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A REVIEW OF NORTHERN PACIFIC SPERM WHALE *Physeter macrocephalus* ABUNDANCE AND STOCK STRUCTURE

By Megan Peterson

ABSTRACT: North Pacific sperm whales (*Physeter macrocephalus*) were extensively harvested in the 19th and 20th centuries. Sperm whale populations are no longer in danger of extinction from commercial harvesting. However, less quantifiable threats, such as interactions with fisheries and the unknown impacts on anthropogenic sound, still pose a danger to sperm whale populations. Enhancing our understanding of sperm whale abundance and stock structure in the North Pacific will enable researchers to monitor the recovery of sperm whale populations and effectively allocate conservation resources based on current threats (Hill & Demaster, 1998).

This paper reviews our understanding of sperm whale life history and available abundance and stock structure data (historic and current) for Northern Pacific sperm whales. This review also addresses types of research necessary to adequately assess sperm whale status going forward.

INTRODUCTION

Conservation of large whales has been an international concern since commercial whaling, lasting into the 1980's, depleted certain stocks so severely that harvesting was no longer profitable (Swartz & Taylor & Rugh, 2006). Sperm whales were the last of the great whales to be extensively harvested in the 20th century. Despite the great historical and commercial significance of sperm whales, there are surprisingly limited abundance and stock structure data in the Northern Pacific Ocean (Whitehead, 2002). Sperm whales have been listed as an endangered species under the Endangered Species Act since the Act's inception in 1973. Sperm whales are also a protected stock under the Marine Mammal Protection Act. Stocks of marine mammals are typically defined as group of animals that share a common spatial arrangement, interbreed when mature, and are managed under specific regulations or laws (NMFS website). Legal designations and resultant conservation measures for sperm whales are difficult to manage and quantify due to gaps in our knowledge of sperm whale abundance and stock structure.

GENERAL BIOLOGY

Sperm whales are the largest toothed whales (Ondoceti). They are also the most sexually dimorphic of all cetaceans, with mature males reaching over twenty meters in length, nearly twice the size of mature adult females (Gosho & Rice & Breiwisck, 1984). Sperm whales have the largest brains on Earth and are renowned for their disproportionately large head, often reaching one-third to one-fourth of their total body length (NOAA website). Sperm whales are also one of the deepest diving marine mammals. When foraging for food, they are typically submerged for around forty minutes, followed by ten minutes at the surface. It is estimated that sperm whales spend as much as 83% of their time underwater (Harill, 2001).

DISTRIBUTION AND SEGREGATION

Sperm whales are found in all deep (>1000m) oceans of the world from the equator to the edge of the pack ice in the North and South. While females and calves often stay in warmer tropical and temperate waters, the majority of male sperm whales typically make extensive migrations. Sperm whale distribution and migratory patterns vary seasonally in most regions, such as the Northern Pacific. There is less evidence for significant seasonal movements in sperm whale tropical populations (Whitehead, 2003).

Sperm whale social structure varies by age and sex. Breeding schools of female social/family units are largely matrilineal. Immature males eventually leave their breeding schools and form "bachelor schools." As males mature, they become more solitary and migrate farther North and South and return to more temperate waters for breeding seasons (NOAA Protected Resources website).

SOCIAL STRUCTURE & LONG-TERM KNOWLEDGE

Long-term knowledge is an important component of sperm whale societies as they are a long-lived species. Female sperm whales have been documented to live into their 80's and possibly even 100's (Whitehead, 2003). Like most large marine mammals, sperm whales mature slowly and reproduce at a relatively low rate, averaging one calf every four to six years (Best & Canham & Macleod, 1984). Calves are raised communally within sperm whale breeding schools, and calves will suckle from both kin and non-kin group members. Newborn calves are unable to undertake extremely deep dives, and therefore, other members of the group will remain shallow to protect a calf while the rest forage at greater depths (Gero & Whitehead, 2007).

Sperm whales primarily feed upon bathypelagic cephalopods or squid (Mitchell & Mesnick, 2002), a prey resource strongly affected by El Ninos and other oceanographic fluctuations (NOAA website). Sperm whale movement patterns over time indicate that long-term knowledge of prey distribution patterns and oceanographic conditions may determine certain migration routes.

The complex nature of the sperm whale social structure, segregated by sex and age, makes sperm whale populations difficult to study. Additional life history traits, such as their wide distribution and deep diving ability, similarly make sperm whales logistically very challenging to survey (Whitehead, 2003). Thus, it is important that studies continue to examine sperm whale abundance and stock structure in the North Pacific.

A HISTORY OF MODERN WHALING

Historical catch data from 19th and 20th century Japanese and Soviet whaling vessels in the North Pacific provides unique insight into sperm whale abundance, stock divisions, and movement patterns. However, the validity of historical Japanese and Soviet catch data is uncertain due to false reporting (Brownell & Yablokov & Zemsky, 1998).

The North Pacific was recognized as the world's premier whaling ground for sperm whales in the 19th and 20th centuries (Ohsumi, 1980). Sperm whales were subject to two, economically significant, periods of commercial hunting. Open boat or "Yankee" whaling occurred primarily between 1800-1880. Although there are no accurate counts for the number of whales taken, Best (1976) estimated that around 60,842 sperm whales were taken in the North Pacific between 1800-1909. Whitehead (2002) estimated that Yankee whaling reduced the population of sperm whales globally by about 10%-30% of pre-whaling numbers.

Modern whaling, with engine powered vessels and harpoon guns, began in the late 19th century and expanded into the 20th century. Although open boat whaling undoubtedly impacted sperm whale populations, modern whaling for sperm whales had a more severe impact on North Pacific sperm whale stocks. This review will examine data from modern whaling only.

Japan and Russia were the primary modern whalers in the 19th and 20th centuries. The Soviets first obtained a modern whaling vessel in 1887, operating the vessel primarily off the eastern waters of Korea. As capacity increased, Soviet vessels expanded into the Sea of Japan (Ohsumi, 1980). Landing stations were initially necessary for processing harvested whales. In 1925, the advent of the floating factory ship gave whalers the ability to travel further and remain at sea longer. In 1932, the first major Soviet factory ship, the *Aleut*, began pelagic whaling in the Tropical and Northern Pacific. Soviet whaling fleets expanded significantly after 1962. Four large fleets operated throughout pelagic waters in the North Pacific from 1963-1967. Soviet whaling efforts also eventually expanded into the Gulf of Alaska and Southern Pacific (Ohsumi, 1980).

Modern whaling in Japan began in 1897 and spread rapidly throughout coastal Korean and Western Kyushu waters. Japanese whaling expanded significantly around the turn of the century, and efforts extended throughout the Western North Pacific (Ohsumi, 1980). Major Japanese landing regions in the mid 20th century occurred between 33.5°N- 43°N (Kasuya & Miyashita, 1988). With the introduction of factory ships, Japanese whalers moved into the Bering Sea and surrounding northern areas. The Japanese whaling fleet was hit hard by the World Wars but resumed large-scale pelagic whaling in 1952. Japanese whaling efforts were primarily focused around the Aleutian Islands during the 1960's. As Northern Pacific populations were depleted, sperm whale harvesting by both Japanese and Soviet whalers expanded and focused efforts in the 1970's into Southern waters south of 40°N.

Modern whaling began along the Western coast of the United States and Canada around 1905. Landing stations were built all along the Western coast of the U.S., British Columbia and Alaska. The last of these stations closed in California in 1972 (Ohsumi, 1980). Significant harvesting of sperm whales by Japanese and Soviet whalers eventually stopped in the early 1980's, largely due to a loss in the profitability of harvesting North Pacific sperm whales as stocks had become critically depleted. Additionally, the loss in market value of the spermaceti oil, the endangered status of sperm whales, and the International Whaling Commission (IWC) moratorium contributed to ending sperm whale harvests. Small levels of subsistence whaling and Japanese scientific whaling continue today.

PART 1: HISTORICAL CATCH, SEX RATIO, DISTRUBUTION, MOVEMENT

Harvesting rates from the Northern Pacific are an important component to understanding historic and current abundance estimates and stock structure. However, recent studies have shown that both Soviet and Japanese whaling operations falsified reported sex ratios of males to females, size, poaching by small-type whalers and overall catch rates for sperm whales (Kasuya, 1998). Therefore, all abundance estimates and/or stock boundaries based upon historic catch records must be qualified in their application to current research and conservation.

1910-1976: SEX RATIO

Throughout modern whaling, the intensity of whaling efforts not only varied by the sex of the whale, but also by region and country. Ohsumi (1980) calculated total sperm whale catch rates within the primary whaling grounds in the Northern Pacific from 1910-1976 to be approximately 268,972.

The majority of the catches occurred after 1946, and reliable catch data by sex are available after 1947. It is important to note that although additional sperm whales were caught between 1910-1976, they were not properly documented, and therefore, are not figured into any sums (Ohsumi, 1980). Male sperm whales were generally targeted more than female sperm whales. From 1910-1976, males comprised around 75% of the total documented catch (188,892), while females accounted for only 25% (60,473). Figure 1 (*below*) contrasts the rate of female catches with total catches by modern whaling in the North Pacific from 1910-1976 (Ohsumi, 1980).

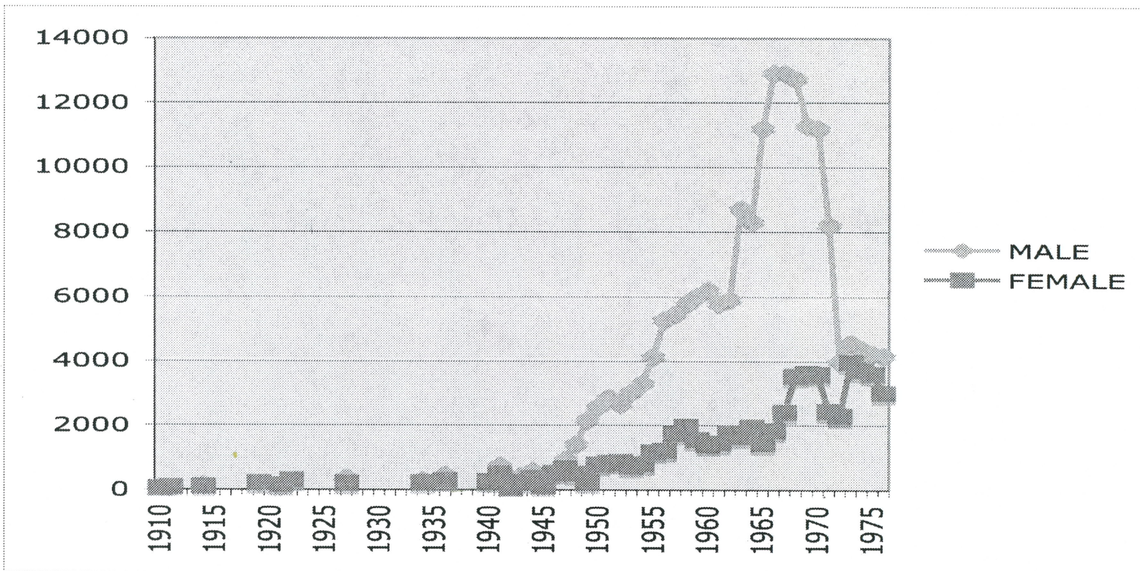

Figure 1: Yearly change in catch of sperm whales by modern whaling in the North Pacific, 1910-1976. Solid line: Total catches, Broken line: Female catches. (see text for references) ****this will be revised per Barb's comments*

Ohsumi's (1980) catch data also highlights the extensive harvesting of male sperm whales in Soviet pelagic waters. Male catches from Soviet pelagic waters comprised approximately 33% of the total catch and 74% of total male catches. Figure 2 (*below*) shows male and female catches in different regions throughout the North Pacific from 1910-1976 (Ohsumi, 1980). The reported ratio of males to females caught in Japanese and Soviet pelagic waters was also significantly higher (~6/1 – 8/1) than the ratio of males to females in coastal waters (~1/1 – 4/1).

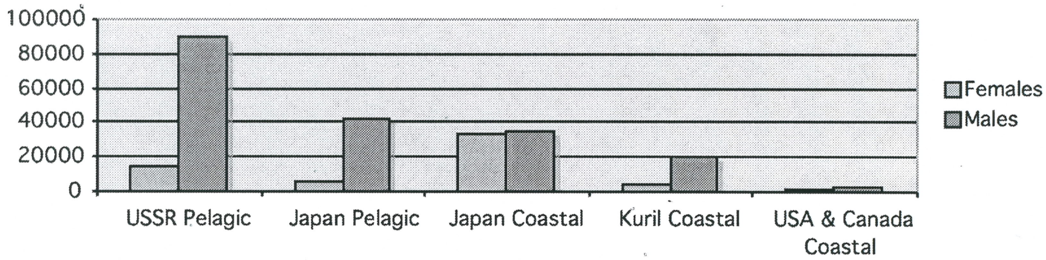

Figure 2: Female (blue) and male (red) harvests in North Pacific coastal and pelagic regions from 1910-1976 (see text for reference) ****this will be revised per Barb's comments*

Female sperm whales were extensively harvested in Southern Japanese pelagic and coastal waters and along the Kuril Islands. Japanese catches historically focused efforts on females and breeding schools during the summers off Haokkaido (>43ºN) and winters in Sanriku (36ºN - 40ºN). Females harvested along the Kuril Islands and Japanese coastal and pelagic regions comprised approximately 72% of all harvested females in the Northern Pacific (Ohsumi, 1980). Female sperm whales also comprised large percentages of catches in the Central Tropical Pacific south of 35º N for Japanese pelagic catches from 1954-1975 (*see figure 3 below*) (Ohsumi & Masaki, 1977).

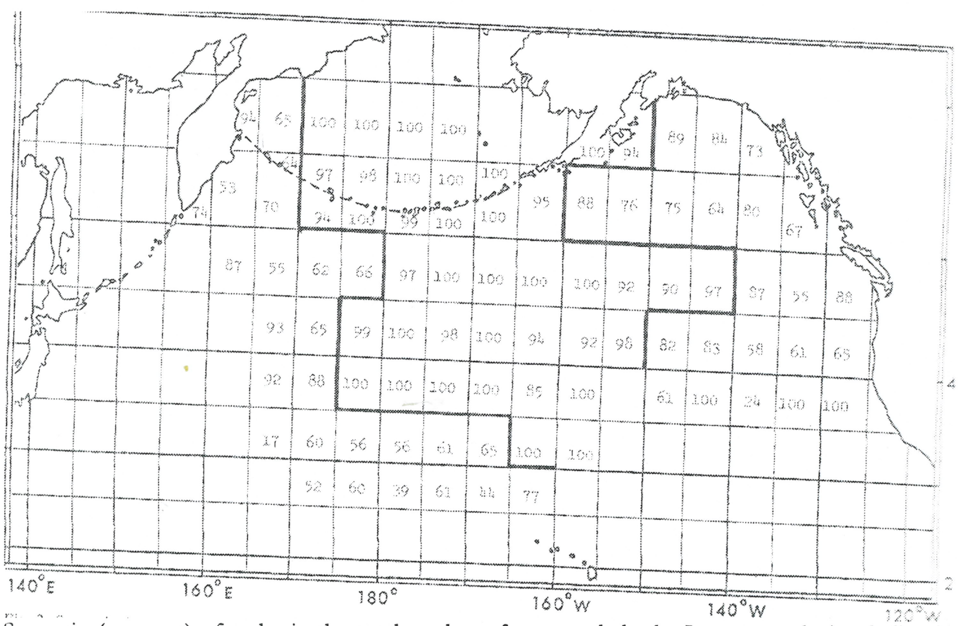

Fig 3. Sex ratio (per cent) of males in the total catches of sperm whales by Japanese pelagic whaling in each 5º square during the years 1954-1975 Broad lines show the margin of 90% of males (see text for reference) ***image will be rescanned*

SEX RATIO ANALYSIS:

Although male sperm whales bore the brunt of commercial exploitation, it is important to note that Japanese and Soviet whalers significantly underreported female harvesting. And as whaling efforts moved south in the second half of the 20th century, females comprised larger percentages of the overall catch.

From 1963-1977, the actual female catch was determined to be 9.6 times greater than the official record kept by Soviet whalers (Brownell et. al, 1998). Furthermore, the Whaling Research Institute purports that from 1959 – 1965, Japanese whalers frequently underreported female catches to avoid violating minimum size requirements (Kasuya, 1999). Underreporting by whalers complicates the use of historic catch data in abundance estimate and stock division studies.

1910-1976: DISTRIBUTION OF CATCH

In addition to understanding the sex ratio of historic catches, it is also critical to understand geographic and seasonal distributions of harvested sperm whale individuals and groups. It is important to note that harvesting areas or "whaling grounds" were not wholly indicative of sperm whale seasonal distributions as "whaling grounds/seasons" were determined by socio-economic and logistical factors as opposed to actual sperm whale distributions. Nonetheless, the locations of the catches or "whaling grounds" serve as strong indicators of potential stock boundaries.

In the Western North Pacific, coastal catches of sperm whales generally increased in later summer months through early fall, where groups of younger bulls and mother/calf pairs were intensively harvested (Nishiwaki, 1966). According to Nishiwaki (1966), almost 40% (15,291) of the total sperm whales (41,225) harvested by Japanese whalers in the North Pacific between 1945-1962 were taken between 40°- 50°N in the Japanese coastal waters of the Okhotsk Sea.

Around 14% of the sperm whales harvested by Japanese pelagic whalers between 1945-1962 occurred just north of the Aleutians (Nishiwaki, 1966). Japanese harvests of sperm whales in the Aleutian waters generally extended from late May into August. Historical whaling data also suggests that male sperm whales where the most abundant at longitude 180° (*see figure 4 below*) around the Bering Sea (Ohsumi & Masaki, 1977).

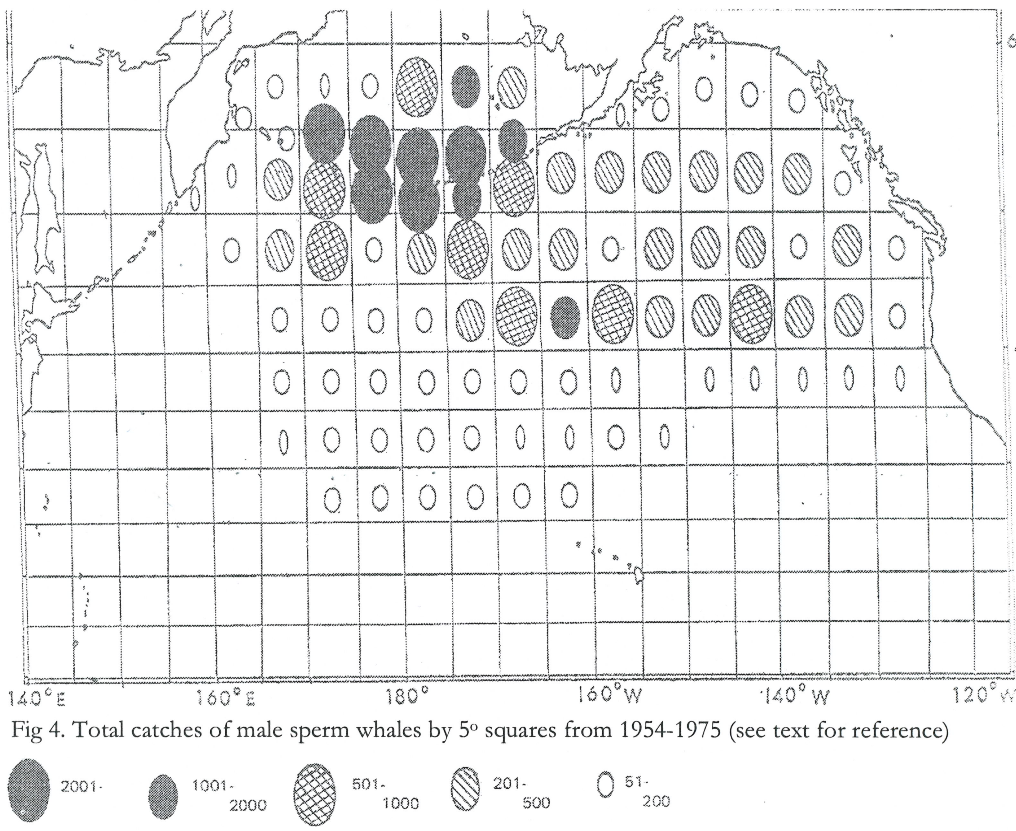

Fig 4. Total catches of male sperm whales by 5° squares from 1954-1975 (see text for reference)

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Female sperm whales were most heavily exploited in the later years of Japanese whaling in coastal Japanese waters and the Okhotsk Sea (Tillman, 1977). Although females were previously thought to remain mostly in tropical waters, there are documented cases of females as far north as the Aleutians and Attu and Kiska Islands (Nishiwaki, 1966). Japanese data also shows that extensive harvesting of female sperm whales did occur as far north as 50°N between 1954-1975 *(see figure 5 below)* (Ohsumi & Masaki, 1977).

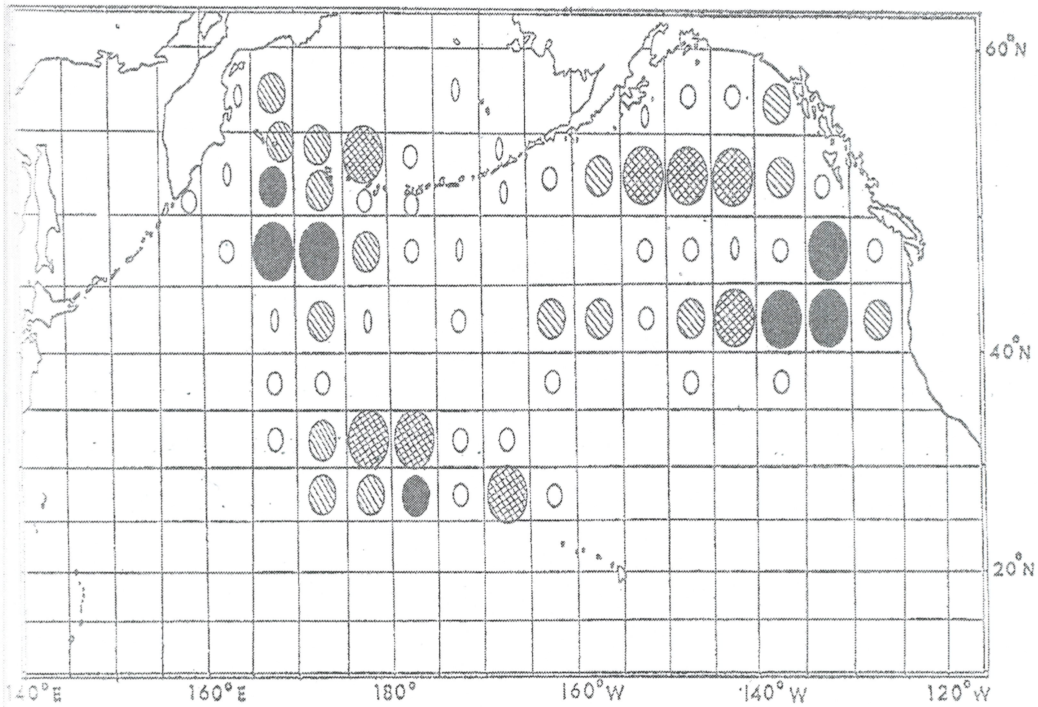
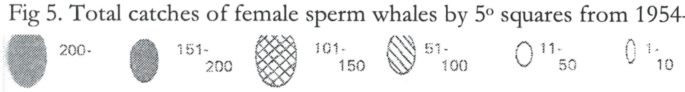


Fig 5. Total catches of female sperm whales by 5° squares from 1954-1975 (see text for reference)



DISTRIBUTION ANALYSIS:

In summary, historical catch data demonstrate that female sperm whales were actually harvested further north than previously believed. Harvesting of females was most intense in Japanese coastal waters in latitudes from 40°- 50°N (Ohsumi & Masaki, 1980). Male harvest efforts were most intense around the Aleutian Islands and Bering Sea.

Historic data also reveals the trend of whalers shifting effort south in the 1970's. Kasuya & Miyashita (1988) explain the southern shift as an indication that northern stocks of sperm whales in the Western North Pacific were depleted earlier than southern sperm whale stocks. Furthermore, due the selective harvesting of northern males and their resultant depletion, southern females increasingly became a relatively profitable target for whalers in the 1970's and early 1980's *(see figures 6 &7 showing southern shift of whaling efforts)* (Ohsumi, 1980).

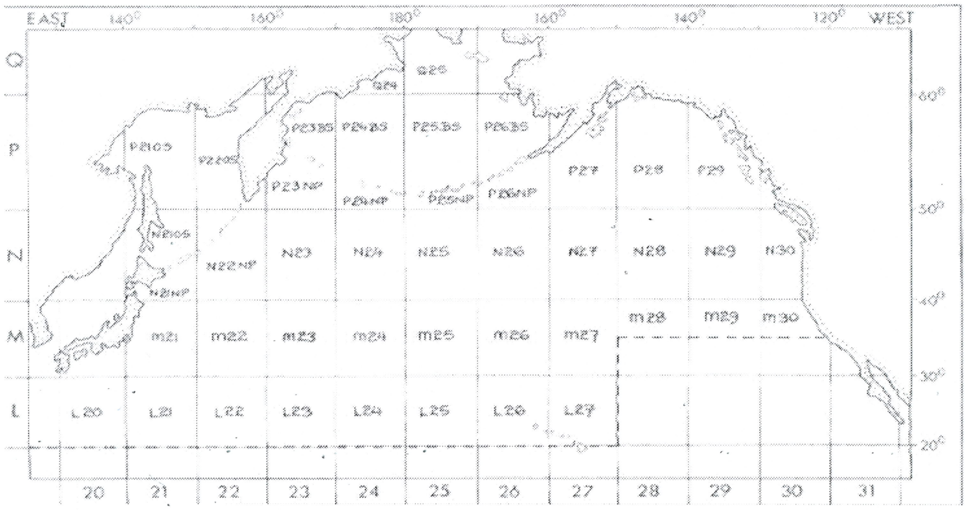


Fig 6. Map of the North Pacific and positions of 10° squares for figure 8 (see text for reference)

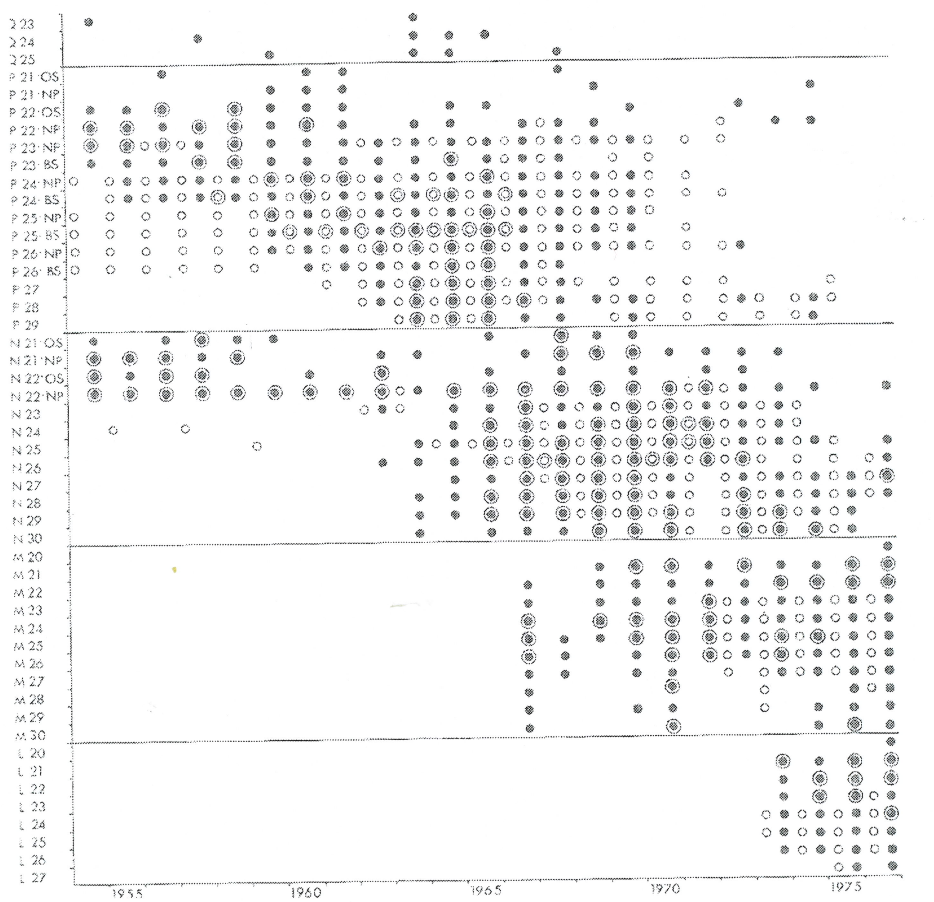


Fig 7. Yearly change in the pelagic whaling grounds of the Japanese and Soviet fleets in the North Pacific (see text for reference) ***image will be rescanned*

It is again critical to note the significant underreporting of harvested sperm whales. Between the years of 1966-1973, official Soviet data reported a catch of 32,374 sperm whales. An alternate report tallied actual harvests at approximately twice the initial reported value, or 66,950 between 1963 and 1979 (Kasuya, 1999). It is also estimated that Soviet whaling expeditions harvested 180,000 sperm whales from 1949-1979, having underreported harvests by about 60% (Brownell et. al, 1998). Similarly, Japanese whaling statistics were inaccurately low as they did not represent poaching by small-type whalers and discarded whales due to quota limits, small size, and/or insufficient processing capability (Kasuya, 1998).

1949-1976: SPERM WHALE MOVEMENTS BASED ON TAGGING DATA

As the sperm whale industry grew post World War II, whalers attempted to learn more about the migratory patterns of sperm whales in the North Pacific. Soviet and Japanese whalers used "discovery tags" to be applied and then retaken with data upon the harvesting of the whale (Jaquet, 1996).

The Japanese began their tagging program in 1949. Soviet whalers later deployed Russian tags, and tagging studies continued into the 1970's. Tagging effort primarily focused on the Northwest Pacific, where approximately 4,400 sperm whales were tagged (Jaquet, 1996). The maximum distance recovered from the movement of a marked male was 7,593 km (Best, 1979) and 3,704 for a marked female (Best, 1969).

Low recovery rates of Japanese tags in the North Pacific resulted in fairly inconclusive data (Jaquet, 1996). Findings by Ohsumi & Masaki (1977), based solely Japanese results, did confirm that whales in the Central and Western Pacific make extensive north/south migrations. The data also demonstrated that Western males tend to migrate farther North than Central or Eastern males (Jaquet, 1996).

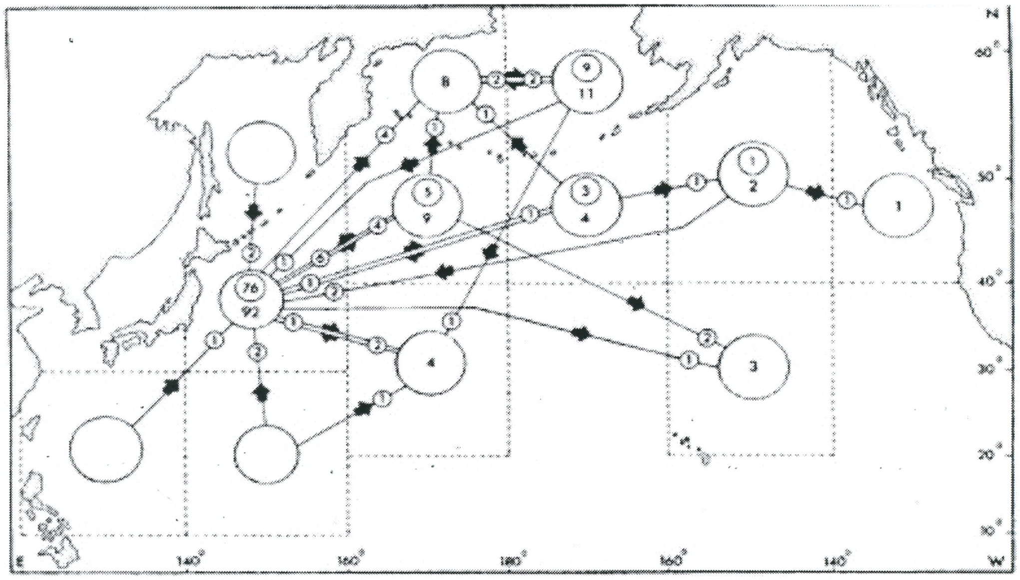


Fig. 8. Movements of marked male sperm whales. Numerals in large circle: Number of marked whales recaptured in each area. Numerals in small circle: Number recaptured in marked area. Numerals in small circle with arrow: Number of whales moved to different areas.

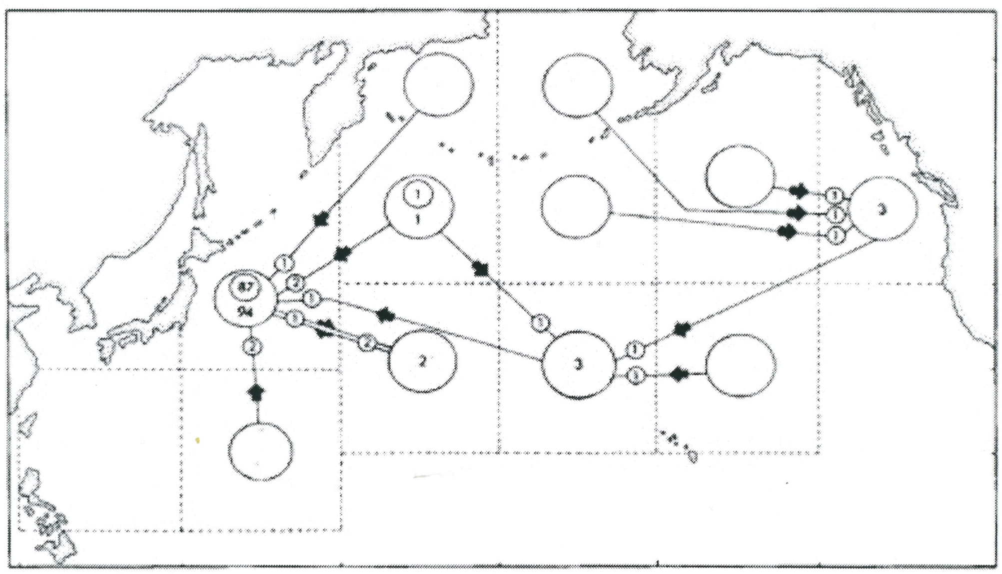


Fig. 9. Movements of marked female sperm whales. Notations are the same as in Fig. 8.

Wada (1980) updated Ohsumi and Masaki's 1977 (*figures 8 & 9 above*) report by incorporating fifty-three Russian tags and four more Japanese tags. The additional Russian data indicated that Western and Eastern male sperm whales intermingle with Central stocks more than was previously thought. The data also showed that two, relatively distinct concentrations, of adult males exist in the Western North Pacific and Bering Sea. Kasuya & Miyashita (1988) suggest that these two concentrations of adult males migrate north after breeding season to capitalize upon prey resources in northern regions. Marked juvenile male movements shared characteristics of both female and adult male movements, indicating that once close to maturity, males leave their breeding stock and migrate further north (Kasuya & Miyashita, 1988).

MOVEMENT ANALYSIS:

An important finding from the additional recovered Japanese and Soviet tags contradicted previous assumptions that female sperm whales were extremely discrete with their distribution and site fidelity. Recovered tags showed Western and Eastern female sperm whales migrating to the Central stock region, proving site fidelity of females was not as certain as once presumed (Jaquet, 1996) (Kasuya & Miyashita, 1988). There is no evidence of direct Western female and Eastern female stock interaction.

Although tagging data provides unique insight into sperm whale movements and stock structure, there are still associated problems such as tag shedding (only 4% of Japanese tags were retrieved) and the inability to calculate mortality data (Jaquet, 1996). Such complicating factors can result in either population over-estimates or upwardly biased data (Whitehead, 2003). There remains much room for additional sperm whale movement research in the Northern Pacific.

PART II: CURRENT ABUNDANCE ESTIMATES

Recent technological advances have enabled researchers to conduct comprehensive surveys using acoustic, aerial, visual and genetic sampling methods. Modern visual and aerial surveys provide a unique opportunity for scientists to examine sperm whale populations over spatially broader areas.

It is important to note that sperm whales, spending much of their life under water, can be easily missed by observers. Visual surveys from ships generally employ line-transect survey methods. Researchers have developed a model for visual surveys that requires multiple observers simultaneously, using the probability of multiple sightings to estimate a realistic count along the transect lines (Barlow & Sexton, 1996).

Scientists are increasingly incorporating acoustic survey techniques as well. The use of passive acoustic survey methods provides an exciting opportunity for researchers to supplement and/or compare visual data with acoustic findings. This method has even greater potential for determining accurate abundance estimates for animals such as sperm whales that are highly vocal and spend the majority of their time under water.

Notwithstanding advances in the technology of survey methods, abundance and stock structure data for sperm whales remain elusive. Since the 1980's, there have been a number of surveys throughout the Northern Pacific Ocean designed to provide updated abundance estimates. The section below will focus on five survey *(see figure 10 below for survey area map)* areas in the Northern Pacific Ocean that estimate abundance based upon aerial, visual and/or acoustic data. It is important to note that these studies employed different survey methods and are by no means conclusive as they represent only fractions of the regions inhabited by sperm whales.

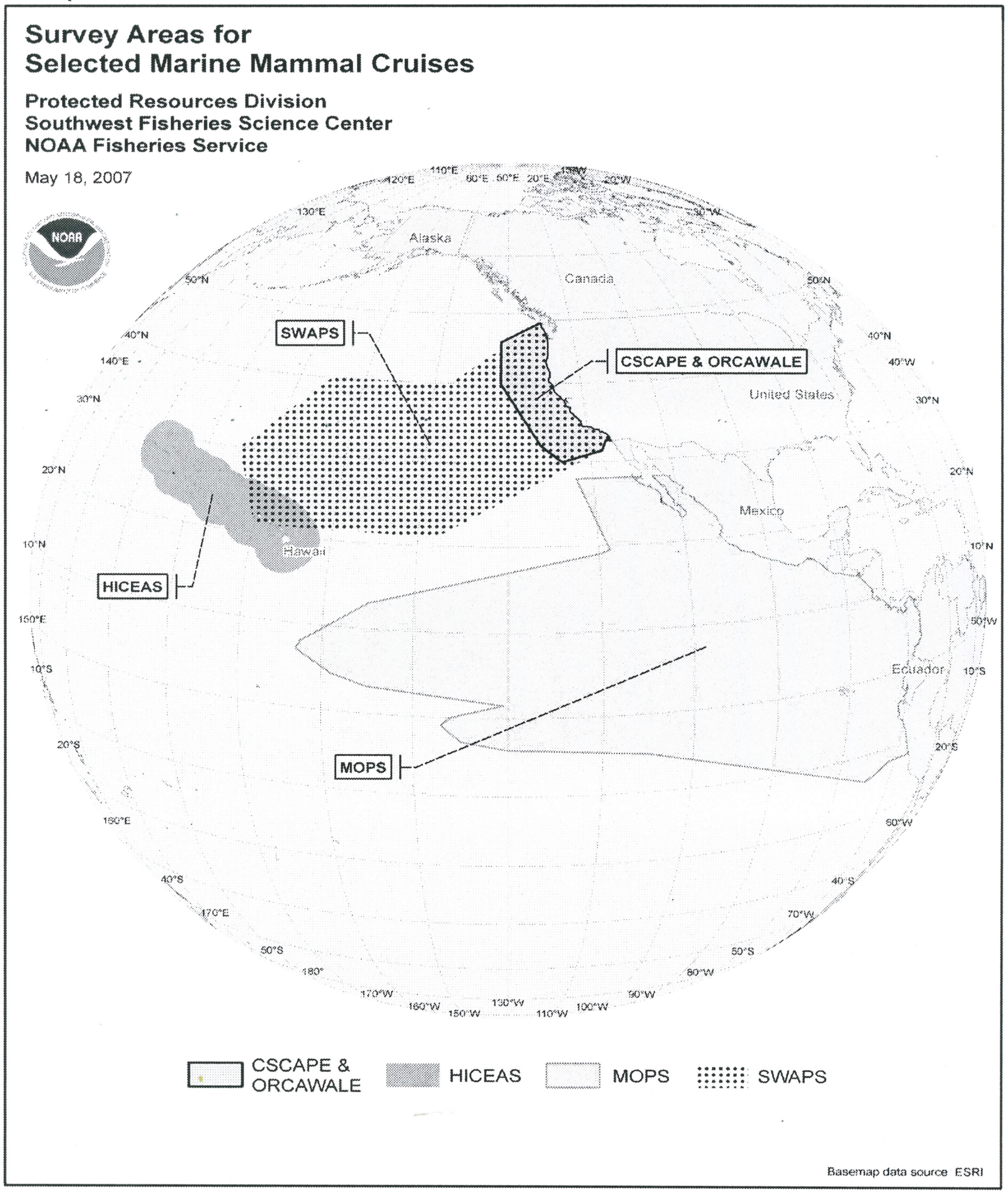


Fig 10. Four survey areas in Central and Eastern Pacific (does not include Western Pacific survey)

NORTHEASTERN TEMPERATE PACIFIC (SWAPS):

Between March and June of 1997, NOAA researchers conducted a survey using ship-based acoustic and visual line-transect study methods to estimate sperm whale abundance along the western coast of the United States out to Hawaii. The survey was designed to estimate sperm whale abundance during the breeding seasons when densities should be relatively high. The entire study area extends from the U.S. Western coast to the Northern Hawaiian Islands from approximately 20° – 45°N. There was some area overlap between the Hawaiian Island

EEZ survey (discussed below) and the North Eastern Temperate survey. However, the area overlapped was minimal, and the total study area was 7.8 million km^2 (Barlow & Taylor, 2005).

The abundance estimate from the analysis of the visual survey data was 26,292 sperm whales for the survey area (CV=.81). The average estimated density was 3.38 per 1000 km^2. The abundance estimate from the acoustic research was slightly higher at 32,068 sperm whales and 4.25 whales per 1,000 km^2 (CV=.36) (Barlow & Taylor, 2005).

U.S. COASTAL WATERS (CSCAPE & ORCAWHALE)

The primary goal for the surveys off the California coast (30°– 42°N) was to establish more accurate abundance estimates for cetaceans susceptible to potential injuries and/or mortalities from gillnet fisheries (Barlow, 1995). The survey was examining seasonal variations in addition to abundance. The survey used ship line-transect survey methods during the fall and summer of 1991. An aerial survey was also conducted within a smaller area (185-278 km) off the coast during the winters of 1991 and 1992.

Results from the initial ship line-transect survey in 1991 indicated an abundance of 756 sperm whales (CV=.49) (Barlow, 1995). The smaller aerial survey conducted during the winters and springs of 1991 and 1992 found an estimated 892 sperm whales (CV=.99) throughout the 264,270 km^2 study area (Forney & Barlow & Carreta, 1995). A more recent study by Forney and Barlow (1998) addressing seasonal abundance patterns modified the aerial data survey to incorporate diving times for sperm whales, increasing the estimate to 2,679 (CV=.99).

Although these surveys served to enhance our understanding of sperm whale stocks off the California coast, data results were varied and sightings were relatively infrequent throughout the surveys. Fewer sightings compounded by data biases serve to reduce the accuracy of abundance estimates (Forney & Barlow, 1998).

EASTERN TROPICAL PACIFIC (MOPS):

Five surveys were conducted annually between July and December from 1986 to 1990 in the Eastern Tropical Pacific. The total study area was 19 x 10^6 km^2, and two vessels were used each year for the stratified line-transect surveys from approximately 15°S – 30°N (Wade & Gerrodette, 1993). The surveys were designed to replicate each other as much as possible each year. Although this study extends into the Southern Hemisphere and may be less applicable to abundance estimates of the Northern Pacific, it represents a very large survey area and, therefore, should be included in this review.

Wade & Gerrodette (1993) estimated an abundance of 22,700 sperm whales (CV=.23) for the entire surveyed area. The individual sperm whale density was approximately 1.2 per 1,000 km^2 (Barlow & Taylor, 2005). Wade & Gerrodette (1993) hypothesized that the surveyed sperm whale population may be a local tropical stock or perhaps a migrating population.

HAWAIIAN EXCLUSIVE ECONOMIC ZONE (HICEAS):

In the summer and fall of 2002, two NOAA research vessels conducted a ship line-transect survey in the U.S. Economic Exclusive Zone (EEZ) around the Hawaiian Islands using visual and acoustic methods. The primary motivation for this survey was to determine if cetaceans surrounding the Hawaiian Islands were sufficiently abundant to support the estimated levels of bycatch from Hawaii-based longline fisheries (Barlow, 2006).

The survey area was comprised of areas with different survey effort levels. The higher density of survey effort, known as the "Main Island stratum," (212, 892 km^2) occurred within 140 km of the Hawaiian Islands. The second stratum, the "Outer EEZ stratum," (2,240, 024 km^2) with less survey effort, occurred between 140 km - 200 km from the Islands (Barlow, 2006).

Despite relatively low densities found on the 2002 cruise, abundance estimates were established for twenty-four species observed during the cruise. Sperm whales were widely distributed throughout the survey area and were by far the most abundant of the large whales during the summer/fall season. As expected, sperm whales were sighted more frequently in the deeper waters of the Outer EEZ stratum. Overall abundance for the region was estimated to be 6,919, with an individual density of 2.82 per 1,000 km^2 (CV= .81) (Barlow, 2006).

WESTERN PACIFIC:

One of the most comprehensive surveys in the Northern Pacific Ocean, both geographically and temporally, was conducted in the Western North Pacific from 1982-1996 using Japanese whale scouting vessels and vessels chartered by the Fisheries Agency (*see figure 11 below*). The survey was conducted over 344, 199 nm. Survey effort was limited to the Japanese coastal waters during the winter and spring months (Dec. – May). Effort then expanded to the pelagic zone as far East as 170°E during summer and fall months (Kato & Miyashita, 1998).

Kato and Miyashita (1998) calculated the abundance estimate for sperm whales by focusing on the Western North Pacific (0° – 50°N, 130° to 180°E) as that was where effort was consistently the highest. Throughout the fifteen-year survey, a total of 2,523 animals were sighted. The final abundance estimate, considering the effect of single animals and group stratification, was 102,112 (CV=.155) (Kato & Miyashita, 1998).

**figure 11 will show western pacific survey area*

ABUNDANCE ANALYSIS:

Region	Survey	Type	Abund. Estimate	CV	Area (1,000 km2)	Density / (1,000 km2)	Reference
California	CSCAPE/ ORCA	Ship	756	0.49	250		Barlow 1995
California	CSCAPE/ ORCA	Aerial	892	0.99	250		Forney & Barlow & Caretta 1995
California	CSCAPE/ ORCA	Aerial	2,679	0.99	250		Forney & Barlow 1998
Eastern Temperate North Pacific	SWAPS	Ship	26,292	0.81	7,786	3.38	Barlow and Taylor 2005
Eastern Temperate North Pacific	SWAPS	Acoustic	32,068	0.36	7,786	4.25	Barlow & Taylor 2005
Hawaii	HICEAS	Ship & Acoustic	6,919	0.57	81	0.94	Barlow 2006
Eastern Tropical Pacific	MOPS	Ship	22,700	0.24	19,148	1.2	Wade & Gerrodette 1993
Western North Pacific		Ship	102,112	0.155	25,681	1.16	Kato & Miyahsita 1998

Fig 12. Summary of North Pacific survey results ***have questions about this data*

The estimated density of individual sperm whales (3-5 per 1,000 km^2) in the Northeastern Temperate Pacific had the highest of abundance estimates of the Northern Pacific survey. However, it is important to remember Northeastern Temperate Pacific survey was designed to assess abundance during the breeding season when densities should be at their highest. Sperm whale density calculated from the Hawaiian EEZ survey (2.82 per 1,000 km^2) was slightly lower than the Northeastern Temperate estimated density but higher than densities off the shore of California (approximately .9 per 1,000 km^2) and in the Eastern Tropical Pacific (approx. 1.2 per 1,000 km^2) (Wade & Gerrodette, 1993) (Barlow, 2006).

The California aerial and visual surveys provided an interesting opportunity to contrast survey results based on sampling methods and seasonal variations. Unfortunately, seasonal comparisons between the two survey methods could not be made due the fact that the ship survey covered a larger area than the aerial survey. Nonetheless, it is important that future surveys address seasonal and temporal changes when calculating abundance estimates.

The recent surveys from the Northern Pacific Ocean are an important step towards estimating sperm whale abundance and delineating stocks. Nonetheless, these surveys represent only a small fraction of the North Pacific, and calculating an abundance estimate for the whole North Pacific would be extremely complex and problematic. Limited areas studied, insufficient stock structure data, and the need to find an appropriate proxy for an algorithm estimating sperm whale abundance over large scales make such a calculation very difficult at this time.

Whitehead (2002) did attempt such a calculation. Assuming that densities in un-surveyed areas are similar to surveyed regions and that density is roughly proportional to primary productivity, Whitehead (2002) estimated that global sperm whale populations are currently around 360,000 (CV=3.6) or 1.02 per 1,000 km^2. Whitehead's (2002) global abundance estimate is an interesting step towards calculating cetacean abundance over larger scales. However, the assumptions the calculation necessitates leave much room for error. Thus, it is crucial that comprehensive surveys continue to be conducted throughout the North Pacific Ocean to better understand sperm whale abundance and populations.

PART III: STOCK STRUCTURE

Historical whaling data and more recent abundance surveys demonstrate that sperm whale regional abundance fluctuates according to various extrinsic biotic and/or abiotic factors such as primary productivity, season, and prey availability. There may also be more intrinsic cultural differences between certain stocks of sperm whales in the Northern Pacific.

The IWC's sperm whale stock delineation has varied over time. In 1978, the "Canberra Line" was established to enable the IWC to more effectively assess sperm whale populations. The line divides sperm whales into Eastern and Western Divisions (*see figure 13*) (Ohsumi, 1980). The division occurs along 150°W, 50°N, then moves east to 160°W and down towards the equator (Bannister & Mitchell, 1980).

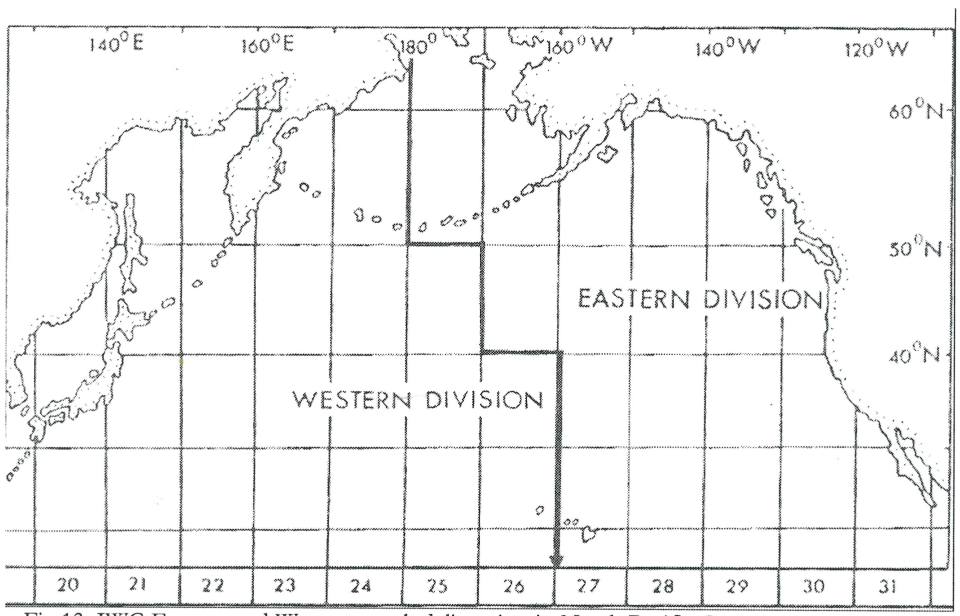
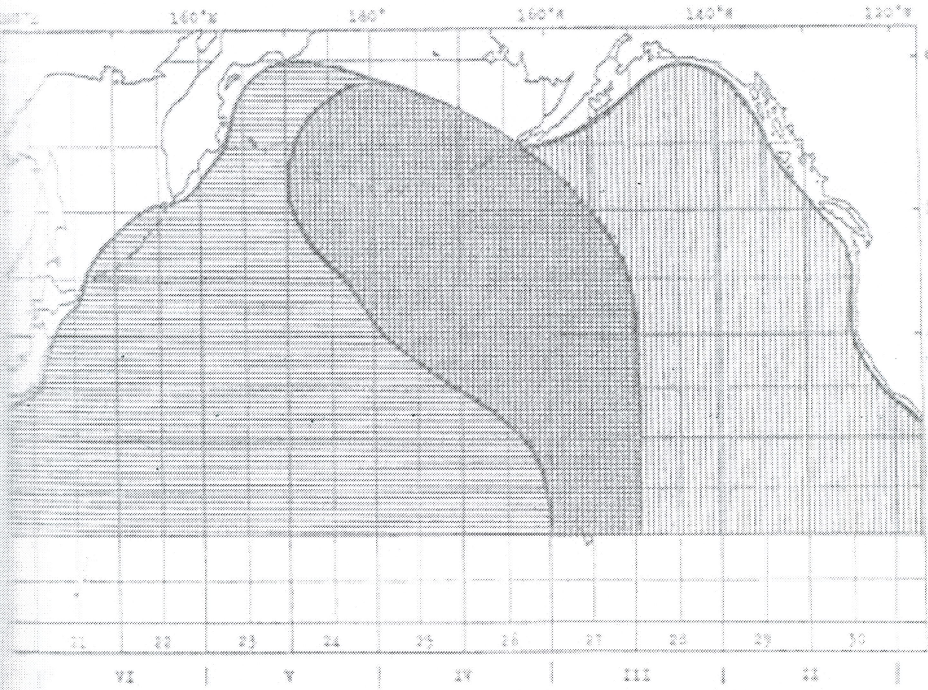


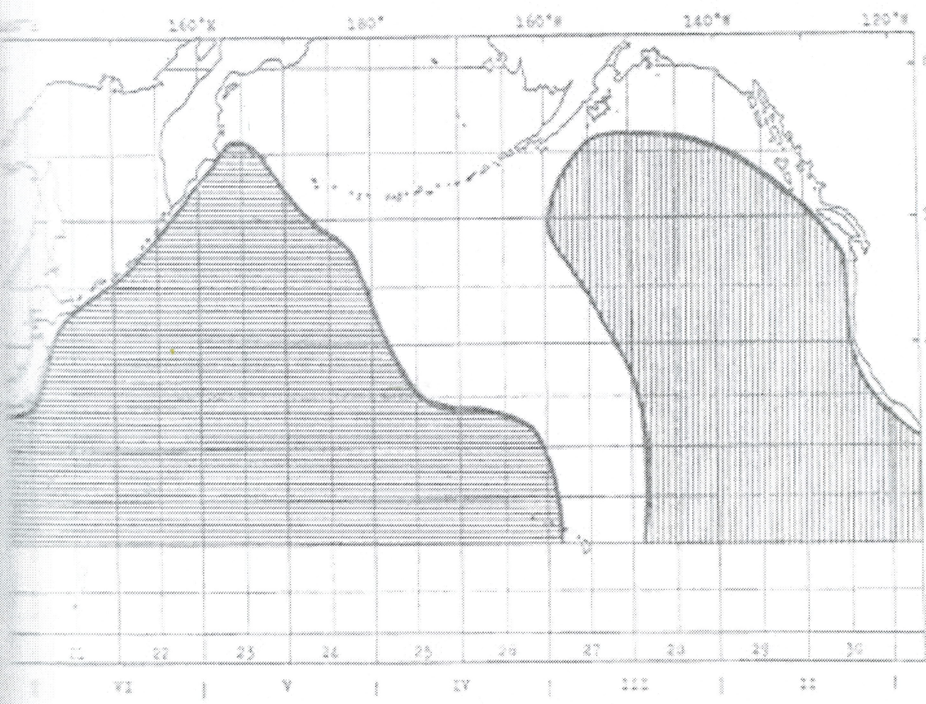
Fig 13. IWC Eastern and Western stock delineation in North Pacific Ocean

The IWC sperm whale stock designation was more political than scientific and much remains to be discovered with regards to sperm whale stock structure. Critical data for determining stock divisions includes the recognition of geographically separate entities during breeding season, tag-recapture data, and evidence for genetic dissimilarity or morphological features (Bannister & Mitchell, 1980). Currently, data are insufficient to definitively delineate sperm whale stocks. Tillman (1977) argued that mistakenly treating population components in aggregate can lead to incorrect conclusions about the status of individual stocks. We must continue to improve our study stock boundary data to ensure that conservation measures are allocated according to the health and abundance of current sperm whale stocks.

Ohsumi & Masaki (1977) reviewed data pertaining to catch distribution, mark and recapture, catch per unit efficiency (CPUE) and pregnancy rates as indicators of sperm whale stock units. Ohsumi & Masaki's (1977) results suggested that female sperm whales can be clearly divided into two (Eastern and Western) stocks with a boundary of 160°W (*figure 14*). Male sperm whales were more difficult to divide into separate stocks as they appear to intermingle substantially in the Northern and Central regions of the North Pacific Ohsumi & Masaki (1977) proposed two general stocks of male sperm whales with a large boundary area where substantial mixing occurs between 180° - 160°W (*figure 15*).



Schematic figure of distribution of two stocks for the North Pacific male sperm whales.



Schematic figure of distribution of two stocks for the North Pacific female sperm whale.

this image *will be figures 14 & 15 (see text for reference)*

Bannister & Mitchell (1980) generally concurred with Ohsumi & Masaki's (1977) longitudinal stock divisions. Their conclusions in support of a distinct Western stock were based on the high percentage of tags deployed and returned in the Western region. The Eastern stock was also distinguishable on the basis of the discrete distribution of both sexes and tagging data. Bannister & Mitchell (1980) also recognized a potentially separate Central stock. The Central stock purportedly intermingles more frequently with the Western stock, while Eastern sperm whale stock is relatively more separate.

Tillman (1977) asserted the existence of three distinct female and male sperm whale stocks. Tillman (1977) defined the three stocks as follows: an Asian stock living West of 170°E (coastal Japan, Kuril Islands, Kamchatka), an American stock East of 150°W (Gulf of Alaska, North American Coastal Waters), and a Central stock 180°-160°W (central North Pacific, Aleutian Islands). Acceptance of Tillman's (1977) three stock boundaries would require reexamination of Asian and Central stock status classifications due to particularly severe historic exploitation (Tillman, 1977). For instance, Asian female sperm whales are estimated to have declined in 1975 to 50% of their 1968 abundance while American female populations remained relatively more robust (Tillman, 1977).

Kasuya & Miyashita (1988) conducted one of the most comprehensive surveys of sperm whale stocks in the North Pacific. The study was designed to investigate both latitudinal and longitudinal segregation of sperm whale stocks using historical catch data, mark recapture studies, genetic analysis, and more recent surveys. The results supported the basic division of East and West sperm whale stocks in the North Pacific Ocean. More specifically, Kasuya & Miyashita (1988) concluded the Central North Pacific region is comprised of more than one stock, acting as a mixing ground for Eastern and Western stocks.

The data also showed that a distinct Eastern North Pacific population is widely distributed above of 20^0 N. Breeding is thought to occur throughout the Mexican and Southeast waters of the Hawaiian Islands, the Alaskan Gyre and the south side of the Aleutian Chain. The population roughly extends from the Aleutians in the north down the North American coast and out to the Hawaiian Islands. Adult males from this population are segregated and migrate to the west of the females as opposed to northern migration (Kasuya & Miyashita, 1988).

Additionally, Kasuya & Miyashita (1988) divided the Western stock into two, latitudinally separate, populations based on seasonal variations and school composition. Evidence supporting the Western North/South division includes potential morphological differences, behavioral variations of breeding schools, and genetic structure (Kasuya & Miyashita, 1988). The breeding population division occurs at 35^0N in winter and 40^0N in summer. Adult male stock division occurs at 35^0N in winter and 50^0N in summer.

STOCK STRUCTURE ANALYSIS:

In summary, the Eastern population of sperm whales is thought to be relatively discrete. Preliminary sampling data indicates sperm whales from the Western coast of the United States out to Hawaii are genetically similar to one another (Mesnick et. al, unpub.). Western North Pacific sperm whales also purportedly represent an individual stock. Kasuya & Miyashita (1998) suggested that the Western stock is actually comprised of two, latitudinally distinct, stocks. It remains to be seen whether the Central North Pacific sperm whales should be classified as a boundary between Eastern and Western stocks or as an entirely separate Central stock.

It is important to note that Tillman (1977), Bannister & Mitchell (1980), and Ohsumi & Masaki (1977) used catch per unit effort (CPUE) statistics to define sperm whale stock boundaries. Using the CPUE method, abundance estimates can be determined based on the historical rate at which whales were caught (Whitehead, 2003). Despite the relative availability of CPUE data, there are problems intrinsic to the CPUE method, and data are flawed. For instance, CPUE does not account for differences in the composition of the catch or technological variations over time and/or between vessels (Cooke, 1986).

Defining the stock structure of Northern Pacific sperm whales is essential to their management and our ability to assess the health and robustness of various populations. Technological advances in oceanographic research, such as genetic sampling and satellite tracking, must build upon previous studies based on historical data. Not only should research strive to elucidate sperm whale stock structure, there must also be an investigation of the fundamental biological and physical forces shaping sperm whale stock delineation.

<u>PART IV: DISCUSSION & FUTURE RESEARCH:</u>

The unqualified message of every study of North Pacific sperm whale abundance and stock structure is the critical need for additional research. Historic threats to sperm whales centered around commercial whaling and the resultant threat of extinction. Over time, anthropogenic threats have evolved into less quantifiable dangers, such as interactions with fisheries, threats from vessel strikes, and the unknown impacts of anthropogenic noise. Although less tangible, current threats still pose a real danger to complex sperm whale populations.

For instance, there is no estimate for sperm whale abundance off the coast of Alaska. This is an especially poignant issue for fisherman and conservationists in Alaska as sperm whale depredation on sablefish longline fisheries appears to be increasing. Lack of data will only hinder lawmakers abilities to effectively manage this type of conflict.

Sperm whales remain "endangered" under the ESA. The Western North Pacific stock was also designated a "Protected Stock" by the IWC, having dropped dangerously under their estimated carrying capacity (NMFS Manuscript, 1999). But without accurate abundance estimates or a much improved understanding of sperm whale stocks, such federal and international designations will always be questionable and, therefore, more difficult to monitor and manage.

RESEARCH

1. Historic mark and recapture studies provided a useful look into the migration patterns and levels of interactions between sperm whale stocks in the North Pacific. Due to the relatively low number of tags recaptured by Japanese and Soviet whalers, much remains to be discovered with regards to sperm whale movements throughout the Northern Pacific Ocean.

Developments in satellite tracking systems provide a unique opportunity to monitor sperm whale movements over significant spatial and temporal formats. Satellite tracking and Global Positioning Systems (GPS) have been used to study habitat use, diving depths and times, and migration routes for numerous cetacean species including belugas, Northern right whales, and humpbacks. Additional goals for satellite tracking studies should seek to improve the success rate of device deployments while reducing the invasiveness of the devices themselves.

2. Acoustic research is another example of a technology with important applications in sperm whale studies. Passive acoustic research has recently been used to supplement visual surveys estimating cetacean abundance, and is particularly effective when studying sperm whale. Acoustic surveys offer advantages to visual surveying alone, including detecting submerged animals, extending search distances, and allowing nighttime surveys. For instance, recent acoustic surveys have shown that sperm whales are present (at varying densities) year-round in Gulf of Alaska (Mellinger & Stafford & Fox, 2004).

   "Despite recent advances in acoustic survey methods, few acoustic surveys have actually produced estimates of whale abundance (Barlow & Taylor, 2005)." As acoustic survey methods improve technologically, we will be able to gather more data and better estimate sperm whale abundance throughout the Northern Pacific.

3. Genetic research represents another important component to understanding sperm whale stock structure. Initial results from genetic sampling of sperm whale tissue biopsies indicate a significant north/south division between Eastern stocks off the U.S. coast versus more southern groups around the Gulf of California (Mesnick & Lyrholm, unpublished). As sample sizes increase, genetic studies may shed additional light on sperm whale stocks.

4. Investigating the role that physical oceanographic features play in shaping sperm whale stock structure can also be helpful for delineating stocks in the North Pacific. Kasuya & Miyashita (1988) asserted that current fronts and oceanic gyres may be responsible for delineating three separate sperm whale stocks in the Northern Pacific Ocean. Biological oceanography can also influence sperm whale distribution. Sperm whales have also been shown to congregate in areas with steep underwater topography or high underwater relief and areas with high levels of secondary productivity (Jaquet & Whitehead, 1996).

5. Sperm whale culture may also serve to elucidate certain aspects of sperm whale stock structure. For instance, researchers are examining vocalizations within groups or "social units" of sperm whales as an example of cultural transmission influencing population structure. Initial results from these studies show that sperm whale vocalizations or dialects are grouped into "codas" used within distinct "vocal clans." Codas are stereotyped sequences of a series of broadband clicks made primarily by females, generally lasting around three seconds (Rendell & Whitehead, 2002). Rendell & Whitehead (2002) asserted that sperm whale social units using the same coda are more

likely to come together and form larger groups with one another. Coda variations, likely influencing sperm whale social interaction, may be helpful for delineating sperm whale stock boundaries.

Foraging strategies represent another cultural trait that can influence sperm whale population structure. For instance, differences in foraging strategies/prey between transient and resident killer whales off the coast of Washington delineate distinct population groups that rarely interact with each other. Similarly, this type of distinction may occur between stocks of sperm whales. For instance, sperm whales off the Gulf of California feed primarily on jumbo squid (*Ommastrephidae*) (Jaquet & Gendron, 2002), whereas other sperm whales off the Azores Islands feed more heavily on giant squid (*Architeuthidae*) (Whitehead, 2003). Such differences in prey may result in learned foraging strategy variations and potential stock distinctions between sperm whales.

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