FINAL REPORT

ABUNDANCE OF BLUE WHALES OFF THE US WEST COAST USING PHOTO IDENTIFICATION

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INTRODUCTION

Blue whales (*Balaenoptera musculus*) are considered endangered and their populations were depleted by whaling throughout most of their range. Blue whales feed off California from May through November (Dohl *et al.* 1983) and migrate to waters off Mexico and Central America in winter and spring (Calambokidis *et al.* 1990, Stafford *et al.* 1999, Mate *et al.* 1999, Chandler *et al.* 1999). Photographic identification of blue whales has revealed that animals identified off California have been seen as far north as the Queen Charlotte Islands (Calambokidis *et al.* 2004) and the Gulf of Alaska and as far south as the Costa Rica Dome (Chandler *et al.* 1999).

Blue whales occur in both coastal and offshore waters of the US West Coast. Accurate estimates of blue whale abundance off California using capture-recapture methods have only been possible when at least one representative sample is obtained from surveys systematically covering both inshore and offshore waters (Calambokidis and Barlow 2004). This is because a portion of the blue whale population feeds offshore beyond the reach of small-boat surveys. Although there is interchange between inshore and offshore areas, there is not complete mixing. To avoid heterogeneity of capture probabilities which would bias capture-recapture estimates, past estimates have relied on at least one sample coming from identifications obtained during systematic ship surveys covering both coastal and offshore waters, similar to that obtained by Southwest Fisheries Science Center (SWFSC) on the Collaborative Survey of Cetacean Abundance and the Pelagic Ecosystem (CSCAPE) cruise in 2005 (Forney 2007).

OBJECTIVES AND GENERAL APPROACH

The primary objective of the research was to obtain a new estimate of blue whale abundance. To achieve this we sought to:

1. Obtain a large and representative sample of blue whale identifications from coastal waters and, where possible, offshore waters of the West Coast in 2006 to supplement that already available for past years.
2. Compare identification photographs obtained during 2005 CSCAPE systematic surveys with those available from dedicated photo-ID surveys.
3. Generate an abundance estimate of blue whales for the 2004-2006 period using mark-recapture, where the non-systematic identifications gathered from 2004 to 2006 are treated as one sample and those obtained on the CSCAPE cruise as a second independent sample.
4. Compare this estimate with the three similarly obtained estimates during the last 15 years to evaluate potential trends in blue whale abundance.

METHODS

Survey effort

A major focus of our field effort was to obtain as large a sample of photographic identifications as possible with broad geographic and temporal coverage. Strategies for achieving this included: 1) conduct small boat operations in many different areas, 2) cover large areas both offshore and inshore, 3) effectively sample large concentrations of whales, and 4) achieve broad temporal coverage. We achieved these objectives with a combination of dedicated small boats surveys, opportunistic identifications during our other field research, and identifications from other opportunistic sources.

We conducted dedicated photo-identification surveys off California, Oregon, and Washington in the summer and fall of 2004 to 2006 (Table 1). These were primarily conducted between June and November. Timing and exact locations of these surveys were based on weather patterns and anticipated whale abundance based on sighting reports and historical data. The primary vessels employed in these dedicated photo-identification surveys were three 5.3-5.9m rigid-hull inflatables equipped with outboard engines operated by Cascadia Research and used extensively in our past photo-identification research. Vessels covered up to 200 nmi/day and operated up to 50 nmi offshore. The boats were transported from one region to another by trailer.

Cascadia Research also conducted a number of other research efforts off the coast of California, Oregon, and Washington that provided additional opportunities to obtain identification photographs. These included efforts to tag and track humpback and blue whales, monitoring of marine mammals of areas in conjunction with acoustic monitoring, surveys conducted as part of collaborations with Channel Islands and Olympic Coast National Marine Sanctuaries, effort associated with the SPLASH project (in 2004 and 2005), and effort associated with underwater filming of blue whales. A number of other more opportunistic platforms were used to obtain additional identification photographs. The most extensive contribution of opportunistic photographs came from our collaboration with the Channel Islands Naturalist Corps as well as whale watch operations out of Monterey Bay and San Francisco Bay.

Photographic identification from ship surveys

A critical part of the mark-recapture estimates for blue whales was the systematic identifications obtained in conjunction with broad-scale SWFSC marine mammal ship surveys. Key samples for the current study were the identifications obtained during the 2005 CSCAPE surveys covering waters out to 300 nmi off California, Oregon, and Washington. Additional fine-scale survey effort was completed during CSCAPE 2005 in waters of four West Coast National Marine Sanctuaries, providing additional blue whale identifications in nearshore waters.

Data analyses

All photographs were judged using a three-tier quality criterion. This score, along with associated sighting information (date, latitude, longitude), was entered into the identification database for analysis. Identification photographs of suitable quality were internally compared to identify resightings (and remove duplicates) of animals for each year. Each individual was then compared to Cascadia's historical catalog (archived photographs) of all blue whales identified off northern Baja, California, Oregon and Washington. Individual whales identified each year that did not match past years and which were of suitable quality were assigned a new unique identification number and added to the catalog annually.

Estimates of humpback and blue whale abundance were made using several capture-recapture methods (Calambokidis and Barlow 2004). The primary methods were two-sample Petersen capture-recapture estimates (Chapman modification for sampling without replacement) conducted using the identifications obtained in different pairs of samples including: 1) pairs of adjacent years as the two samples, 2) identifications from the systematic broad-scale and fine-scale ship surveys in 2005 as one sample and the second sample from the coastal surveys for the 3-year surrounding period (2004-2006), 3) all identifications in the year of the SWFSC survey as one sample and identifications from the year before and after as the second sample. An unbiased estimate of blue whale abundance using the two-sample Petersen estimate requires that all animals in the population have an equal probability of being photographed in at least one of the samples. The second sample does not have to meet this criterion as long as it is independent of the first sample. This approach of using the identifications from the systematic ship surveys as the one representative sample provided reliable estimates of blue whale abundance for similar surveys in the past (Calambokidis and Barlow 2004, Calambokidis and Steiger 1995, Barlow and Calambokidis 1995). We also used a multi-year open population model (Jolly-Seber) to examine rates of natality and mortality for the population using the Model A (standard Jolly-Seber) from the Program Jolly.

RESULTS AND DISCUSSION

Identifications of 481 different blue whales were obtained on dedicated photo-ID surveys and opportunistic surveys mostly in coastal waters from Northern Baja to Oregon from 2004 to 2006 (Table 1). Photographs of both sides were not obtained for all individuals potentially preventing reconciliation of some individuals. The systematic broad-scale surveys during CSCAPE 2005 obtained identifications of 38 blue whales and the fine-scale CSCAPE surveys conducted in sanctuary waters added an additional 7 individuals (there were no resightings of the same animal between the broad-scale and fine-scale surveys). Resightings of only four whales were made between the 2004-2006 coastal effort and those obtained on the CSCAPE broad-scale surveys (3 and 2 matches isolated by left or right sides, respectively). Inclusion of the seven identifications on the CSCAPE fine-scale surveys into the CSCAPE sample raised the number of matches to the coastal effort to six (Table 1).

The locations of blue whale identifications by survey type for 2004 to 2006 are shown in Figure 1. There was a fairly dramatic geographic separation between identifications from the coastal surveys and those from the CSCAPE surveys, especially the broad-scale survey lines. Identifications from the CSCAPE broad-scale surveys came mostly from offshore areas (Figure 1). Tracklines from the CSCAPE cruise (Figure 2, Forney 2007) indicate a tendency for incomplete transect lines nearshore due to poor weather and there were some difficulties launching a small to get photo-IDs due to concern about fog or other logistics during some of the encounters near shore (Forney, pers. com.).

Table 1. Summary of number of unique blue whales photographically identified in different surveys during 2004 to 2006 in the eastern North Pacific and matches between collections.

Survey	**Any side**	**L side**	**R side**
CSCAPE systematic - 2005	38	29	34
CSCAPE Fine scale - 2005	7	6	4
Coastal effort N Baja to Washington - 2004-2006	481	352	365
Other (AK, BC, Sea of Cortez)	21	15	13
Matches			
CSCAPE Broad scale vs. Fine scale and coastal	4	3	2
All CSCAPE to Coastal	6	5	3

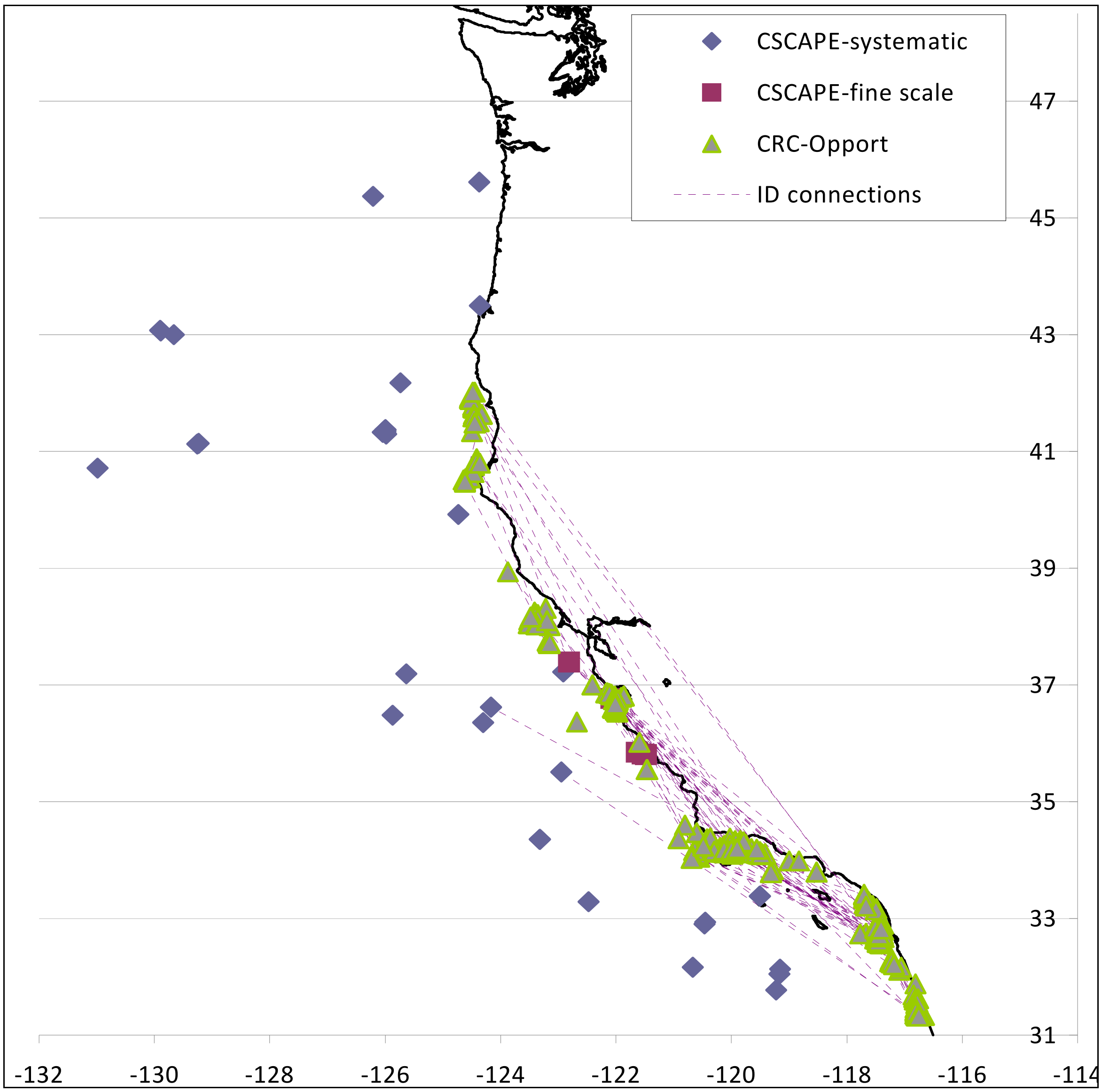

Figure 1. Locations of identifications of blue whales from 2004 to 2006 from both CSCAPE and coastal surveys. Dashed lines connect resightings of the same individual.

The few matches between the CSCAPE broad-scale surveys and those on the coastal surveys came from CSCAPE identifications made closer to shore. Although there were high numbers of blue whale sightings in some inshore parts of the CSCAPE surveys, especially in the southern-most area (Figure 2), CSCAPE fine-scale surveys yielded few identifications overall (7 total by either a right or left side).

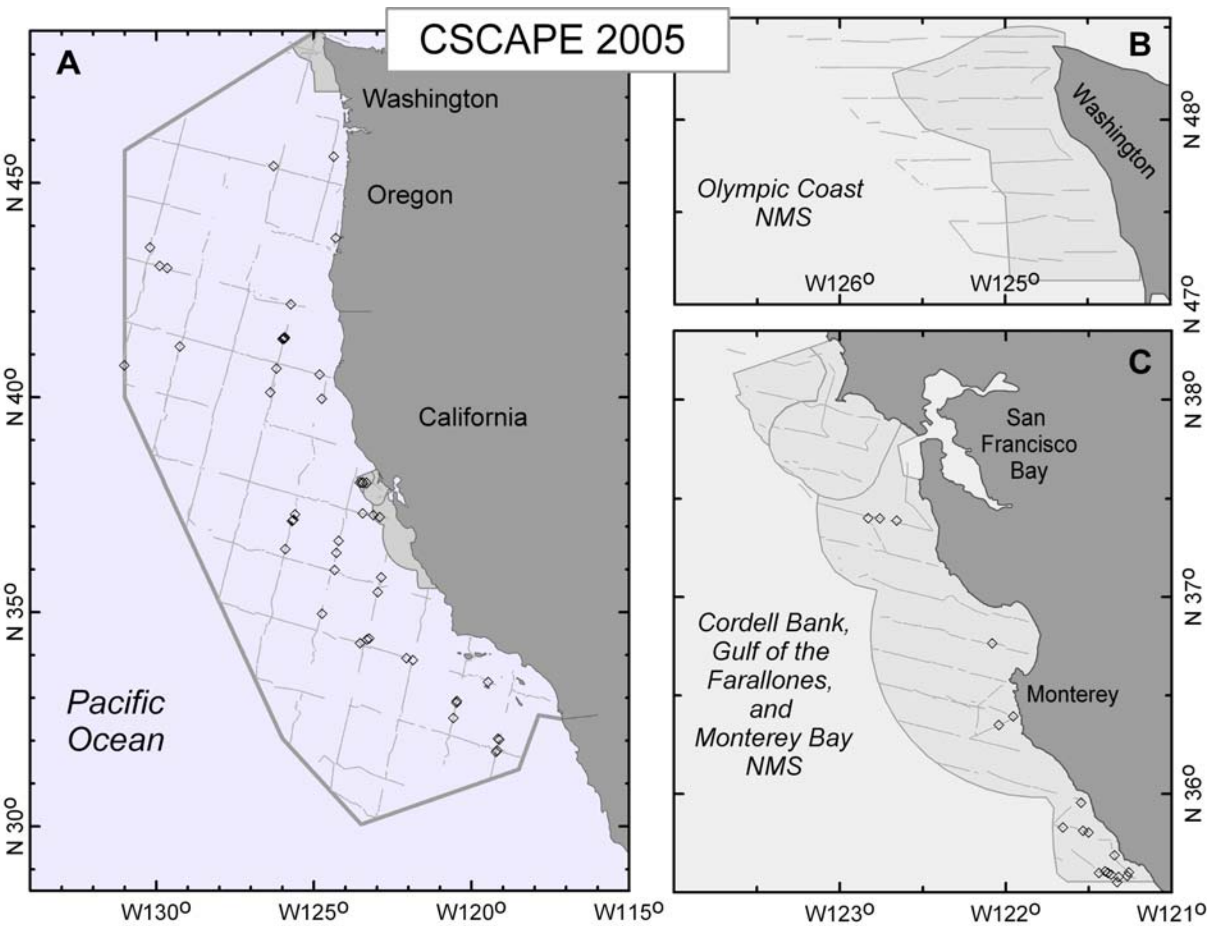

Figure 2. CSCAPE effort and blue whale sightings on CSCAPE broad-scale surveys (left panel) and fine-scale surveys (right panels) in 2005 (from Forney 2007).

To calculate blue whale abundance estimates using the 2005 CSCAPE effort we decided to pool the small number of identifications from the fine-scale effort in with the identifications obtained in the broad-scale CSCAPE surveys. This was done to help balance the small number of identifications obtained from CSCAPE in coastal waters and also to improve the available sample size. The small number of identifications from the fine-scale surveys (7) only slightly altered the predominant offshore distribution of the identifications obtained from the greater CSCAPE broad-scale survey effort.

Petersen mark-recapture estimates using all CSCAPE as one sample and the coastal effort for 2004-2006 as another, yielded higher estimates of abundance than previous similar calculations for 1991 to 2001 (Table 2). With the small sample sizes and few matches (5 and 3 for left and right sides, respectively), the estimates were variable and had fairly high CVs (0.34 and 0.42). The average of the two sides was 2,842, higher than the 2,000 blue whales estimated for 1991 to 1993 but not out of line given the high CVs with these estimates.

Table 2. Petersen mark-recapture estimates of blue whale abundance using survey type as samples. CSCAPE surveys were used as the first sample and identifications from the more shore-based effort in the 3-year period surrounding the systematic survey as the other sample.

Samples used	**Left sides**					**Right sides**					**Mean**
	n1	**n2**	**m**	**Est.**	**CV1**	**n1**	**n2**	**m**	**Est.**	**CV1**	
Pooled years using survey type as samples											
1991-93 all qualities	61	293	8	**2,024**	0.29	74	289	10	**1,976**	0.26	**2,000**
1995-97 all qualities	43	350	7	**1,930**	0.30	34	361	7	**1,583**	0.29	**1,756**
2000-2002 all qualities	20	452	5	**1,585**	0.32	24	474	5	**1,978**	0.33	**1,781**
2004-2006 all qualitites	35	352	5	**2,117**	0.34	38	365	3	**3,568**	0.42	**2,842**

We also examined abundance using Petersen mark-recapture with pairs of samples using all the identifications from the year with the systematic survey (2005) as one sample and all identifications from the adjacent years as the other sample (Table 3). The combined identifications from both the coastal effort and ship surveys in 2005 represent the most complete and thorough effort of any year. These estimates were lower than those obtained using only the systematic effort and showed a steady increase from 816 in 1991-93 to 1,428 in 2004-06.

Table 3. Summary of Petersen mark-recapture estimates for blue whales off California and W. Baja Mexico. Sample 1 consists of all the identified whales from the year of the SWFSC systematic ship surveys and n2 is from coastal small-boat work in the adjacent years. The number of matches or recaptures (m) are indicated. Coefficients of variation (CV) are based on analytical formulae.

	n1 (systematic yr)		**n2 (adjacent yrs)**				
Period	**Year**	**n1**	**Years**	**n2**	**m**	**Est.**	**CV**
1991-93	1992	281	1991 & 1993	193	66	**816**	0.09
1995-97	1996	183	1995 & 1997	368	56	**1,190**	0.10
2000-2002	2001	286	2000 & 2002	449	99	**1,291**	0.07
2004-2006	2005	179	2004 & 2006	388	48	**1,428**	0.11

Estimates based on all pairs of years regardless of whether they included a systematic survey also tended to show a general increasing trend in abundance (Table 4). While CVs were generally low for these estimates (because they made use of the entire annual samples), the estimates tended to fluctuate over a fairly wide range from 755 to 1,739 with highest estimates in recent years (2003 to 2006).

Abundance estimates were similar using the Jolly-Seber open population model (Table 5). Annual abundance estimates ranged from 617 to 1,543. While the range and some of the fluctuations was similar to the results from some of the Petersen models that used adjacent years as samples, the Jolly-Seber did not show as clear a trend toward increasing abundance. Estimates of annual rate of mortality/emigration averaged 0.91 (SE = 0.012) and number of births/immigration averaged 149 (SE=12), however, there was a high degree of variation among annual estimates that often exceeded levels that were biologically reasonable for blue whales.

Table 4. Annual estimates of abundance of blue whales using adjacent annual years for the region from northern Baja to Washington with no selection by quality or side.

	Sample 1			Sample 2					
Period	**Year**	**Ident.**	**n**	**Year**	**Ident.**	**n**	**Match**	**Est.**	**CV**
1991-92	1991	113	76	1992	674	281	26	**803**	0.14
1992-93	1992	674	281	1993	214	125	46	**755**	0.10
1993-94	1993	214	125	1994	433	211	20	**1,271**	0.18
1994-95	1994	433	211	1995	373	228	40	**1,183**	0.13
1995-96	1995	373	228	1996	297	183	34	**1,203**	0.14
1996-97	1996	297	183	1997	322	181	35	**929**	0.13
1997-98	1997	322	181	1998	404	228	54	**757**	0.10
1998-99	1998	404	228	1999	416	177	47	**848**	0.11
1999-2000	1999	416	177	2000	348	182	41	**775**	0.12
2000-01	2000	348	182	2001	573	286	51	**1,009**	0.11
2001-02	2001	573	286	2002	535	310	61	**1,439**	0.10
2002-03	2002	535	310	2003	537	292	67	**1,339**	0.09
2003-04	2003	537	292	2004	265	189	31	**1,739**	0.15
2004-05	2004	265	189	2005	310	179	27	**1,220**	0.16
2005-06	2005	310	179	2006	427	217	24	**1,569**	0.17

n-Number of unique individuals in sample used in mark-recapture estimate
Est.-Estimated abundance
CV-Coeficient of variation based on Chapman

Table 5. Results of Jolly-Seber mark-recapture open population model using all identifications with years as samples. Output is from program Jolly based on Model A (full Jolly-Seber).

Period	**PHI**	**SE(PHI)**	**M**	**SE'(M)**	**N**	**SE(N)**	**p**	**SE(p)**	**B**	**SE(B)**
1991	0.778	0.071								
1992	1.038	0.077	59	4.0	**617**	95	0.440	0.071	198	146
1993	0.853	0.071	326	24.1	**839**	107	0.147	0.022	393	129
1994	0.987	0.069	345	19.0	**1,108**	120	0.188	0.023	450	177
1995	0.841	0.061	485	28.4	**1,543**	167	0.146	0.018	-84	152
1996	0.859	0.058	541	29.5	**1,214**	115	0.150	0.017	-45	101
1997	1.057	0.071	554	26.0	**998**	79	0.181	0.018	94	86
1998	0.816	0.060	672	36.3	**1,148**	87	0.198	0.019	-14	64
1999	0.875	0.062	627	33.3	**923**	68	0.191	0.019	156	64
2000	1.048	0.073	601	30.1	**964**	73	0.188	0.019	105	69
2001	0.905	0.072	703	37.9	**1,115**	77	0.256	0.022	281	71
2002	0.957	0.100	734	46.5	**1,290**	101	0.240	0.022	92	76
2003	0.851	0.132	833	73.9	**1,327**	131	0.220	0.024	331	110
2004	0.832	0.183	807	107.7	**1,459**	215	0.129	0.021	-16	99
2005			753	137.7	**1,199**	230	0.149	0.030		
MEAN	0.907	0.0125	574	15	**1,125**	37	0.202	0.008	149	12

Abundance estimates that used all the identifications in a year or combination of years as a sample showed fairly good agreement with each other both in terms of their average values and some of the patterns of annual variation (Figure 3). The estimates that used the systematic surveys as a single sample and the bracketing 3-year period as the other sample consistently showed higher estimates than the other methods although the value of this difference varied, with the 1991 to 1993 and 2004 to 2006 estimates differing the most.

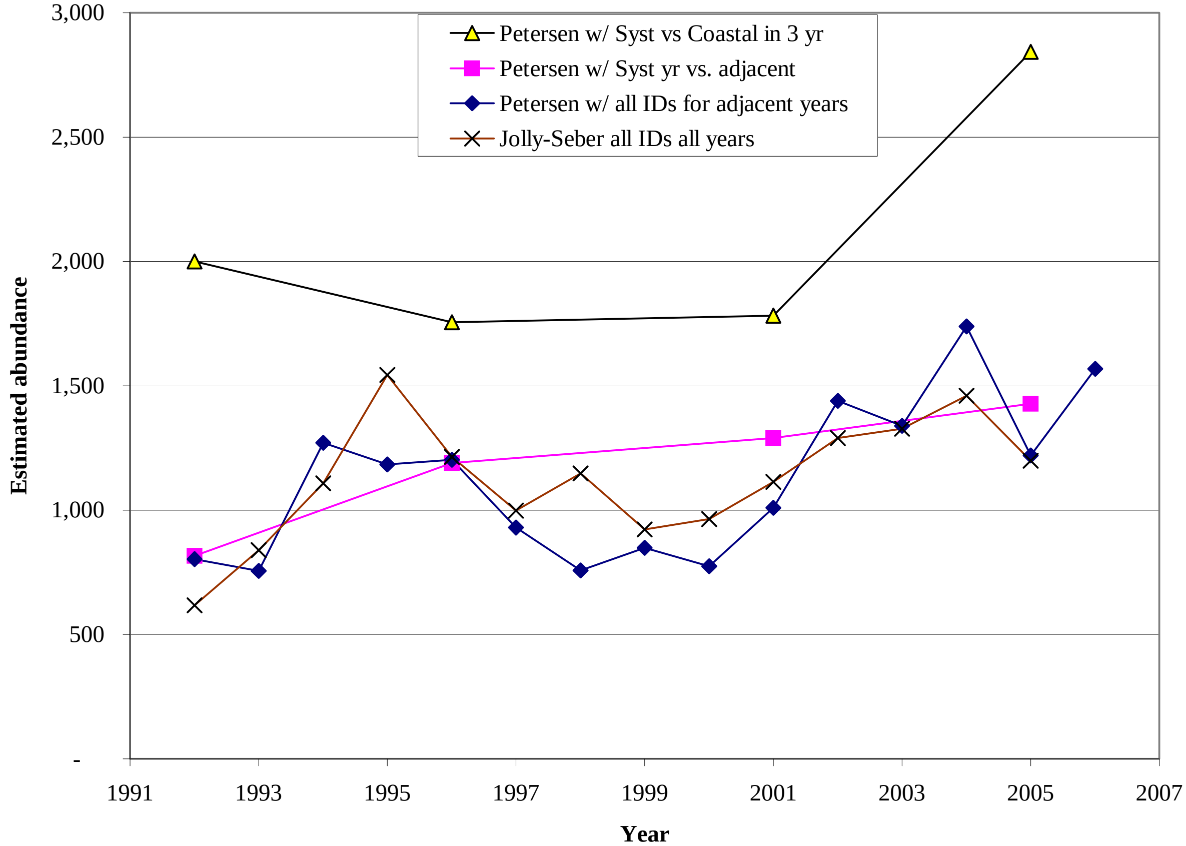

Figure 3. Comparison of abundance estimates using different mark-recapture models (Tables 2-5).

Identifications were not obtained consistently in the same locations among years, and therefore may explain some of the observed patterns in abundance. In the early 1990s the coastal effort was more concentrated in specific areas with primary effort in specific areas off central California (Farallons and Monterey Bay) and southern California (Santa Barbara Channel). The consistency of some of this annual effort may have caused a higher rate of heterogeneity of capture probabilities and hence tended to bias these annual estimates downward. Our overall effort was more broadly geographically distributed in later years and also tended to vary from year to year potentially reducing the bias from geographic heterogeneity. The single high estimate using CSCAPE in 2005 as one sample may just be the result of variation from small sample size with the possible influence of this sample not tending to be truly geographically representative as in past years. The high proportion of identifications from offshore areas in 2005 may have lead to the reduced matches and causing an upward bias to this estimate.

We report mark-recapture abundance estimates of blue whales showing a stable or possibly increasing abundance, which is in sharp contrast to estimates generated from line-transect survey efforts off the US West Coast and derived from the same systematic surveys used here for the mark-recapture estimates. Barlow and Forney (2007) report a dramatic decline in estimated blue whale density and abundance off the US West Coast between the surveys conducted in 1992 and 1996 and those in 2001 and 2005. This was after an apparent increase in blue whale numbers off California between 1979/80 and 1991 (Barlow 1994). There was agreement between estimates of abundance of blue whales from line transects and those from mark-recapture in the 1990s indicated the vast majority of the blue whale population being estimated by mark-recapture was present off the US West Coast during the Summer-Fall line-transect surveys (Calambokidis and Barlow 2004). The decline in the line-transect estimates but not the mark-recapture estimates for the surveys from 2001 to 2005, and the resultant differences in estimates of abundance in recent years is likely the result of a significant number of blue whales now spending portions of the Summer-Fall outside the area systematically surveyed off the US West Coast. If blue whales reduced their time inside the survey area by being present only part of the season or only in some years, they would still be available to be identified and therefore included in the mark-recapture estimates but might be missed by line-transect surveys (effectively lowering their apparent density and hence abundance).

There have been several indications of blue whale use of areas outside of the US West Coast in recent years. Calambokidis et al. (in prep.) report sightings of blue whales off British Columbia and in the Gulf of Alaska, both areas where blue whales were heavily hunted during whaling (Rice 1963, 1974, Gregr and Trites 2001) but where blue whales had only very rarely been seen during the 1990s. In our surveys in 2006, we found large numbers of blue whales both in the summer and fall using waters off northern Baja California just south of the US/Mexico border, an adjacent area that would have not been included in the line-transect surveys.

There have been indications of changes in krill abundance off California that could be altering the availability of prey for blue whales and causing a shift in distribution. Roemmich and McGowan (1995) reported declines in plankton abundance off California. Seabirds also provide an indicator of krill and ocean conditions (Hyrenbach and Veit 2003). Sydeman et al (2006) reported breeding failure in Cassin's auklet, a krill-feeding seabird, off northern California and the apparent shift of these animals to southern California in response to reduced krill abundance they attributed to an anomalous atmospheric condition. In our research on humpback whales off California, we have noted an increase in the proportion of humpback whales feeding on fish rather than krill in recent years compared to the 1990s (Cascadia Research, unpubl, data). Because of their more limited diet, blue whales would not have the same option to switch prey and instead would have to adapt to changes in prey availability by shifting feeding locations. Given the evidence that blue whales during whaling days were mostly taken off British Columbia and Alaska, it is possible that blue whale are returning to those habitats used historically.

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