9

Sperm Whale Catches and Encounter Rates during the 19th and 20th Centuries: An Apparent Paradox

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On a global scale, the number of sperm whales caught during the 20th century greatly exceeded the 19th-century catch. However, in at least two whaling grounds – the Japan Ground in the central North Pacific and the Galápagos Ground in the eastern tropical Pacific – the rate at which American whalers encountered sperm whales during the 19th century declined rapidly over the years, suggesting significantly decreased whale abundance (Bannister et al, 1981; Hope and Whitehead, 1991). The discrepancy can be seen in Figure 9.1, which shows catches peaking and encounter rates declining markedly in the 19th century, with catches peaking again at much higher levels in the 20th century. Declines in encounter rates during the 19th century seem inconsistent with the fact that much larger catches were made on these and in adjacent regions during the 20th century (Tillman and Breiwick, 1983; Whitehead, 2002).

Two published analyses have used 19th- and 20th-century whaling data from the Pacific to compare population models, one for the Japan Ground (Tillman and Breiwick, 1983) and the other for both that ground and the Galápagos Ground (Whitehead, 1995), while a third assessment has examined whaling and population data at the global scale (Whitehead, 2002). All three assessments identified the same discrepancy between catches and encounter rates, but none was able to resolve it. Tillman and Breiwick's (1983) analysis indicated that the number of sperm whales in the North Pacific during the mid 20th century was substantially larger than it had been before significant whaling began in the 19th century, a conclusion that does not accord with conventional understanding of the effects of whaling.

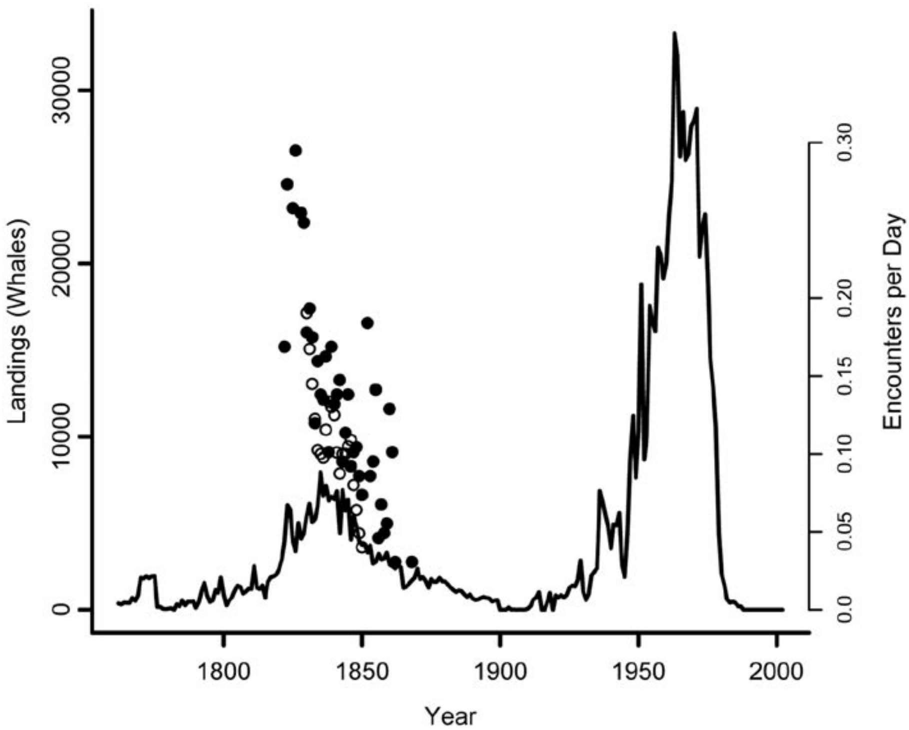

Figure 9.1 *Estimated annual global removals of sperm whales, circa 1750–2000, and encounter rates in the mid-19th century*

Note: Encounter rates from 19th-century whaling are denoted by closed circles on the Japan Ground and open circles on the Galápagos Ground.

Source: Japan Ground encounter rates from Bannister et al (1981); Galápagos Ground encounter rates from Hope and Whitehead (1991); 19th-century catches from Best (2005); 20th-century catches from International Whaling Commission

Examining both the Japan and Galápagos grounds, Whitehead (1995) enquired: 'If open-boat whaling so reduced sperm whale numbers, why were modern whalers able to take more whales over a shorter period (Best, 1983) from smaller initial stocks and not drive the populations to extinction?' Revisiting the problem at a global rather than regional scale, Whitehead (2002) concluded that 19th-century whaling had been intensive enough to inflict a moderate decline in the abundance of sperm whales without being sufficiently aggressive to reduce numbers to the extent suggested by the declines in 19th-century encounter rates. Thus, there remains a discrepancy, an apparent paradox, and it arises regardless of whether the catch data are considered regionally in the Pacific or at the global scale.

This chapter investigates this apparent paradox by exploring the implications of possible violations of four assumptions that underpin the three published analyses (see Table 9.1). First and most obviously, all three assessments, despite identifying uncertainties in the removal statistics, assumed that the estimated or reported catch levels were approximately correct. However, 20th-century removals may have been substantially lower, or pre-1900 removals substantially higher, than has been estimated. Examining the former possibility, Allison and Smith (2004) reviewed reported 20th-century catches. For the latter, information pertaining to 19th-century American whaling was assessed to determine whether the oil landing data used to estimate total catches and removals could have been much higher, or the yield of oil per whale considerably lower, than has generally been assumed.

The second assumption made by the analyses is that sperm whale populations were not only closed, but also affected by 19th-century whaling in the same

Table 9.1 *Four assumptions underlying the apparent paradox revealed by three analyses of 19th- and 20th-century sperm whaling*

Assumption	*Ways Assumption Might Be Violated*	*Relevant Information*
1. Removal estimates correct	20th-century catches over-reported	20th-century catch data from IWC
	19th-century oil landings underestimated	19th-century oil landings
	19th-century barrels per whale overestimated	19th-century American whaler logbooks
	Number of 19th-century voyages under-reported	Lists of 19th century American voyages
	19th-century whaling killed many more whales than were secured and processed	19th-century American whaler logbooks
	Paradox regional rather than global	Catches by ocean region
2. Separate regional populations or one global population	19th-century whaling of same populations on multiple grounds	Geographic location of 19th-century whaling grounds
	20th-century whaling of populations not subjected to 19th-century whaling	Geographic locations of 19th-century versus 20th-century whaling
	Whales changed their behaviour	Daily American voyage logbook data
3. Encounter rates proportional to whale abundance	Whalers changed their behaviour	Whalers changed their behaviour
	Heterogeneity in whale behaviour	Modern movement data from Galápagos Islands, and model
4. Equilibrium environmental conditions	Population carrying capacity changed	Alternate model formulations
	Ocean climate changed	Climate time series

Source: Tillman and Breiwick (1983); Whitehead (1995, 2002) way – that is, there were no refuges. Both Tillman and Breiwick (1983) and Whitehead (1995) assumed that during the 19th century, sperm whales formed isolated populations that were only subjected to catching effort on single grounds. Whitehead (2002), in contrast, treated all sperm whales as though they belonged to a single global population. To explore the possibility of multiple populations, catch data by ocean region for both centuries were analysed and distances between the various 19th-century whaling grounds were considered in the light of known migration and distribution patterns. The spatial overlap between catches during the 19th and 20th centuries was then evaluated to determine whether refuges from 19th-century whaling activity might have existed.

A third assumption made by Tillman and Breiwick (1983) and Whitehead (1995) was that whale encounter rates derived from logbook data (as in Bannister et al, 1981, and Hope and Whitehead, 1991) are reliable indicators of actual declines in whale abundance. However, the quantitative interpretation of catch and encounter rates is difficult for several reasons. For example, just as whalers, like all fishermen, might alter their searching strategy over time, their prey could have responded to whaling pressure by changing their avoidance and flight behaviour, as well as their distribution. Indeed, Whitehead (2002) suggested that 'the discrepancy between the severe drop in the sighting rates of the whalers over this period [1830–1850] and the results of the model may be at least partially explained if the whales changed their schooling behavior or distribution as exploitation… progressed'. In addressing this issue, data from the Japan Ground were analysed to compare encounter rates and interpret changes over time and space, while evidence from both the Japan and Galápagos grounds was assessed to judge whether the proportion of encountered whales that were killed changed over time. Another potential cause of mismatch between whale abundance and encounter rate is behavioural heterogeneity. If some whales were easier to find and kill because of their behaviour, the rate of encountering individuals would have declined more quickly than the population as a whole, which over time would include a higher proportion of the more elusive animals. Sperm whale populations in the South Pacific are culturally structured into 'clans' (Rendell and Whitehead, 2003) that consistently behave in different ways (Whitehead and Rendell, 2004). Whether such differences could explain the apparent paradox was investigated using modern data and theories regarding the movements of sperm whales of different clans.

Fourth, according to all three analyses, environmental constancy is assumed to have prevailed during the 1800 to 2000 period. Tillman and Breiwick (1983, p267) acknowledged that a significant increase in carrying capacity of 'the North Pacific sperm whale population' was a 'possible speculation', but found 'no information giving this supposition any great substance'. Whitehead (1995) also considered this possibility; but in his 2002 paper he did not raise the issue, implicitly assuming a constant environmental carrying capacity for sperm whales globally. At least two types of change in the environment could have occurred. On the one hand, ecological relationships may have altered as whale numbers were reduced by whaling – for example, the competitive balance between sperm whales and their unexploited competitors for squid could have led to disequilibrium conditions (cf. May et al, 1979). On the other hand, climate change may have affected the inherent productivity of the oceans over the two centuries. Of course, these two types of change may have interacted as well.

In the sections that follow, these four assumptions, and several alternative hypotheses, are examined in detail. The results of several specific comparisons and suggestions for further research are then discussed in the concluding part of the chapter.

Removal estimates

Two distinctly different sources of data on sperm whale catches are available for the periods before and after circa 1900. During the 18th and 19th centuries, the catches were recorded in terms of the amount of sperm whale oil produced by the fishery, while most 20th-century catches were assembled by the Secretariat of the International Whaling Commission (IWC) and reported as numbers of individual animals killed and processed. A painstaking review of data sources by the secretariat has not revealed any substantial problems with the 20th-century data, although several instances of misreported and under-reported catches have come to light in recent years. Allison and Smith (2004) concluded that, at least in the case of sperm whales, such problems were insignificant in comparison to the overall magnitude of the catches. The reported catches for most whaling operations were judged reliable; in any event, the more likely downward bias would be in the wrong direction to help resolve the apparent paradox.

Estimates of sperm whales killed prior to 1900 are much more complicated and the uncertainties greater. Best (2005) developed estimates of total catches of sperm whales by dividing the volume of oil imported by the yield of oil obtained from an average whale. For American whaling returns, Best relied on tables of landings published in Starbuck (1878), Hegarty (1959) and a major trade newspaper, the *Whalemen's Shipping List* (*WSL)*. To evaluate whether Best could have underestimated 19th-century American catches to such an extent as to explain the apparent paradox, two new data sets were constructed. First, drawing on Lund (2001), a new list of American whaling voyages, which included the volume of sperm oil produced by each voyage, was assembled. The annual total volume of oil landed from all voyages during the year that they were completed was then compared to the total yearly imports of sperm oil into the US. Second, data on the yield of oil per whale were compiled from American logbooks and compared to the average oil yield values used by Best (2005).

Oil production based on American whaling voyages

In this analysis, voyages are defined according to customs house records of departure and arrival because that was the basis for reported landings. We supplemented Lund's (2001) comprehensive and meticulously documented list of US whaling voyages with data relating to landings and whaling grounds derived from voyage lists (Wood, 1831–1873), inbound customs manifests (especially for New London, Connecticut) and logbooks and journals (Sherman et al, 1986), as well as information in Starbuck (1878), Hegarty (1959) and Davis et al (1997). Starbuck (1878) did not describe his methods or sources; but in a flier circulated to potential collaborators (Sherman et al, 1986), he acknowledged his reliance on the New Bedford Shipping List. By this he presumably meant the *WSL*, a trade newspaper published from 1843 to 1914 that attempted to cover the entire industry, not just the fleet sailing from New Bedford. For vessels from New Bedford, the most active port, we relied on production data assembled by Davis et al (1997).

Lund (2001) had identified some voyages unknown to Starbuck (1878) and Hegarty (1959), and we further checked the voyage data by comparing the information given in more than one source (see Table 9.2). Where possible, inconsistencies were resolved and errors corrected, while data on some voyages that had not appeared in Lund (2001) were added. The final database included nearly 15,000 voyages that sailed from 112 US ports from the early 18th century to circa 1900.

The annual totals of the amount of sperm oil produced by each voyage were compared to the yearly quantities of oil imported that Best (2005) had derived largely from Starbuck (1878, Table I) and Hegarty (1959). It is evident that Starbuck (1878, Table I), and presumably also Hegarty (1959), had, in turn, reproduced the *WSL* annual totals of sperm oil landed by port from 1843 to 1914, the only differences being minor transcription errors. For this period, there were substantial year-to-year differences between the *WSL*'s annual total imports and the corresponding totals of our voyage-based landings. One cause of divergence was that oil freighted during a voyage appeared in the import totals in the year that it was received, whereas in our voyage data, freighted oil was assigned to the year during which the voyage was completed. Indeed, for this entire period, the annual differences nearly averaged out (see Table 9.3), with the total oil imported being slightly less (1.8 per cent) than the total oil estimated from individual voyages. Similarly, Starbuck (1878, Table I) gave annual total oil importation by port for the 38 years (1804 to 1842) prior to the publication of the *WSL*, although he did not indicate his sources. Again there were annual differences between those import aggregates and our voyage-based total production, with the former 4.5 per cent greater than the latter. The differences in the measures of total oil production for pre- and post-1843 are not consistent with the proportion of voyages without reported production figures: 15.2 per cent and 8 per cent for the two periods, respectively.

Table 9.2 *Information regarding 18th- and 19th-century American open-boat whaling voyages derived from published sources*

Information	*Lund (2001)*	*Starbuck (1878)*	*Davis et al (1997)*	*Sherman et al (1986)* [1]
Captain name	•	•	•	•
Vessel name	•	•	•	•
Rig type	•	•	•	•
Home port	•	•	•	•
Tonnage		•	•	•
Day depart		•		•[2]
Month depart		•	•	•[2]
Year depart	•	•	•	•[2]
Day return[3]		•		•[2]
Month return[3]		•	•	•[2]
Year return[3]	•	•	•	•[2]
Geographic locations		•[4]	•[5]	•[6]
Product information		•	•	
Logbook existence	•[7]			•[7]

Notes: 1 Covers all voyage logbooks and journals in most public collections.
2 Dates covered in logbook or journal.
3 Dates of vessel's return to port or of loss of vessel.
4 One of more than 125 destinations recorded at the beginning of each voyage.
5 One or more of roughly 25 destinations derived from the destinations recorded at the beginning of each voyage.
6 One or more of 12 oceanic regions where the logbook indicated 'significant whaling'.
7 The present-day location of logbooks and journals pertinent to a voyage.

Table 9.3 *Aggregate sperm oil imports to US ports and voyage-based oil production*

	Pre-WSL *Publication*	*During* WSL *Publication*
Period	1803–1842	1843–1876
Aggregate oil imports (1000s of bbls)	2595	2645
Voyage-based oil production		
Barrels of oil (1000s of bbls)	2477	2692
Number of voyages represented	4110	6376
Percentage of all voyages	84.8	92.0

Source: aggregate oil imports from Starbuck (1878, Table I); voyage-based oil production data generated by methods described in text

Three factors may have contributed to the differences between the import-based and voyage-based total oil production in Table 9.3:

1 accuracy of the estimated figures for the barrels of oil;
2 oil production for voyages that were incompletely reported; and
3 completeness of the reporting of freighted oil.

To explore these factors, we compared our voyage information with additional voyage-specific information reported in the *WSL* (see Appendix 1 at the end of this chapter) and arrived at the following conclusions about each of the three factors. First, the amount of oil landed for each voyage was initially estimated at the end of each voyage and measured subsequently, barrel by barrel. The differences between estimated and measured landings for individual voyages in two years examined, 1849 and 1859, were small (less than 2 per cent) and not systematic. Second, the average production of voyages where the amounts of oil landed were missing was probably lower than for voyages where those data were available. This is indicated by the fact that 19 voyages ending in 1859 were reported by Starbuck but not by the *WSL*, and these landed only 31.7 per cent as much per voyage as the voyages that were reported in both sources. Third, while most of the 20.8 per cent of the sperm oil production shipped back to New England could be assigned to specific voyages, this was not true for 14 per cent of the oil from vessels that embarked in 1859. Such oil was unlikely to be represented in the voyage-based totals.

These findings suggest that 19th-century sperm whaling returned more oil than has generally been assumed, and that the difference could be approximated by adjusting the totals of the voyage-based oil production (see Table 9.3) to account for the voyages without recorded output (15.2 per cent for 1804 to 1842 and 8.0 per cent for 1843 to 1878). However, such adjustments would have to account for their likely lower production, which was perhaps as low as 31.7 per cent of that returned by other voyages. Furthermore, 20.8 per cent of all oil was freighted and as much as 14.7 per cent of such oil was probably not assignable to a voyage. If these proportions are representative, the voyage-based landings may be biased downward by as much as 7.7 per cent during 1804 to 1842 (= 15.2 per cent × 31.7 + 20.8 per cent × 14 per cent), and 5.5 per cent during 1843 to 1878 (= 8.0 per cent × 31.7 + 20.8 per cent × 14 per cent). However, the magnitude of these corrections might well have varied over time, and additional data for other years would be necessary to adjust the total figures more precisely.

Oil yield per whale

Best (2005) estimated the landed catch of whales by dividing the total oil imports as discussed above by the average amount of oil obtained from individual whales (yield). In order to obtain average yields for over 800 voyages, he divided the total barrels produced (Starbuck, 1878; Hegarty, 1959) by the number of whales landed (Townsend, 1935). For voyages that returned more than ten sperm whales, the average of this ratio was greater for whales taken by ships and barques (33.6 barrels, or bbls) than for those taken by brigs and schooners (19.1 bbls).

We explored this further using information in logbooks as recommended by Best (1983), selecting those cases in which the amount of oil obtained from one or more whales processed on board had been reported. This included data extracted for more than 60 complete voyages (under Josephson's supervision), the Japan Ground sections for 100 voyages (Bannister et al, 1981) and the Galápagos Ground entries for more than 30 voyages (Hope and Whitehead, 1991). The average yield was significantly lower (p = 0) for schooners than for vessels with other rigs (see Tafble 9.4), but the averages for all vessel types were larger than those obtained by Best (2005). For example, these new estimates, assuming that the sample sizes in Table 9.4 reflected the relative contribution of the different rigs, would imply an average yield that was 41.5 per cent higher. Because this enters the calculations as a divisor, the net effect would be to reduce estimated catches by 29.3 per cent. The cause of the differences between our estimates and Best's (1983, 2005) is not apparent, although Best identified a number of uncertainties in his data sources. Further examination of Townsend's (1935) logbook extractions, and the voyage production figures in Starbuck (1878) and Hegarty (1959), together with more logbook research, is needed to resolve the differences and to determine more precisely the variability of the yield by both vessel type and geographic region.

Hunting losses

Hunting loss was a feature of all whaling operations, and therefore the total number of whales actually 'removed' was undoubtedly larger than the catches alone. Nineteenth-century whalers sometimes struck (harpooned, lanced or shot) whales that they were unable to secure and process. Not all of the so-called 'struck and lost' component of the 'catch' died. This is known because some previously struck whales were subsequently killed and secured, their bodies bearing scars, wounds, lines and harpoons from encounters with whalers. However, some previously struck whales did die of their wounds, as demonstrated by logbook entries noting that some whales were found dead with harpoons still attached. The carcasses that were not too putrefied were processed for their oil, which was included in the voyage production figures. This would have partially offset the struck-and-lost mortality. Accordingly, 'correcting' the catch data (whether number of individuals processed

Table 9.4 *Average oil yield of sperm whales reported in 19th-century logbooks for voyages by vessels of different types*

Vessel type	*Average (bbls)*	*Sample size (individuals)*	*Standard error of the average (bbls)*
Bark	46.1	342	1.47
Brig	43.1	72	3.33
Schooner	31.3	200	1.55
Ship	45.9	946	0.74

Source: see text

or amounts of product obtained) to account for hunting loss is clearly neither simple nor straightforward.

Bannister et al (1981) concluded on the basis of 19th-century logbook data on the Japan Ground that landings should be increased by at least 20 per cent, but no more than 61 per cent, to account for hunting loss of sperm whales. Similarly, Hope and Whitehead (1991) used the same method to estimate hunting loss in the Galápagos Ground at between 4 and 23 per cent. They suggested that their lower loss rates might be explained by the fact that the sperm whales hunted in tropical waters were smaller and easier to catch. Indeed, based on our logbook data, the average yield from Galápagos Ground whales was independent of vessel rig ($p = 0.47$) and smaller (31.4 bbls, 1.10 standard error) than the average yield for all observations (see Table 9.4). The issue is more complex, however, because our logbook data for more than 60 complete voyages show that the proportion of the 7795 animals struck and lost differed significantly ($p = 0$) for whales encountered alone or with others (11.8 per cent, 0.39 standard error, and 18.3 per cent, 1.19 standard error, respectively). These observations suggest that the proportion of struck whales that were lost varied substantially by ground and by the nature of the group of whales encountered. Further investigation of the numbers reported struck and lost on different whaling grounds is required to clarify this issue.

Were 19th-century removals underestimated?

The foregoing analyses suggest that 19th-century sperm whaling landed more oil than has generally been assumed. While oil production has probably been underestimated, the average amount of oil per whale may also have been underestimated. This latter factor could more than offset the former. Furthermore, the appropriate factor for 'correcting' catch data to account for hunting loss appears to vary between whaling grounds and perhaps with the size of the whales being hunted. Despite the uncertainties, it is unlikely that the paradox can be explained solely by the underestimation of removals during the 19th century.

Population structure

The assessment by Tillman and Breiwick (1983) posited that the Japan Ground 'corresponds to a major portion of the presently defined Western Division of the North Pacific sperm whale population', as then recognized by the IWC. Similarly, the assessment by Whitehead (1995) assumed that whales taken on the Japan Ground and on the Galápagos Ground belonged to separate populations and that neither was subject to whaling on other grounds. Whitehead's (2002) global assessment made no attempt to incorporate population structure and thus implicitly assumed a single worldwide population of sperm whales, although he considered some alternatives in the form of sensitivity tests.

Table 9.5 *Estimated number of sperm whales removed (thousands)*

Region	*1700s*	*1800s*	*1900s*
North Atlantic	25	48	39
South Atlantic	0	23	14
Indian Ocean	<1	30	64
South Pacific	0	110	110
North Pacific	0	60	283
Antarctic	0	0	64
All regions	29	271	721

Source: see text

We explored an intermediate spatial scale between the regional populations of the first two assessments and the global population of the third using Best (2005) and Allison and Smith (2004) to allocate the global catch estimates by century into six large oceanic regions (see Table 9.5). Twentieth-century catches were less than or equal to 19th-century catches in three of the regions: the North Atlantic, South Atlantic and South Pacific. Twentieth-century catches in the Indian Ocean were only about twice those of the earlier era, while the catches in the North Pacific were more than 4.5 times larger, and those in the Antarctic were restricted to the 20th century. These differences suggest that the apparent paradox relates more to the Antarctic and North Pacific than to other areas. Referring to the Antarctic, Best (1979) argued that catches there were mainly of males that migrated seasonally to lower latitudes. The populations to which such whales belonged therefore would have been subjected to 19th-century whaling. With regard to the North Pacific, the relationship between encounter rates and catches was markedly different from that evident in the South Pacific (see Figure 9.2).

Twentieth-century whaling grounds in the North Pacific overlapped with, and extended north of, those used during the 19th century (see Figure 9.3). Because the oceanography of the North Pacific is more complex than that of the Southern Hemisphere (Best, 1979), it cannot be assumed, by analogy to the Antarctic, that sperm whales found in high latitudes of the North Pacific would have migrated seasonally to lower latitudes where sperm whaling occurred during the 19th century (mostly south of 40° N). Indeed, Kasuya and Miyashita (1988) inferred from 20th-century sightings, catches, movements of marked whales and oceanographic data that there are two populations of sperm whales in the North Pacific which occur mainly north of 40° N latitude, one in the west and the other in the east. In the eastern North Pacific, data from 20th-century shore whaling stations have been interpreted to indicate that sperm whales mated (April to May) and calved (July to August) off British Columbia (Gregr et al, 2000), well north of the 19th-century sperm whaling grounds. Accordingly, the region north of 40° N may have been a refuge from 19th-century whalers. It is nonetheless perplexing, given the

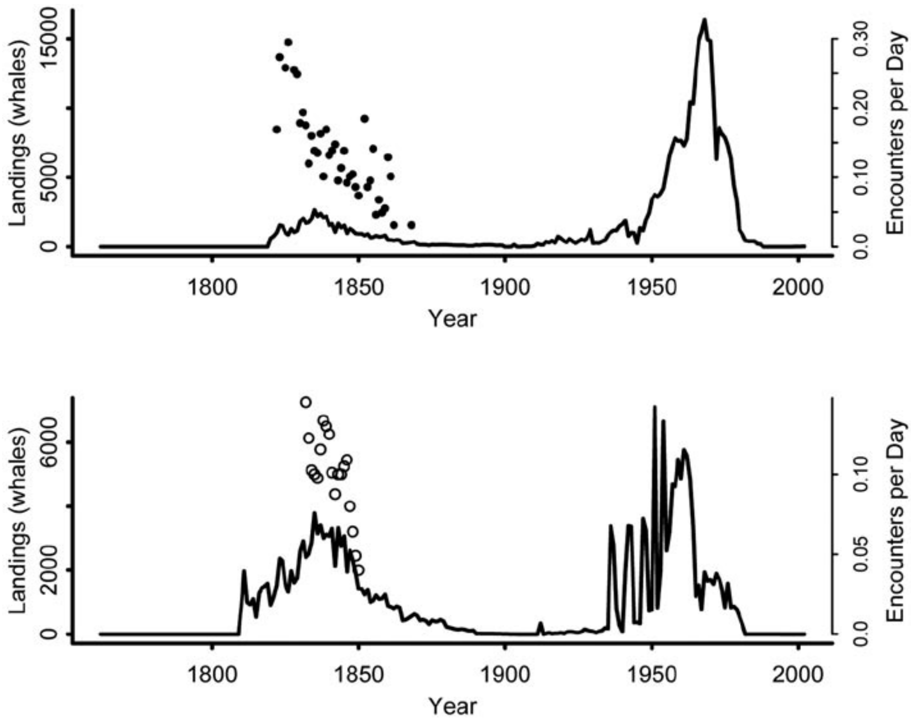

Figure 9.2 *Estimated annual removals of sperm whales, circa 1750–2000, for North Pacific (top) and South Pacific (bottom)*

Note: Encounter rates from 19th-century whaling are denoted by closed circles on the Japan Ground and open circles on the Galápagos Ground.

Source: see text

large numbers of sperm whales taken north of 40° N during the 20th century (see Figure 9.3), that so few sperm whales were reported from this region in whalers' logbooks. For example, in data compiled by Maury from 59 logbooks from the 1840s (see Chapter 8 of this volume), sperm whales constituted only 17 of 3791 sightings of whales identified to species during 59 voyages reporting in 10,995 days north of 40° N. In addition, given the potential of sperm whales to move over long distances (Best, 1979), many of the 19th-century Pacific whaling grounds would have been close enough to one another (see Figure 9.3) to allow some animals from the population using the Japan Ground or the Galápagos Ground to have been taken on other grounds. These removals would not have been included in the assessments by either Tillman and Breiwick (1983) or Whitehead (1995). To explore this possibility as a way of explaining the paradox, estimates of removals from the other whaling grounds are needed.

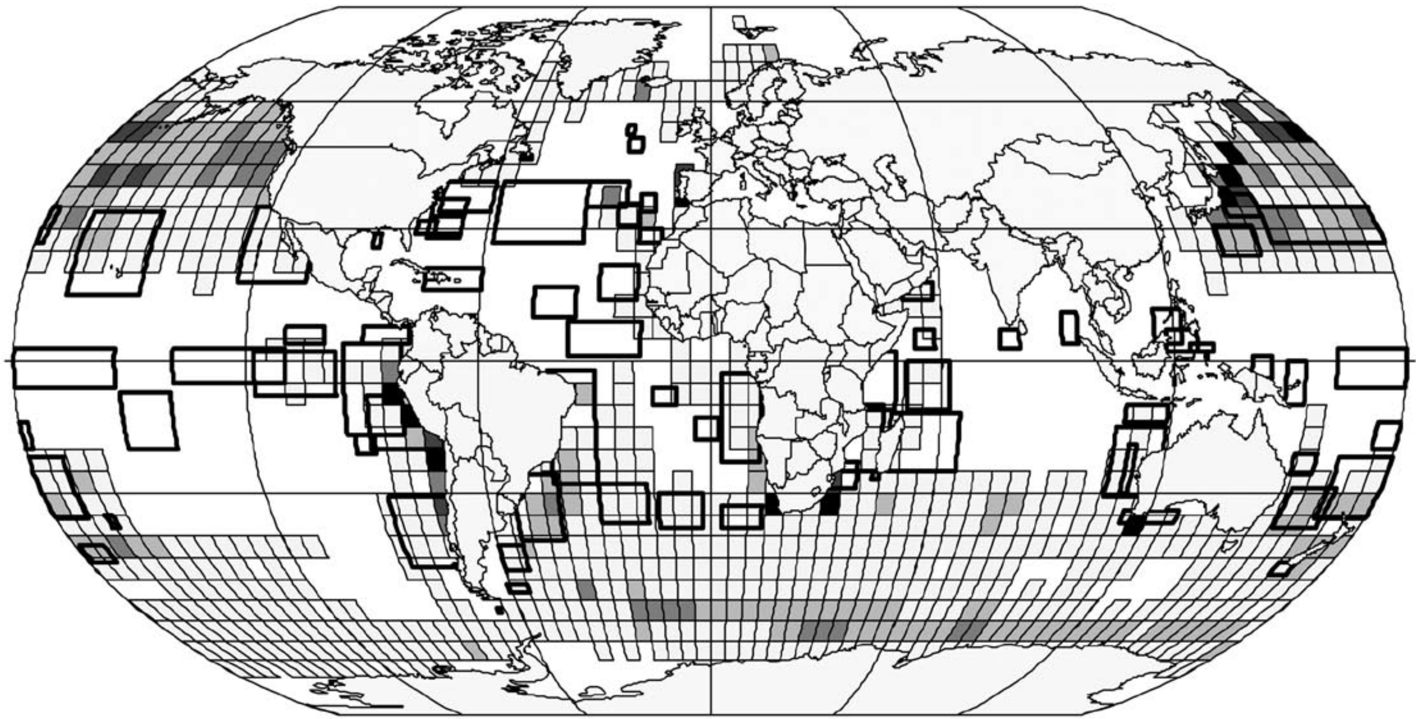

Figure 9.3 *The locations of 20th-century catches shown by shaded 5° squares of latitude and longitude*

Note: Darker shading depicts larger catches; 19th-century whaling grounds are shown by rectangles bounded with darker lines.

Source: see text

Encounter rates proportional to whale abundance

The rates at which whalers encountered sperm whales in the Japan and Galápagos grounds declined as whaling continued (see Figure 9.2). Such declines were the norm according to many authors. For example, Herman Melville (1851, p458) wrote: 'In former years these Leviathans … were encountered much oftener than at present.' The apparent paradox has arisen because declines in encounter rates have been interpreted to imply that whale numbers also declined. Whitehead (2002) suggested that the correlation between encounter rates and whale numbers might not be as tight and direct as is generally assumed, and that the paradox could be at least partially explained by changes in the whales' 'schooling behaviour or distribution as exploitation progressed'.

We made estimates of encounter rates on the Japan Ground using a sample of logbook data from the Maury Abstracts (Josephson et al, this volume). They exhibited a pattern similar to that found by Bannister et al (1981), with both data sets showing a possible initial increase followed by a long-term decline (see Figure 9.4).

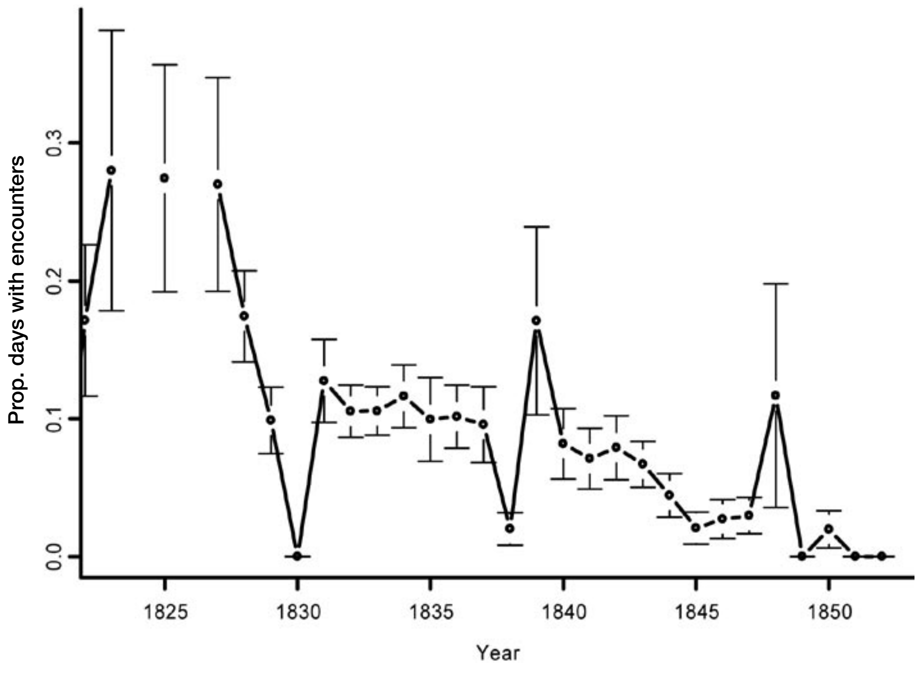

Figure 9.4 *The annual proportion of whaling days with encounters of sperm whales on the Japan Ground, 1822–1852*

Source: data derived from American whalers' logbooks, as extracted for Maury (1852 *et seq*), with 95 per cent confidence intervals

If sperm whales altered their behaviour after exposure to whaling, then the rate of encounter might have changed faster than abundance. This could have occurred if the animals became more evasive as they gained experience of whalers. However, this possibility is more about tendencies than absolutes as sperm whales continued to be taken, albeit at decreasing rates; moreover, not all individuals learned to avoid whaling ships. For example, the log of the whaler *Sarah* of Edgartown recorded that on 5 February 1850, at 27° S and 55° W: 'saw a skule [sic] of sperm whales ENE. Saw some of the whales past within 20 rods of the ship that would have made 100 bbls and some come within 10 feet of the ship. They were all lob tailing and breaching all around the ship'.

A partial test of the increasing tendency of the whales to avoid the whalers is to determine if the success in striking or securing animals once sighted decreased over the years. For the period of 1830 to 1850, we examined the ratio of whales taken to whales sighted for each voyage over time for both the Japan Ground (using data from Bannister et al, 1981) and the Galápagos Ground (using data from Hope and Whitehead, 1991). The ratio declined over time (–0.0076, $p = 0.02$) for the former ground, but did not decline (0.0051, $p = 0.61$) for the latter ground. These results are contradictory, but the nature of the two grounds was rather different and the fishery on the Japan Ground progressed westward over time. Moreover, even if the results for the two grounds had been consistent, they still would have represented only a partial test because the whales may have learned to avoid whale ships from a considerable distance before they were within range of being sighted.

The whales could also have changed their distribution. For example, Melville (1851, p458) suggested such changes when he argued against interpreting encounter rates as indicating a decline in abundance:

> *And equally fallacious seems the conceit, that because the so-called whale-bone [baleen] whales no longer haunt many grounds in former years abounding with them, hence that species also is declining. For they are only being driven from promontory to cape; and if one coast is no longer enlivened with their jets, then, be sure, some other and remoter strand has been very recently startled by the unfamiliar spectacle.*

Although Melville was referring to other species of whales, we examined our encounter rate data for evidence of a shift by sperm whales into areas adjacent to the Japan Ground. There was no increase in encounter rates over time (see Figure 9.5). However, this test is complicated because, as is apparent in Bannister et al (1981), the focus of whaling on the Japan Ground shifted westward over the course of the fishery. A more spatially resolved analysis is therefore needed to account for the effect of that shift.

Other changes in the searching and catching processes may have caused encounter rates to decline more slowly than abundance, or indeed even to increase over time regardless of any trend in abundance. Although such changes would

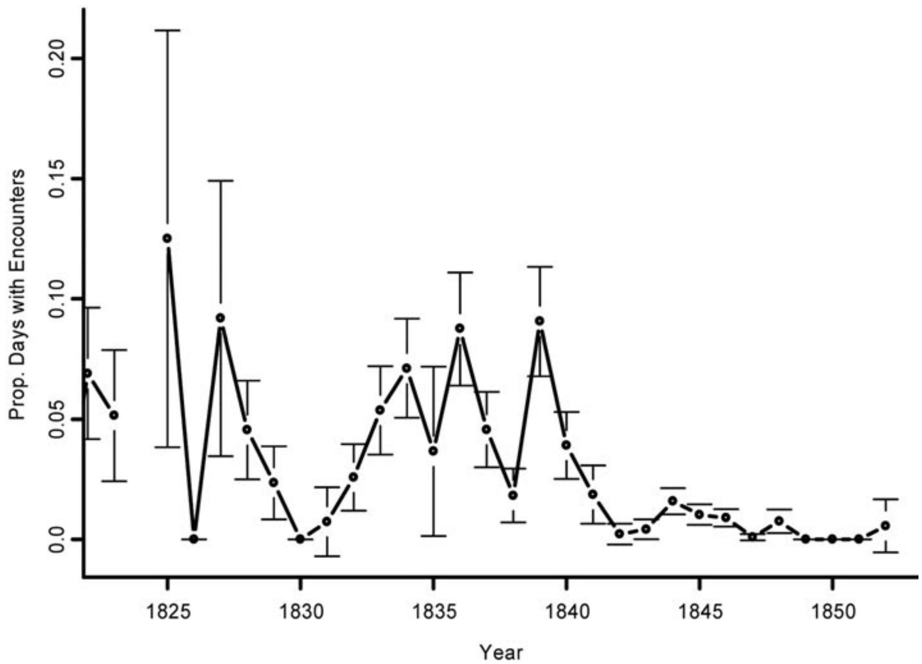

Figure 9.5 *The proportion of whaling days with encounters of sperm whales in areas adjacent to the Japan Ground, 1822–1852*

Source: data derived from American whalers' logbooks, as extracted for Maury (1852 *et seq*), with 95 per cent confidence intervals

not help to explain the apparent paradox, they might have tempered the effect of any alterations in the behaviour of whales. For example, searching effort might have become more efficient over time. The distribution of whales is not uniform spatially, with greater concentrations in some regions than in others. Differences in distribution can occur at small spatial scales relative to the distances whalers searched (at least several tens of miles per day). Whalers clearly used accumulated information about successful whaling grounds, as can be seen in lists and manuscript notebooks from the 19th century, such as are found in the Nicholson Collection of the Providence (Rhode Island) Public Library. Unpublished manuscripts with titles such as *Abstracts of the Latitude and Longitude of Whaling Grounds Right and Sperm 1871–1883* and *Whaling Grounds, 1840–1881* make it clear that whalers left port armed with information based on more experience than just their own (see Maury, 1854). Accordingly, they may have become better at finding whales as they gained experience on a particular ground. This is suggested, for example, by the initially increasing encounter rates in Figure 9.4, a feature that is also suggested in Bannister et al's (1981) independent sample of encounter rates for this same ground. Examining changes in encounter rates for the early years on several whaling grounds might reveal if this initial increase was a common pattern.

Another factor affecting encounter rates is the time spent processing killed whales. When encounter rates were higher, more whales were caught (Bannister et al, 1981), implying that proportionally more time would have been devoted to towing, cutting, boiling blubber, packing oil and other processing tasks. Logbooks do not distinguish consistently between hunting (searching, chasing and killing) and processing time, so the only measure of hunting time is days on the whaling ground. Because vessels tended not to move during at least the initial processing of a whale, it is conceivable that fewer whales would have been sighted on the days immediately following a catch. Accordingly, the number of whales encountered per day might have been lower when catches were higher and higher when catches were lower. This would have the effect of levelling out trends in encounter rates over time. Such effects might be detected by comparing the numbers of encounters per day in the days immediately before and after a catch.

Heterogeneity in whale behaviour also might lead to encounter rates declining faster than population size if one segment of the population is being encountered and killed preferentially. Off the Galápagos, female sperm whales principally belong to one or the other of two clans with quite different movement patterns (Whitehead and Rendell, 2004). If whalers are moving at speeds comparable to, or slower than, those of the whales, their encounter rates will depend upon the movement patterns of the whales. Thus, for slow-moving open-boat whalers, the differential movement patterns of the clans might explain the sperm whale paradox. We used the actual tracks of groups of whales in each clan followed off the Galápagos in 1987 and 1989 (Whitehead and Rendell, 2004) to calculate expected encounter rates by whalers moving at different speeds (see Appendix 2). The differences in encounter rates are real (about 15–20 per cent for whalers moving at one knot, and 5–7 per cent for whalers moving at two knots), but even these unrealistically slow speeds make only a tiny difference (a factor of about 1.0008 for whalers moving at two knots) to the reduction in sighting rate as compared to the contraction in true population size (see Appendix 2 at the end of this chapter). In fact, a huge difference in sighting rates between the two types of animals (about sixfold; see Appendix 2) would be needed to produce a decline in sighting rate twice as large as the decline in population size. It is therefore unlikely that behavioural heterogeneity resolves the sperm whale paradox.

Taken together, these possible changes in the behaviour of whales or whalers would have served to either increase or decrease the rate of decline of encounter rates. Further investigation is needed to determine if the net effect is in one direction or the other. In any event, there is no evidence to suggest that this factor alone would explain the paradox.

Equilibrium population dynamics

An underlying assumption of most analyses is that populations would tend to increase towards their pre-whaling levels – the environmentally determined carrying capacity – with the decline and eventual cessation of whaling. This concept is at best an approximation, and it presumes the reversibility of changes in the ecosystem due to decreases in whale population sizes, as well as a lack of long-term changes in oceanic productivity due, for example, to climate change. Although such an approximation may be reasonable over a short time frame, its validity over two centuries is less credible. For example, changes in population dynamics of humpback whales in the North Atlantic were addressed in a recent modelling study (Punt et al, 2007), where the assumption of constant carrying capacity was relaxed to determine if that would resolve apparent inconsistencies between the model's output and the empirical evidence for that population. Similar consideration of models that do not make equilibrium assumptions may be useful in the present case to determine if they would help to resolve or remove the apparent paradox.

Conclusion

The paradox appears to apply to sperm whales in the North Pacific. Large discrepancies in catches between the 19th and 20th centuries occurred there and in the Antarctic. Animals taken in the latter region almost certainly belonged to populations that were subjected to 19th-century whaling in lower latitudes, at least seasonally. It is possible, however, that in the North Pacific the whales subjected to 20th-century whaling to the north of 40° N latitude belonged to populations that were not affected significantly by whaling during the 19th century. This would mean that relatively unexploited refuge populations existed in the North Pacific during the early 20th century. If these were sufficiently large to have supplied enough whales to account for the very high 20th-century catches, the apparent paradox might be at least partially explained.

Some other possible explanations of the apparent paradox (see Table 9.1) can be essentially ruled out. For example, it is unlikely that 20th-century removals have been greatly overestimated. Further, it is unlikely that 19th-century removals have been underestimated to an extent that would explain the paradox, although the available estimates are subject to several forms of uncertainty that do not entirely preclude this. Some of the biases are upward and some are downward, but the magnitudes are generally small. One exception could be hunting loss, although further information on struck-and-lost rates on specific whaling grounds is needed. It also seems unlikely that behavioural heterogeneity within sperm whale populations would be the sole explanation for the paradox.

Further possible explanations warrant more research. One is the possibility that the behaviour of either the whales or the whalers, or possibly both, changed. The mixed results of the partial test of behavioural change do not allow this possibility to be ruled out. Additional data from logbooks may help with the interpretation of changes in encounter rates that are crucial elements of the apparent paradox. We also cannot rule out the possibility that the problem is rooted in unrecognized population structure or, alternatively, in the incorrect assumption of equilibrium conditions. Further studies are needed to improve definitions of sperm whale populations and provide better understanding of long-term environmental variability. New and emergent research tools that are being applied to these issues, such as genetic analyses and satellite-linked tagging and tracking of individual whales, will, in time, greatly improve the state of knowledge. In the meantime, attention should be devoted to developing estimates of 19th-century removals from additional Pacific whaling grounds and identifying long time series of data for use in assessing environmental change. These types of data could be used with population modelling to determine which, if any, combinations of population structure and environmental change explain the apparent paradox.

Appendix 1: Completeness of voyage-based data

We obtained additional data on individual voyages from the weekly issues of the *WSL* for 1849 and 1859 to examine the completeness of the voyage data assembled. First, relative to the accuracy of the landings data themselves, while most of Starbuck's voyage landings corresponded to entries in the *WSL* that were measured in port in preparation for sale (marked as 'gauged'), some values were preliminary estimates given by the captain when the vessel entered port. This was probably because the preliminary values were published in the *WSL* immediately upon arrival, and the gauged values became available only later. In order to determine the accuracy of the preliminary values, we extracted both preliminary and measured values for all voyages ending in 1849 and 1859. We compared these values pair-wise and determined that there was no systematic difference and, further, that the average difference was less than 2 per cent in both years.

Second, undocumented and poorly documented voyages were probably ones with lower-than-average production. To investigate this question, we examined in detail the voyages reported by Starbuck and by the *WSL* as having ended in 1859, a sample year at the height of the sperm whale fishery (see Table 9.6). During that year, Starbuck reported that 194 voyages produced a total of 86,431 barrels of sperm oil (oil landed by the ship plus oil freighted or 'sent home'). We matched those voyages as closely as possible to the 176 voyages reported by the *WSL* for that year, which produced 83,357 bbls. The 18-voyage difference reflected 19 voyages that appeared only in Starbuck and one that appeared only in the *WSL*.

Completed voyages (i.e. voyages with a specified date for return to the port of departure) that were reported in both Starbuck and the *WSL* had very similar stated production. The freighted oil amounted to 20.8 per cent of the total production.

Table 9.6 *Sperm oil landed and freighted for voyages ending in 1859*

		Starbuck (1878, Table K)				*Whalemen's Shipping List*			
		Number of voyages	*Oil landed (bbls)*	*Oil freighted (bbls)*	*Oil per voyage (bbls)*	*Number of voyages*	*Oil landed (bbls)*	*Oil freighted (bbls)*	*Oil per voyage (bbls)*
Complete voyages	Both Sources	165	68,333	13,115	493.6	165	67,431	13,793	492.3
Incomplete voyages	One Source	4	89	45	33.5	1	0	0	0
	Both Sources	10	0	2133	213.3	10	0	2133	213.3
	One Source	15	0	2716	181.1	0			
Total		194	68,422	18,009	445.5	176	67,431	15,926	473.6

Source: Starbuck (1878, Table K); WSL

Table 9.7 *Sperm oil freighted and the number of shipments arriving in New England in 1859*

Port of origin	*Vessel Type*	*Assigned to voyage*			*Not assigned to voyage*		
		Number of shipments	*Oil shipped (bbls)*	*Oil per shipment (bbls)*	*Number of shipments*	*Oil shipped (bbls)*	*Oil per shipment (bbls)*
Known	Freighter	24	13,058	544.1	3	886	295.3
	Whaler	9	5149	572.1	0		
Unknown	Freighter	0			11	1482	134.7
	Whaler	16	2007	125.4	12	935	77.9
Total		49	20,214	412.5	26	3303	127.0

Source: see text

The four completed voyages reported in Starbuck but not in the *WSL* had much lower production, and the one voyage in the *WSL* but not in Starbuck did not return any sperm oil. The remaining voyages (25 reported by Starbuck and 10 by the *WSL*) were not completed back to the port of departure – the vessels were either lost, condemned or sold during the voyage. The incomplete voyages had no recorded landings, of course; but significant amounts of oil were freighted. For example, Starbuck's 25 incomplete voyages freighted an average of 194 bbls, substantially more than the average amount freighted by the 165 complete voyages (79.4 bbls). The average production of the 19 voyages reported only by Starbuck was 150 bbls, 31.7 per cent of the average production of all voyages reported in the *WSL*.

Third, to learn more about how freighting oil back to New England may have affected our voyage-based data, we identified in the *WSL* 75 shipments of whaling products (oil and baleen) arriving in 1859 aboard freighters and whaling vessels, and attempted to match the oil in these shipments with voyages in Starbuck's list. We were unable to assign 26 of these 75 shipments (34.7 per cent) to the voyages that produced the oil, and it is probable that Starbuck was likewise unable to attribute these shipments to specific voyages. They accounted for only 3303 of the 23,513 barrels (14.0 per cent) of oil shipped (Table 9.7). This difference arose because the average amount of oil per shipment differed according to whether the shipment could be assigned to a voyage. The averages also differed for shipments according to whether the port of origin was known or unknown. Specifically, the average was much smaller for shipments that could not be assigned to voyages than for those that could (127.0 versus 412.5 bbls).

Table 9.8 *Encounter rates of different clans of sperm whales for whaling vessels moving at different speeds*

Year	*Clan*	*Days*	*Whaler speed (knots)*					
			0.0	*1.0*	*2.0*	*3.0*	*4.0*	*5.0*
1987	Reg.	19	141.8	160.3	212.3	277.9	347.5	417.6
	Plus-1	7	172.0	184.8	223.3	284.4	351.8	420.8
1989	Ratio: Plus-1/Reg.		1.213	1.153	1.052	1.023	1.012	1.008
	Reg.	8	124.3	154.8	210.9	276.6	346.6	417.0
	Plus-1	5	170.9	185.3	224.9	284.7	351.9	420.8
	Ratio: Plus-1/Reg.		1.375	1.197	1.066	1.029	1.015	1.009

Source: see text

Appendix 2: Behavioural heterogeneity and encounter rates

Movement patterns and encounter rates

We calculated the proportional difference in the encounter rates of groups of sperm whales of the 'regular' and 'plus-one' clans (Rendell and Whitehead, 2003) off the Galápagos in 1987 and 1989 for whalers moving at different speeds. We considered days spent following groups with positions at 06:00, 09:00, 12:00, 15:00 and 18:00 hours when the group being followed was either of the regular or plus-one clan. We linearly interpolated a track between these positions and drew a grid of resolution 0.5 nautical miles (nm) around the track. For each whaling vessel's speed (0, 1, 2, 3, 4, 5 knots) and direction of travel (in 15° increments relative to true north), we calculated the number of cells of the grid in which such a vessel could have been at 06:00 hours and seen the whales at some point during daylight (06:00 to 18:00 hours) given a range of visibility of three nm (results were robust to changes in this). The total area of these cells is proportional to the encounter rate for whalers heading in that direction at that speed. The areas (in square nautical miles) of the 06:00 positions of whalers who encountered whales are averaged over the headings for that day to give an overall encounter rate for each speed.

The results indicate that if the whaling vessels moved at an average of 2 knots, then the plus-one clan groups were visible at a rate about 5 to 7 per cent greater than the regular clan groups (see Table 9.8). This diminishes with increasing vessel speed and increases sharply for vessels moving more slowly.

Rates of decline in encounter rates

If groups of one clan are encountered proportionally more often than groups of the other, how does this affect the decline in encounter rates with exploitation? Supposing there is initially a proportion p of clan 1 encountered at rate α_1, and $q = 1 - p$ of clan 2, encountered at rate α_2, in a population of size N and that animals are killed in proportion to the rate at which they are encountered. Then, the rate of change of population size with time is:

$$dN/dt = -k(\alpha_1 Np + \alpha_2 Nq)$$

and the proportional rate of change in population size per unit of time is:

$$(dN/dt)/N = -k(\alpha_1 p + \alpha_2 q).$$

This is the real rate of proportional decline.

The apparent rate of decline from encounter rates ($S = \alpha_1 Np + \alpha_2 Nq$) is:

$$dS/dt = \alpha_1 d(Np)/dt + \alpha_2 d(Nq)/dt = \alpha_1(-k\alpha_1 Np) + \alpha_2(-k\alpha_2 Nq) = -kN(\alpha_1^2 p + \alpha_2^2 q).$$

Proportionally, this is:

$$(dS/dt)/S = -kN(\alpha_1^2 p + \alpha_2^2 q)/(\alpha_1 Np + \alpha_2 Nq) = -k(\alpha_1^2 p + \alpha_2^2 q)/(\alpha_1 p + \alpha_2 q).$$

Then the 'paradox coefficient' (PC), i.e. the ratio of the proportional change in encounter rates over the proportional change in population size, is:

$$PC = [(dS/dt)/S]/[(dN/dt)/N] = (\alpha_1^2 p + \alpha_2^2 q)/(\alpha_1 p + \alpha_2 q)^2.$$

By differentiating PC with respect to p and setting the derivative to zero, we find that the maximum paradox coefficient for a given α_1/α_2 occurs when $p = 1/(1 + \alpha_1/\alpha_2)$ and has maximum value $PC = (1 + \alpha_1/\alpha_2)^2/(4\alpha_1/\alpha_2)$.

Then, the maximum paradox coefficient in the case of the movement difference of the sperm whale clans and whaling vessels moving at 2 knots for which $\alpha_1/\alpha_2 = 1.06$ (see Table 9.8) is 1.0008, a tiny difference between the decline in sighting rate and decline in population size.

This does not mean that behavioural differences could not explain the sperm whale paradox, as there could be other behavioural causes of differences in sighting rates between groups of whales. However, behavioural heterogeneity has to be very large to explain the paradox entirely. To get a decline in sighting rates that is twice as large as the decline in population size, one needs differential sighting rates of $\alpha_1/\alpha_2 > 5.8$ (from max $PC = (1+\alpha_1/\alpha_2)^2/(4\alpha_1/\alpha_2)$). This is huge.

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