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Original Article

Classification of Southern Ocean krill and icefish echoes using random forests

Niall G. Fallon[1]*, Sophie Fielding[2], and Paul G. Fernandes[1]

[1] *Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen AB24 2TZ, UK*
[2] *British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK*

**Corresponding author: tel: + 44 1224 272648; fax: + 44 1224 272396; e-mail: n.fallon@abdn.ac.uk*

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Target identification remains a challenge for acoustic surveys of marine fauna. Antarctic krill, *Euphausia superba*, are typically identified through a combination of expert scrutiny of echograms and analysis of differences in mean volume backscattering strengths (S_V; dB re 1 m^{-1}) measured at two or more echosounder frequencies. For commonly used frequencies, however, the differences for krill are similar to those for many co-occurring fish species that do not possess swimbladders. At South Georgia, South Atlantic, one species in particular, mackerel icefish, *Champsocephalus gunnari*, forms pelagic aggregations, which can be difficult to distinguish acoustically from large krill layers. Mackerel icefish are currently surveyed using bottom-trawls, but the resultant estimates of abundance may be biased because of the species' semi-pelagic distribution. An acoustic estimate of the pelagic component of the population could indicate the magnitude of this bias, but first a reliable target identification method is required. To address this, random forests (RFs) were generated using acoustic and net sample data collected during surveys. The final RF classified as krill, icefish, and mixed aggregations of weak scattering fish species with an overall estimated accuracy of 95%. Minimum S_V, mean aggregation depth (m), mean distance from the seabed (m), and geographic positional data were most important to the accuracy of the RF. Time-of-day and the difference between S_V at 120 kHz ($S_{V\ 120}$) and that at 38 kHz ($S_{V\ 38}$) were also important. The RF classification resulted in significantly higher estimates of backscatter apportioned to krill when compared with widely applied identification methods based on fixed and variable ranges of $S_{V\ 120} - S_{V\ 38}$. These results suggest that krill density is underestimated when those S_V-differencing methods are used for target identification. RFs are an objective means for target identification and could enhance the utility of incidentally collected acoustic data.

Keywords: acoustics, fish survey, South Georgia, target identification.

Introduction

Mackerel icefish, *Champsocephalus gunnari*, hereafter "icefish", is a semi-pelagic finfish occurring across shelf areas in the Southern Ocean (Kock, 2005a). The population at South Georgia, South Atlantic, is the target of a commercial pelagic trawl fishery constrained by quotas of 1000–5000 tonnes per season in recent years (Barnes *et al.*, 2011; CCAMLR, 2014). Icefish are assessed using bottom trawl surveys which may yield biased estimates of abundance as a result of limited availability to the sampling method due to pelagic feeding migrations undertaken by the species (Hill *et al.*, 2005, 2012; Fallon *et al.*, 2015). Adaptive acoustic-trawl surveys (Everson *et al.*, 1996), or other implementations of combined acoustic-trawl survey (Mcquinn *et al.*, 2005; Kotwicki *et al.*, 2013), have the potential to address this issue.

The hypothesis that bias in icefish abundance estimates results from their vertical distribution can be explored using data from an echosounder. Acoustic data can be collected concurrently with bottom trawling (Bez *et al.*, 2007) to estimate the density of fish, which are unavailable to the trawl (e.g. Aglen *et al.*, 1999). However, to incorporate acoustic estimates into the assessment of the population, backscatter from icefish must first be identified (Horne, 2000). When attributing acoustic data to species, a number of spatial scales can be considered (e.g. that of the school; the elementary distance sampling unit, EDSU; or the region of interest; Reid *et al.*, 2000). Distinguishing between groups of objects with different scattering properties (e.g. fish or plankton with or without gas inclusions) is often achievable using data processing on an EDSU or regional scale (Madureira *et al.*, 1993; Korneliussen *et al.*, 2009).

This typically involves resampling acoustic data across some range of depth and distance or time, followed by classification according to assumptions regarding scattering properties of the group or groups of interest (Madureira *et al.*, 1993; Hewitt *et al.*, 2004). Assumptions are based on the backscatter vs. frequency, the frequency response, of the target organism. This is a function of its orientation relative to the incident sound wave, the incidence angle, as well as its size and composition (Korneliussen and Ona, 2003). Classification may also depend on the target location and depth, associated seabed type, or other distributional co-variates (Reid *et al.*, 2000). However, organism aggregations are often geometrically complex, and resampling methods can degrade identifying characteristics (Reid and Simmonds, 1993). A school-level analysis preserves finer spatial-scale information, which could improve classification accuracy and avoid any problems which might arise from several different target types occurring in a single EDSU.

Although the acoustic-scattering properties of icefish need further study, information can be inferred from physical characteristics, which will aid in the identification of candidate echoes. Icefish lack swimbladders, so the frequency response could be similar to that of mackerel (Korneliussen, 2010): dominated by a flesh component at lower frequencies (e.g. 38 kHz) and by a bone component at higher frequencies [e.g. 120 kHz; see Gorska *et al.* (2007)]. The flesh component should be relatively frequency independent across the typical operating frequencies (38–200 kHz) and may vary according to factors such as temperature and individual condition. The bone component would be characterized by a rising frequency response, peaking at $\sim$200 kHz, varying with fish orientation (Gorska *et al.*, 2005; Korneliussen, 2010). The frequency response of icefish schools may therefore be low and flat at lower echosounder frequencies (38–100 kHz) relative to 120 and 200 kHz (Gorska *et al.*, 2007). Krill (*Euphausia superba*), icefish, and much of the South Georgia groundfish assemblage have similar frequency responses across commonly used frequencies (i.e. 38, 120, and 200 kHz), and therefore, may be indistinguishable on an echosounder display (Kock and Kellermann, 1991; Kock, 2005a; Lavery *et al.*, 2007; Collins *et al.*, 2008). When such similarities exist, non-acoustic characteristics may be more important to accurate classification (Reid and Simmonds, 1993). Therefore, the data processing and analysis should incorporate all available variables.

Ideally, an objective target identification method should be applied due to the extensive training required for an operator to consistently and objectively identify a given species (Horne, 2000; Fernandes, 2009). In the Southern Ocean, Antarctic krill density and distribution are routinely estimated using the difference in volume backscattering strength (S_V; dB re 1 m^{-1}) measured at multiple frequencies (Madureira *et al.*, 1993; CCAMLR, 2010). Initially, a constant range of S_V measured at 120 kHz ($S_{V\ 120}$) minus S_V measured at 38 kHz ($S_{V\ 38}$) was used (Madureira *et al.*, 1993; Hewitt *et al.*, 2004). This has changed to include variable ranges of differences between $S_{V\ 38}$, $S_{V\ 120}$, and $S_{V\ 200}$ (Reiss *et al.*, 2008; Fielding *et al.*, 2014). However, these methods are typically applied at the EDSU level and may not differentiate well between species at the school level (Lawson *et al.*, 2008). The latter may require additional classification rules regarding target location, depth, or time of day. Woodd-Walker *et al.* (2003) compared an S_V-difference method with school-level classification of plankton using discriminant function analysis (DFA) and artificial neural networks (ANN). Although reasonable classification results were attained for krill, classifications for other groups in the analysis had higher error rates. In addition, the DFA required some transformation of variables to account for non-normality, and a simplified ANN had to be used because only a small training dataset was available. Tree-based methods (e.g. classification trees, bagged trees, and random forests, RFs; Breiman, 2001; Hastie *et al.*, 2009) have also been explored as a means for acoustic target identification and have yielded promising results though in a small number of case studies (Fernandes, 2009; D'Elia *et al.*, 2014).

The objective of this study is to explore and develop an RF method for discrimination between weak acoustic-scattering organisms at South Georgia. Given the many varied properties of trawl-verified echoes collected during fish surveys, an RF approach is employed to distinguish between three classes of echoes (krill, mackerel icefish, and mixed groundfish). Tree-based classification methods do not require variables to be linear and can be used to process large, high-dimensional datasets efficiently. In addition, RF classification accuracy is not affected by correlations or interactions between variables (James *et al.*, 2013). Further to the development of the method, the RF algorithm is tested against fixed and variable S_V-difference approaches (Madureira *et al.*, 1993; Fielding *et al.*, 2014) to compare outcomes. The intention of this comparison is to explore whether the alternative methods may overestimate the amount of backscatter attributable to krill due to the inclusion of backscatter from all weak scatterers, including icefish.

Methods

Data sources

Data were from South Georgia groundfish surveys, conducted during the Austral summers of 2004–2006, and the Austral winter of 2007 aboard the Fisheries Patrol/Research Vessel (FPRV) *Dorada* (Figure 1). The surveys followed a stratified design across five areas (Mitchell *et al.*, 2010), in which icefish density (kg km^{-2}) is estimated for two depth strata, 50–200 m and >200 m (generally <300 m) using demersal trawl data (FP-120 trawlnet; Pilling and Parkes, 1995). At the end of each of these surveys, a small number of pelagic hauls (International Young Gadoid Pelagic Trawl) targeted krill swarms and pelagic aggregations of icefish. During these surveys, echosounders (Simrad EK500) collected $S_{V\ 38}$ and $S_{V\ 120}$ following synchronized 1.0-ms pulse transmissions every 2.170 s. The echosounders were calibrated using a standard 38.1-mm diameter tungsten carbide sphere (Foote *et al.*, 1987), during each survey, at Husvik, Stromness Bay. In the Austral summers of 2010–2013, krill abundance was surveyed on the South Georgia shelf aboard the Royal Research Ship (RRS) *James Clark Ross* (*JCR*). During these surveys, $S_{V\ 38}$, $S_{V\ 120}$, and $S_{V\ 200}$ (Simrad EK60) were collected following 1.024-ms pulse transmissions every 2 s. The scatterers of interest were sampled using a

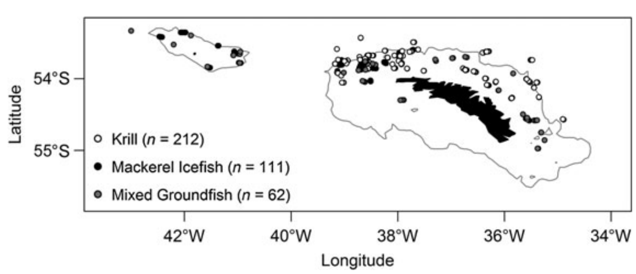

Figure 1. Locations of trawl-verified echoes used in the training dataset for generating random forests.

Rectangular Midwater Trawl (RMT8; Fielding *et al.*, 2014). The echosounders were calibrated using copper spheres (Foote *et al.*, 1987), during each survey, at Stromness Harbour [see Fielding *et al.* (2014) and Supplementary Table S1 for more details].

Post-processing of echosounder data

The echosounder data were post-processed using the commercial software (Echoview, Sonardata; Higginbottom *et al.*, 2000). Aboard FPRV Dorada, the transmit power for the 120-kHz pulses was 1000 W instead of the recommended 250 W (Korneliussen *et al.*, 2008), which likely caused non-linear distortion in the collected data. A non-linearity correction factor was thus applied to the $S_{V\ 120}$ data to compensate for non-linear distortion. The correction factor was derived as the simulated ratio of S_V corrected for non-linear attenuation to measured S_V, where finite amplitude effects were assumed to be influential during both echosounder calibration and survey data collection due to high transmit power [see Pedersen (2006) and Lunde and Pedersen (2012) for further details]. A multifrequency threshold [similar to that used in Fernandes (2009)] was applied to the S_V data as a series of virtual echograms (Higginbottom *et al.*, 2000) to remove data outside of animal aggregations from the analysis for the sole purpose of improving on the single-frequency threshold normally required for "school" detection using the Shapes algorithm (Coetzee, 2000). Single-frequency S_V data, thresholded at -70 dB, were summed across all available frequencies (ICES, 2015). Thresholds for these virtual echograms, determined empirically to retain schools and eliminate non-school echoes, were -135 dB for $S_{V\ 38} + S_{V\ 120}$ and -240 dB for $S_{V\ 38} + S_{V\ 120} + S_{V\ 200}$. A 5×5 median convolution kernel, giving each pixel in the acoustic data matrix the median value of the surrounding set of 5×5 pixels, was then applied to remove single target observations and noise spikes (Fielding *et al.*, 2014). A 7×7 dilation convolution kernel (giving the maximum value in each 7×7 set of pixels) was then applied to the summed S_V data to mitigate any removal of data within schools by the other filtering steps. Finally, a bitmap was used to mask the S_V data, removing data outside of schools from the analysis and retaining data assumed to originate in aggregations of organisms.

The SHAPES school detection algorithm (Barange, 1994) was then applied to the virtual echograms arising from the image analysis steps described above. The SHAPES parameters were: minimum total school length = 5 m; minimum school height = 1 m; minimum candidate length = 5 m, minimum candidate height = 1 m, maximum vertical-linking distance = 5 m, and maximum horizontal linking distance = 20 m. The school polygons defined by the algorithm were then used to compile variables associated with each school and to serve as a training dataset for the purpose of classification. Echoes were assigned one of the following categories according to trawl composition data, assuming that the composition of echoes is represented by the complementary evidence collected by trawl: "Krill" schools, or swarms, were 100% *Euphausia* spp., almost exclusively *E. superba*; "Mackerel Icefish" schools were >85% *C. gunnari*; and "Mix" were mixed aggregations of groundfish without swimbladders, consisting of <85% of any single fish species. Aggregations including fish possessing swimbladders (e.g. myctophid species such as *Electrona carlsbergi*) were excluded from the analysis. The inclusion of "Mix" was necessary to represent the wide assemblage of weak scattering species present in the area, to avoid misclassification of backscatter as "Mackerel Icefish", which occupies an overlapping location-depth niche.

The random forest algorithm

All the variables exported from the acoustic data were evaluated for collinearity, to identify superfluous variables that might be discarded. The final vector of variables (p) consisted of: mean $S_{V\ 120}$, maximum $S_{V\ 120}$, minimum $S_{V\ 120}$, standard deviation of $S_{V\ 120}$, $S_{V\ 120}$ skewness, mean height of school (m), mean aggregation depth (m), mean distance from seabed (m), latitude at the centre of school, longitude at the centre of school, corrected school length (m), corrected school thickness (m), corrected school perimeter (m), corrected school area (m), attack angle (°; Diner, 2001), image compactness (a ratio of the perimeter to the area of a school), corrected mean amplitude ($m^2\ m^3$), horizontal roughness coefficient (Nero and Magnuson, 1989), $S_{V\ 120}-S_{V\ 38}$, time of day, and estimated school volume assuming a cylindrical shape (m^3). An RF was then generated using this training dataset (Breiman, 2001). Each tree within an RF was generated by recursive partitioning of the data, using the best splitting variable from a vector m randomly selected from p to partition the data at each node on the bth tree (Tb), where m was of length $2 \times \sqrt{p}$. Vectors (m) of length $\sqrt{p}$ and $\sqrt{p}/2$ were also tested, but resulted in higher error rates. Nodes were split until they reached a specified minimum number of echoes ($nmin$) of $n = 1$. The RF was then used to make predictions according to the following equation:

$$\hat{C}_{rf}^{B}(x) = \mathrm{mode}\{\ \hat{C}_b(x)\}_1^B \tag{1}$$

where $\hat{C}_b(x)$ is the classification prediction of the bth tree in the ensemble of $B = 1 \times 10^4$ trees, and $\hat{C}_{rf}^{B}(x)$ is the prediction of the RF. Out-of-bag (OOB) error estimates were inspected as a means of cross-validation of prediction accuracy (Breiman, 2001; Hastie *et al.*, 2009). In addition to the RF generated using all available variables, RFs were generated using acoustically derived variables only (to explore how well the method might be generalized to other regions in the Southern Ocean) and using variables from schools around the main South Georgia shelf only (i.e. excluding Shag Rocks where krill data were not collected).

Confusion matrices were generated from OOB classifications, providing both overall and class-specific estimates of generalization error. The kappa statistic (κ; Cohen, 1960) was used to measure classification performance by indicating the proportion of classification agreement beyond that expected to occur by chance. Variable importance was examined to assess the ranked importance of each variable to classification accuracy. The two typical measures of variable importance were calculated for the RF: mean decrease in accuracy and the mean decrease in Gini Importance Index (GII; left and right panels, respectively, in Supplementary Figure S1; Breiman, 2001). The first gives a measure of the decrease in prediction accuracy when the best node splitting variable is randomly permuted for all variables in p. The mean decrease in accuracy across all trees gives a measure of variable importance (Breiman, 2001). Second, the Gini Impurity Criterion (GIC) is a measure of the rate of misclassification of randomly chosen elements of a given node when classified according to the distribution of classes in its daughter node. The sum of decreases in the GIC for each variable across all trees results in a GII. As these two measures may be biased by correlated variables (Strobl *et al.*, 2008), a third measure of conditional variable importance was calculated to verify their validity (Figure 2). The RF analyses were implemented in the R software environment using the "randomForest" and "party" packages (Liaw and Wiener, 2002; Strobl *et al.*, 2009; R Development Core Team, 2015).

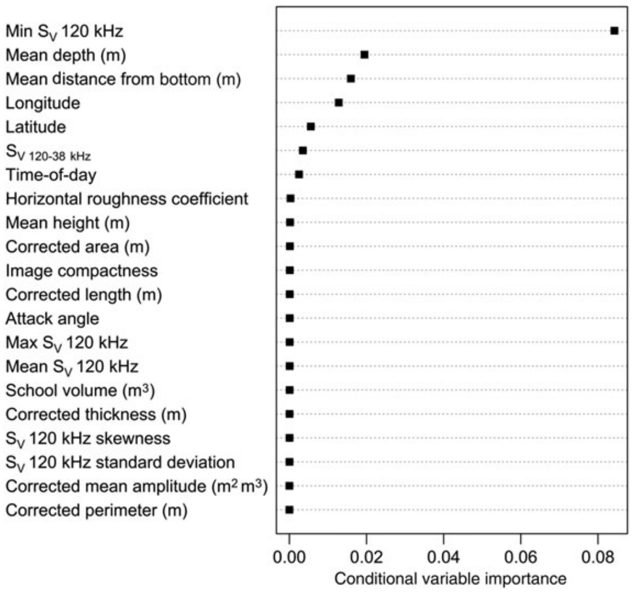

Figure 2. Conditional variable importance plot for the random forest using the full training dataset.

Comparison of methods

Other methods for krill identification were also used to apportion backscatter to weak scatterers, i.e. krill, icefish, and other fish species without swimbladders (Madureira *et al.*, 1993). Acoustic data collected during the course of the 2006 South Georgia groundfish survey were resampled to mean values within 5-m vertical by 100-m horizontal data bins (Demer, 2004; Fielding *et al.*, 2014). It was then assumed that resampled values of $S_{V\ 120}–S_{V\ 38}$ which fell within the range of 2–12 dB represented bins in which weak scattering targets which might be classified as krill would be found [as applied in Woodd-Walker *et al.* (2003) and Fielding *et al.* (2014)]. This method was also applied using a wider range, 2–16 dB (Watkins and Brierley, 2002). A third range, 0.37–12 dB, was also tested based on the values used in the application of the variable window method (Fielding *et al.*, 2014), although the accuracy of this approach would likely be improved with the availability of additional frequencies. Data were then integrated from 12 m below the transducer to 0.5 m above the echosounder-detected seabed to give nautical area scattering coefficient (s_A; m^2 nautical mile^{-2}) values per 1-nautical mile EDSU. The derived s_A would be classified as krill within the integration volume, according to Madureira *et al.* (1993) and Fielding *et al.* (2014), but that energy could have been reflected by many weak scatterers. The 2006 survey data were also classified using the above RF method. Integration over each region defined by the SHAPES algorithm gave s_A apportioned to each RF classification group for each EDSU. As $S_{V\ 200}$ data were not available in all datasets, it was not considered in this part of the analysis.

Results

Trawl-verified echoes across the three classification categories exhibited a range of variability in morphological, spatial (both vertical and horizontal), and acoustic properties. Krill echoes are the most highly studied of the three classes and are known to exhibit temporal and spatial variability across a number of descriptors, including estimated density and echo morphology (Tarling *et al.*, 2009; Klevjer *et al.*, 2010). Krill echoes verified in the trawl data were broadly similar to those described elsewhere. Krill were most often found in discrete, dense swarms, which were relatively easily visually identifiable, given some experience (Figure 3a). However, more dynamic and patchy echoes were also observed, which could be mistakenly associated with other weakly scattering organisms (Figure 3b). This ambiguity is exemplified by a trawl-verified echo from the 2006 groundfish survey (Figure 3c), where a monospecific catch of icefish was obtained from the scatterers rising as much as 100 m above the seabed. Krill was caught during a separate haul targeting the relatively small dense scatterer aggregations <50 m below the surface. The fish and krill echoes in this example are difficult to visually distinguish with certainty (e.g. Figure 3b). Mixed groundfish typically formed more diffuse aggregations extending <20 m from the seabed (Figure 3d), but were also observed to form denser, more extensive echoes in some cases.

A value of $\kappa = 0.92$, 95% confidence interval $\pm$ 0.04, was calculated from the RF confusion matrix (Table 1), where values of $\kappa > 0.75$ are considered as an indication of an excellent classifier (Fielding and Bell, 1997). The total OOB estimate of error rate (i.e. the ratio of the sum of misclassified echoes from each category to the total number of samples) gave an estimate of overall prediction accuracy for the full RF of 95.08%. The top seven variables in order of importance for both indices were identical although the order was different (Supplementary Figure S2 shows an alternative means of visualizing the contribution of each variable to classification; Welling *et al.*, 2015). The most important variable using each metric was the minimum $S_{V\ 120}$ (dB). The next four most important variables were those pertaining to position, depth, and time of day. The remaining variables related to measures of the acoustic and geometric properties of echoes whose order of importance varied in each case. The order of importance suggests that the use of acoustic descriptors alone is not a comprehensive basis for target identification. It is noteworthy that the distributions of $S_{V\ 120}–S_{V\ 38}$ values exhibited substantial overlap across all three groups (Figure 4) although Kolmogorov–Smirnov tests detected significant differences between them ($p < 0.05$). Crucially, the fixed 2–12 dB range, which designates backscatter as krill in the Madureira *et al.* (1993) method, only accounted for ~61% of the trawl-verified krill echoes. The RF models using only acoustically derived variables and South Georgia shelf data proved similarly effective, with estimated generalization accuracies of 88 and 97%, and κ values of 0.84 ± 0.05 and 0.94 ± 0.04, respectively (see also Supplementary Tables S2 and S3).

The spatial distributions of s_A classified as krill by each method were in broad agreement (Figures 5 and 6a). Variability in the spatial distribution of s_A was similar in both cases, with relatively larger values occurring to the northwest and east of the South Georgia shelf, as well as to the west of Shag Rocks. Due to the school-based nature of the RF method, only aggregations above some background density were detected; so, there are several EDSUs associated with this method where no krill was detected. The corresponding EDSUs from the other methods often contained low densities. Overall, however, the s_A per EDSU attributed to krill using the RF method was significantly higher than those resulting from both the fixed 2–12 dB range (Wilcoxon signed-rank test, $V = 1\,815\,149$, $p < 0.05$) and the variable 0.37–12 dB range (Wilcoxon signed-rank test, $V = 1\,833\,645$, $p < 0.05$). The fixed 2–16 dB range resulted in significantly higher s_A per EDSU than the RF (Wilcoxon signed-rank test, $V = 1\,944\,337$, $p < 0.05$). Relatively small amounts of s_A were attributed to icefish using the RF, mainly to the northwest of the South Georgia shelf and the

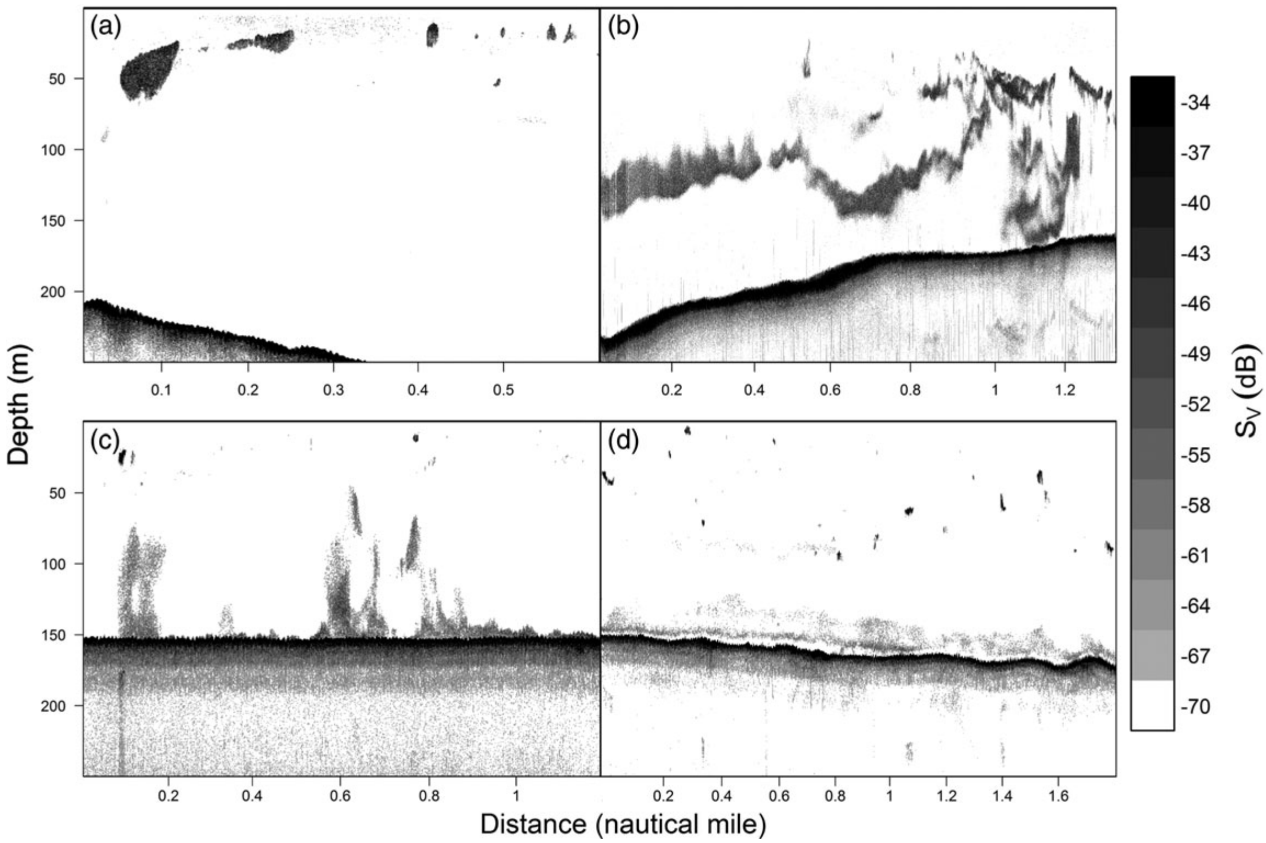

Figure 3. (a) Krill (*E. superba*) echo from the JR245 research cruise. Echoes such as this, discrete dense backscatter formations in a relatively shallow position in the water column, are typically easy to distinguish as krill. (b) Krill (*E. superba*) echo from the JR245 research cruise. Large, dynamic echoes were less typical of krill and more difficult to visually distinguish from pelagic icefish echoes. (c) Echo from the 2006 South Georgia groundfish survey. Pelagic trawl catches targeting dynamic echoes extending up to ~150 m from the seabed included only mackerel icefish. Krill was caught when the dense echoes <50 m below the surface were targeted during a separate trawling event. (d) Echo from the 2006 South Georgia groundfish survey. Relatively weak backscattering close to the seabed, such as this, was typical of mixed groundfish trawls, although more extensive and dynamic aggregations were observed in a minority of cases. Targeting this aggregation with a demersal trawl yielded a catch made up of mostly humped rockcod (*Gobionotothen gibberifrons*), blackfin icefish (*Chaenocephalus aceratus*), and South Georgia icefish (*Pseudochaenichthys georgianus*). All echoes were generated from 120 kHz S_V data thresholded at −70 dB.

Table 1. Confusion matrix for random forest generated using the full trawl-verified dataset, with class-specific estimates of generalization error.

	Predicted			
Actual	**Mackerel icefish**	**Krill**	**Mix**	**Class generalization error (%)**
Mackerel Icefish	104	3	3	5.45
Krill	6	206	3	3.73
Mix	4	1	57	8.06

east of Shag Rocks (Figure 6b). These correspond to areas where the commercial fishery mainly operates, as well as where the highest densities of icefish are typically recorded during groundfish surveys (Main *et al.*, 2008). s_A attributed to mixed groundfish aggregations by the RF method was fairly uniformly distributed across the South Georgia shelf, with some small amounts at Shag Rocks (Figure 6c). This pattern is again in agreement with groundfish survey observations of the benthic assemblage. Of the RF-assigned backscatter, 93% of icefish s_A and 62% of mixed groundfish s_A were above the 6-m mean headline height of the bottom trawl (Parkes, 1991).

Discussion

RF models classify echoes based on their empirically observable attributes while making few assumptions after the data have been collected. RF models may be improved with the addition of new data to the training dataset, and selection of variables according to the particular attributes of the species being classified (Genuer *et al.*, 2010). Expert knowledge can thus be incorporated via case-specific variable selection. Relative to other methods, RF models are also simple to implement and accept variables with diverse statistical properties (Hastie *et al.*, 2009). For identifying icefish in the water column, the RF in this study had an estimated 94% accuracy and an overall prediction accuracy higher than other methods (Woodd-Walker *et al.*, 2003; D'Elia *et al.*, 2014). Accepting the need to develop reliable target strength models for icefish, the method presented here could be used in the quantification of any bottom trawl sampling bias and may be integrated into survey analyses that inform the icefish assessment. The RF method was

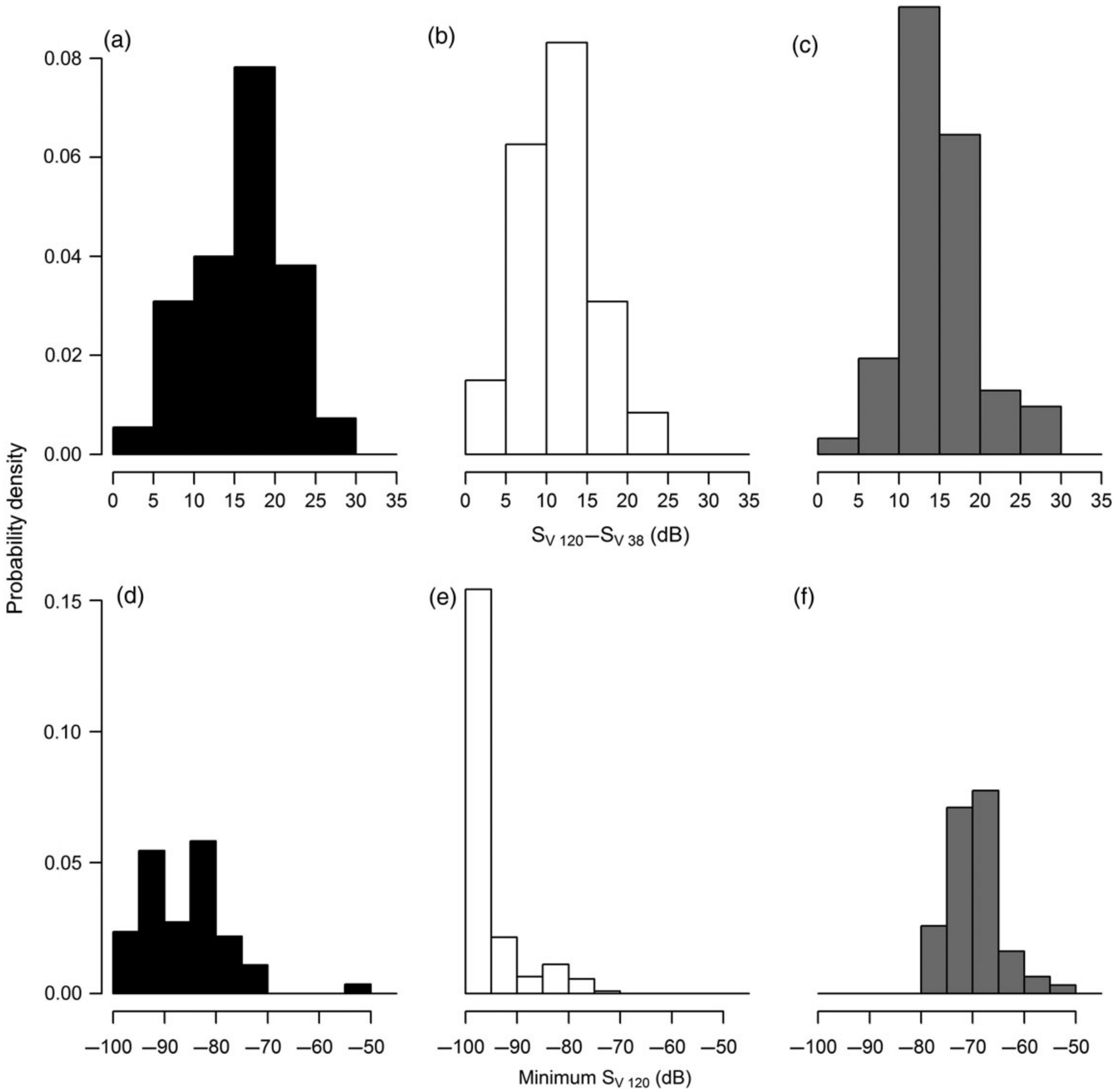

Figure 4. Distributions of school-level minimum $S_{V\ 120} - S_{V\ 38}$ (dB) values (a–c) and $S_{V\ 120}$ (dB) values (d–f) from trawl-verified echoes for mackerel icefish (black), krill (white), and mixed groundfish (grey).

preconditioned on schools, and so, unlike the S_V-difference methods, it did not function in the detection and classification of backscatter below a given density, for example backscatter which is observed in some dispersed krill layers (Watkins and Murray, 1998). However, the fact that krill s_A as defined by the RF method was still significantly higher than that from the fixed 2–12 dB method illustrates that excluding those diffuse layers from the analysis may not substantially bias density estimates, and that most krill biomass is contained in swarms (Fielding *et al.*, 2014).

Although this study was motivated by the investigation of the pelagic component of the icefish stock, there is also potential for acoustic data collected during groundfish surveys to supplement other analyses, such as the Western core box krill survey and ecosystem modelling. To provide more accurate data on the various pelagic scatterers detected during groundfish surveys, some effort should be allocated to the collection of krill data around Shag Rocks. In reality, krill is not absent from the Shag Rocks shelf, but as longitude has a relatively strong influence in the RF the lack of training data in that area might have biased classification. Another inherent challenge will be in dealing with the non-systematic nature of this incidentally collected data, which should be surmountable through the specification of spatially explicit models. Provided the above issues are addressed, species- or assemblage-level acoustic indices could give valuable insights into uncertainties regarding the composition of the pelagic ecosystem at South Georgia. For example, given that most s_A attributed to the various fish species was recorded above the bottom trawl headline height, with a greater understanding of bottom trawl catchability discrepancies between survey-based

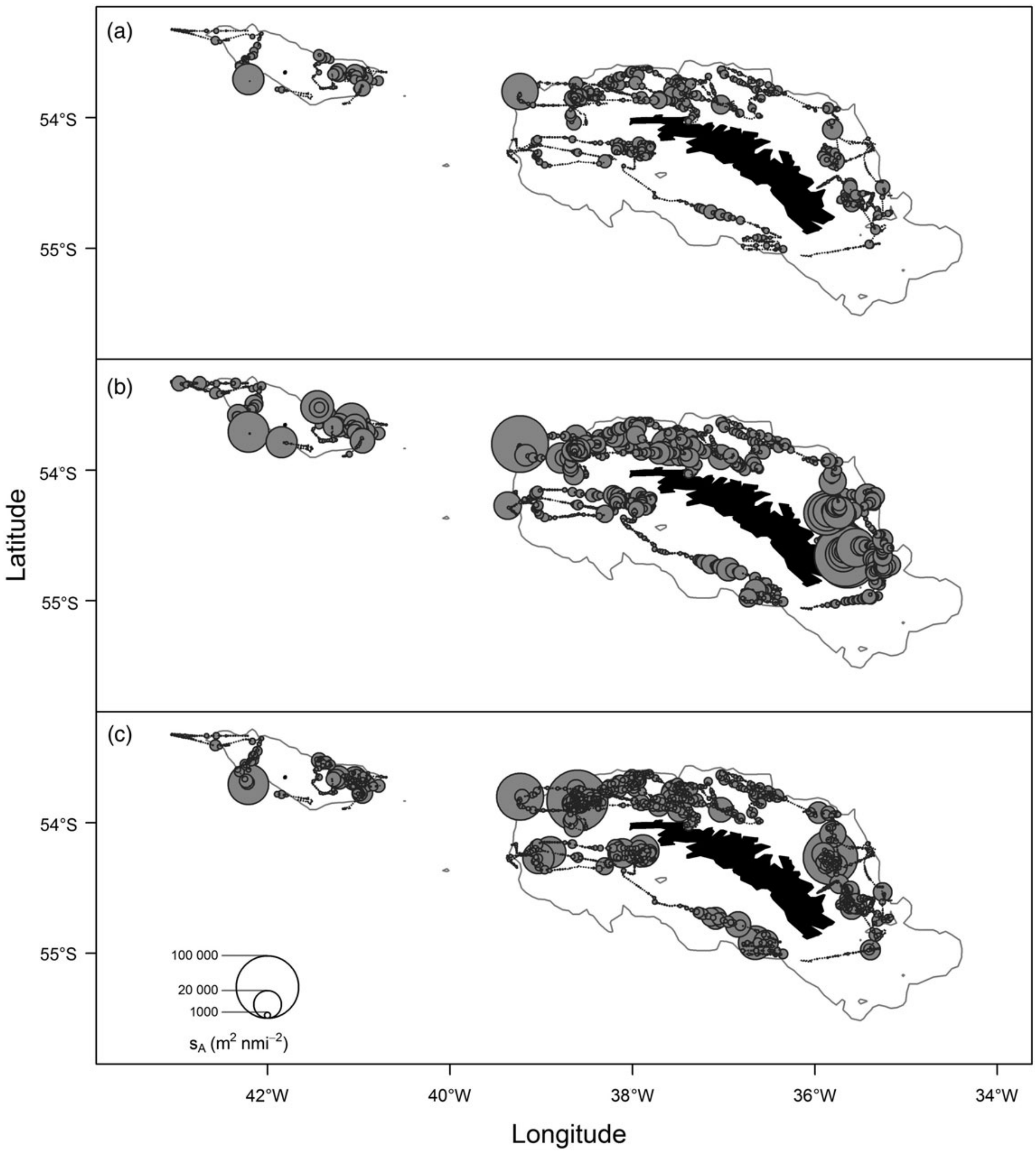

Figure 5. Spatial distributions of s_A (m^2 nautical mile^{-2}) for krill using: (a) the 2–12 dB fixed window method, (b) the 2–16 dB fixed window method, and (c) the variable window method.

abundance estimates and estimated piscivore food requirements (Hill *et al.*, 2012) might be explained.

The methods using fixed and variable ranges of $S_{V\ 120}-S_{V\ 38}$ may provide inaccurate estimates of krill backscatter, but not only because they include echoes from other zooplankton. Echoes from fish without swimbladders may also be erroneously classified as krill. This is because the distributions of school-level $S_{V\ 120}-S_{V\ 38}$ for krill, icefish, and mixed fish overlap (Figure 4). Conversely, krill backscatter may be underestimated because only a portion of the $S_{V\ 120}-S_{V\ 38}$ values measured from krill swarms were included in the S_V-difference ranges assumed for krill. For example, some haul-verified krill swarms had $S_{V\ 120}-S_{V\ 38}$ values >12 dB, which Madureira *et al.* (1993) defined as non-krill zooplankton. Therefore, a 2- to 12-dB range of $S_{V\ 120}-S_{V\ 38}$ alone is unlikely to account for all krill backscatter and may include backscatter from other zooplankton and fish species. Similarly, the wider 2–16 dB

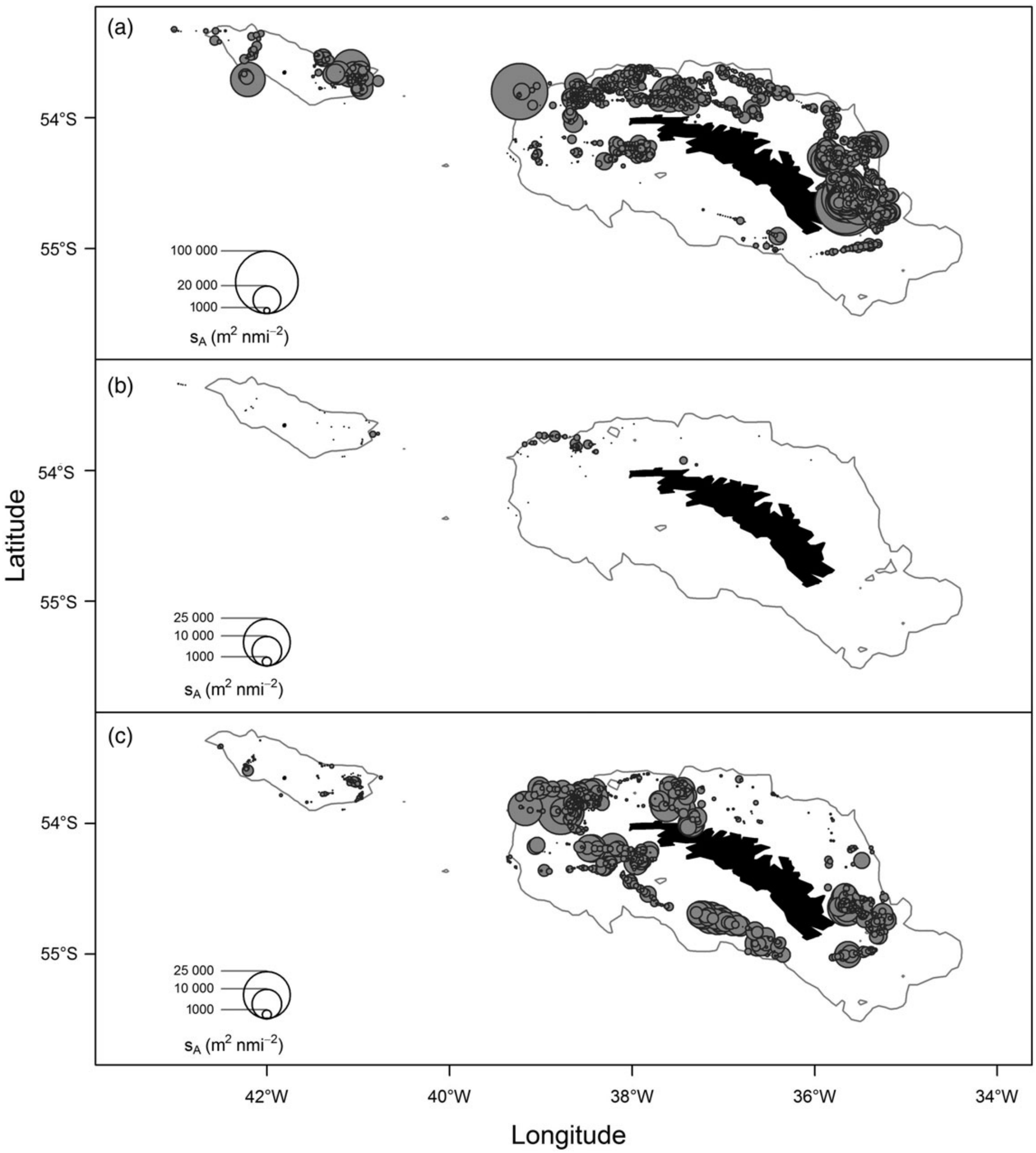

Figure 6. Spatial distributions of s_A (m^2 nautical mile^{-2}) for: (a) krill, (b) icefish, and (c) mixed groundfish, where s_A was classified using the random forest method trained on the full dataset.

range may result in significantly higher s_A than the RF method due to the inclusion of non-krill echoes (Watkins and Brierley, 2002). This exemplifies a trade-off in the EDSU-level approach; an excessively conservative $S_{V\ 120}$–$S_{V\ 38}$ range excludes both non-krill targets and some krill echoes, whereas a wider range includes most types of weak scatterers.

Minimum $S_{V\ 120}$ was the most important predictor variable in the RF. A wider range of minimum $S_{V\ 120}$ was observed across icefish echoes than from those of mixed groundfish aggregations, with minimum values in both categories being generally higher than those of krill swarms. For fish schools, minimum $S_{V\ 120}$ is perhaps most likely to be a function of orientation, with lower values recorded for icefish which spends more time swimming vertically in the water column than other species (Kock, 2005b). Many species included in the mixed aggregation category also have a larger mean body size (Kock and Kellermann, 1991), which could account for the generally higher minimum $S_{V\ 120}$ values. It is apparent (Figure 4) that a large portion of minimum $S_{V\ 120}$ values in krill echoes were between −95 and −100 dB, clearly distinguishing it from the other categories. A single 40 mm krill per m^3 at a near horizontal orientation has an approximate $S_{V\ 120} = -70$ dB (Lawson *et al.*, 2006, 2008), and so, values of $S_{V\ 120} = -100$ dB would most likely represent a discontinuity in density within the swarm under those assumptions. At fine scales, krill within swarms have been shown to exhibit measurable levels of uniformity in terms of their orientation (Kubilius *et al.*, 2015). Most typically, they assume a near horizontal position, particularly when actively swimming (Demer and Conti, 2005; Lawson *et al.*, 2006), but are assumed to vary in orientation across swarms. It was thus posited that these minimum S_V samples between −95 and −100 dB could either represent vacuoles or variability in krill orientation within dense swarms, but are perhaps most likely observed due to low density regions where krill are oriented vertically, minimizing their profile in the acoustic beam.

Including a "mixed groundfish" category was necessary, as a sufficient number of trawl-verified echoes were not available to subset the data any further. Operator intervention was thus required to verify some RF classifications. For instance, the yellowfin notothen, *Patagonotothen guntheri*, another weak scattering species, forms dense pelagic feeding aggregations around Shag Rocks (Collins *et al.*, 2008). If monospecific aggregations such as this are known to occur, then it is preferable to include a corresponding class in the RF method. However, few trawl-verified echoes were available for *P. guntheri* in this case, and so, further scrutiny was essential to verification of some RF classifications. It is also apparent from Table 1 that the dataset was not balanced in terms of the number of observations on each group, which can affect the interpretation of results. For example, if echoes designated as "krill" were to make up ∼5% of observations in the confusion matrix of a binary classifier, 95% accuracy could be achieved by labelling all schools as "mackerel icefish" (Fielding and Bell, 1997).

The properties of echoes considered in this analysis exhibited variability, non-linearity, interaction, and collinearity. Therefore, classification of echoes at the level of the school is complex. Compiling a training dataset that adequately represents the distributions of those variables of interest can be a significant hurdle to reliable classification (Woodd-Walker *et al.*, 2003). This should be considered when choosing which approach to adopt to a given echo classification problem, and emphasizes that the choice of a method is sometimes as dependent on the properties and quality of the available data as it is on the question being addressed (Reid *et al.*, 2000). Indeed, there are situations where considering the data at broader spatial scales (i.e. EDSU-level analysis) is more appropriate (Reid *et al.*, 2000). This can reduce or eliminate the need for training data entirely, with the caveat that more generalized assumptions will need to be accepted regarding the acoustic properties of the target species. To that end, EDSU-level analyses have been developed which can provide more accurate classification than the fixed S_V-difference method applied in this study (Fielding *et al.*, 2014). However, the loss of fine-scale detail of individual schools makes accurate classification beyond broad categories (e.g. weak scatterers) challenging.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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