**Description of how rorqual prey resources were calculated**

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**Methods**

*Prey data processing*

Hydroacoustic data were imported into Echoview 9 and each field day was analyzed independently. Standard acoustic processing resulted in the removal, across all frequencies, of data below the sea floor, general background noise (De Robertis & Higginbottom 2007), additional regions of high noise (common when the ship was maneuvering or in rough seas) and signals from other sonar systems (Ryan *et al.* 2015). The geometry of the high-frequency (HF, 120 or 200 kHz) and 38 kHz data were matched, and the SHAPES algorithm for school detection (Barange 1994; Coetzee 2000) was applied to a HF-38 dB differenced echogram thresholded at 8 dB (see rationale below).

Mean krill lengths in both ecosystems under study were substantially smaller than the mean lengths of *Euphausia superba* on which nearly all Euphausiid hydroacoustic literature focuses (techniques summarized in Jarvis *et al.* 2010). While *E. superba* have seasonal mean lengths that range from 30 to 50 mm (Atkinson *et al.* 2009), measured *E. lucens*, the dominant Euphausiid in SA, during a cruise concurrent to our field efforts were 14 ± 1.4 mm, and adult *E. pacifica* and *Thysanoessa spinifera*, the dominant Euphausiids in MRY (Croll *et al.* 2009) and in blue whale diets (Croll *et al.* 2005; Nickels, Sala & Ohman 2018b) range from 10.2 ± 3.0 to 16.0 ± 2.0 mm and 15.3 ± 0.2 to 23.7 ± 0.4 mm, respectively, with krill in blue whale fecal samples consistently bigger than those found in net tows (Croll *et al.* 2005; Nickels, Sala & Ohman 2018a). At a nominal sound speed of 1500 m s-1 the wavelengths of 38, 120 and 200 kHz signals are 39.5, 12.5 and 7.5 mm respectively, implying that for zooplankton lacking a resonator (like an air-filled swim-bladder), animals smaller than the wavelength of the signal will have strongly reduced signals (Stanton *et al.* 1994; Stanton, Chu & Wiebe 1998) and additionally implying that dB differencing and target strength (TS) models for larger krill like *E. superba* will not be appropriate for the smaller krill in this study. Instead, TS of these krill were calculated using an SDWBA scattering model (as in Conti & Demer 2006), but parameterized with inputs (e.g., animal density and sound speed relative to seawater and krill morphology) measured on krill species which are found in the MRY study site, *T. spinifera* and *E. pacifica,* and also applied to the similarly-sized *E.* *lucens*. An average TS for each ecosystem was calculated by averaging (in the linear domain) 1000 simulated krill with lengths from normal distributions determined from representative krill sizes. For *E. lucens* we used our measured lengths, and for MRY data we used the fecal-sample-determined distribution of *T. spinifera* (the most common blue whale prey as per Nickels, Sala & Ohman 2018a; Nickels, Sala & Ohman 2018b) from Croll et al. (2005) of 19.3 ± 1.5 mm. Using *E. lucens* length-wet weight curves (Pérez Seijas 1987) and averaging male and female values gave 0.026 g/krill, similar to the 0.025 g/krill derived from a cross-species relationship (Mauchline 1967). We applied the smaller value since our mean sizes were larger than the juvenile *E. lucens* data measured by Pérez Seijas. *T. spinifera* wet weight (0.040 g/krill) was also calculated from the Mauchline curve but restricted to Pacific Ocean *Thysanoessa sp.* and *E. pacifica* measurements*.* TS calculated from these lengths and our SWDBA model were -93.2 (@120 kHz) and -93.6 dB (@200 kHz) for MRY *T. spinifera* and SA *E. lucens* respectively. At these size ranges, HF-38 kHz dB differences ranged from 16-18 dB in MRY and 23-24 dB in SA (mean size ± 2 s. d.).

At high frequencies (120 and 200 kHz), Euphausiid TS are highly susceptible to changes in orientation, with, for instance, orientation changes of 5 degrees potentially resulting in 200 kHz TS differences up to 20 dB (CCAMLR 2005). Additionally, these relatively large dB differences (compared to the differences centered around 9 dB for *E. superba*, Jarvis *et al.* 2010) often spanned to levels below the detection threshold used for 38 kHz analysis. Consequently, for exclusion of likely non-euphausiid backscatter, a lower threshold of 11.4 dB was used for 200 kHz data and 9.5 dB for 120 kHz data so that krill would not be inappropriately excluded (Warren *et al.* 2001). These thresholds are the mean of the low value used for *E. superba* (Jarvis *et al.* 2010) and the HF-38 differences for the largest krill we measured (18.7 dB at 200 kHz, 14.3 dB at 120 kHz for 35 mm *T. spinifera*). These values should allow our values to be comparable to previous studies that used lower thresholds and also confirmed high krill abundances (using net tows) collocated with high acoustic backscatter in MRY (Schoenherr 1991; Croll *et al.* 2009; MBNMS 2009; Santora, Ralston & Sydeman 2011).

Siphonophores are known contributors to acoustic backscatter and their presence can bias results (Warren *et al.* 2001; McGarry 2014). To minimize this source of error, we linearly subtracted the backscatter at 38 kHz from the HF backscatter; since siphonophores have resonant air pockets they have similar backscatter at HF as at 38 kHz (Stanton, Chu & Wiebe 1998; Warren *et al.* 2001). All Sv reported are this linearly subtracted value, which were 0.2 ± 0.3 dB and 0.1 ± 0.1 dB lower than the HF values in MRY and SA respectively.

Finally, it should be noted that there are many avenues for error propagation when converting acoustic backscatter to biomass: krill, which can swarm facing any direction (Calise 2009), have orientation-dependent TS (Conti & Demer 2006; Levine, Williams & Ressler 2018), efforts to ground truth estimates are inhibited by unknown krill escape from nets (Everson & Bone 1986; Brierley 1999) which may be size dependent (Hill *et al.* 1996), even with concurrent net-sampling the krill ensonified may be of different size classes than the krill sampled, and all models are subject to normal stochastic variation (Simmonds & MacLennan 2008). We report these derived biomass units using the best available techniques as they are the most biologically relevant, but we also report the directly measured backscatter data in all cases so that any future improved models may be retroactively applied, including models that may directly link acoustic backscatter of krill with energy content, as proposed in Benoit-Bird and Au (2002). For comparability, all statistical comparisons were based on acoustic data and were not performed across ecosystems.

*Distributions of prey resources*

Krill are patchily distributed (Watkins & Murray 1998; Kaartvedt *et al.* 2005; Benoit-Bird, Waluk & Ryan 2019) and the density of gulp sized cells, like other resources in patchy environments (Preston 1962a; Preston 1962b; Lie 1969; White 1978; Bennett & Denman 1985; Pagel, Harvey & Godfray 1991; Anand & Li 2001), is lognormally distributed (Fig S1). As such, prey data were analyzed at three different spatial scales: 1) the detected schools, 2) cells the size of an average whale dive (see below), and 3) cells the size of an average whale engulfment (see below). These are referred to throughout as “schools”, “dive scale” and “gulps”. There is no generally agreed upon practice in the literature regarding the most appropriate method for describing the distribution of krill patches, particularly regarding how they are available to baleen whales. General surveys of krill use large scale areal measures to determine the total biomass of krill in large areas (Croll *et al.* 2009; Jarvis *et al.* 2010; Santora *et al.* 2011), and this method has been adapted by others to describe the total abundance of krill over large areas in cetacean habitat (Croll *et al.* 1998; Benson *et al.* 2002; Cox *et al.* 2009; Nickels, Sala & Ohman 2018a). Recognizing that the patchiness of ecosystems is a fundamental driver of foraging success (Piatt & Methven 1992; Russell *et al.* 1992; Marquet *et al.* 1993; Parker, Simmons & Ward 1993; Benoit-Bird *et al.* 2013; Richerson *et al.* 2015), others have used the density of prey within discrete acoustic patches to describe the availability of resources to baleen whales (e.g. Nowacek *et al.* 2011; Parks *et al.* 2011; Hazen, Friedlaender & Goldbogen 2015; Owen *et al.* 2016). Baleen whales are the largest predators of all time, and rorqual whales like blue and humpback whales can engulf volumes of water (means ~ 130 and 14 m3, respectively) that approach or exceed their own body masses (Goldbogen *et al.* 2012; Kahane-Rapport & Goldbogen 2018). When patches are small such that a lunge-feeding whale feeds on it only once, describing patch density with a single number for each school is an appropriate strategy. However, krill are also commonly distributed in aggregations 100s of m to km across and 10s of m thick (Falk-Petersen & Kristensen 1985; Watkins & Murray 1998), especially during daytime periods of less activity at depth before they migrate to the surface at night. These dense aggregations are the primary target of deep-diving whales and the schools we describe in this study in both SG and NSG areas are of this large type.

Across a wide variety of ecosystems, patchy biological resources are best described with a lognormal distribution (Preston 1962a; Preston 1962b; Lie 1969; White 1978; Bennett & Denman 1985; Pagel, Harvey & Godfray 1991; Anand & Li 2001), and we found krill distributions to be no exception (Fig S1). Although most statistical tests for normality are not appropriate for large sample sizes like the distribution of krill in an ecosystem and are sensitive to outliers (Ghasemi & Zahediasl 2012), a Box Cox transformation on all gulps (defined below) results in a parameter of 0, suggesting the appropriateness of a log transform. These findings support previous observations that krill concentrations in whale foraging areas were two or more orders of magnitude higher than areas without whales (Schoenherr 1991; Croll *et al.* 2005; McGarry 2014). Given this distribution within a patch, linearly averaging all acoustic data into a single value will skew the value to a degree dependent on the size of the patches and inaccurately represent the resources that are available to foraging whales. For each school identified, we used a rank sum test to see if the gulp medians in a school were significantly different than the linearly averaged Sv (Fig S1), and results suggest that resources the size of a whale gulp are not represented by linearly averaged Sv. Hydroacoustic data is stochastic in nature and must be averaged at some level to accurately represent data (Simmonds & MacLennan 2008). Accordingly, we processed data by averaging consecutive pings, and then averaged data within cells the size of a representative gulp of the species of interest (*B. musculus* = 22.5 m, *M. novaeangliae* = 10.5 m in length), with the jaw length used for the vertical size of the cell (*B. musculus* = 4.3 m, *M. novaeangliae* = 2.3 m) and the ventral groove blubber length (*B. musculus* = 12.8 m, *M. novaeangliae* = 6.0 m) used for the horizontal cell size (lengths calculated from regression relationships in Kahane-Rapport & Goldbogen 2018). At the depths used, all return echoes had y-axis values larger than the head width, so the extracted cells accurately represented a 2D projection of the gulp size.

The gulp-sized cell was the primary unit of analysis, which includes comparisons of cells both horizontally (across pings) and vertically (within pings). When ensonifying dense schools, care must be taken to ensure that neither artefacts due to extinction (e.g. Foote 1990), nor artefacts in the opposite direction due to multiple scattering (Stanton 1983) influence results. In some cases these two artefacts may offset (Stanton 1983), but in both cases they are more prevalent when ensonifying organisms with stronger TS. These effects are mostly relevant when enumerating fish (with TS ~ -50 to -20 dB, Foote 1980) but have been observed to lesser extents in larger krill species like *E. superba* (TS @ 40 mm ~ -77 dB, Conti & Demer 2006), and are not commonly reported with extremely small TS of the krill in our ecosystem (~-93 dB). However, to confirm that our results are not influenced by these effects, we examined both gulp density as a function of location in the water column as well as the strength of the bottom return echo in dense krill and outside of dense krill. If gulp depth is plotted again gulp Sv, no relationship is noted (r2 = 0.036), and if a Generalized Linear Mixed Effects model (GLME) is run treating each column of data as a random effect, a slightly increasing relationship is noted (slope estimate 0.08 dB/gulp height, p < 0.001) implying that any extinction effect would be small. When examining the bottom echo, we calculated the strength of all bottom echos for data from 05 Nov 2015, the day shown in Fig. 4 in which we recorded some of the strongest returns near the bottom that would be strong candidates to demonstrate acoustic artefacts (if they were present). Bottom return in each ping was calculated in two ways: as the sum of scattering (Sa) from 0.5 to 5.5 m below the sounder detected bottom, and as the 95th percentile of 0.1 m Sv bins in the same depth window. Comparisons of bottom strength in strongly scattering regions to adjacent regions were either not significantly different or had small differences in opposing directions (Fig S2). We also compared Sa in that 5 m bin below the bottom line to Sa in the water column above the line (down to 1.5 m above the line) in Fig S3 and found nearly no relationship. The small size of these effects, combined with the inconsistent direction, suggests that any effect would be small and less than the error of the estimates of the means described in Results. When applying this method to new ecosystems with more reflective target organisms, similar precautions should be taken.

In addition to gulp-sized cells, we also extracted cells the length and height traveled in a mean *B. musculus* or *M. novaeangliae* dive in order to look at the distribution of gulps within a region that a whale could be expected to search on a typical foraging dive. The species-specific sizes of these cells were calculated from georeferenced pseudotracks (i.e. dead reckoned reconstructed tracks, Wilson *et al.* 2007) of foraging whales as the mean vertical and horizontal extent of foraging from 10 s before the first lunge in a dive to 10 s after the last lunge in a dive, for dives with at least two lunges (see samples sizes and population descriptions in foraging analysis methods below). The maximum of the northing and easting extent of foraging was used as the horizontal distance. The resulting cells were 240 m long × 44 m deep for *B. musculus* and 125 × 35 m for *M. novaeangliae*. Cells of size one s. d. above and below the mean were also used in analysis. Significance occasionally increased with larger sample sizes (more, smaller cells), but the direction of the effects did not change. The Sv of each school as well as both gulp and dive scale size cells that were identified to be in a school were extracted and additional analysis was performed in Matlab 2019a.

Histograms of backscatter in gulp-sized cells were examined on a day by day basis and in total, and data were best described with a lognormal distribution (Fig S1). As an additional line of evidence to determine if there would be a difference between analyzing ecosystem data at the gulp scale from the detected school scale, we looked at the distributions of gulps within schools and used a nonparametric rank sum test to test if the linearly averaged Sv were likely to have been sampled from the observed distribution of gulp sizes. The frequency of times when the null hypothesis could be rejected on each day is shown in Fig S1 and demonstrated significance in 505 of 1422 tests (p from Fisher’s combined probability test = 0). We also performed the same test for dive sized cells within schools and found that only 24 of 1325 schools rejected the null hypothesis (Fisher’s p-value = 1). This suggested that the distributions of gulps within a school were often significantly different than the linearly averaged mean value in the school. To remove any outliers due to acoustic noise that were missed during the data preparation process, the lowest and highest 0.5% of each day’s gulp sized cells were removed from analysis. Additional statistical comparisons were done with GLME with SG status as a fixed effect and day and year as random effects. Specific GLME response and predictor variables are listed in Table S1.

**Discussion**

*Hierarchical prey distributions associated with super group foraging*

The high-quality foraging conditions we describe coincident with super-groups of humpback and blue whales in SA and MRY, combined with increased foraging rates of whales in those aggregations, strongly indicates that SG formation is driven by high-quality foraging conditions. We found that the distribution of gulp-sized cells within dive-sized cells and the distribution of gulp-sized cells within just the top half of dive-sized cells are both strong indicators of preferential foraging habitat, with means 40-50% higher in SG implying high λρ, and small standard deviations facilitating increased λ*f* (Fig 1) by decreasing the time and distance traveled between lunges (Table 1). These two metrics fit particularly well with krill-feeding rorqual whales whose foraging style utilizes characteristics of both filter-feeding, whereby energy cost per foraging event is independent of the quality of the prey, and raptorial feeding whereby prey (i.e. in bulk patches) are engulfed in discrete units. The combination of these feeding modes distinguishes rorquals from right whales (*Eubalaena glacialis*), whale sharks (*Rhinocodon typus*) and other continuous ram filtration feeders. From our meta-analysis of data from 45 *B. musculus* and 21 *M. novaeangliae* that lunge fed multiple times per dive and for which georeferenced tracks could be calculated, we found that those two species travel on average 177 ± 51 and 73 ± 34 m between lunges and average 4.1 ± 1.4 and 5.2 ± 2.3 lunges per dive, respectively – despite feeding within prey patches that often exceeded the size of the dive (Fig. 3) – yet the distance traveled for one lunge is only the length of the buccal cavity (12.8 and 6.0 m, respectively, for a 22.5 m *B. musculus* and 10.5 m *M. novaeangliae*). Right whales, approximately the same length as humpback whales, are continuous ram filtration filters that filter an average of 670 m3 of water on every dive (van der Hoop *et al.* 2019). At 14 m3 of water engulfed per lunge (Kahane-Rapport & Goldbogen 2018), a humpback whale would have to lunge 48 times per dive (an order of magnitude more than their average) to filter an equivalent volume. These factors, combined with the ability to feed on more maneuverable prey enabled by high-speed, raptorial approaches (Goldbogen *et al.* 2017; Cade *et al.* 2020), imply that rorqual whales may also increase their foraging efficiency by making active choices regarding what patch and what part of a patch to feed on.

Matching the spatial scale of analysis to the scale of the event under study is particularly critical in patchy environments (Levin 1992; Benoit-Bird *et al.* 2013); as such we introduced the species-specific gulp-sized cell as a unit of prey field analysis for baleen whales. Our analyses suggest that a specific hierarchical structure, both the mean and distribution of gulp-sized cells within dive-sized cells, best describes the prey available to gulp-feeding rorqual whales and may more appropriately quantify measurement error than the commonly-reported metric of mean prey patch density. Considering that SG of two species of whales aggregated in regions with less variability in the upper half of the cell, and given that rorquals are likely not feeding indiscriminately, we suggest that the actual prey consumed will be between the mean of mean gulp log(biomass) within dive-sized cells, and the mean of the mean of the upper 50% of gulp log(biomass) within dive-sized cells. We found these ecosystem level values to be between 1.05 •**:** 1.8 kg m-3 (-49.0 ± 2.6 dB) and 1.6 •**:** 1.3 kg m-3 (-47.2 ± 1.2 dB) in MRY and between 0.29 •**:** 2.1 kg m-3 (-53.0 ± 3.2 dB) and 0.48 •**:** 1.4 kg m-3 (-50.8 ± 1.5 dB) in SA. Although we also found density at the dive scale to be a strong indicator of high-quality foraging conditions, use of this metric underestimates the availability of resources across all data by 20% (p << 0.001) in MRY compared to the lower (conservative), randomly lunging gulp-sized cell analysis, and is comparable (p = 0.08) to the lower gulp-analysis in SA (37% lower than the high value, p << 0.001).



**Fig 4-** Biomass determination depends on the scale of analysis. A&B) hydroacoustic data from SG and NSG regions on 05 Nov 2015, averaged into 1 m x 1 m cells. C&D) The NSG krill swarm in D higher krill density overall than the swarm in proximity to an SG. E&F) The patch divided into cells the average size of a (2D) humpback whale foraging dive (125 m x 35 m). G&H) if the patch is divided into gulp sized cells, the distribution of krill within the patch is preserved. The mean of the gulp sized cells within dive-sized cells is higher in the SG proximal patch. I) acoustic data in a dive-sized cell at the resolution of collection. J) acoustic data in a dive-sized cell averaged into gulp-sized cells.

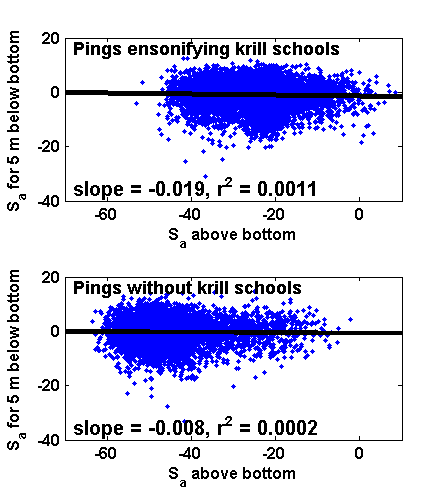


**Fig S1-** Distribution of gulp sized cells of acoustic energy (dark) bars and biomass (light bars) for each day. Acoustic energy (described in logarithmic units) is normally distributed while biomass is skewed. Green pie charts show the proportion of identified schools that day that have median gulp-sized

cells significantly different (at p < 0.05) than the mean of the patch.



**Fig S2-** Comparisons of bottom echo strength in adjacent regions of varying water column echos, for determining if there is an acoustic shadowing effect from dense scatterers. Gray regions have higher water column strength and pink regions have lower water column strength, histograms are plots of all pings in the highlighed regions. Method 1- the 95th percentile of 0.1 m Sv bins 0.5 to 5.5 m below the sounder-detected bottom for each ping. Method 2- the sum of scattering (Sa) from 0.5 to 5.5 m below the sounder detected bottom. Data was collected at 200 kHz data on 05 Nov 2015.



**Fig S3-** Plots of Sa for each 200 kHz ping on 05 Nov 2015 from 0.5 to 5.5 m below the sounder-detected bottom as a function of Sa in the water column. The flat lines suggests no (or very minimal) acoustic shadowing effects.

*Supplemental References-*

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