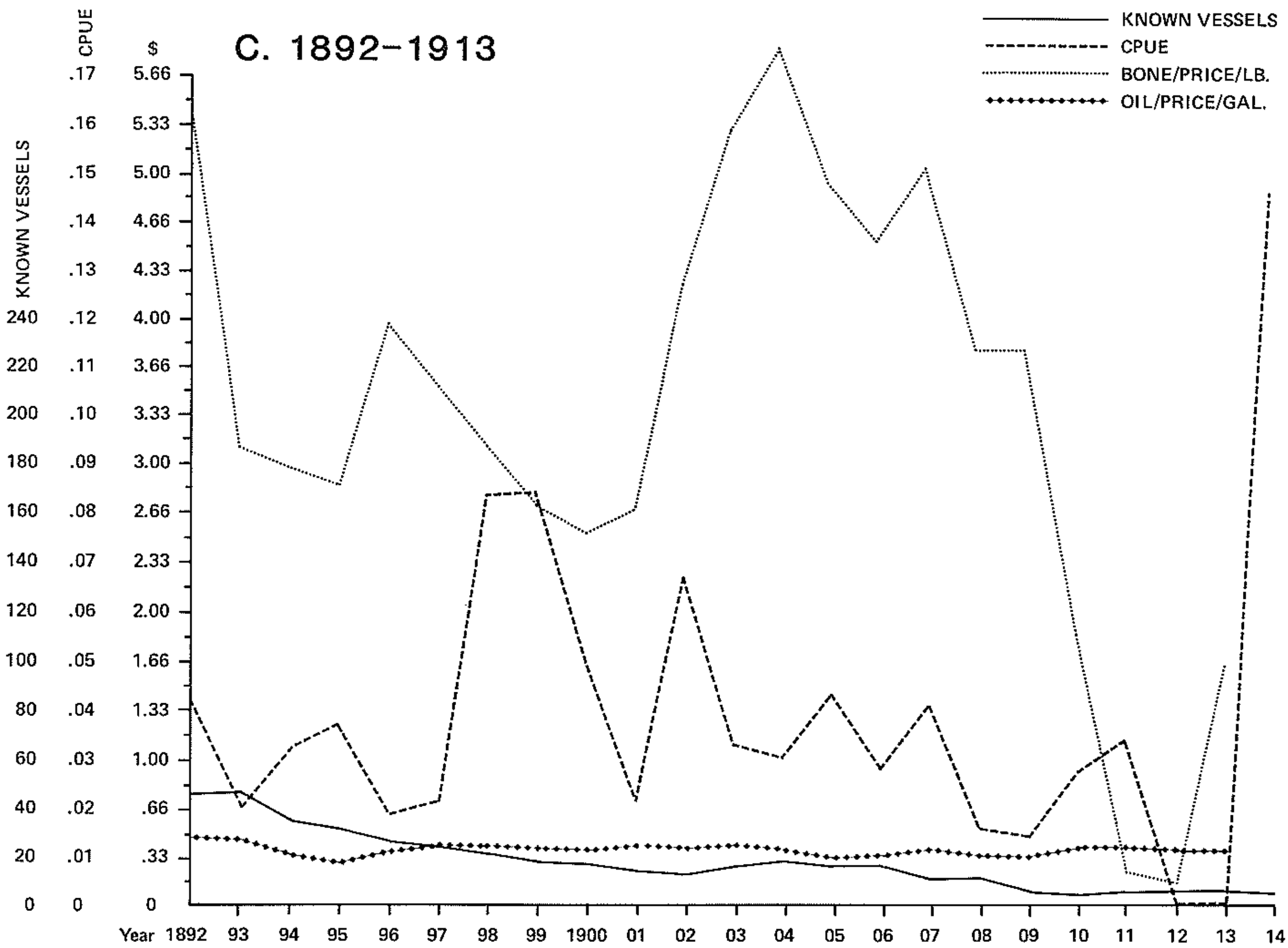


Fig. 2 (*cont.*)

acceptable we were pleasantly surprised to find that they were spread relatively evenly throughout the duration of the fishery, representing about 20% of the voyages to the western Arctic in each year.

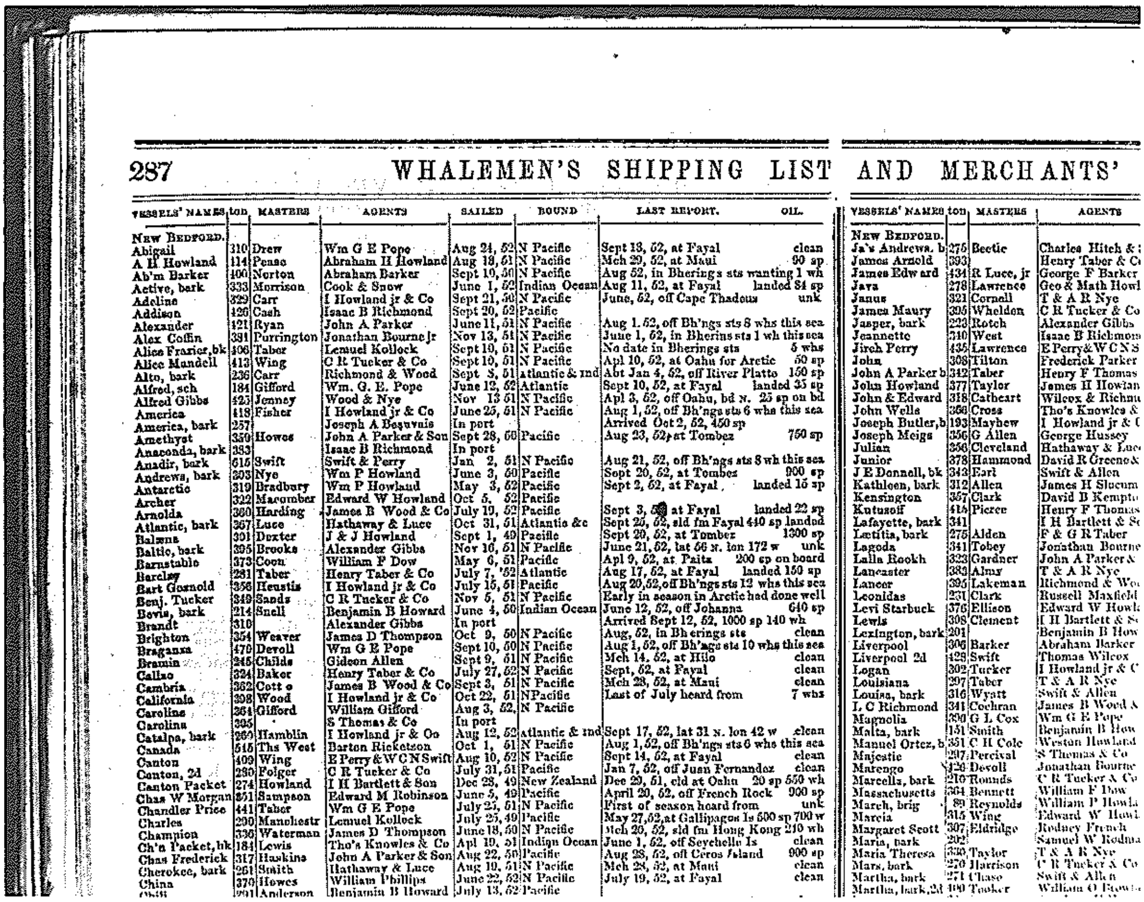
While the work mentioned above was going on we were also at work designing a useful format for the data extraction. Our aim was to extract and store as much information from the documents as possible (bearing in mind the constraints of budget and time) not only including information on the bowhead but also on other fauna that might affect the hunting effort. Fig. 5 gives our format for the 80-line data sheet and computer card.

A team of six spent 36 person-months extracting and encoding more than 66,000 daily observations from documents representing 516 seasonal cruises, which are equal to 19% of the total number of whaling cruises conducted in the western Arctic. For one of the years, 1867, documents from an exceptionally large percentage of the cruises have survived, and we were able to extract data for 28 (33.7%) of the 83 vessels operating in the western Arctic that year.

Because of the necessity of having a large body of reference works and supporting documents available during the actual extraction of data, virtually all of this phase of the project was carried out in the New Bedford Whaling Museum, using either the logbooks and journals directly or microfilm copies of documents held in repositories outside the New Bedford area. To aid speed and accuracy the extractors sat before $1:1\times10^6$-scale aeronautical charts of the area (Fig. 6) which, conveniently, were hachured at each minute of latitude (one nautical mile) and at one- or five-minute intervals of longitude. Also provided were hydrographic charts (for depth and bottom composition information), ice charts, current charts, and American, Canadian and British compendia of sailing directions.

These research aids allowed us to overcome a number of problems in data interpretation that arose from the nature of the documents. Principal among these was the practice among whalemen, once within sight of land, to change from recording their daily positions in degrees and minutes of latitude and longitude to their distance and direction from a visible geographical feature. Thus if, for instance, a position was recorded as '20 miles southwest of King Island', it was a comparatively simple matter, upon consulting the aeronautical charts, to convert this information to 64° 44′ N, 168° 34′ W.

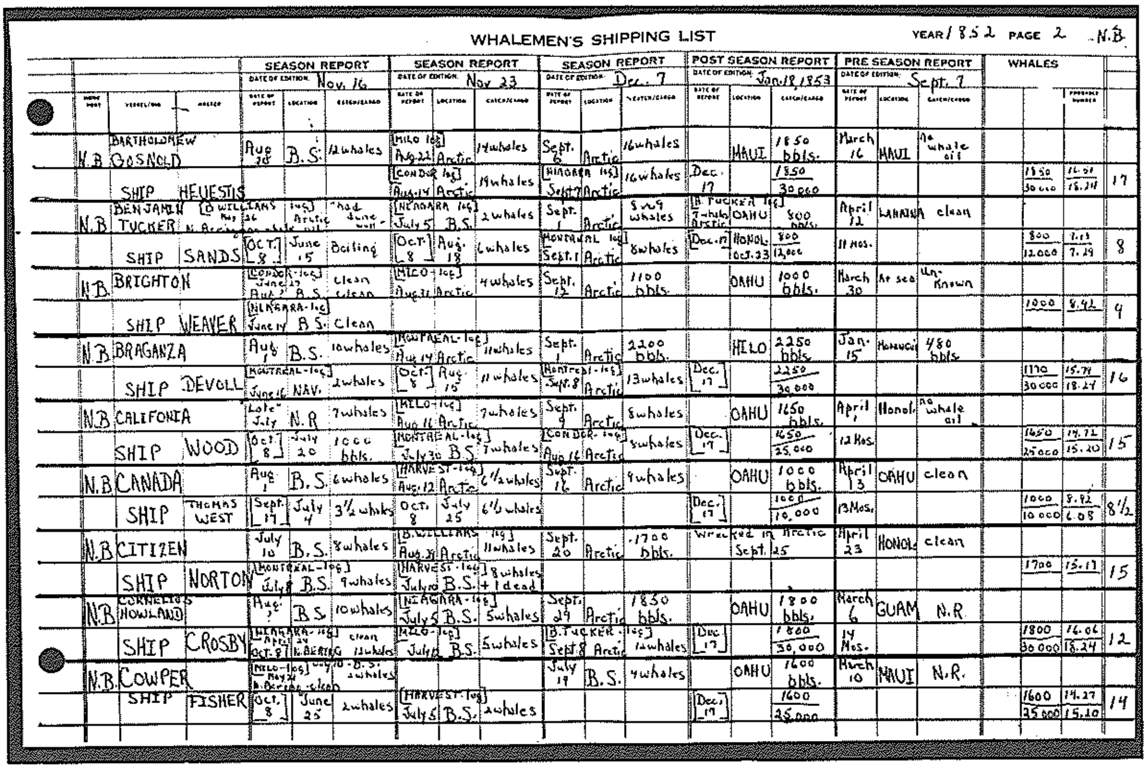
A related problem arose when whalers used obsolete or obscure geographical terminology. Because the landforms of the western Arctic had only been rudimentarily charted when the whalers arrived there (in a few cases the whalers were the discoverers), they quickly developed their own nomenclature for the geographical features of the area or adopted or adapted nomenclature from Russian or British charts. The official committees for geographical names in the United States, Canada, and the Soviet Union have not accepted many of these names for standard usage and others have been substantially



287 WHALEMEN'S SHIPPING LIST AND MERCHANTS'

VESSELS' NAMES	TON	MASTERS	AGENTS	SAILED	BOUND	LAST REPORT.	OIL.

Fig. 3. A page from the *Whalemen's Shipping List and Merchant's Transcript* (courtesy of the New Bedford Whaling Museum).



WHALEMEN'S SHIPPING LIST YEAR/ 1852 PAGE 2 N.B.

	SEASON REPORT	SEASON REPORT	SEASON REPORT	POST SEASON REPORT	PRE SEASON REPORT	WHALES
DATE OF EDITION	Nov. 16	Nov 23	Dec. 7	Jan. 18 1853	Sept. 7	

Fig. 4. Ledger sheet for New Bedford vessels, 1852 (courtesy of the New Bedford Whaling Museum).

changed through translation or transliteration; thus, although they were widely used in the 19th century, they remain obscure today. Consequently, it was necessary to compose a gazetteer of the region's more than 350 obsolete place names for the reference of our data extractors (see, for instance, an abridged version: Bockstoce and Batchelder, 1978).

Line number	Description
1	blank
2–4	document repository number
5–8	document identification number
9–12	vessel identification number
13	sail or auxiliary power vessel
14–17	year of observation
18–19	month of observation
20–21	day of observation
22	latitude: extractor's estimate or logbook data
23–27	latitude
28	longitude: extractor's estimate or logbook data
29–34	longitude
35	wind direction
36	wind velocity
37	visibility in miles
38	ice cover
39–40	fauna seen: none, bowhead, gray whale, humpback, 'whale feed', unspecified, etc.
41–43	number of animals seen
44	sex of animal if taken: male, female, calf, unspecified, etc.
45	type of encounter: seen only, lowered and chased only, struck and lost alive, struck and lost dying, captured and processed, found dead and not processed, etc.
46–48	if processed: barrels of oil yielded
49–52	if processed: pounds of baleen yielded
53–66	second encounter of day: repeat of categories in lines 39–52
67–80	third encounter of day: repeat of categories in lines 39–52

Fig. 5. Data reduction sheet format.

Another difficulty which had to be overcome was the logbook entries that were recorded on days when inclement weather made it impossible for the whalemen to determine their position. If, during periods of fog, snow, gales or overcast skies, they recorded their estimated position, we entered this on our data forms, but often they simply recorded no information on their position. In such cases it was necessary for us to interpolate between previous and succeeding positions, making an educated estimate, tempered by information both from our modern charts and sailing directions and from the logbook's data on wind, sea states, ice conditions and – if they were recorded – on depth, current and bottom characteristics.

Lastly it was occasionally necessary for the data extractors to make subjective judgments from the data when the logbook keeper's remarks were particularly opaque. These judgments were required infrequently and in three categories only: to derive an estimate of visibility; to convert remarks on sea ice into an estimate of its sea coverage; and, when a whale was reported as struck and lost, to judge whether it was moribund (struck and lost dying) or likely to live (struck and lost alive). A struck-and-lost-dying whale was considered to be any whale that had been bombed (struck with a shoulder or darting gun), lanced, or severely wounded by one or more harpoon irons.

As the data extraction progressed, the data sheets were transferred to the Marine Biological Laboratory in Woods Hole, Massachusetts where the information was key-punched onto computer cards, converted to nine-track standard computer tape, and stored on discs (Fig. 7).

ANALYSIS AND RESULTS

Analysis of the data was carried out as follows. First, programs were written to reorder the data originally

Fig. 6. Data extractors at work (courtesy of the New Bedford Whaling Museum).

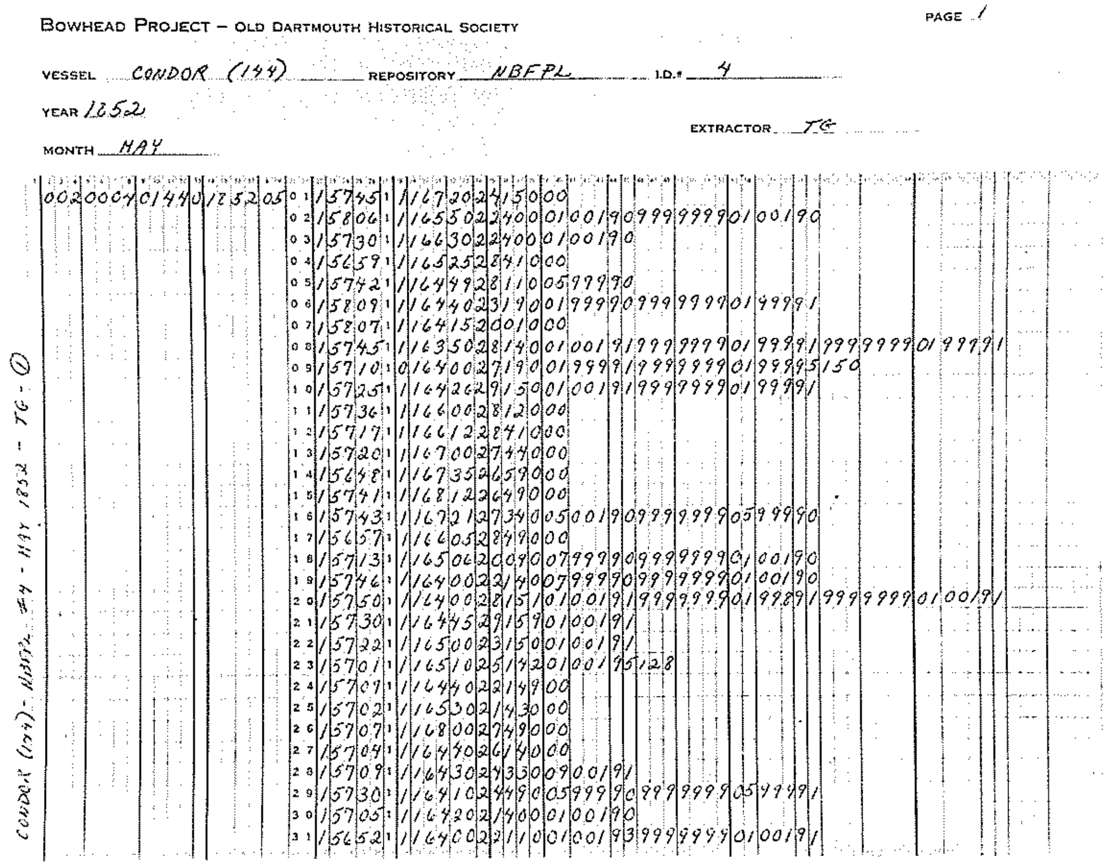


Fig. 7. Sample of data reduction sheet (courtesy of the New Bedford Whaling Museum).

entered onto the computer tapes so that they appeared chronologically. Second, programs were written to provide summaries on an annual or seasonal basis for any information of interest. In September 1979 the data were transferred from the Woods Hole Oceanographic Computer Center to that at the University of California, Santa Barbara. Manipulations of the original data were thenceforth carried out on the Itel AS/6 computer. Summarized data representing annual or seasonal information, were then transcribed onto diskettes and final statistical analyses carried out on an IBM 5110 computer.

Data summaries

Table 1 summarizes the annual whaling activities from 1849 to 1914 (15 whales were taken on the lone voyage in 1848; however, no data on effort were available so this voyage was excluded from our analysis). In the extracted voyages (our data sample), representing approximately 19% of the total voyages, 3,198 whales were caught and 3,573 killed during the entire period. One-third of the total number of whales caught during the entire 66-year period were taken during the first nine years and almost two-thirds during the first 20 years. Even more striking is the observation that one-third of the total number of whales killed were killed during the first six years, and two-thirds during the first 20 years (Fig. 8). These results suggest that the bowhead whale population was rapidly depleted during the first 20 years even though the industry continued to hunt the bowhead in those waters for another 47 years.

Table 2 gives the total catch and kill annually as derived from the logbook records. Annual catches and kills for the entire whaling fleet were calculated by dividing the values in the data sample by the fraction of the voyages those samples represented for that year. From the annual totals we have calculated the weighted cumulative catch and kill. We estimate that during the entire period of commercial pelagic bowhead whaling 16,600 were caught and 18,650 were killed, a figure which accords well with Bockstoce's (1978) preliminary estimate of 19,142 (see also Figs 9 and 10).

Implicit in this analysis is the assumption that the information extracted from logbooks and journals for the 516 cruises that make up our data base is representative of all the cruises to the western Arctic. Although we believe this is a reasonable assumption, a person without an intimate knowledge of these historical documents may believe that their use could lead to bias in our catch and kill estimates. One might suggest, for example, that the logbooks that have survived over this long period of time are a preferred type of record, perhaps being the records of only the most successful voyages or those records that are the most detailed. One might also suggest that there is some connection between the success of the whale hunt and the amount of detail the logkeeper incorporated into the daily entries of the logbook. Contrary to these suggestions, we cannot isolate any reasons for the survival of any one logbook over another (apart from an illustrated logbook, which calls for an artistic judgment on its preservation rather than an historical one), and we have no evidence that a greater number of a specific type of logbook exists. We have logbooks of usually successful whalers who suffered poor voyages; logbooks of unsuccessful whalers who had lucky voyages; highly

(continued on p. 117)

Table 1

Primary data extracted by season, where Kill is the number of whales caught plus those struck and lost dying, Cumcatch and Cumkill are the cumulative values from 1849–1914, Days is the total number of days whaling in all voyages, Docs is the number of documented voyages from which we extracted information and Percent is the proportion of total voyages included in our sample.

Year	Catch	Kill	Cumcatch	Cumkill	Days	Docs	Voyages	Percent
1849	71	80	71	80	499	7	50	14.00
1850	316	380	387	460	2,675	25	136	18.38
1851	142	168	529	628	3,427	33	176	18.75
1852	381	467	910	1,095	5,329	39	224	17.41
1853	101	128	1,011	1,223	3,402	27	168	16.07
1854	21	26	1,032	1,249	1,178	9	45	20.00
1855	0	1	1,032	1,250	232	3	7	42.86
1856	0	0	1,032	1,250	41	1	9	11.11
1857	12	13	1,044	1,263	153	2	12	16.67
1858	83	90	1,127	1,353	1,966	19	97	19.59
1859	78	85	1,205	1,438	1,966	20	86	23.26
1860	43	45	1,248	1,483	1,238	10	49	20.41
1861	65	68	1,313	1,551	1,205	10	45	22.22
1862	45	47	1,358	1,598	766	6	20	30.00
1863	74	78	1,432	1,676	1,194	9	35	25.71
1864	94	103	1,526	1,779	2,148	19	80	23.75
1865	103	133	1,629	1,912	2,137	19	84	22.62
1866	149	160	1,778	2,072	3,307	24	81	29.63
1867	191	202	1,969	2,274	4,172	28	83	33.73
1868	114	129	2,083	2,403	2,367	15	60	25.00
1869	89	97	2,172	2,500	1,765	11	42	26.19
1870	162	169	2,334	2,669	2,224	15	55	27.27
1871	29	31	2,363	2,700	1,093	10	43	23.26
1872	42	50	2,405	2,750	1,118	9	35	25.71
1873	21	21	2,426	2,771	794	5	35	14.29
1874	15	15	2,441	2,786	539	3	19	15.79
1875	30	30	2,471	2,816	367	3	20	15.00
1876	3	4	2,474	2,820	184	1	19	5.26
1877	53	57	2,527	2,877	728	5	23	21.74
1878	9	10	2,536	2,887	460	3	24	12.50
1879	7	9	2,543	2,896	195	1	29	3.45
1880	59	60	2,602	2,956	482	3	23	13.04
1881	17	19	2,619	2,975	189	1	22	4.55
1882	15	15	2,634	2,990	265	2	32	6.25
1883	3	3	2,637	2,993	591	3	39	7.69
1884	6	7	2,643	3,000	354	2	38	5.26
1885	27	28	2,670	3,028	767	4	41	9.76
1886	12	13	2,682	3,041	531	4	41	9.76
1887	15	17	2,697	3,058	523	3	36	8.33
1888	15	17	2,712	3,075	843	5	39	12.82
1889	4	5	2,716	3,080	711	4	42	9.52
1890	13	13	2,729	3,093	668	4	39	10.26
1891	41	42	2,770	3,135	1,133	7	39	17.95
1892	35	36	2,805	3,171	843	5	44	11.36
1893	16	16	2,821	3,187	790	5	44	11.36
1894	30	32	2,851	3,219	958	7	33	21.21
1895	22	22	2,873	3,241	602	7	30	23.33
1896	14	14	2,887	3,255	761	6	25	24.00
1897	19	19	2,906	3,274	904	6	23	26.09
1898	54	57	2,960	3,331	649	5	20	25.00
1899	51	52	3,011	3,383	611	4	16	25.00
1900	28	28	3,039	3,411	567	4	16	25.00
1901	9	9	3,048	3,420	435	4	13	30.77
1902	33	33	3,081	3,453	484	3	12	25.00
1903	19	19	3,100	3,472	580	3	15	20.00
1904	12	13	3,112	3,485	402	3	17	17.65
1905	27	29	3,139	3,514	624	5	16	31.25
1906	9	9	3,148	3,523	324	4	16	25.00
1907	19	19	3,167	3,542	472	3	11	27.27
1908	9	9	3,176	3,551	571	3	11	27.27
1909	2	2	3,178	3,553	142	1	5	20.00
1910	4	4	3,182	3,557	147	1	4	25.00
1911	6	6	3,188	3,563	179	1	5	20.00
1912	0	0	3,188	3,563	84	1	5	20.00
1913	0	0	3,188	3,563	92	1	5	20.00
1914	10	10	3,198	3,573	69	1	4	25.00

Table 2

Estimated catch and kill by season for the entire pelagic whaling fleet, where WCATCH is the weighted catch (Catch × WFACTOR), WKILL is the weighted kill (Kill × WFACTOR), WCUMCAT and WCUMKIL are the cumulative values from 1849–1914 and WFACTOR is the weighting factor derived as the inverse of Percent from Table 1

Year	WCATCH	WKILL	WCUMCAT	WCUMKIL	WFACTOR
1849	507	571	507	571	7.14
1850	1,719	2,067	2,226	2,639	5.44
1851	757	896	2,984	3,535	5.33
1852	2,188	2,682	5,172	6,217	5.74
1853	628	796	5,800	7,013	6.22
1854	105	130	5,905	7,143	5.00
1855	0	2	5,905	7,146	2.33
1856	0	0	5,905	7,146	9.00
1857	72	78	5,977	7,224	6.00
1858	424	459	6,401	7,683	5.11
1859	335	366	6,736	8,049	4.30
1860	211	221	6,947	8,269	4.90
1861	293	306	7,240	8,575	4.50
1862	150	157	7,390	8,732	3.33
1863	288	303	7,677	9,035	3.89
1864	396	434	8,073	9,469	4.21
1865	455	588	8,529	10,057	4.42
1866	503	540	9,031	10,597	3.38
1867	566	599	9,598	11,196	2.96
1868	456	516	10,054	11,712	4.00
1869	340	370	10,393	12,082	3.82
1870	594	620	10,987	12,702	3.67
1871	125	133	11,112	12,835	4.30
1872	163	194	11,275	13,029	3.89
1873	147	147	11,422	13,176	7.00
1874	95	95	11,517	13,271	6.33
1875	200	200	11,717	13,471	6.67
1876	57	76	11,774	13,547	19.00
1877	244	262	12,018	13,810	4.60
1878	72	80	12,090	13,890	8.00
1879	203	261	12,293	14,151	29.00
1880	452	460	12,746	14,611	7.67
1881	374	418	13,120	15,029	22.00
1882	240	240	13,360	15,269	16.00
1883	39	39	13,399	15,308	13.00
1884	114	133	13,513	15,441	19.00
1885	277	287	13,789	15,728	10.25
1886	123	133	13,912	15,861	10.25
1887	180	204	14,092	16,065	12.00
1888	117	133	14,209	16,197	7.80
1889	42	53	14,251	16,250	10.50
1890	127	127	14,378	16,377	9.75
1891	228	234	14,607	16,611	5.57
1892	308	317	14,915	16,927	8.80
1893	141	141	15,055	17,068	8.80
1894	141	151	15,197	17,219	4.71
1895	94	94	15,291	17,313	4.29
1896	58	58	15,349	17,372	4.17
1897	73	73	15,422	17,445	3.83
1898	216	228	15,638	17,673	4.00
1899	204	208	15,842	17,881	4.00
1900	112	112	15,954	17,993	4.00
1901	29	29	15,983	18,022	3.25
1902	132	132	16,115	18,154	4.00
1903	95	95	16,210	18,249	5.00
1904	68	74	16,278	18,323	5.67
1905	86	93	16,365	18,415	3.20
1906	36	36	16,401	18,451	4.00
1907	70	70	16,471	18,521	3.67
1908	33	33	16,504	18,554	3.67
1909	10	10	16,514	18,564	5.00
1910	16	16	16,530	18,580	4.00
1911	30	30	16,560	18,610	5.00
1912	0	0	16,560	18,610	5.00
1913	0	0	16,560	18,610	5.00
1914	40	40	16,600	18,650	4.00

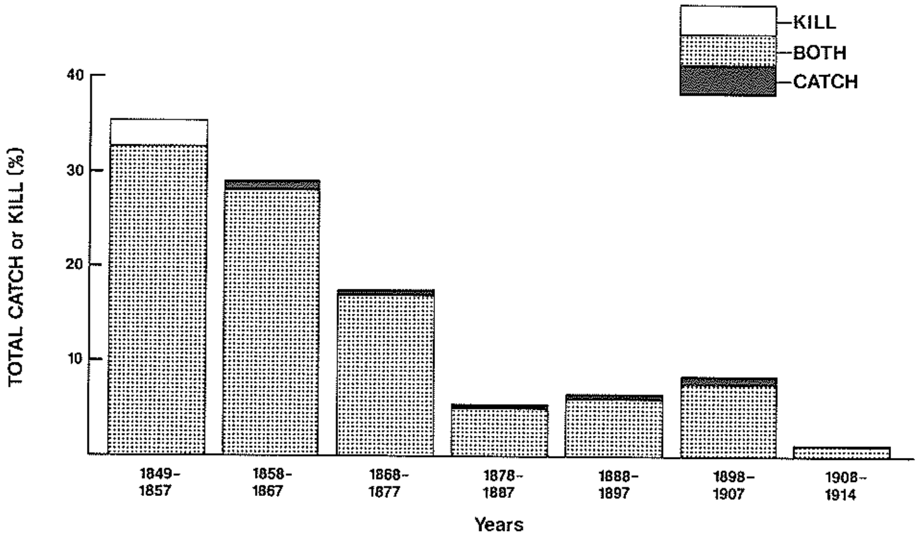


Fig. 8. Percentage of the total catch and kill by periods. The CATCH in each decade is plotted as a percentage of the TOTAL CATCH for the entire period; similarly, the KILL in each decade is shown as a percentage of the TOTAL KILL. (The shaded portion labeled BOTH indicate overlap.) Thus, in the first decade, the percentage of KILL exceeded the percentage CATCH, whereas in all subsequent decades the percentage CATCH is greater than percentage KILL.

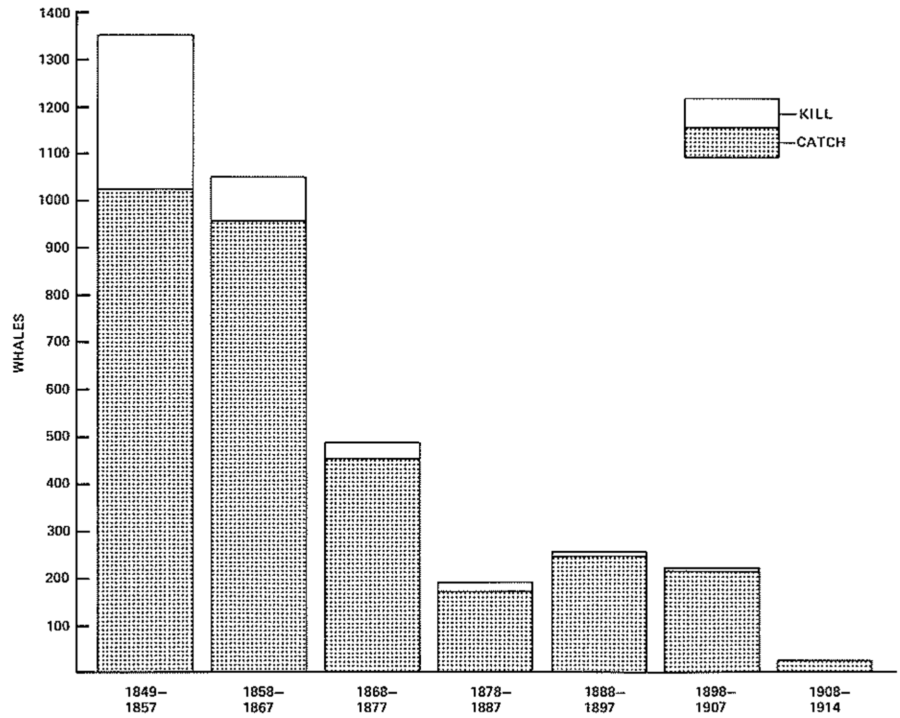


Fig. 9. The catch and kill by period from the primary data, representing 19% of the known voyages from 1849 to 1914.

detailed logbooks of unsuccessful voyages; and poorly detailed logbooks of successful voyages. Furthermore, the relationship between the abilities of a captain and his crew to catch whales and the desire of a single man (usually not the ship's captain) to maintain detailed records is an obscure one at best. But the relationship is even more tenuous because a significant fraction of the data was derived from journals (personal records kept by anyone aboard ship) and not from the official logbooks of the ships. One of our most detailed journals, kept by Captain Frederick A. Barker, was of a particularly unsuccessful voyage. Thus we believe that the information from these historical documents does not bias our estimates and that our data base is a representative one.

Seasonality of effort and catch

Table 3 lists the number of whales caught per month and period as compiled from our data sample, together with a total by month over all years. The logbook records indicate that about 25%, a sizeable fraction of the total whales caught, were taken before July. Most whales, however, were caught during July, August and September (71%). Nevertheless, the percentage taken early in the season declined abruptly after the second decade, reflecting the depletion of the whales in the lower latitudes. In the first decade 33% of the whales were caught before July, in the second decade 28%; in the third, fifth, sixth and seventh decades, 8%, 11%, 9%, and

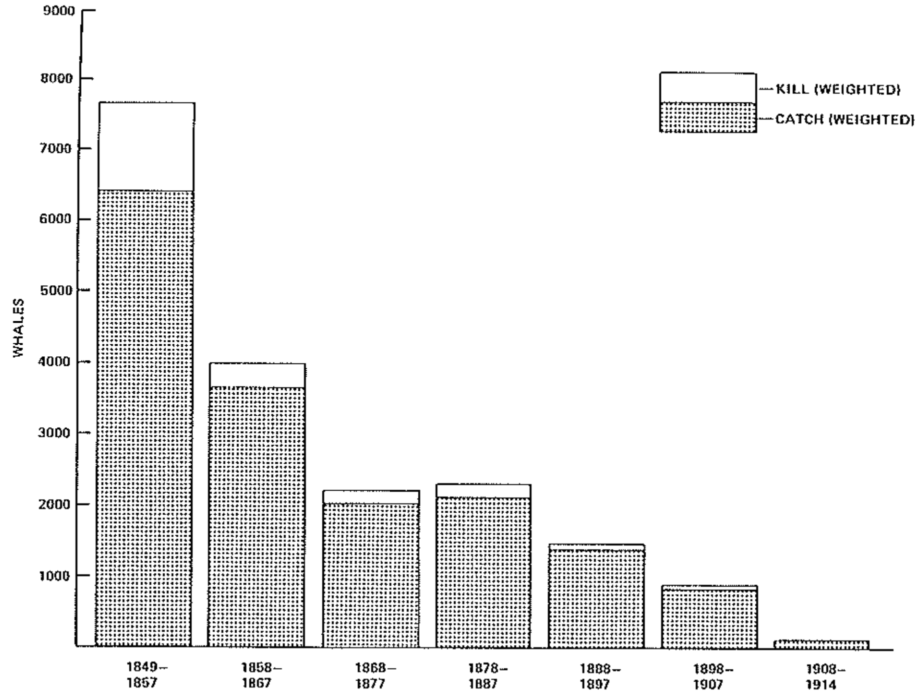


Fig. 10. The weighted catch and kill by period, estimated to be the total catch and total kill from 1849 to 1914.

Table 3

Catch by month and 10-year period

	Period														Total 1849–1914	
	1849–58		1859–68		1869–78		1879–88		1889–98		1899–1908		1909–14			
Month	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
April	1	< 1	3	< 1	2	< 1	4	2	2	1	2	1	—	—	14	< 1
May	81	8	61	6	15	3	25	15	14	7	13	5	1	3	210	7
June	264	25	205	22	30	5	18	11	6	3	7	3	—	—	530	17
July	276	26	100	11	6	1	18	11	5	2	32	12	—	—	437	14
August	338	32	295	32	107	19	37	22	66	32	111	43	12	39	966	30
September	82	8	228	25	332	60	49	29	92	44	74	28	14	45	871	27
October	2	< 1	30	3	65	12	19	11	24	11	22	8	4	12	166	5
November	—	—	2	< 1	—	—	—	—	—	—	—	—	—	—	2	< 1
December	—	—	1	< 1	—	—	—	—	—	—	—	—	—	—	1	< 1
Total	1,044		925		557		170		209		261		31		3,197	

3% respectively, were taken before July. Only the fourth decade's data repeat the early trends, with 28% taken before July (and this probably reflects the introduction of the more maneuverable steam-auxiliary vessels), but this decade had the smallest total catch except for the period after 1909.

Changes in the location of catch and effort

For the purpose of this report we subdivided the Bering, Chukchi and Beaufort Seas into 19 regions which we constructed empirically to segregate areas where the greatest concentrations of whaling activity had occurred.

Figs 11A–H show the distribution of the catch and ship days recorded in the logbooks read for the entire whaling period. Figs 11A–G give this distribution by decade, and Fig. 11H gives the distribution for the entire pelagic whaling era. The distributions indicate that the bowhead population was essentially eliminated from a large part of its original range by 1914. In the first decade (1849–1858), a sizeable number of whales were caught south of 60° N: off the Asian coast, 36 were taken between 54° and 57° N, 38 between 57° and 60° N; 23 were taken in the Abyss area between Asia and North America, and a total of 105 whales were taken below 60° N. During the second decade (1859–1868), only 27 whales were taken there, and most of these in the Abyss area.

During the third decade (after 1868) whales were caught only occasionally below 60° N, and only one was caught below there after 1888. Similarly, after 1878 the whales seem to have been essentially eliminated from the region between 60° and 63° N, few having been caught there even though ships continued to spend a considerable number of days in this region. The whales were also gradually eliminated from the Anadyr and Narrows areas, between 63° and 66° N: although 292 whales were caught in this region in the first decade (1849–1858) and 130 in the second (1859–1868), only 23 were caught there in the third decade (1869–1878), 20 in the fourth (1879–1888), 10 in the fifth (1889–1898), 15 in the sixth (1899–1908) and none in the last period (1909–1914).

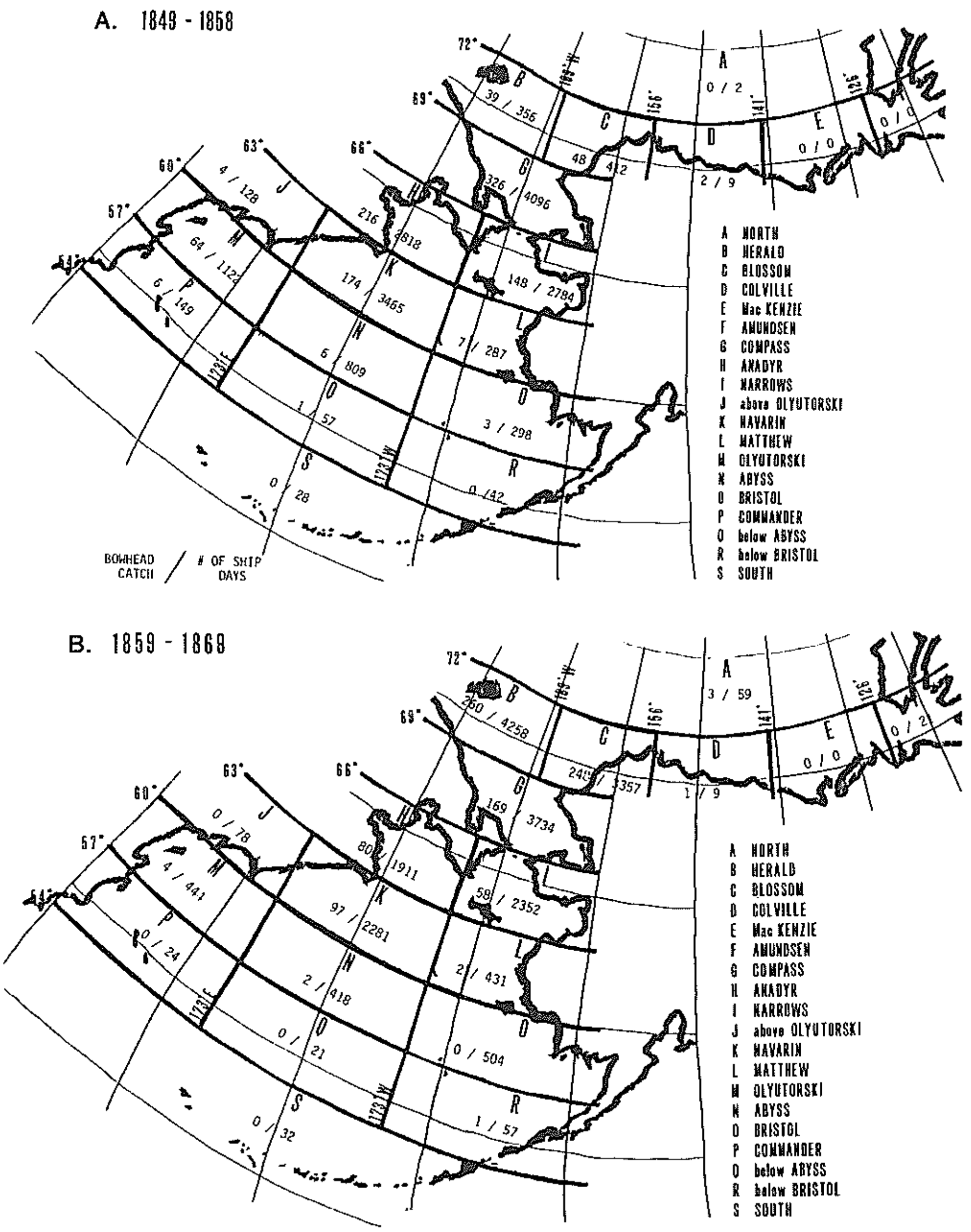


Fig. 11. Distributions of catch and ship-days whaling by period. Values plotted are: bowhead catch/number of ship days.

The catch of bowhead whales during the first period of exploitation (1849–1858) indicates that this species was taken from April through October as far south as 54° N, from the coast of Asia to 173° W, and as far north as 69° N in the southern Chukchi Sea. As the population was reduced, however, the whalers were forced to push farther and farther north and east to maintain their catch levels, finally reaching as far as 73° N and as far east in the Canadian Arctic as 114° W. We take this entire area as the original range of the bowhead: in the southern Bering Sea above 54° N from the coast of Asia to 173° W; throughout the northern Bering Sea above 60° N; throughout the Chukchi and Beaufort Seas; and perhaps scattered in contiguous waters.

Because in the first period of commercial exploitation the whalers successfully caught bowheads in the north and southwest Bering Sea throughout the spring, summer and fall, it seems reasonable to assume that the bowheads in these areas were on feeding grounds and not merely in a migratory phase. We believe therefore, that the records we have analyzed suggest that the pre-exploitation feeding areas were vastly larger than contemporary ones, and that the bowhead seems to have been eliminated, for reasons not completely understood, from the use of large parts of its once greater range.

It is possible that the western Arctic bowhead population was originally made up of several discrete subpopulations, each with its own feeding area. This is consistent with the observation that the whales appear to have been eliminated from large parts of the original feeding grounds. It is equally possible, however, that the bowheads were a single population that responded rapidly to the presence and activities of the whaling ships, and fled areas of intensive hunting, receding farther and farther north and east to the comparatively safer areas either near the ice or where exploitation had not yet occurred. By the end of the 19th century the whaling fleet, through the use of auxiliary power and Arctic wintering sites (such as Herschel Island), had reached all known areas where the bowheads traveled and fed.

The whales' only refugium then remained amid the pack ice (where during their spring migration they were

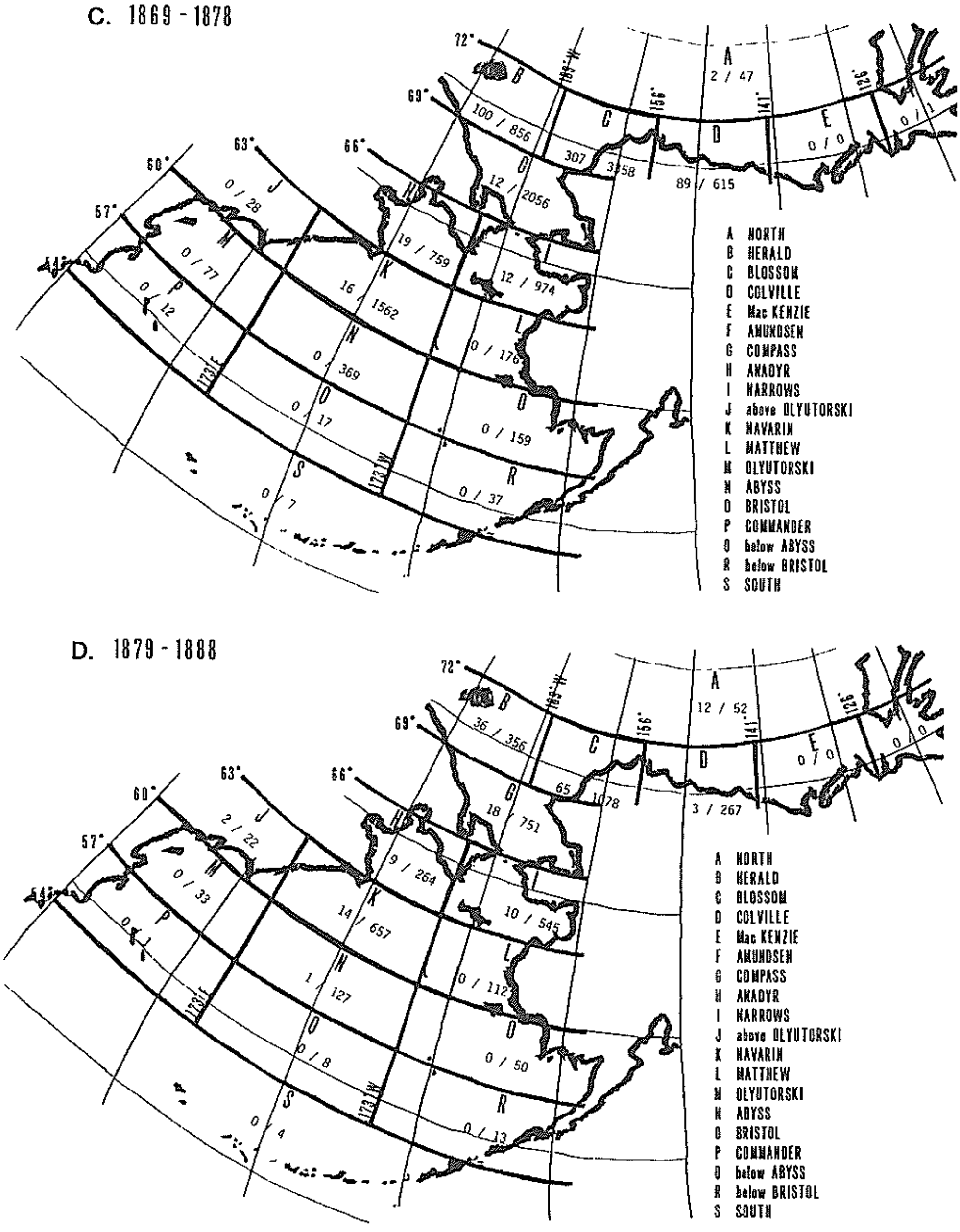


Fig. 11 (*cont.*)

prey to the shore-based whalers of northwest Alaska). This suggests that the response of the bowhead to the intensive hunting by the whaling ships was to restrict their entire annual migration and remain as near as possible to the relative safety of the pack ice. This is speculative, for it is impossible from the data on hand to determine whether there were distinct subpopulations of bowhead or one single well-mixed population. Nevertheless it is possible that the great contraction in the feeding areas of the modern population (in comparison to the 1847 population's feeding area), coupled with the modern Eskimo shore-based hunt may be important factors in the failure of the species to have increased significantly more than six decades after the last whaling ships hunted in the western Arctic.

In summary, after ten years of pelagic whaling, the bowhead was apparently eliminated from its habitats along the Asian coast; few whales were caught below 60° N after 20 years; few below 63° N after 30 years, and few below 66° N after 40 years. After 40 years, bowheads were caught almost exclusively either as they passed near Bering Strait, or in the Chukchi and Beaufort Seas later in the season.

Whaling effort

Estimates of the abundance and distribution of populations of wild animals involve sampling methods that require some measure of the searching effort, a requirement which has been a primary limitation of the reliability of the estimates of populations of marine mammals and marine fishes. Where direct measurements are lacking, scientists have attempted to determine long-term time series for animal populations by analyzing the records of commercial hunting. The longest historical documentation of any wildlife population is the Hudson Bay Company's fur trade records. First analyzed by Elton (1942), they chronicle more than 100 years of the catch of several terrestrial mammals. Although the Hudson Bay fur trading records are of great interest, they contain no direct measure of hunting effort. Elton and others have assumed that the effort of the hunters (and numbers of

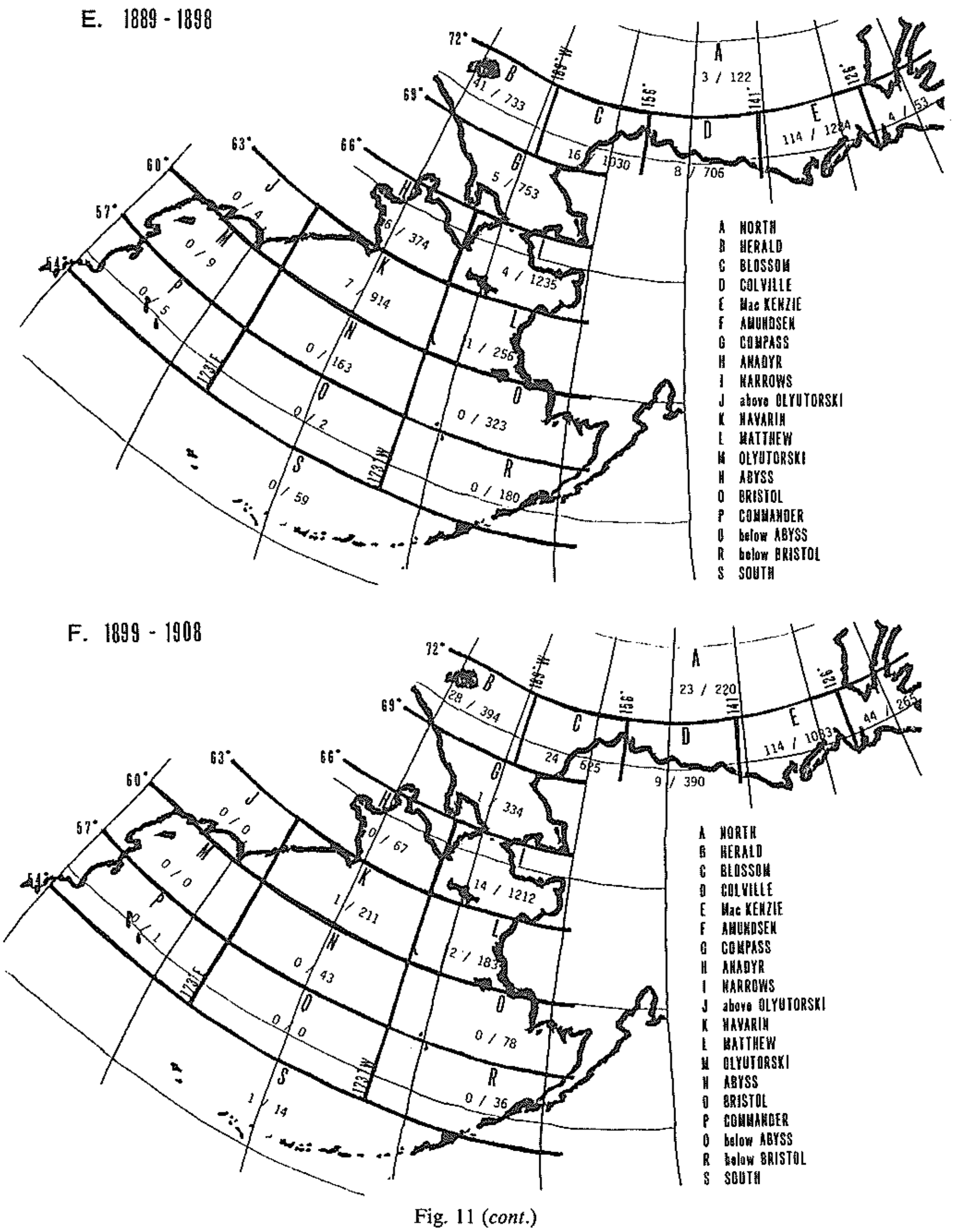


Fig. 11 (*cont.*)

their traps) always greatly exceeded the numbers of prey that might be caught, so that effort could be viewed as large and constant and could be ignored as a factor in the observed temporal patterns of catch. That is, they assumed, with little basis in fact, that changes in catch were totally due to changes in population abundance.

In previous attempts to reconstruct population histories of marine mammals from historical records, the measure of effort has been imprecise (the number of ships hunting in an area per year has, for instance, merely been used as the indicator), thus greatly limiting the usefulness of the data.

As is well known among those who study fisheries and marine mammals, DeLury (1947) suggested that estimates of the abundance of a population can be made assuming that, for a given population size, there is a constant relationship between the number of animals caught and the effort expended in catching them. Changes in the catch per unit effort, therefore, are a direct index of population abundance. The assumption that this relationship is constant, as DeLury noted, is 'seriously open to doubt, and must be tested carefully against observations before any conclusions are based on it'.

Thus those interested in determining the present and past abundance of marine mammals have been confronted with a dilemma. The animals are difficult to count, there are few long-term records, and the few that exist lend themselves only to relatively poor estimates of effort, allowing no means for testing whether the relationship between catch and effort remains constant over time. It is generally assumed that catch per unit effort will decrease monotonically as the population of prey decreases.

The records that we have accumulated on the bowhead whale have the distinct advantage of offering one of the best measures of hunting effort over a long period of time. In fact, the 66-year record we present here represents both one of the longest detailed mammalian population records in existence and one of the best long-term records of hunting and catch effort.

Where analyses are made of contemporary fisheries under direct observation, effort is usually reported as the

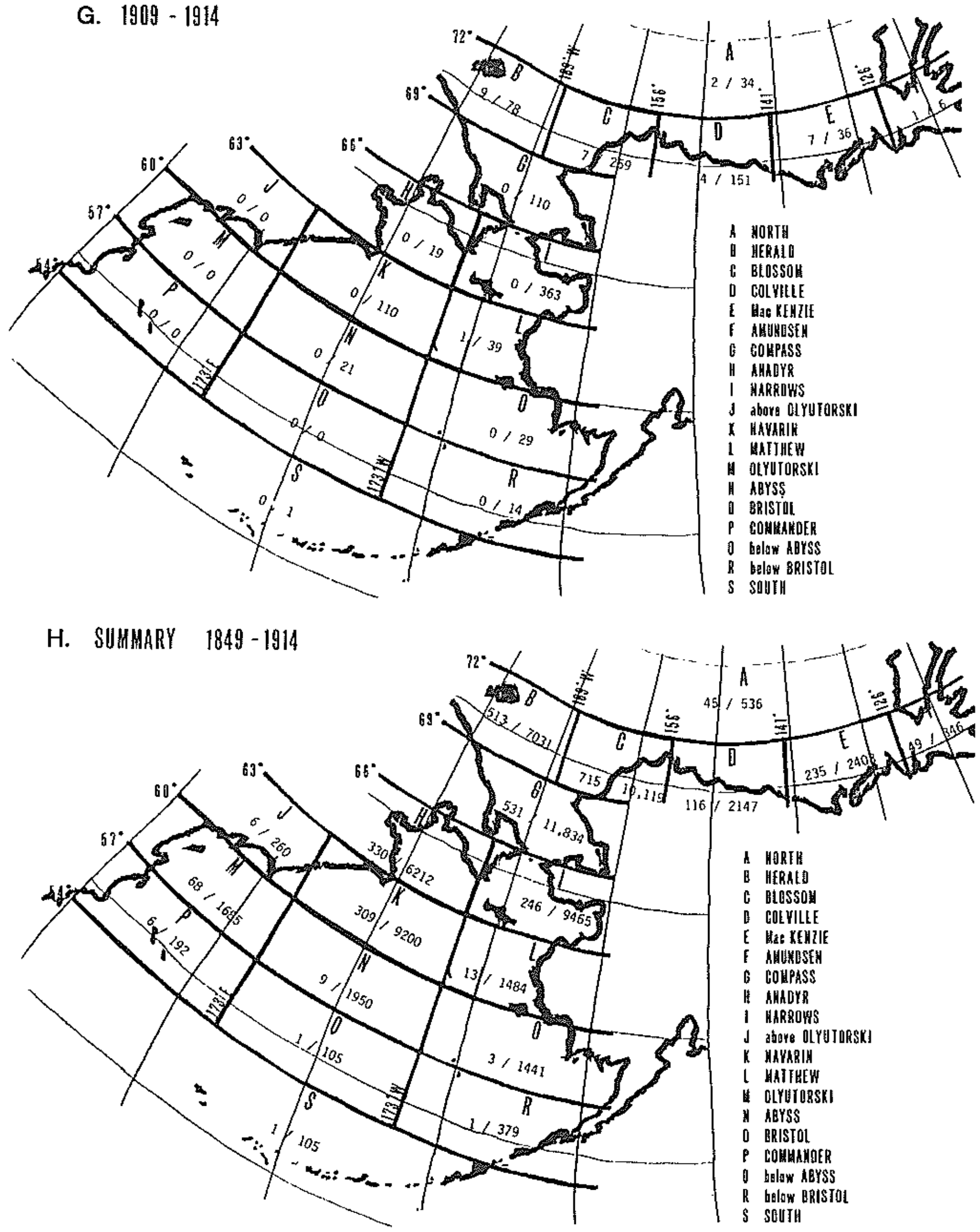


Fig. 11 (*cont.*)

catchers' effective days' work, sometimes weighted to account for non-working periods. In previous attempts to use historical records, the measures usually have been limited to the number of ships per year, with little account taken of the number of days whaling per ship or of the changes in techniques available. In contrast, the data reported here yield measures of effort based on days of effort.

Whaling effort as number of ship-days

From the daily observations in the whaling logbooks, we are able to determine the total number of days whaling of each voyage, and the simplest measure of effort we can provide is the total number of ship-days whaling per year. Because this is of interest to those who wish to compare our results with other studies that use this definition of effort, we use the total number of days whaling as one measure of effort to estimate the 1847 (pre-exploitation) bowhead whale population.

The catch per unit effort (CPUE), defined as the number of whales caught per ship-day, is shown in Fig. 12. It can be seen (Tables 1 and 2; Figs 2A–C and 13) that CPUE varies greatly, in contrast to the usual assumption that the effort remains constant but the catch declines as the population size declines. In Fig. 14 we have plotted CPUE and kill per unit effort (KPUE, defined as kill per ship-day) from 1849 to 1914 and inserted the available information (derived from historical newspaper accounts, principally) about whalers' perceptions of the availability of the whales and of the weather and ice conditions. We present these data recognizing that they are impossible to control statistically. Nevertheless, they do suggest that foul weather and heavy ice, as the whalers perceived them, hampered their hunting and, conversely, good weather and little ice contributed to their success.

We wonder, too, whether the bowheads quickly learned to avoid the ships in the very first years of the fishery; for the rapid decline of the CPUE from 1849 to 1854, accompanied by reports as early as 1851 that the whales were 'scarce and shy' may well indicate that the whales were adapting their behavior to this new threat.

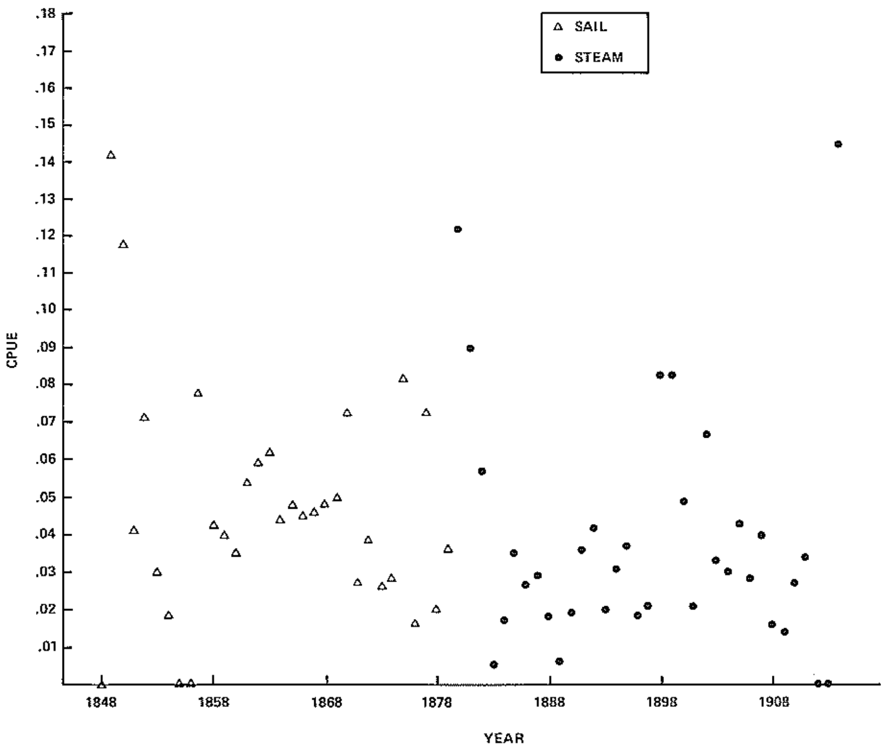


Fig. 12. Catch per unit effort (CPUE) versus time, where SAIL indicates sailing ship effort only and STEAM indicates both sailing and steam ship effort.

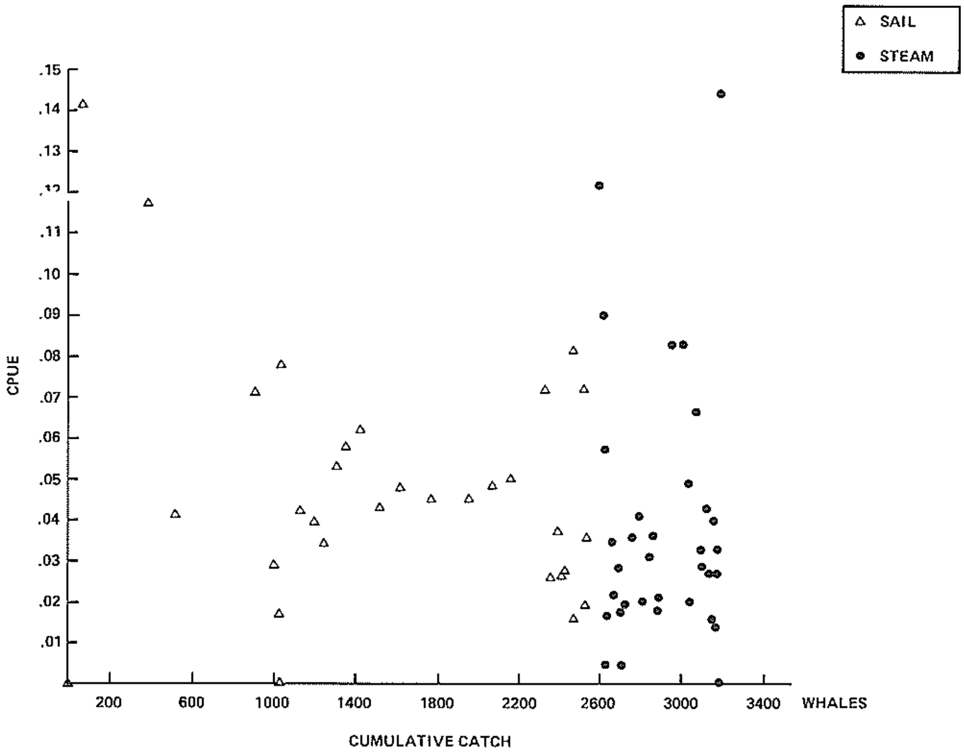


Fig. 13. CPUE versus the cumulative catch, where SAIL indicates sailing ships only and STEAM indicates both sailing and steam ships.

These figures suggest that the whalers did not operate on the naive policy that they would continue hunting at a high level regardless of the abundance of whales, nor were they immune to the vagaries of ice and weather. The plot of CPUE over time (Fig. 12) shows that there are periods of rise and fall. For example, CPUE is very high in 1849, and then declines steadily to a low in the mid-1850s, then increases again, only to decline. This rise and fall occurs at least four times during the whaling era. It suggests that the whalers annually made a rational decision about whether or not to pursue the whales in the western Arctic based on the success or failure of the ships there in the immediately preceeding years.

Thus, after a single ship first located and caught a number of bowheads in 1848 and a small fleet did as well in 1849 (resulting in a high CPUE), more and more ships

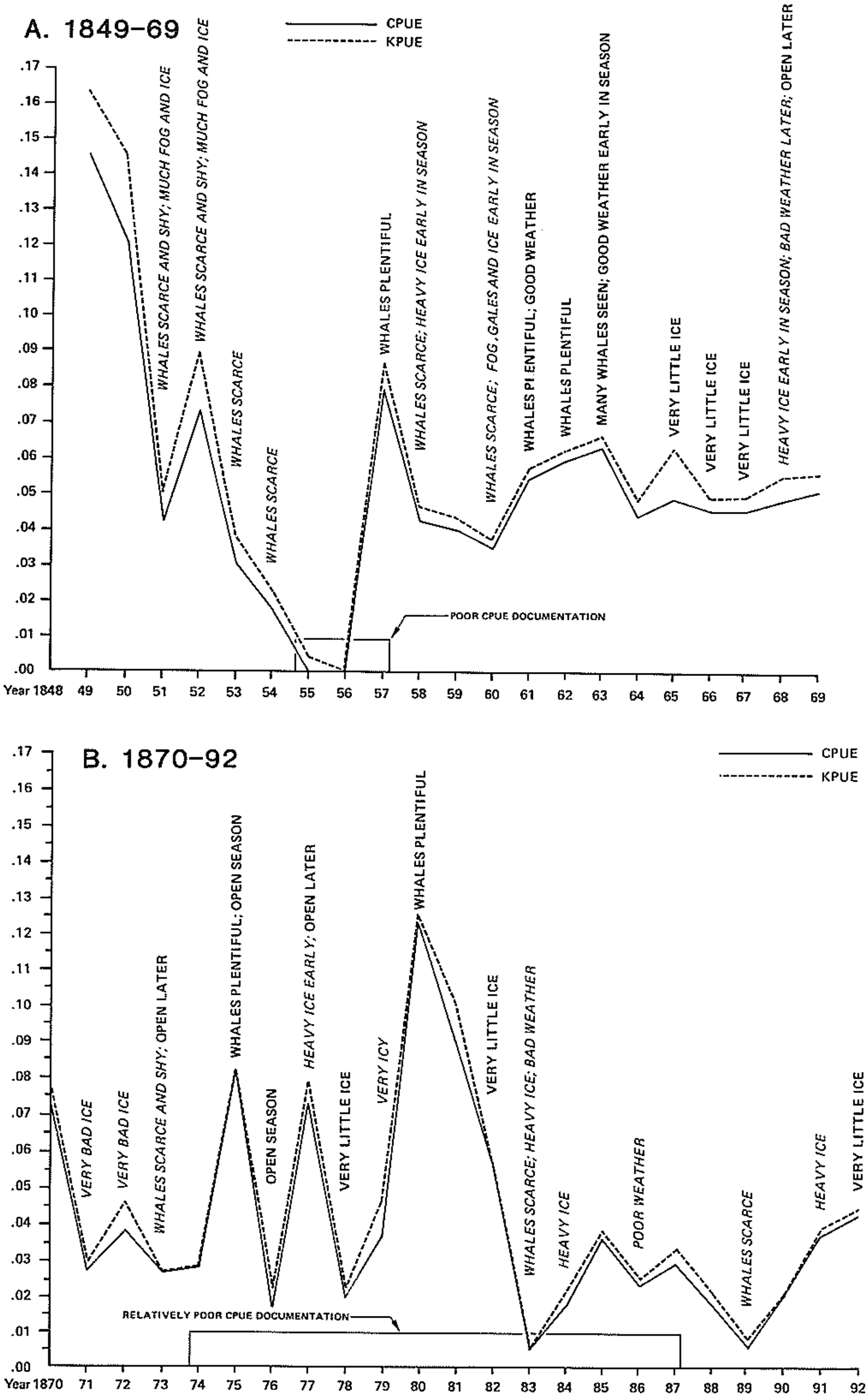


Fig. 14. Catch per unit effort (CPUE) and kill per unit effort (KPUE) versus time, annotated by whalers' reports on availability and environmental conditions.

joined the effort until, within 10 years, there was a great decline in the catch and in the CPUE. Following this was a short period (1855–1857) when only a few ships sought the bowheads in the western Arctic. But when, in 1857, they pushed farther into the Arctic, they again caught many whales, increasing the CPUE, leading to a subsequent increase in the number of ships and number of ship-days, another decline in CPUE, and another decline in the number of ships. The pattern repeats itself throughout the whaling era, suggesting that the whalemen followed a rational if informal strategy in deciding whether to invest their resources in the risk of an Arctic cruise. Any real group of fishermen, and for that matter many natural predators, could be expected to follow this procedure rather than to invest heavily in energy, effort and time regardless of the recent success of the hunt.

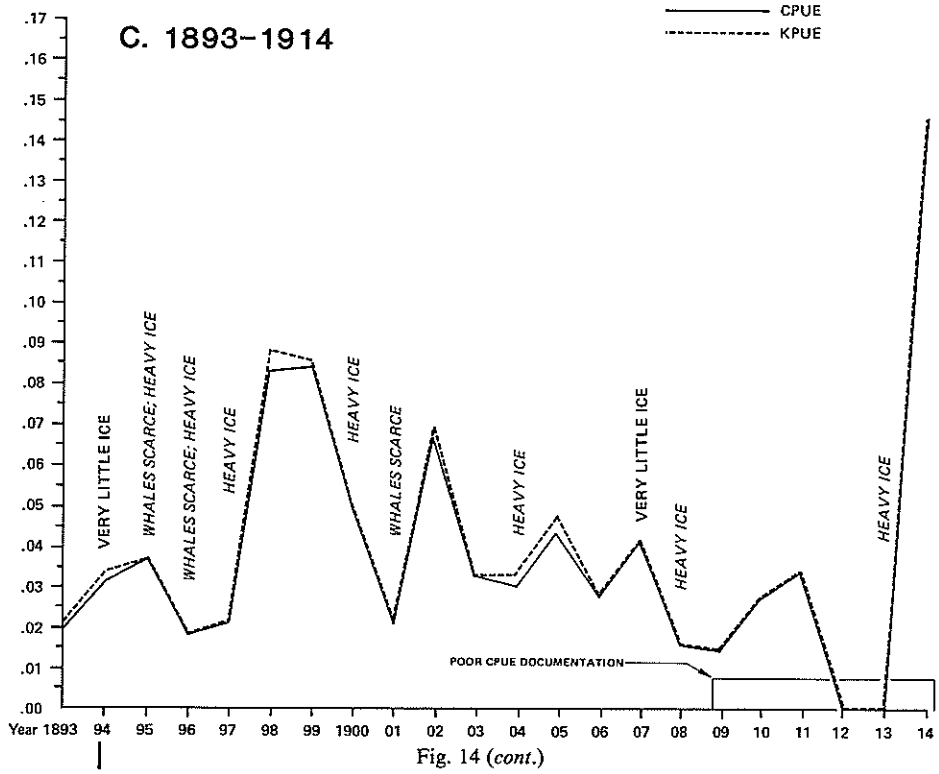


Fig. 14 (*cont.*)

Correcting the effort for weather conditions

Because, as we have noted, weather and ice conditions apparently affected the hunting effort, it is fortunate that the logbook records allow us to make corrections for those periods of time in which the weather prevented whaling. Once the whaleships reached their hunting ground there was relatively little time when the ships were not ready or able to chase a whale if it were sighted. The logbooks make clear that under almost all conditions a lookout was kept and the crew was ready to give chase if a whale appeared. Thus the primary limitations on the chase were the weather and ice.

It is not clear from direct written statements in the logbooks what weather and ice conditions made whaling impossible. We have therefore analyzed the records in several ways, and each of these are used later in estimates of the pre-exploitation population.

Two types of corrections were made for the weather conditions from the logbook data. First, an analysis was carried out to determine those combinations of weather conditions (ice, wind and visibility) under which no whales were ever caught during the 66-year period examined. These analyses show, for example, that only four whales were caught when the ice covered five-eighths of the visible ocean, and only a small percentage was caught when the ice covered one-half of the visible ocean. A few whales (22) were caught under visibilities of less than one mile; but these occurred under calm conditions with relatively little ice cover. Few whales (15) were caught under wind condition 7 (a strong gale), and only 19 under wind condition 6 (a moderate gale). For purposes of our analysis we grouped these conditions under the rubric of 'type 1 non-whaling days'. We then made one calculation of the size of the original bowhead population, defining 'type 1 effort' as the total number of whaling days minus the type 1 non-whaling days. The KPUEs used are given in Tables 4 and 5.

Apart from the previous calculation, we then assumed that certain weather and ice conditions would prevent successful whaling. (Not surprisingly, most whales were caught under conditions of moderate winds, moderate visibility and low percentage ice cover. Few were caught under visibilities exceeding five miles, but this indicates the relative rarity of such visibility in the Arctic summers.) We defined 'type 2 non-whaling days' as the days on which either or both of the following extreme conditions occurred: ice coverage of five-eighths or more of the ocean; wind in excess of a 'fresh gale' (wind condition 5). Another set of estimates of the original bowhead population was then calculated, defining 'type 2 effort' as the total number of whaling days minus the type 2 non-whaling days. The KPUEs used are given in Tables 6 and 7.

Estimates of effort using area searched

Because the logbook records provide daily information about both the location of the ship and a measure of visibility, we had originally thought that it might be possible to define effort in terms of the area of ocean searched by the whaling ships. Our examination of the logbook data made clear, however, that the position of a ship on two consecutive days was not a good index of the actual distance the ship traveled. Often ships would sail back and forth in an area where whales were thought to be, and the actual distance sailed was therefore much greater than that indicated by the change in latitude and longitude in a 24-hour period. Because of this problem we adopted a different method of analysis.

For this measure of effort, we conceived of both the ships and whales as floating in a uniform medium in which the area traveled by either could be ignored, and thus only the visible area and the time this area was viewed mattered as a measure of effort. The visible area was defined as a circle with a radius of the visibility listed for a day of observation. An average area seen multiplied by time was calculated for each ship for each year.

Table 4

Kill per unit effort (KPUE) from the data sample and weighted kill per unit effort (WKPUE) using type 1 effort[1]

Year	KPUE	WKPUE	WKPUE/KPUE
1849	0.16032	0.52288	3.26
1850	0.14206	0.37438	2.64
1851	0.04902	0.12009	2.45
1852	0.08763	0.27278	3.11
1853	0.03762	0.10509	2.79
1854	0.02207	0.06436	2.92
1855	0.00431	0.02222	5.16
1856	0.00000	0.00000	1.00
1857	0.08497	0.19697	2.32
1858	0.04578	0.16364	3.57
1859	0.04323	0.12782	2.96
1860	0.03635	0.12129	3.34
1861	0.05643	0.14286	2.53
1862	0.06136	0.13352	2.18
1863	0.06533	0.20856	3.19
1864	0.04795	0.13239	2.76
1865	0.06224	0.19617	3.15
1866	0.04838	0.14122	2.92
1867	0.04842	0.13855	2.86
1868	0.05450	0.13231	2.43
1869	0.05496	0.12500	2.27
1870	0.07599	0.17586	2.31
1871	0.02836	0.07828	2.76
1872	0.04472	0.09901	2.21
1873	0.02645	0.06287	2.38
1874	0.02783	0.06696	2.41
1875	0.08174	0.20833	2.55
1876	0.02174	0.04348	2.00
1877	0.07830	0.19930	2.55
1878	0.02174	0.08696	4.00
1879	0.04615	0.08654	1.87
1880	0.12448	0.38710	3.11
1881	0.10053	0.76000	7.56
1882	0.05660	0.17241	3.05
1883	0.00508	0.00974	1.92
1884	0.01977	0.03211	1.62
1885	0.03651	0.06321	1.73
1886	0.02448	0.04676	1.91
1887	0.03250	0.05556	1.71
1888	0.02017	0.04416	2.19
1889	0.00703	0.01639	2.33
1890	0.01946	0.02579	1.33
1891	0.03707	0.06818	1.84
1892	0.04270	0.08889	2.08
1893	0.02025	0.09467	4.67
1894	0.03340	0.08989	2.69
1895	0.03654	0.09565	2.62
1896	0.01840	0.04651	2.53
1897	0.02102	0.04715	2.24
1898	0.08783	0.19930	2.27
1899	0.08511	0.17391	2.04
1900	0.04938	0.09655	1.96
1901	0.02069	0.03586	1.73
1902	0.06818	0.32039	4.70
1903	0.03276	0.07917	2.42
1904	0.03234	0.04467	1.38
1905	0.04647	0.11197	2.41
1906	0.02778	0.07692	2.77
1907	0.04025	0.06786	1.69
1908	0.01576	0.03169	2.01
1909	0.01408	0.04545	3.23
1910	0.02721	0.09756	3.59
1911	0.03352	0.10345	3.09
1912	0.00000	0.00000	1.00
1913	0.00000	0.00000	1.00
1914	0.14493	0.17544	1.21

[1] 'Non-whaling Days', defined as those days with a combination of ice, wind, and visibility conditions under which no whales were caught during the entire 66-year period, were subtracted from total whaling days in each year, and the resulting 'Type 1 Days' used to calculate WKPUE = KILL/TYPE 1 DAYS. This measure of effort assumes that whaling on 'Non-whaling Days' was futile and hence that such days should not be included in the calculation of effort.

Initially, calculations were made to determine the daylight hours for each date and latitude, but the average daylight hours per ship, or per ship-year, was for all years almost exactly equal, and the years could not be distinguished from one another on this basis. Therefore the average visibility squared (to account for area viewed), multiplied by whaling days was used as a third measure of corrected effort (Table 8). These measures of effort are used in a subsequent section to estimate the pre-exploitation number of whales.

Catch and kill

Another problem encountered in estimating population abundance from catch reports is the lack of information about the number of animals killed but not caught, therefore decreasing the population size, but not appearing in the records. This is a particularly important problem with whale records where population sizes tend to be small and whales are frequently struck by harpoons and lost. This is all the more crucial in bowhead history because the struck whales were sometimes able to flee into the pack ice where the ships could not follow. A further advantage of the bowhead whale history presented here is that the logbooks contained not only the number caught, but also the number struck and lost, and the number found dead and processed as well as 'stinkers', whales found dead but too decomposed to process.

Fig. 15 presents the kill per unit effort from the data sample, where kill is taken to be the sum of the number caught plus those struck and lost dying. This figure shows a pattern similar to that of the CPUE over time (Fig. 12). As will be seen later, most of our estimates of the pre-exploitation population are made from the number killed. Later we use both a high and low estimate of kill to estimate the 1847 population size. The high estimate includes all whales struck and lost plus those caught; the low estimate uses only those recorded as struck and lost dying plus those caught (see also Fig. 16).

Estimates of the 1847 bowhead whale population

The DeLury method and several of its modifications have been used in the literature on marine mammals to estimate pre-exploitation population sizes (Tillman, 1977; Breiwick, 1978). We have estimated the 1847 population of the bowhead whale (the number present the year prior to the beginning of the pelagic bowhead whaling activity), using several of these methods. In the following discussion, we use the nomenclature of Tillman (1977). Methods are given in detail in Appendix 1.

Simple, unmodified DeLury method

Estimates of the 1847 populations using the simple, unmodified DeLury method, the weighted cumulative kill and the kill per unit effort, are given in Table 9. This method was chosen because it is a standard technique used in analyzing whale populations, familiar to those who have worked on this subject, and provides an estimate most readily comparable to estimates for the abundance of other whale populations. The DeLury method requires the use of two well-known, stringent assumptions that may bias the results: that the numbers of whales caught per unit effort is constant within a year, and that the recruitment or reproductive rate of the whale population is negligible compared to the catch and can,

Table 5

WKPUE determined using KPUE from the data sample and a weighting factor accounting for the percentage of type 1 whaling days[1]

Year	WKPUE	WKPUE/KPUE	Year	WKPUE	WKPUE/KPUE
1849	0.16176	1.01	1882	0.05047	0.89
1850	0.14807	1.04	1883	0.00471	0.93
1851	0.05052	1.03	1884	0.01672	0.85
1852	0.09118	1.04	1885	0.03506	0.96
1853	0.03923	1.04	1886	0.02319	0.95
1854	0.02296	1.04	1887	0.03220	0.99
1855	0.00443	1.03			
1856	0.00000	1.00	1888	0.02035	1.01
1857	0.09088	1.07	1889	0.00732	1.04
			1890	0.01918	0.99
1858	0.04748	1.04	1891	0.03763	1.02
1859	0.04471	1.03	1892	0.04096	0.96
1860	0.03702	1.02	1893	0.02071	1.02
1861	0.05895	1.04	1894	0.03453	1.03
1862	0.06376	1.04	1895	0.03820	1.05
1863	0.06941	1.06	1896	0.01907	1.04
1864	0.04848	1.01	1897	0.02016	0.96
1865	0.06354	1.02			
1866	0.04880	1.01	1898	0.08372	0.95
1867	0.05072	1.05	1899	0.08303	0.98
			1900	0.04868	0.99
1868	0.05333	0.98	1901	0.01934	0.93
1869	0.05390	0.98	1902	0.07009	1.03
1870	0.07226	0.95	1903	0.03138	0.96
1871	0.02654	0.94	1904	0.03291	1.02
1872	0.04460	1.00	1905	0.04646	1.00
1873	0.02665	1.01	1906	0.02893	1.04
1874	0.02900	1.04	1907	0.03889	0.97
1875	0.08501	1.04			
1876	0.02081	0.96	1908	0.01479	0.94
1877	0.07768	0.99	1909	0.01450	1.03
			1910	0.02916	1.07
1878	0.02141	0.98	1911	0.03157	0.94
1879	0.04287	0.93	1912	0.00000	1.00
1880	0.12765	1.03	1913	0.00000	1.00
1881	0.10431	1.04	1914	0.12544	0.87

[1] The weighting factor was based on the ratio of Type 1 days to readings in each year. 'Type 1 Days' were defined as those days with a combination of ice, wind and visibility under which a whale was caught in any year. 'Readings' was the number of days for which all three weather conditions were recorded. The actual weighting factor was calculated as: (TYPE 1 DAYS/READINGS)/[AVG OF (TYPE 1 DAYS/READINGS) for 66 YRS]. This method weights years in which there were more Type 1 days more heavily; it weights the KPUE by applying the ratio of (TYPE 1 DAYS/READINGS) in each year to all records, including those in which all three weather conditions were not recorded (39% of all records).

therefore, be ignored. This method gives an estimated population size in 1847 of 30,843 whales ($R = 0.681$; $F = 10.65$, significant at the 99% confidence level). Using three-year moving averages of the weighted cumulative kill and the kill per unit effort, this method yields an estimated 1847 population of 34,734 ($R = 0.794$; $F = 16.23$, significant at the 99% confidence level).

Chapman's modified DeLury method

Table 10 gives the results for Chapman's modified DeLury method, using several values of M, the natural mortality rate, in the range common for great whales. In this method the recruitment each year is assumed to be constant and approximated as the initial population size multiplied by M. The adjusted cumulative catch is calculated using either the weighted catch, the weighted kill, or the weighted total of kill and whales struck and lost alive. Excluding the cases with no natural mortality, the significant estimates ($F \geqslant 4$) vary from 10,000 to 22,000.

The 'q' method

Using estimates of q (the 'catchability coefficient' for the whales) obtained from Chapman's modified DeLury method, other estimates of the size of the bowhead population in 1847 were calculated according to the q method. These are shown in Table 11, for the same values of natural mortality rate and adjusted cumulative catch used in Chapman's method (Table 10). Excluding the cases with no natural mortality and those derived from non-significant Chapman method estimates ($F < 4$), the q method estimates range from 17,000 to 36,000.

Allen's modified DeLury method

Table 12 gives the results for Allen's modified DeLury method assuming either a constant recruitment rate or a time-lagged, density-dependent recruitment model. The second option introduces a time lag into the recruitment rate, under the assumption that the age of first breeding will cause such a delay. Although little is known about the actual age of first breeding of the bowhead, a reasonable estimate, based on our knowledge of whales in particular and large mammals in general, is most likely between 5 and 10 years, but might range from as low as 3 to as high as 16.

For the values of M and R examined, the constant recruitment rate model yields estimates of the 1847 bowhead population ranging between 11,000 and 47,000.

For the most reasonable time lags, between 5 and 10

Table 6

WKPUE determined using type 2 effort[1]

Year	WKPUE	WKPUE/KPUE
1849	0.17131	1.07
1850	0.14740	1.04
1851	0.05068	1.03
1852	0.09068	1.03
1853	0.03831	1.02
1854	0.02265	1.03
1855	0.00457	1.06
1856	0.00000	1.00
1857	0.08609	1.01
1858	0.04705	1.03
1859	0.04495	1.04
1860	0.03763	1.04
1861	0.05738	1.02
1862	0.06326	1.03
1863	0.06707	1.03
1864	0.04957	1.03
1865	0.06385	1.03
1866	0.05092	1.05
1867	0.04927	1.02
1868	0.05623	1.03
1869	0.05640	1.03
1870	0.07810	1.03
1871	0.02975	1.05
1872	0.04570	1.02
1873	0.02760	1.04
1874	0.02830	1.02
1875	0.08427	1.03
1876	0.02247	1.03
1877	0.08097	1.03
1878	0.02262	1.04
1879	0.04712	1.02
1880	0.12739	1.02
1881	0.10674	1.06
1882	0.06173	1.09
1883	0.00519	1.02
1884	0.01994	1.01
1885	0.03670	1.01
1886	0.02500	1.02
1887	0.03282	1.01
1888	0.02036	1.01
1889	0.00709	1.01
1890	0.01949	1.00
1891	0.03747	1.01
1892	0.04317	1.01
1893	0.02046	1.01
1894	0.03401	1.02
1895	0.03685	1.01
1896	0.01849	1.01
1897	0.02130	1.01
1898	0.10088	1.15
1899	0.08581	1.01
1900	0.05072	1.03
1901	0.02133	1.03
1902	0.06947	1.02
1903	0.03339	1.02
1904	0.03250	1.00
1905	0.04731	1.02
1906	0.02786	1.00
1907	0.04060	1.01
1908	0.01610	1.02
1909	0.01439	1.02
1910	0.02778	1.02
1911	0.03468	1.03
1912	0.00000	1.00
1913	0.00000	1.00
1914	0.14925	1.03

[1] 'Non-whaling Days', defined as days with extreme conditions of ice and/or wind, were subtracted from total whaling days in each year, and the resulting 'Type 2 Days' used to calculate WKPUE = KILL/TYPE 2 DAYS. This measure of effort assumes that whaling on 'Non-whaling Days' was futile and hence that such days should not be included in the calculation of effort. (Whales were apparently caught under all conditions of visibility.)

years, the density-dependent recruitment model yields estimates of the 1847 population ranging between 23,000 and 25,000. This method is relatively insensitive to time lags above 10 years, and a lag of more than 16 years seems biologically unreasonable. Thus, unless bowhead whales mature much more rapidly than would be expected for great whales and other larger mammals, this method suggests that the 1847 population numbered about 25,000.

Using an age of first breeding of eight, and therefore a time lag of eight years, we have investigated the effects of variations in other parameters, including the rates of annual natural mortality and recruitment, on the estimate of the 1847 population. Varying annual natural mortality from 0.08 to 0.03 and recruitment from 0.08 to 0.03, this method gives estimates of the 1847 population ranging from 15,000 to 35,000.

Estimates of the 1847 population with weather and area corrections

In our previous discussion of hunting effort, we gave three methods of weighting the effort by weather conditions. Two of these corrected for weather conditions under which whales could not be chased or caught, and the third attempted to correct the number of whaling days by the area of the ocean visible from a ship. Here these three methods are used as a measure of effort, and employed with the unmodified DeLury method to provide additional estimates of the pre-exploitation bowhead population. As can be seen in Table 13, the corrections for weather result in somewhat lower estimates that overlap with the unweighted estimates, providing values ranging from 20,000 to 30,000 whales.

One estimate using the area seen by whaling ships also gives a lower value, 18,573 ± 3,711. This estimate has the appearance of greater precision, and was one for which we had high hopes at the beginning of the project; however, our work in abstracting and analyzing the logbook records leads us now to doubt the reliability of this method. It was impossible either to estimate the amount of zig-zagging a ship might have done during the 24 hours between the recording of its positions (which usually occurred at noon) or to know about possible fluctuations in visibility, wind conditions or ice coverage during a 24-hour period when the logbook record usually included only the weather at the time of observation. A further limitation of this technique is that we could not distinguish visibilities greater than five miles with any precision and all visibilities of five miles or more are recorded merely as five miles.

As noted before, it is not possible to determine the ultimate fate of all whales that were judged to have been

Table 7

WKPUE determined using KPUE from the data sample and a weighting factor accounting for the percentage of type 2 whaling days[1]

Year	WKPUE	WKPUE/KPUE	Year	WKPUE	WKPUE/KPUE
1849	0.15285	0.95	1882	0.05305	0.94
1850	0.13988	0.98	1883	0.00509	1.00
1851	0.04846	0.99	1884	0.02028	1.03
1852	0.08709	0.99	1885	0.03767	1.03
1853	0.03820	1.02	1886	0.02457	1.00
1854	0.02217	1.00			
1855	0.00420	0.97	1887	0.03320	1.02
1856	0.00000	1.00	1888	0.02070	1.03
1857	0.08664	1.02	1889	0.00723	1.03
			1890	0.02019	1.04
1858	0.04605	1.01	1891	0.03784	1.02
1859	0.04263	0.99	1892	0.04375	1.02
1860	0.03620	1.00	1893	0.02087	1.03
1861	0.05732	1.02	1894	0.03391	1.02
1862	0.06060	0.99	1895	0.03764	1.03
1863	0.06563	1.00	1896	0.01904	1.03
1864	0.04764	0.99	1897	0.02146	1.02
1865	0.06267	1.01			
1866	0.04691	0.97	1898	0.07296	0.83
1867	0.04922	1.02	1899	0.08752	1.03
			1900	0.04898	0.99
1868	0.05417	0.99	1901	0.02027	0.98
1869	0.05498	1.00	1902	0.06954	1.02
1870	0.07598	1.00	1903	0.03320	1.01
1871	0.02772	0.98	1904	0.03317	1.03
1872	0.04498	1.01	1905	0.04714	1.01
1873	0.02575	0.97	1906	0.02885	1.04
1874	0.02824	1.01	1907	0.04122	1.02
1875	0.08125	0.99			
1876	0.02137	0.98	1908	0.01585	1.01
1877	0.07763	0.99	1909	0.01427	1.01
			1910	0.02760	1.01
1878	0.02161	0.99	1911	0.03346	1.00
1879	0.04634	1.00	1912	0.00000	1.00
1880	0.12574	1.01	1913	0.00000	1.00
1881	0.09815	0.98	1914	0.13106	0.90

[1] The weighting factor was based on the ratio of Type 2 days to readings in each year. 'Type 2 Days' were defined as days without extreme conditions of ice and wind. (Whales were apparently caught under all conditions of visibility). 'Readings' was the number of days for which all three conditions were recorded. The actual weighting factor was calculated as: (TYPE 2 DAYS/READINGS)/[AVG OF (TYPE 2 DAYS/READINGS) FOR 66 YRS]. This method weights years in which there were more Type 2 days more heavily; it weights the KPUE by applying the ratio of (TYPE 2 DAYS/READINGS) in each year to all records, including those in which all three conditions were not recorded (39% of all records).

struck and lost alive. We can consider the maximum effect these whales might have had on the population by assuming that all whales struck and lost alive later died. Adding these to the number known killed, we obtain a high estimate of the kill and we find that an unmodified simple DeLury method results in an estimate of the pre-exploitation bowhead population of 38,500 ± 12,692, a value slightly higher than our previous estimates.

Discussion of 1847 population estimates

With the DeLury method one is caught on the horns of a dilemma. The method assumes one is sampling from a closed population, and there are several ways that one can violate this assumption, including: the population has a significant density-dependent reproductive response, so that as the population is harvested the net recruitment rate increases; the population sampled is not the entire population; and the fraction of the population sampled varies over time, with immigration of the prey population and changes in the distribution of the whaling ships. Our approach was to attempt to use the method in a way that did least violence to the assumptions. This is not a simple task.

Length of data series used

Tillman, Breiwick, and Chapman (1983) argue that the appropriate time period to apply the DeLury method to the bowhead whale is for the first 7 to 10 years. They argue that 'it is only reasonable to apply this model to data obtained during the first t_r years of exploitation, where t_r is the average age at recruitment into the fishery'. The basis for this argument is first that the population is assumed to be sufficiently constant at the beginning of the harvesting to allow one to use the method at all. Second, it assumes that there is a strong density-dependent response of the net recruitment rate to a decrease in the population accompanying the harvesting. Third, it is assumed that this density-dependent effect will be strong enough so that the DeLury method will result in a significantly distorted estimate when applied to longer time periods. Fourth, it is also assumed that time lags in the population's response to displacement from the supposed equilibrium will have significant effects on population size.

While these effects are possible, it is also true that the shorter the time period, the less likely that enough data points will be involved to obtain a statistically significant regression line or to represent accurately the real trend for

Table 8

WKPUE determined using effort measured as the area viewed by ships in each year

Year	WKPUE	WKPUE/KPUE	Year	WKPUE	WKPUE/KPUE
1849	0.01746	0.11	1882	0.00440	0.08
1850	0.01654	0.12	1883	0.00103	0.20
1851	0.00780	0.16	1884	0.00339	0.17
1852	0.01068	0.12	1885	0.00644	0.18
1853	0.00574	0.15	1886	0.00366	0.15
1854	0.00282	0.13	1887	0.00609	0.19
1855	0.00055	0.13			
1856	0.00000	1.00	1888	0.00250	0.12
1857	0.02012	0.24	1889	0.00082	0.12
			1890	0.00594	0.31
1858	0.00470	0.10	1891	0.00472	0.13
1859	0.00488	0.11	1892	0.00421	0.10
1860	0.00305	0.08	1893	0.00144	0.07
1861	0.00618	0.11	1894	0.00298	0.09
1862	0.00920	0.15	1895	0.00346	0.09
1863	0.00822	0.13	1896	0.00216	0.12
1864	0.00602	0.13	1897	0.00256	0.12
1865	0.00639	0.10			
1866	0.00531	0.11	1898	0.01320	0.15
1867	0.00537	0.11	1899	0.01335	0.16
			1900	0.00873	0.18
1868	0.00564	0.10	1901	0.00390	0.19
1869	0.00654	0.12	1902	0.00622	0.09
1870	0.00910	0.12	1903	0.00472	0.14
1871	0.00295	0.10	1904	0.00895	0.28
1872	0.00606	0.14	1905	0.00669	0.14
1873	0.00382	0.14	1906	0.00327	0.12
1874	0.00411	0.15	1907	0.00819	0.20
1875	0.01264	0.15			
1876	0.00428	0.20	1908	0.00222	0.14
1877	0.00762	0.10	1909	0.00201	0.14
			1910	0.00581	0.21
1878	0.00173	0.08	1911	0.00554	0.17
1879	0.00849	0.18	1912	0.00000	1.00
1880	0.01188	0.10	1913	0.00000	1.00
1881	0.00838	0.08	1914	0.03279	0.23

the entire population. Tables 14–16 give the 1847 population estimates obtained with the DeLury method for every set of consecutive years (the first two, the first three, the first four, etc.). Indeed one can see from these tables that, with the first 7 to 10 years of data, the DeLury method results in very low values of R and R^2. For example, in Table 15, using years 1 to 8, the method accounts for only 7% of the variation ($R^2 = 0.07$); using years 1 to 10, only 17% of the variation is accounted for.

A rule of thumb for the use of regression analysis is that, even for statistically significant relationships (that is, when the F test is significant), the regression is only meaningful and worth reporting when the R^2 is close to 0.50, meaning that near to 50% or more of the variation is accounted for. For example, Breiwick (1978) used 'highest R^2 (percent variation explained by the regression) and largest sample size' as criteria for selecting the best fit. As can be seen from Tables 14–16, by the time R^2 approaches 0.45 or 0.5, the estimates of the original population are approximately 20,000 or greater. The exact value depends on which measure one uses for whales killed: the catch (Table 14); the reported kill, the catch plus those reported struck and lost dying (Table 15); or the upper bound of the kill, the reported catch plus all struck and lost, both lost dying and lost alive (Table 16).

Another consideration in our analysis was the changes in the distribution of the catch and kill over time which indicated that the whaling ships found new geographical areas that were previously unexploited (Fig. 11). These areas apparently were either refuges to which the whales fled to avoid pursuit in the areas they had previously occupied, or pockets of essentially isolated sub-populations. If the latter were the case, then it would not be legitimate to assume that the reductions observed in the first 7 to 10 years could be used as a basis for an estimate for the entire population. If the first were true, one would still expect that there were whales in the previously unexploited areas that could not be considered part of the population hunted in the first 7 to 10 years. Again, the use of this short period alone would violate the assumption that one had a closed population. One would expect that a DeLury method estimate for the first 7 to 10 years, when only part of the bowhead habitat was being exploited, would be less than that in the final estimate, and this is exactly what one finds. That is, the DeLury estimates reported by Tillman *et al.* (1983) are consistent with the idea that the whales hunted during the first ten years were only part of the bowhead whale population.

It is instructive to consider the time series of DeLury method regressions (Tables 14–16) and compare them with the changes in the geographic distribution of the ships and the kill (Fig. 11) and with the changes in total catch and kill by decade (Figs 9 and 10). Considerable economic and social change impinged on the bowhead fishery during the first decade. Part of the bowhead whaling area was discovered in 1848, was rapidly

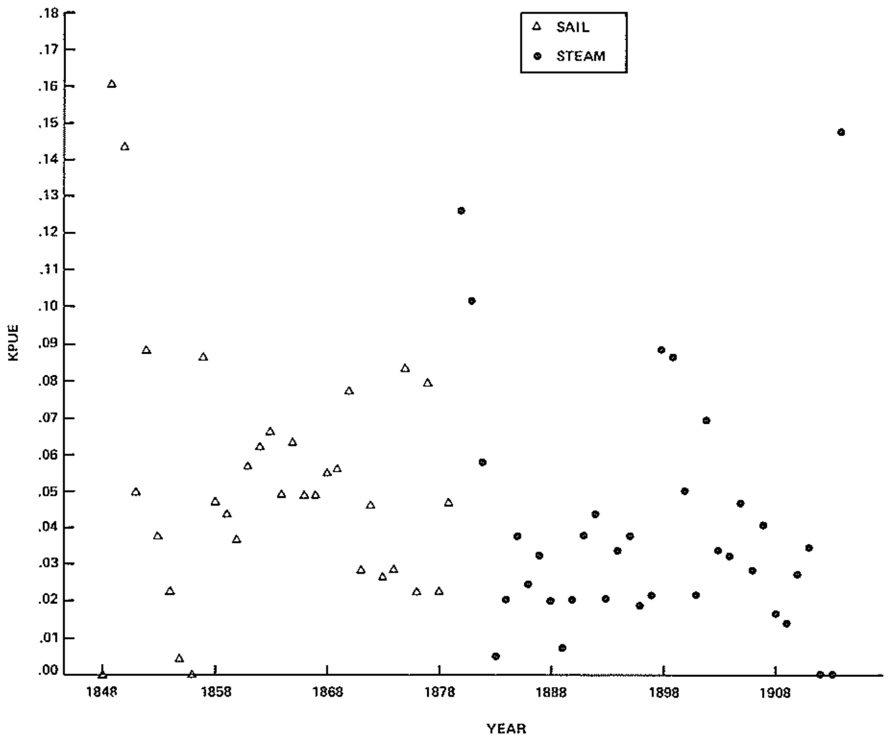


Fig. 15. KPUE from the data sample versus time, where SAIL indicates sailing ship effort only and STEAM indicates both sailing and steam ship effort.

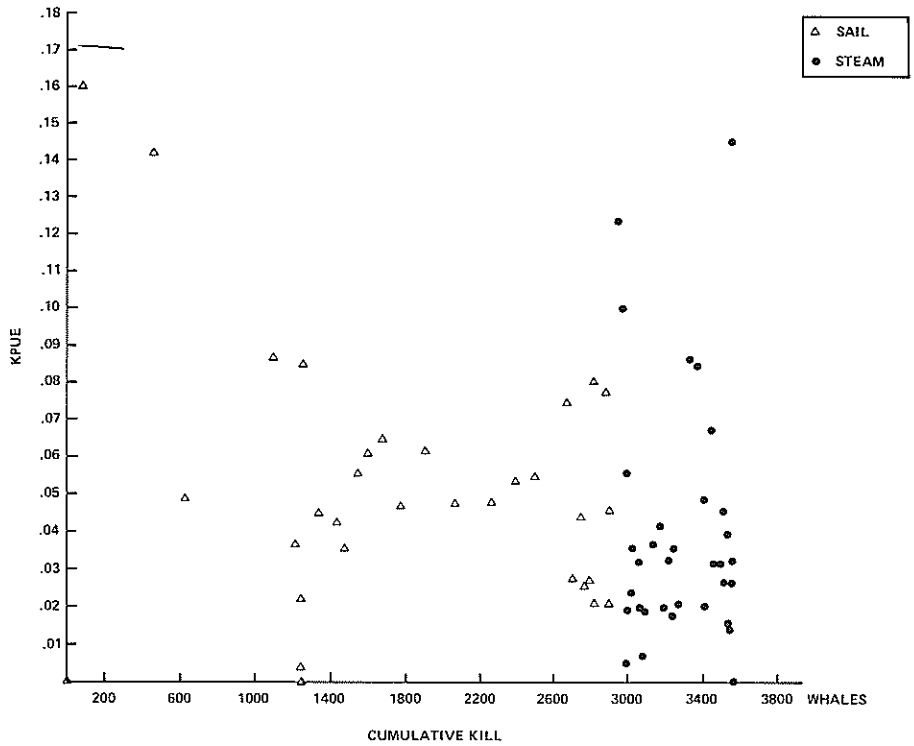


Fig. 16. KPUE versus cumulative kill, where SAIL indicates sailing ships only and STEAM indicates both sailing and steam ships.

exploited during the next few years, and was apparently depleted. Then there was a rapid temporary decrease in the whaling activity. It is not surprising therefore that the regression analysis shows a great deal of variation, since the catch per unit effort changed rapidly during this period. This is consistent with the observation that the R^2 reaches its minimum value for estimates during the period of 7 to 10 years from the beginning.

Density-dependent, time-lagged recruitment

We have also examined the possibility of whether a strong density-dependent relationship between recruitment and population size and the occurrence of time lags would have a large effect on our results. Because so little is known about the life history and population dynamics of bowhead whales, such considerations are highly specula-

Table 9

Unmodified DeLury method estimates of the 1847 bowhead whale population

Measure of catch or kill	Measure of effort	Population estimate 95% confidence interval	R	F
Cumulative catch	Total days	34,255±15,764	0.69	5.37
Cumulative kill	Total days	32,653±11,677	0.68	9.34
Cumulative kill+struck and lost alive	Total days	35,837±9,546	0.67	17.85
Cum. weighted catch	Total days	31,837±13,701	0.69	6.21
Cum. weighted kill	Total days	30,843±10,396	0.68	10.65
Cum. wtd. kill+struck and lost alive	Total days	38,500±12,692	0.69	11.27
3-year moving avg. of cum. wtd. kill	Total days	37,172±12,828	0.80	9.30
3-year moving avg. of cum. wtd. kill	Total days	34,734±9,293	0.79	16.23
3-year moving avg. of cum. wtd. kill+struck and lost alive	Total days	43,574±11,533	0.80	16.79

Table 10

Estimates of the 1847 bowhead population using Chapman's modified DeLury method[1]

M	Weighted catch	Weighted kill	Weighted kill plus struck and lost alive
0.00	28,660 (5.7)	29,293 (9.9)	31,966 (18.5)
0.01	18,728 (7.8)	19,214 (13.1)	21,601 (24.4)
0.02	13,301 (9.4)	14,370 (14.5)	16,072 (24.2)
0.03	10,643 (8.7)	11,619 (11.1)	14,130 (14.4)
0.04	9,504 (6.1)	10,869 (6.4)	13,511 (6.4)
0.05	8,943 (3.9)	10,496 (3.4)	13,184 (2.7)
0.06	8,242 (2.5)	9,014 (1.8)	6,618 (1.1)
0.07	6,889 (1.7)	4,219 (1.0)	0 (0.0)
0.08	4,574 (1.2)	0 (0.0)	0 (0.0)

[1] Each estimate is followed by the value of F enclosed in the parentheses. $F \geqslant 4$ is significant at the 95% level; $F \geqslant 7$ at the 99% level.

Table 11

q method estimates of the 1847 bowhead population

M	Weighted catch	Weighted kill	Weighted kill plus struck and lost alive
0.00	67,722	60,886	59,503
0.01	36,304	32,761	32,053
0.02	22,155	20,890	21,493
0.03	17,452	18,364	21,372
0.04	17,872	21,442	28,743
0.05	20,962	28,098	43,063
0.06	25,296	37,242	66,207
0.07	30,030	48,315	—
0.08	34,683	—	—

tive. Ideally, one would want to construct a model of the population that included age and sex structure, because for any long-lived species such structure may have important effects on the long term and short term expectations for the populations (Wu and Botkin, 1978). However, almost all the information about the bowhead required to construct such a model with any accuracy is lacking. Therefore we resorted to very simple methods and developed the following model:

Given an initial population of N_0, a rate of increase of

Table 12

Estimates of the 1847 bowhead population using Allen's modified DeLury method

A. Assuming constant recruitment (No lag or density dependence)

M	R	Population
0.08	0.08	21,153
0.08	0.055	38,447
0.08	0.03	47,049
0.055	0.08	14,570
0.055	0.055	20,602
0.055	0.03	34,752
0.03	0.08	11,356
0.03	0.055	14,303
0.03	0.03	20,077

B. Using Allen's model of recruitment rate ($M = 0.04$ $R_0 = 0.03$ $N_I = 30{,}000$)

Lag	Population
0	25,169
1	21,086
2	22,360
3	23,428
4	23,613
5	23,389
6	23,947
7	23,951
8	24,240
9	24,702
10	24,529
15	25,486
20	26,535

r and a lag time in years, lag, this model calculates the annual change in population in year t due to causes other than pelagic hunting as:

$$\Delta N_t = N_{t-1} r(1-(N_{t-\text{lag}}/N_0)).$$

The population in year t is then calculated by adding the annual change, ΔN_t, and subtracting the number of whales estimated to have been killed in that year:

$$N_t = \Delta N_t + N_{t-1} - \text{HUNTING}_t$$

where HUNTING_t is the appropriate value from the time series of weighted catch (WCATCH), weighted kill (WKILL) or weighted sum of kill and whales struck and lost alive

Table 13

Unmodified DeLury method estimates of the 1847 bowhead whale population using corrected measures of effort

Measure of catch or kill	Measure of effort	Population estimate 95% confidence interval	*R*	*F*
Cum. weighted kill	No. of Type 1 whaling days	27,374 ± 10,138	0.58	9.24
Cum. weighted kill	Percentage of Type 1 whaling days[1]	29,216 ± 8,854	0.67	13.44
Cum. weighted kill	No. of Type 2 whaling days	30,519 ± 10,272	0.67	10.72
Cum. weighted kill	Percentage of Type 2 whaling days[2]	30,899 ± 10,085	0.69	11.35
Cum. weighted kill	Days x area visible	41,197 ± 25,434	0.68	2.93
Cum. weighted kill	Total days weighted by area visible.	18,573 ± 3,711	0.34	39.68

[1] See Table 5, footnote 1. [2] See Table 7, footnote 1.

Table 14

DeLury method estimates of initial bowhead population size for all consecutive sets of years, using weighted catch

Years included	Population estimate	R^2	*F*	Years included	Population estimate	R^2	*F*
2	2,988	0.41	0.0	34	34,718	0.55	1.5
3	3,141	0.12	6.3	35	29,625	0.52	2.4
4	4,729	0.23	6.7	36	27,539	0.51	3.0
5	6,032	0.16	11.7	37	27,431	0.51	3.3
6	6,375	0.12	21.3	38	26,434	0.50	4.0
7	6,205	0.08	36.1	39	26,050	0.49	4.4
8	6,126	0.06	51.7	40	25,102	0.48	5.2
9	7,031	0.14	15.5	41	23,761	0.46	6.4
10	7,342	0.17	16.1	42	23,300	0.46	7.2
11	7,667	0.19	16.5	43	23,596	0.46	7.4
12	7,943	0.21	17.5	44	24,134	0.46	7.4
13	8,492	0.25	14.9	45	23,787	0.46	8.2
14	9,151	0.29	12.3	46	23,935	0.46	8.6
15	9,862	0.33	10.3	47	24,297	0.46	8.7
16	10,246	0.35	10.5	48	23,948	0.46	9.6
17	10,787	0.37	10.1	49	23,743	0.45	10.4
18	11,336	0.39	9.8	50	25,857	0.47	8.0
19	12,002	0.40	9.4	51	28,411	0.49	6.1
20	12,870	0.42	8.6	52	29,405	0.50	5.8
21	13,917	0.44	7.8	53	28,811	0.49	6.5
22	16,133	0.47	5.3	54	30,746	0.50	5.6
23	16,097	0.46	6.3	55	30,755	0.50	5.9
24	16,632	0.46	6.6	56	30,614	0.50	6.2
25	16,601	0.45	7.6	57	31,222	0.51	6.2
26	16,663	0.45	8.6	58	30,973	0.51	6.6
27	19,218	0.48	5.6	59	31,394	0.51	6.6
28	18,486	0.46	6.9	60	30,571	0.50	7.4
29	20,649	0.49	5.2	61	29,790	0.50	8.2
30	19,967	0.48	6.3	62	29,639	0.50	8.7
31	20,197	0.48	6.7	63	29,752	0.50	8.9
32	26,065	0.51	2.8	64	28,624	0.48	10.1
33	32,177	0.54	1.7	65	27,674	0.47	11.2
				66	31,837	0.48	6.2

(WSKILL). This process continues until the entire data set has been used (66 years) or the population is driven to extinction by the hunting removals.

The assertion that only the first 7 to 10 years of the whaling record should be used essentially implies that one assumes that the population was close to a stable condition prior to the whaling (and therefore approximated a closed population), and that there is a strong density-dependent effect. As this is similar to the assumptions for a logistic equation, we have used a logistic model with a time lag to study the implications of such assumptions. For the model we have used, the time lag is variable, and we have considered lags of zero (no lag) to 10 years. We have used values for r, the net recruitment rate, which are very optimistic for a large long-lived mammal. As has been shown elsewhere, any long-lived species with calving intervals on the order of four years or greater is unlikely even under the best conditions to have a net recruitment rate of more than 5% (Wu and Botkin, 1980).

The intuitive motivation for this statement is as follows: if the sex ratio is even, and females reproduce every four years, only $\frac{1}{8}$ would reproduce in any year (16%). But when there is a long prepuberty period, and a considerable fraction of the population is immature, the actual fraction of the females in the population available

Table 15

DeLury method estimates of initial bowhead population size for all consecutive sets of years, using weighted kill

Years included	Population estimate	R^2	F	Years included	Population estimate	R^2	F
2	5,016	0.44	0.0	34	31,123	0.53	3.2
3	3,798	0.13	6.1	35	28,198	0.51	4.3
4	5,882	0.24	5.7	36	27,026	0.49	5.2
5	7,509	0.17	10.7	37	26,990	0.49	5.6
6	7,878	0.13	20.5	38	26,394	0.48	6.4
7	7,691	0.10	34.7	39	26,283	0.48	7.0
8	7,542	0.07	49.9	40	25,685	0.47	8.0
9	8,562	0.14	17.6	41	24,721	0.45	9.4
10	8,884	0.17	18.9	42	24,348	0.45	10.5
11	9,218	0.19	19.9	43	24,582	0.45	10.8
12	9,473	0.20	21.7	44	25,009	0.45	10.9
13	10,002	0.24	19.4	45	24,739	0.45	12.0
14	10,618	0.27	16.8	46	24,905	0.45	12.5
15	11,272	0.31	14.6	47	25,169	0.45	12.8
16	11,646	0.33	14.9	48	24,903	0.44	14.0
17	12,348	0.36	13.3	49	24,743	0.44	15.1
18	12,876	0.37	13.2	50	26,434	0.46	12.0
19	13,486	0.39	12.9	51	28,278	0.47	9.8
20	14,363	0.40	11.8	52	28,945	0.48	9.6
21	15,346	0.42	10.7	53	28,552	0.47	10.5
22	17,164	0.45	8.0	54	29,880	0.49	9.4
23	17,219	0.44	9.2	55	29,892	0.49	9.9
24	17,893	0.45	9.4	56	29,897	0.49	10.3
25	17,852	0.43	10.8	57	30,412	0.49	10.3
26	17,890	0.43	12.1	58	30,251	0.49	10.9
27	19,759	0.46	9.0	59	30,529	0.49	11.1
28	19,433	0.44	10.4	60	29,993	0.49	12.1
29	21,183	0.47	8.3	61	29,473	0.48	13.1
30	20,763	0.46	9.6	62	29,373	0.48	13.8
31	21,277	0.47	9.7	63	29,452	0.48	14.2
32	25,422	0.50	5.0	64	28,677	0.47	15.6
33	29,795	0.53	3.2	65	28,006	0.45	17.0
				66	30,843	0.46	10.7

for conception is much smaller. Since calving intervals in reality are often longer, and since females die while pregnant, the upper bound on an expected recruitment rate is certainly below 10%, and rarely as much as 5%.

Using this model, a variety of cases have been considered (Table 17). In each case the initial population level was chosen as the carrying capacity for the model. As can be seen from Table 17, even when $r = 0.07$, if the initial population of the bowhead were 10,000 and the population were harvested as reported, then under all conditions the population would become extinct, with or without density dependency, with or without time lags of 7 or 10 years.

When the initial population is 20,000, the population usually persists under the reported hunting pressure. The predicted absolute abundance differs with different time lags and recruitment rates, but the qualitative result does not change with the addition of a strong density-dependent relationship or a strong time lag.

These results suggest that, for a population like the bowhead whale, the effects of density dependency and time lags will not affect the important qualitative outcomes. Thus on the basis of the simulation results as well as the results of the other considerations discussed earlier, we conclude that less violence is done to the assumption of a closed population by using the entire data set and thereby encompassing all the whales in the known range of the bowhead, than by restricting the estimate to a part of that population in order to avoid the effects of changes in recruitment.

One might prefer, considering our discussion to this point, to use the DeLury estimates for the shortest time periods that give reasonable values of F and R^2. Even so, the result would be that the estimate of the original population is 20,000 or greater.

In summary, we have estimated the pre-exploitation size of the western Arctic bowhead population with the unmodified and modified DeLury methods, using a variety of estimates of catch and kill and of effort. The range of these estimates overlap for the most part and suggest that reasonable bounds for the original number are no less than 20,000 and no more than 40,000, with an average number of approximately 30,000.

The decline of the bowhead whale

Our data indicate that the bowhead whale suffered a decline both in absolute numbers and in the average size of an individual whale during the pelagic whaling period. In the following sections we discuss the significance of these declines and their possible interrelationship.

Changes in size of whales caught

The direct observations of the numbers of whales caught and the distribution of the catch demonstrate that pelagic whaling operations rapidly depleted the number of bowhead whales. However, pelagic whaling operations may have had other effects on the whale population. It has been speculated that pelagic whaling would tend to alter the age and size distribution of a population, because the ships would tend to take larger whales and those whales that are more easily approached and taken,

Table 16

DeLury method estimate of initial bowhead population size for all consecutive sets of years, using the weighted sum of kill plus whales struck and lost alive

Years included	Population estimate	R^2	F	Years included	Population estimate	R^2	F
2	9,097	0.46	0.0	34	32,450	0.51	7.1
3	5,333	0.14	1.2	35	30,662	0.48	8.8
4	8,601	0.27	5.0	36	30,236	0.48	9.9
5	10,794	0.19	10.7	37	30,397	0.48	10.5
6	11,289	0.15	21.0	38	30,010	0.47	11.7
7	10,814	0.11	35.9	39	29,944	0.47	12.6
8	10,533	0.08	51.6	40	29,582	0.46	14.0
9	11,847	0.15	20.4	41	28,861	0.44	15.9
10	12,257	0.17	22.0	42	28,591	0.43	17.4
11	12,708	0.19	23.1	43	28,832	0.43	18.0
12	12,989	0.21	25.7	44	29,182	0.44	18.3
13	13,526	0.23	24.9	45	28,933	0.43	19.9
14	14,283	0.27	21.5	46	29,068	0.43	20.8
15	15,073	0.30	18.7	47	29,419	0.43	21.1
16	15,506	0.32	19.2	48	29,284	0.43	22.6
17	16,361	0.35	17.0	49	29,162	0.42	24.1
18	16,957	0.36	17.0	50	30,769	0.44	19.3
19	17,656	0.37	16.8	51	32,093	0.45	17.0
20	18,525	0.39	16.0	52	32,511	0.46	17.1
21	19,474	0.40	15.2	53	32,196	0.45	18.4
22	21,142	0.43	12.2	54	33,239	0.46	17.0
23	21,499	0.42	13.4	55	33,228	0.46	17.8
24	22,227	0.43	13.6	56	33,348	0.46	18.4
25	22,141	0.42	15.6	57	33,842	0.47	18.3
26	22,209	0.41	17.3	58	33,748	0.47	19.2
27	23,672	0.43	14.5	59	33,869	0.47	19.8
28	23,479	0.42	16.4	60	33,691	0.46	20.9
29	25,130	0.45	13.3	61	33,570	0.46	21.9
30	24,772	0.44	15.1	62	33,441	0.46	23.0
31	26,010	0.45	13.5	63	33,543	0.46	23.6
32	29,252	0.48	8.6	64	32,949	0.45	25.5
33	31,744	0.51	7.0	65	32,421	0.44	27.3
				66	34,316	0.45	20.1

Table 17

Simulated bowhead population declines using density-dependent, time-lagged recruitment model. Tabulated are the population sizes occurring at the end of the 67-year period of pelagic whaling (or year of extinction), given various initial stock sizes (N_0), kill measures, time lags and net recruitment rates (r)

N_0	Kill measure	Estimated population size at end of whaling era for three given time lags: 0	7	10
		$r = 0.03$		
10,000	WSKILL[1]	0 (yr 11)[3]	0 (yr 11)	0 (yr 11)
	WKILL[2]	0 (yr 20)	0 (yr 19)	0 (yr 19)
20,000	WSKILL	3,435	0 (yr 63)	0 (yr 51)
	WKILL	10,588	9,237	8,393
		$r = 0.05$		
10,000	WSKILL	0 (yr 11)	0 (yr 11)	0 (yr 11)
	WKILL	0 (yr 22)	0 (yr 19)	0 (yr 19)
20,000	WSKILL	11,895	8,393	5,029
	WKILL	15,517	15,224	14,785
		$r = 0.07$		
10,000	WSKILL	0 (yr 12)	0 (yr 11)	0 (yr 11)
	WKILL	0 (yr 24)	0 (yr 20)	0 (yr 19)
20,000	WSKILL	16,612	16,549	15,183
	WKILL	17,880	18,575	19,172

[1] WSKILL = weighted sum of kill plus whales struck and lost alive.
[2] WKILL = weighted kill.
[3] Year in which extinction occurred.

such as mothers with calves. If this were true, pelagic whaling might suppress the reproductive potential of a whale population more than would be indicated by a change in numbers alone. This effect might take place if the individuals with greatest reproductive potential were removed at a greater rate than the rest of the population.

Although there is no direct evidence of Arctic whalemen consciously selecting one whale over another (apart from the closest one), it may have been that certain classes of bowheads were, in general, more available to the pelagic whalers. The logbook data provide us with some insight into this question, because frequently (but not always) the logbooks contained records of the barrels of oil obtained from the whales they processed. From these one can calculate the average number of barrels of oil per whale for each year. A significant decrease in the oil yield per whale observed over the whaling era would suggest a decrease in the average size of the whales, as well as in the relative abundance of older members of the population.

Table 18 gives the barrels of oil and the number of whales by year (for those instances when both were given). The table also includes the average barrels per year and, for later reference, the price per barrel and the total average value of a whale.

The number of barrels per whale declines, particularly until 1874, after which the data are rather sparse. A linear regression of the average barrels of oil per whale versus the year indicates a statistically significant decline of 0.6 barrels/whale/year (Table 19). Since we have no reason

Table 18

Bowhead oil production and price by year[1]

Year	Barrels	Whales	Barrels/ whale	Dollars/ barrel	Dollars/ whale
1849	245	2	122.5	12.28	1,505
1850	4,052	31	130.7	15.44	2,018
1851	4,330	36	120.3	14.17	1,705
1852	6,855	56	122.4	21.42	2,622
1853	3,088	23	134.3	18.27	2,453
1854	373	3	124.3	18.74	2,330
1855	0	0	0.0	22.36	0
1856	0	0	0.0	25.04	0
1857	0	0	0.0	22.99	0
1858	1,412	13	108.6	17.01	1,848
1859	2,274	19	119.7	15.28	1,828
1860	1,151	10	115.1	15.59	1,795
1861	860	8	107.5	13.86	1,490
1862	100	1	100.0	18.58	1,858
1863	431	4	107.8	29.92	3,224
1864	824	7	117.7	40.32	4,746
1865	432	7	61.7	45.67	2,819
1866	1,918	19	100.9	38.11	3,848
1867	3,829	40	95.7	22.99	2,201
1868	365	4	91.3	25.83	2,357
1869	870	10	87.0	31.81	2,768
1870	772	8	96.5	21.10	2,037
1871	0	0	0.0	21.73	0
1872	0	0	0.0	20.63	0
1873	0	0	0.0	19.53	0
1874	372	4	93.0	19.06	1,772
1875	127	1	127.0	20.47	2,600
1876	0	0	0.0	19.21	0
1877	851	8	106.4	16.38	1,742
1878	0	0	0.0	13.86	0
1879	0	0	0.0	12.28	0
1880	291	2	145.5	16.06	2,337
1881	0	0	0.0	15.12	0
1882	460	4	115.0	16.85	1,938
1883	70	1	70.0	17.01	1,191
1884	111	1	111.0	17.64	1,958
1885	0	0	0.0	14.17	0
1886	0	0	0.0	10.40	0
1887	234	2	117.0	10.08	1,179
1888	0	0	0.0	11.03	0
1889	0	0	0.0	11.97	0
1890	0	0	0.0	13.23	0
1891	80	1	80.0	14.80	1,184
1892	129	2	64.5	13.39	863
1893	135	1	135.0	13.39	1,807
1894	0	0	0.0	10.24	0
1895	130	2	65.0	8.82	573
1896	147	2	73.5	11.03	810
1897	0	0	0.0	11.65	0
1898	0	0	0.0	10.71	0
1899	0	0	0.0	11.03	0
1900	105	1	105.0	11.65	1,224
1901	0	0	0.0	11.97	0
1902	0	0	0.0	11.65	0
1903	0	0	0.0	11.34	0
1904	0	0	0.0	9.76	0
1905	0	0	0.0	10.40	0
1906	0	0	0.0	11.65	0
1907	0	0	0.0	10.08	0
1908	0	0	0.0	9.76	0
1909	0	0	0.0	11.97	0
1910	0	0	0.0	11.97	0
1911	0	0	0.0	11.34	0
1912	0	0	0.0	11.03	0
1913	0	0	0.0	6.93	0
1914	0	0	0.0	2.83	0

[1] Sources for economic data: Tower (1907); Hegarty (1959).

Table 19

Regression of barrels per whale on year

Intercept	119.52
Regression coefficient	−0.61269
Standard error of regression coefficient	0.23525
Computed *T*-value	−2.6044
Correlation coefficient	−0.4237
Standard error of estimate	20.121

Analysis of variance for the regression

Source of variation	D.F.	Sum of squares	Mean squares	*F*-value
Attr. to regression	1	2,746.138	2,746.138	6.783
Dev. from regression	31	12,550.832	404.866	
Total	32	15,296.970		

to believe that the change in size caught is due to a change in the kind of whale sought by whalers, the change appears to be related to the population, not to the effort. Thus the data suggest that pelagic whaling did cause a change in the age structure of the population, ie., a shift towards smaller and presumably younger individuals.

From analogy with other large mammals one can speculate that the shift from larger to smaller whales would tend to have a negative effect on reproductive potential. For example, such a shift might cause a decrease in the reproductive potential of the population, which in turn would hamper the ability of the population to recover after the period of pelagic whaling. However, too little is known about the social behavior, age at first breeding and other aspects of the bowhead whale to do more than speculate about the effect of this reduction in average size of whales.

The decline of the bowhead population

Estimating the changes in the relative abundance of the bowhead from 1848 to 1914 is the most difficult of all tasks we have attempted. If the life-history characteristics of the bowhead whale were known accurately, including accurate measures of longevity, age at first breeding, calving intervals, the rates and sources of mortality, and changes in birth and death rates with changes in population density, then estimating the changes in the size of the bowhead population would be a relatively straightforward problem. One would need merely to take the population size at the beginning of each year, calculate the number of births and number of deaths due to causes other than to pelagic whaling operations, subtract from that the number of whales killed as a result of pelagic whaling operations, then obtain an estimate of the population size at the beginning of the next year. Unfortunately, the bowhead is among the least studied of all large mammals, and we know little if anything about any of its primary life-history characteristics. This lack of information forces us to use indirect methods to gain insight into change in the relative abundance of the bowhead during the period of pelagic whaling.

If one assumes that the number of whales killed was directly proportional to the abundance, then Fig. 8 and Table 1 suggest that the population decreased rapidly, dropping to two-thirds of its original size by 1858 and one-third by 1868. Biological phenomena are rarely simple, however, and it is possible that the decrease in the whales caught was not only the result of a decrease in the population but also of an increase in the ability of the whales to avoid being caught.

Because recent studies (Braham *et al.*, 1979; Evans and Underwood, 1978) indicate that the present size of the western Arctic bowhead population is approximately 2,000 to 3,000, our estimates suggest that the current population is approximately 5–15% of its size in 1847.

Our estimates of the 1847 bowhead population average approximately 30,000 with limits of the range of reasonable estimates being 20,000 to 40,000. Given the amounts of harvesting by pelagic whaling vessels, one might query under what conditions of birth and mortality from other sources is it reasonable to expect that the bowhead whale population declined to a size of approximately 3,000 by 1915.

As previously noted so little is known about the life history characteristics of the bowhead that it was not reasonable to use complex age structure models to test the consequences of our data. Lacking information of this kind, we have chosen to examine the consequences of whaling on a hypothetical population characterized by a given initial population size, constant birth and natural mortality rates, and the annual catch and kill as determined from our study.

Using a range of reasonable values for recruitment and natural mortality rates for great whales, it is informative to determine whether a population subject to any values within this range, and subject to the annual kill that we have reported, could have declined from a size of 30,000 in 1847 to a population close to its estimated abundance of 3,000 in 1915.

Fig. 17A shows that a population of 30,000 animals with a recruitment of 3% and annual mortality of 3%, with no time lags or density dependent responses, would have declined under our reported annual kill from 30,000 to less than 12,000 by 1915, and that the same population in which all animals struck and lost alive also died would have declined to approximately 6,000 by 1915.

For comparison, Fig. 17B shows the results of the simulation when a starting population of 40,000 is used; Figs 17C and 17D show simulations using annual mortality of 4% and recruitment of 3%; and Figs 17E and 17F show simulations using mortality of 3% and recruitment of 4%. The latter two cases, with a 1% excess of recruitment over mortality, result in a decline followed by an increase after the pelagic whaling era when the kill or the kill plus whales struck and lost alive are subtracted – but no evidence of such recovery has been noted in the natural population. In the cases where mortality exceeds recruitment by 1%, a starting population of 30,000 (Fig. 17C) declines to about 4,000 animals, if the kill is added to natural mortality, and is near extinction if the struck and lost alive are also considered to have died; while a starting population of 40,000 (Fig. 17D) declines to levels very close to those reached under balanced recruitment and mortality (Fig. 17A) by a population of 30,000.

It is interesting to note that a population with recruitment equal to mortality from sources other than pelagic whaling would not have suffered a decline to 3,000 by 1915 if it began with a population size of 30,000 in 1847 and was subjected to the harvest amounts per year that we have given. For such a simple, hypothetical population some excess of mortality from other sources over recruitment is required in addition to pelagic whaling. However it should also be noted that the extremely simple model used here is the most optimistic one; any more complex model that involved time lags or the effects of sex and age structure would give estimates equal to or less than those given here for the decline in a hypothetical population.

During the span of time covered by our data sample (1849–1914) bowheads were also being taken from the population by Eskimos and by commercial shore-based

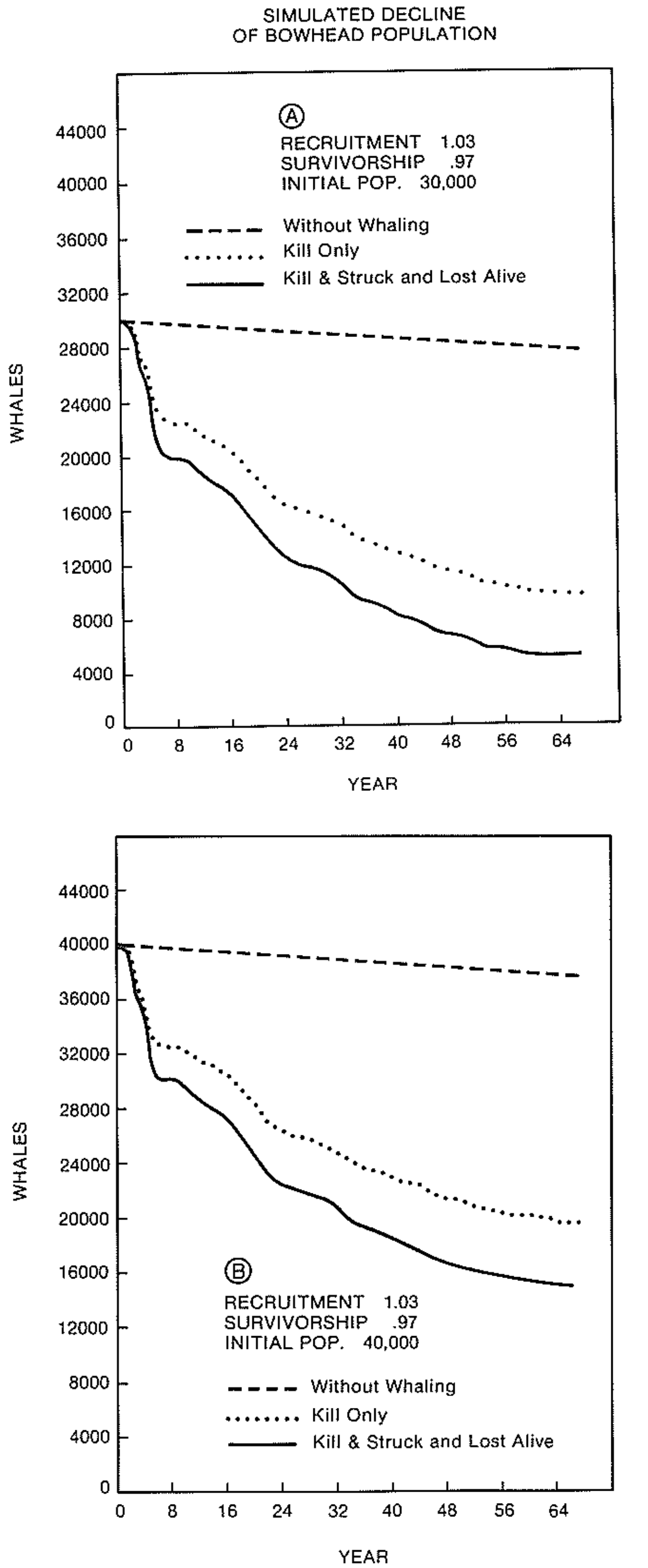


Fig. 17. Simulated decline of the bowhead population, given different initial population sizes, constant rates of recruitment and natural mortality and time series of whaling removals.

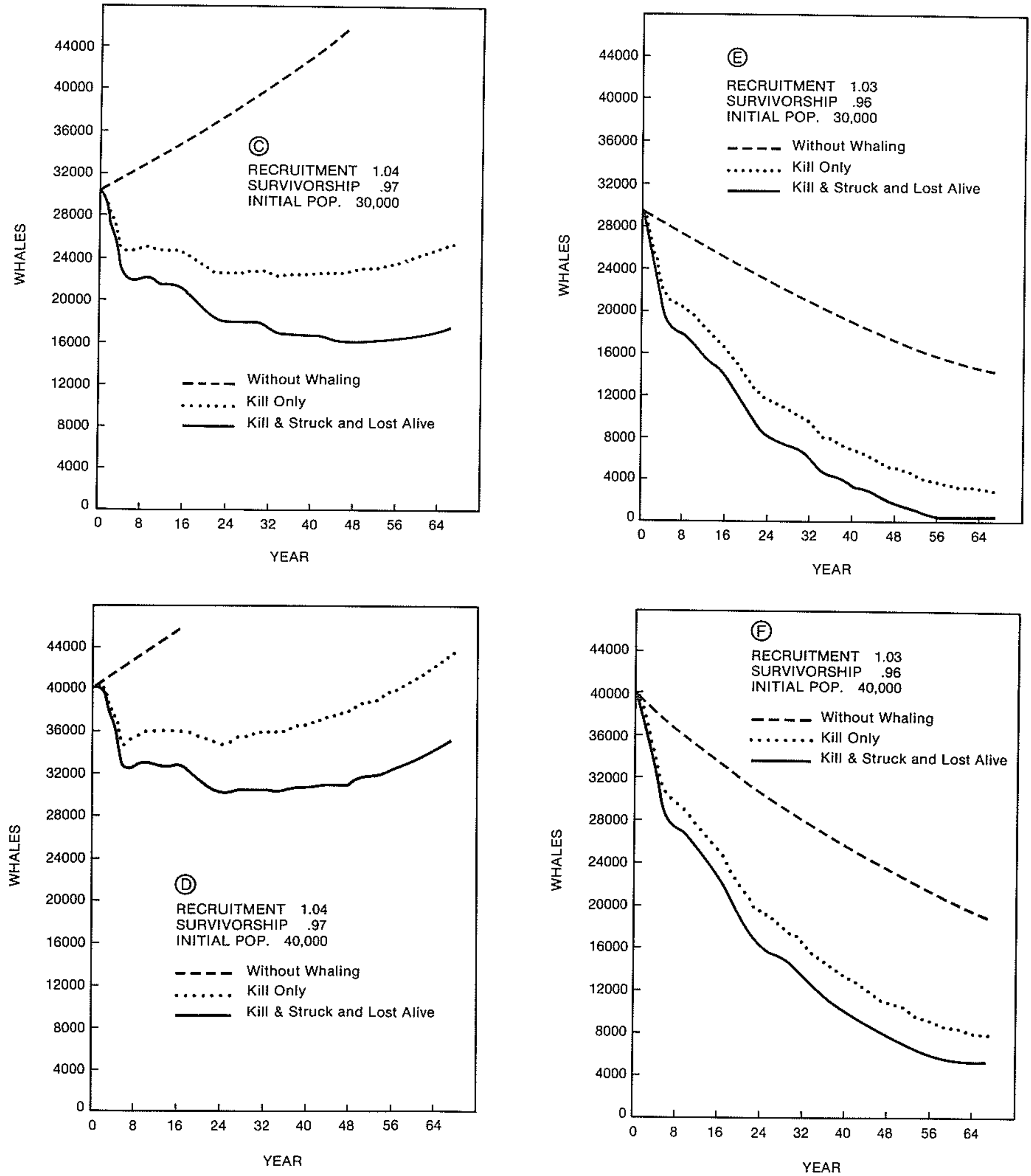


Fig. 17 (*cont.*)

whaling crews (see, for instance, Marquette and Bockstoce, 1980). It is regrettable, however, that, at present, these data are incomplete for the period of our data sample, and hence it would be misleading to incorporate them in this report. It is enough to state that, although the shore-based bowhead kill was a small proportion of the pelagic bowhead kill, it was significant, and future projects should plan to analyze closely the shore-based kill and to amalgamate it with the pelagic data presented here.

Because of the kills from shore-based operations, we must consider cases in which the mortality rate exceeded the recruitment rate. As Fig. 17E shows, a population in which the mortality was 4% and recruitment 3% per year would have declined under our reported kill from 30,000 in 1848 to approximately 4,000 in 1915; and a population in which all whales struck and lost alive by the pelagic fishery also died would have declined to less than 200 whales. (Such a population, not subject to pelagic whaling, would have declined to only 16,000.)

If the pre-exploitation population of bowheads was closer to the upper bounds of our estimates, approximately 40,000 individuals, then such a population with a 3% recruitment rate and 4% mortality rate would have declined to approximately 8,000 if all struck and lost whales died. Such a population not subject to pelagic whaling would have declined to 24,000 by 1915 (Fig. 17F).

Future research

Although the study has produced significant and far-reaching results, we feel that two areas in particular must now be analyzed to give our report its fullest utility. The present state of understanding of the historical shore-based kill is, at best, preliminary. With competent analysis and more thorough research of ephemera it should be possible to obtain a reliable estimate of the changing kill and hunting effort in the period from 1848 to 1914. Such an investigation would complement the data presented in this report and allow a thorough understanding of the total historical bowhead kill.

Second, there is a need for further modeling of the bowhead whale population decline. As we have noted, little is known about the life history of this species, or any of the important population parameters. For that reason, only the simplest of population models was applied in this report. However, we have developed an age-structured, stochastic model for whales that allows great flexibility. It would be instructive to employ this model with a range of reasonable parameter values to learn under which sets of parameters a decline from 30,000 to 3,000 whales could be expected during the 67-year period of pelagic whaling.

SUMMARY

We have carried out a study of the history of the bowhead whale during the period of pelagic whaling, from 1848 to 1914, using as our primary source of information the extant logbooks from whaling ships. From the logbooks we have obtained daily observations of the locations of each ship; its local weather; its reports of whales seen; its hunting procedure, kill and catch. From these we have calculated several measures of hunting effort, including the number of ship-days whaling, the number of ship-days whaling corrected for weather conditions under which whaling was not possible, and the number of ship-days whaling corrected for the area of ocean visible each day. These estimates of catch, kill and effort have been used to estimate the 1847 pre-exploitation population of bowheads. Our results suggest that the population numbered approximately 30,000, and was no less than 20,000 and no more than 40,000.

The data also demonstrate that a statistically significant decrease occurred in the size of the average whale taken during the period of pelagic whaling. We speculate that this change in size of the average whale caught implies a change in the size and age structure of the population, and could have indirect effects on the bowheads' reproductive and mortality rates.

Our data also show that the whales were progressively eliminated from large parts of their original range, and that the rate of reduction was on the order of 3° latitude per decade. We speculate that, if the whales permanently abandoned large areas of their former feeding grounds, the ability of the population to increase may have been greatly impaired, or that any increase toward the pre-exploitation size of the population might take much longer than would be expected simply from typical reproductive and survivorship values for great whales.

Our analysis indicates that 16,600 whales were taken and 18,650 killed during the 67-year period of pelagic whaling. The kill would have greatly reduced a simple, hypothetical whale population which had been in steady-state (with births equal to non-hunting sources of mortality). However, some additional sources of mortality or decrease in reproduction would be required for such a population to be reduced from 30,000 to the present estimates of the population size, which are on the order of 3,000. Possible additional sources of mortality include shore-based whaling stations, not analyzed by our study, and aboriginal hunting. In addition, the indirect effects of whaling, ie., the decrease in the range and changes in the age structure, may have also reduced the net growth potential of the population.

ACKNOWLEDGEMENTS

We are grateful to Mr Richard C. Kugler, Director of the New Bedford Whaling Museum, for his support and advice. We owe a special debt to the custodians of the many manuscript repositories who allowed us to use their collections: Old Dartmouth Historical Society, New Bedford Free Public Library, Providence Public Library, Kendall Whaling Museum, Dukes County Historical Society, Mystic Seaport, Peabody Museum of Salem, International Marine Archives, Brown University, Mitchell Library (Sydney, Australia), Smithsonian Institution, Harvard University's Houghton Library and Business School, National Archives, State Library of Tasmania, Mariners Museum, East Hampton Free Library, New London County Historical Society, Connecticut Historical Society, Connecticut State Library, Glenbow-Alberta Institute, Wethersfield Historical Society, State Archives of Hawaii, California Academy of Sciences, Southampton Colonial Society, Albany Institute, Buffalo and Erie County Public Library, Essex Institute, Falmouth Historical Society, Franklin Delano Roosevelt Library, New Haven Colony Historical Society, and Rhode Island Historical Society.

Likewise we are deeply indebted to the data extractors who diligently and carefully encoded the logbook entries: Jane Bernert, Bruce Courson, Natalie Garfield, Patricia Ridzon and Gail Sleeman. Lastly, we owe our greatest debt to the principal investigators' assistants who contributed so much to the success of the project: Elizabeth Rex, New Bedford Whaling Museum; Tad Reynales, University of California, Santa Barbara; David Schimel, the Marine Biological Laboratory, Woods Hole, Massachusetts; W. E. Little, Woods Hole Oceanographic Institute.

Funding for the project was contributed by the Old Dartmouth Historical Society, Marine Mammal Commission, National Marine Fisheries Service, National Geographic Society and American Philosophical Society.

REFERENCES

Allen, K. R. 1966. Some methods for estimating exploited populations. *J. Fish. Res. Bd Can.* 23(10): 1553–74.

Bockstoce, J. R. 1978. A preliminary estimate of the reduction of the western Arctic bowhead whale (*Balaena mysticetus*) population by the pelagic whaling industry: 1848–1915. *U.S. Dep. Comm., Nat. Tech. Inf. Serv., Publ.* Number PB-286 797. 32 pp.

Bockstoce, J. R. 1980. Battle of the bowheads. *Nat. Hist.* 89(5): 53–61.

Bockstoce, J. R. and Batchelder, C. F. 1978. A gazetteer of whalers' place names for the Bering Strait region and western Arctic. *J. American Name Soc.* 26(3): 258–70.

Braham, H., Krogman, B., Johnson, J., Marquette, W., Rugh, D., Nerini, M., Sonntag, R., Bray, T., Brueggeman, J., Dahlheim, M., Savage, S. and Goebel, G. 1979. Population studies of the bowhead whale (*Balaena mysticetus*): results of the 1979 spring research season. *Rep. int. Whal. Commn* 30: 391–413.
Breiwick, J. M. 1978. Reanalysis of Antarctic sei whale stocks. *Rep. int. Whal. Commn* 28: 345–68.
Caughley, G. 1977. *Analysis of Vertebrate Populations*. John Wiley and Sons, Sydney, Australia. 234 pp.
Chapman, D. G. 1974. Estimation of population size and sustainable yield of sei whales in the Antarctic. *Rep. int. Whal. Commn*. 24: 82–90.
Clark, H. A. 1887. The whale fishery: 1. History and present condition of the fishery. pp. 86–95. *In*: G. B. Goode (ed.) *The Fisheries and Fishery Industries of the United States*. US Government Printing Office, Washington, D.C. 881 pp.
DeLury, D. B. 1947. On the estimation of biological populations. *Biometrics* 3: 145–67.
Draper, N. R. and Smith, H. 1966. *Applied Regression Analysis*. John Wiley and Sons, Inc., New York. 407 pp.
Elton, C. S. 1942. *Voles, Mice and Lemmings. Problems in Population Dynamics*. Clarendon Press, Oxford, England. 496 pp.
Evans, C. D. and Underwood, L. S. 1978. How many bowheads? *Oceanus* 21(2): 17–23.
Hegarty, R. B. 1959. *Returns of Whaling Vessels Sailing from American Ports, 1876–1928*. Old Dartmouth Historical Society, New Bedford, Massachusetts. 58 pp.
Leslie, P. H. and Davis, D. H. S. 1939. An attempt to determine the absolute number of rats on a given area. *J. Anim. Ecol.* 8: 94–113.
Marquette, W. and Bockstoce, J. R. 1980. Statistics on the historical shore-based bowhead whale fishery in Alaska. *Mar. Fish. Rev.* 42(9–10): 5–19.
Seber, G. A. F. 1973. *The Estimation of Animal Abundance and Related Parameters*. Charles Griffin and Co., Ltd., London, England. 506 pp.
Starbuck, A. 1964. *History of the American Whale Fishery From its Earliest Inception to the Year 1876*. Argosy Antiquarian, Ltd., New York. 779 pp.
Tillman, M. F. 1977. Estimates of population size for the North Pacific sei whale. *Rep. int. Whal. Commn* (special issue 1): 98–106.
Tillman, M. F. and Breiwick, J. M. 1977. Estimates of stock size for the Antarctic sei whale. *Rep. int. Whal. Commn* (special issue 1): 107–12.
Tillman, M. F., Breiwick, J. M. and Chapman, D. G. 1983. Reanalysis of historical whaling data for the western Arctic bowhead whale population. Paper SC/32/PS6 (published in this volume).
Tower, W. S. 1907. *A History of the American Whale Fishery*. Philadelphia, University of Pennsylvania. 145 pp.
Townsend, C. H. 1935. The distribution of certain whales as shown by logbook records of American whaleships. *Zoologica* 19(1): 3–52.
Wu, L. S.-Y. and Botkin, D. B. 1978. On population processes of long-lived species. pp. 245–54. *In*: H. H. Shugart, Jr. (ed.), *Time Series and Ecological Processes*. SIAM-SIMS Conf. Series 5. Soc. Ind. Appl. Math., Philadelphia. 303 pp.
Wu, L. S.-Y. and Botkin, D. B. 1980. Of elephants and men: a discrete stochastic model for long-lived species with complex life histories. *Amer. Nat.* 116: 831–49.

Appendix 1

POPULATION ESTIMATES USING THE DELURY METHOD

In the Leslie and unmodified DeLury methods, a population estimate is obtained from the catch and effort data alone (Leslie and Davis, 1939; DeLury, 1947). The catch per unit effort (CPUE) in successive years is plotted against the accumulated catch; a least-squares linear regression line is fitted to the points and extrapolated to CPUE $= 0$; and the intercept on the accumulated catch scale gives an estimate of the initial population size.

The model may be written as:

$$U_t = kN_0 - kC_t \qquad (1)$$

where U_t = CPUE in season t
C_t = accumulated catch to season t
k = proportion of population captured by one unit of effort when $t = 0$
N_0 = initial population size

The least-squares estimate of the initial population size is then obtained by solving (1), which is equivalent to a linear regression of the form ($y = a - bx$), using standard regression methods (Draper and Smith, 1966). The population estimate is then given by:

$$N_0 = [a/b]$$

Alternatively, the logarithm of the CPUE may be plotted against the accumulated units of effort. This form of the method, due to DeLury (1947) is then written:

$$\log[U_t] = \log[kN_0] - k(\log_{10} e)\, U_t \qquad (2)$$

and a regression line is fitted as before. The population is given by:

$$N_0 = \frac{|\text{antilog}\,(a)|}{b/\log_{10} e}$$

The variance of N_0 is estimated as

$$\text{Var}\,(N_0) = (1/b^2)\ \text{Var}\,(a) + (a^2/b^4)\,\text{Var}\,(b) + 2\,(a/b^3)\,\text{Cov}\,(a, b)$$

using the 'delta method' of Seber (1973). Since the estimate of N_0 may be statistically biased, a correction factor, also due to Seber, is calculated as:

$$\text{estimated bias} = -\bar{Y} S^2_{y/x} / (b^3 \sum_{i=1}^{n} (X_i - \bar{X})^2$$

where $\bar{Y}$ = mean value of CPUE
$S^2_{y/x}$ = variance about linear regression
$\bar{X}$ = mean value of cumulative catch
n = number of seasons

The estimated bias is subtracted from the estimate of N_0 if it exceeds 10% of the magnitude of the standard deviation of N_0. An approximate 95% confidence interval may then be estimated as

$$N_0 \pm t[\text{Var}\,(N_0)]^{\frac{1}{2}}$$

where t is the 95% upper tail value of the t-distribution with $(n-2)$ degrees of freedom.

In this report we have not used the logarithmic form (2) of the model; according to Caughley (1977) it has the same constraints and can be derived from the same equation as the first form (1). We have referred to the Leslie/DeLury model as 'the unmodified DeLury method'.

Assumptions underlying the DeLury model:

1. Sampling is from a closed population. Under this assumption, natural mortality and recruitment may be ignored, and the entire population is available to the fishery.

2. 'Catchability' remains constant during the sampling period. Any individual whale is as likely to be caught as any other, and its 'catchability' does not change over the years.

3. There is no competition between ships. Under this assumption, ships do not interfere with one another or otherwise compete.

4. The annual catch represents a significant proportion of the population. The method depends upon the decrease in the CPUE bearing a direct relationship to the decline of the population.

MODIFIED DELURY METHOD ESTIMATES

The DeLury method has been modified by several authors to incorporate estimates of recruitment and natural mortality.

Chapman's modified DeLury model

Chapman's (1974) modification assumes constant, and therefore density-independent, recruitment equal to MN_0, the mortality rate multiplied by the initial population size.

The population in year t is given by

$$N_t = (N_{t-1} - C_t)\, e^{-M} + R_t \qquad (1)$$

and the catch in year t is given by

$$C_t = qf_t \bar{N}_t \qquad (2)$$

where $t = 1, 2, \ldots, n$
N_t = population at start of season $t+1$
C_t = catch during season t
R_t = recruitment during season t
f_t = standardized effort during season t
q = catchability coefficient
M = natural mortality rate (instantaneous annual)
$\bar{N}_t$ = average population during season t

The recruitment, R_t, is approximated by MN_0, and e^{-M} is approximated by $1-M$ (via a Taylor series expansion). Substituting into equation (1) we have the following:

Season	*Population size*
0	N_0
1	$N_1 = (N_0 - C_1)(1-M) + MN_0 = N_0 - C_1(1-M)$
2	$N_2 = (N_1 - C_2)(1-M) + MN_0$
	$= N_0 - C_1(1-M)^2 - C_2(1-M)$
⋮	⋮
t	$N_t = N_0 - \sum_{i=1}^{t} C_i(1-M)^{t-i+1}$ (3)

In the following discussion of these methods, the notation and nomenclature of Tillman and Breiwick (Tillman, 1977; Tillman and Breiwick, 1977) will be followed. The average population size during a season is approximated by subtracting half of the catch from the population size at the beginning of the season

Season	*Average population size*
1	$\bar{N}_1 = n_0 - \frac{1}{2}C_1$
2	$\bar{N}_2 = N_1 - \frac{1}{2}C_2$
⋮	⋮
t	$\bar{N}_t = N_{t-1} - \frac{1}{2}C_t$ (4)

since, as Allen (1966) asserts, '...it is probably better to assume that the catch per unit effort is proportional to the stock at mid season'.

Now substituting (4) into (2) we have

$$C_t = qf_k(N_{t-1} - \tfrac{1}{2}C_t) \qquad (5)$$

while from (3) we obtain

$$N_{t-1} = N_0 - \sum_{i=1}^{t-1} C_i(1-M)^{t-i}$$

and substituting (6) into (5)

$$\text{CPUE}_t = (C/f)_t = q(N_0 - \sum_{j=1}^{t-1} C_j(1-M)^{t-j} - \tfrac{1}{2}C_t)$$

The value of N_0 now may be estimated as in the unmodified DeLury method, with

$$Y_t = \text{CPUE}_t \quad \text{and} \quad X_t = \sum_{j=1}^{t-1} C_j(1-M)^{t-j} + \tfrac{1}{2}C_t$$

The q method

Once a value of N_0 has been obtained from Chapman's modified DeLury method, the value of the catchability coefficient, q, can be estimated. Given the regression coefficients

$$a = qN_0 \quad \text{and} \quad b = q \quad \text{then} \quad a/b = N_0$$

so

$$a/N_0 = q$$

Then q method (Allen, 1966) can be used to obtain a direct estimate of mean population size during season t with the following equation:

$$\bar{N}_t = U_t/q$$

where q = catchability coefficient
U_t = CPUE in season t

An estimate of the population size at the start of the season is obtained by adding half of the harvest for that season to the estimate of the mean population size:

$$N_{t-1} = N_t + \tfrac{1}{2}C_t$$
$$n_0 = \bar{N}_1 + \tfrac{1}{2}C_1$$

Allen's modified DeLury model

Allen's (1966) modification of the DeLury model employs estimates of M and R in the following equation:

$$\bar{N}_1 = \frac{\sum_{i=1}^{t-1} \bar{C}_i}{1 - Y_t - M\sum_{i=1}^{t-1} Y_i + \sum_{i=2}^{t} R_i Y_i}$$

where $\bar{C}_i$ = average catch = $\frac{1}{2}(C_i + C_{i+1})$
Y_i = normalized CPUE = U_i/U_1

Since, Allen notes, the estimate is 'particularly sensitive to the relation between the catch per effort (C/E) in the first and last years of the period', a series of estimates is obtained for increasing values of t up to the last year, each beginning with the same year, and a better (final) estimate is then obtained as the mean of the series. To estimate the population size at the start of the season, one-half of the first years' catch is added. In the absence of recruitment rate data, recruitment was (a) assumed to be constant and (b) estimated using Allen's model of recruitment rate:

$$r_t = r_0 - (r_0 - M)\,(N_{t-\text{lag}}/N_I)^{n+1}$$

where r_0 = initial recruitment rate
N_I = estimate of initial population size
n = 1.3898
M = rate of natural mortality
lag = lag time in years.