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ARTICLE

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Factors affecting the survival of harbor (*Phoca vitulina*) and gray seal (*Halichoerus grypus*) juveniles admitted for rehabilitation in the UK and Ireland

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Abstract

The UK shores are home to approximately 40% of the world's population of gray seals (*Halichoerus grypus*) and 40% of Europe's harbor seals (*Phoca vitulina*). Stranded juvenile seals of both species are frequently rescued and admitted for rehabilitation. This study investigates the causes of *P. vitulina* and *H. grypus* admittance to rehabilitation centers in the UK and Ireland and identifies factors that can affect juvenile seal survival. Rehabilitation records for 1,435 *P. vitulina* and 2,691 *H. grypus* were used from five rehabilitation centers from 1988 through 2020. The most common nonexclusive reasons for seal admission to rehabilitation centers included malnourishment (37%), injuries (37%), maternal abandonment (15%), lethargy (12%), and parasite infections (8%). A mixed effects logistic regression model showed that *H. grypus* had 4.55 times higher survival odds than *P. vitulina* and that the odds of survival to release multiplied by 1.07 for every kilogram over their age-predicted weight. This weight-dependent survival could be attributed to the importance of fat in thermoregulation, hydration, and buoyancy during foraging. We recommend that seal rehabilitators pay special attention to the weight of admitted juvenile seals during triage and treatment to enhance their odds of survival and consequent release to the wild.

KEYWORDS
health, juvenile survival, presenting conditions, rehabilitation records, rescue, stranding

1 | INTRODUCTION

Harbor (*Phoca vitulina*) and gray seals (*Halichoerus grypus*) commonly encounter threats in their habitat that include, but are not limited to, climate change (Kovacs et al., 2012), predation (Brownlow et al., 2016; Deecke et al., 2011), interspecific competition for food (Wilson & Hammond, 2019), pollution (Allen et al., 2012), and diseases (Härkönen et al., 2006). These natural and anthropogenic threats commonly bring about seal strandings, which either result in direct death or rescue (Allen et al., 2012). When rescued, the reason for stranding is determined and the prognosis of the seal is assessed by a trained rescuer/volunteer to establish whether treatment at a rehabilitation center is required. This process of logging the cause of stranding on-site provides an opportunity for the recording and monitoring of trends in the cause of stranding, which may provide early detection of novel conditions at a population level (Lawson et al., 2015). This information is also passed to the rehabilitation centers to inform care and treatment protocols that can potentially result in higher survival rates for stranded seals.

With the United Kingdom being home to approximately 40% of the world's populations of *H. grypus* (Russell et al., 2019) and 40% of the European populations of *P. vitulina* (Thomson et al., 2010), monitoring the state and condition of these populations is of international importance. In the UK, previous studies have investigated the reasons for *H. grypus* admissions to a rehabilitation center in Cornwall (Barnett et al., 2000; Silpa et al., 2015) and the mortality of stranded *H. grypus* along the coasts of the UK and the Isle of Man (Baker et al., 1998). These studies found that *H. grypus* juveniles were commonly admitted for rehabilitation due to trauma, malnourishment, hyperthermia, and respiratory, ocular, and oral conditions (Barnett et al., 2000; Silpa et al., 2015). Baker et al. (1998) found that many deceased *H. grypus* washed up on the shore also had malnourished body conditions, trauma, pneumonia, or were entangled in fishing gear that caused drowning. Rehabilitation records for *P. vitulina* have been investigated in other countries such as the Netherlands and Germany (Osinga & Hart, 2010), but have not yet been investigated in the UK and Ireland.

Therefore, the aims of this study were first to determine the common causes of *P. vitulina* and *H. grypus* admittance to rehabilitation centers across the UK and Ireland, incorporating seals from multiple rehabilitation centers. Secondly, to assess seal intake weights and whether the reasons leading to entering rehabilitation may have led to malnourishment at admittance. And, lastly to identify factors that affect the survival odds of both *P. vitulina* and *H. grypus*.

2 | METHODS

2.1 | Records data

The data set represents seal admissions to five of the 12 rehabilitation centers currently operating in the UK and Ireland. On-site seal rescues were carried out by rescue organizations that include, but are not limited to, the British Divers Marine Life Rescue (BDMLR), the Royal Society for the Prevention of Cruelty to Animals (RSPCA), and the Scottish Society for Prevention of Cruelty to Animals (SSPCA). Records were obtained in digital and hardcopy forms for a total of 4,600 seals from the Welsh Mountain Zoo (n = 209), Seal Rescue Ireland (n = 757), Tynemouth Seal Hospital (n = 30), Natureland Seal Sanctuary (n = 1,293), and the Scottish Society for Prevention of Cruelty to

Animals (SSPCA) ($n = 2{,}311$; see Figure 1 for center locations). The period over which the rescues occurred covered 1966 through 2020. Photocopies of records were transcribed and collated into a single excel document alongside the digital records.

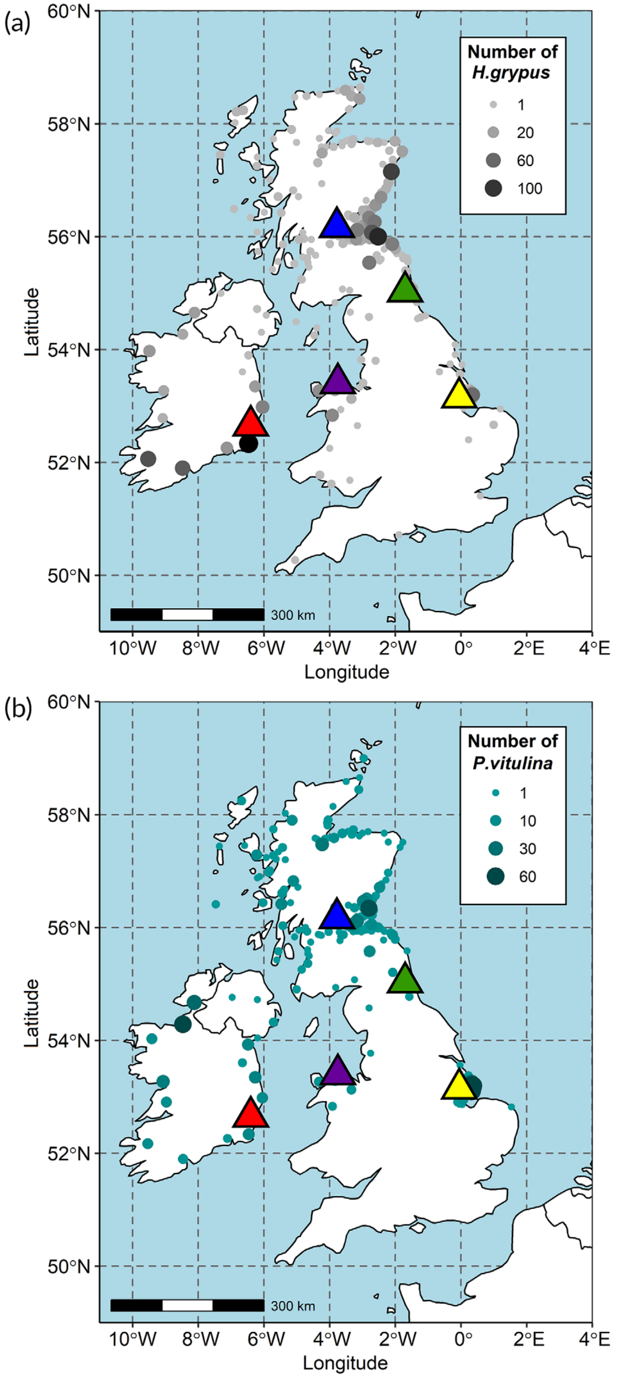

FIGURE 1 Maps of the United Kingdom and Ireland, showing the location of the five seal rehabilitation centers and *P. vitulina* and *H. grypus* rescue locations. Tynemouth Seal Hospital (green triangle), Skegness Natureland (yellow triangle), Scottish SPCA (blue triangle), Seal Rescue Ireland (red triangle), and Welsh Mountain Zoo (purple triangle).

The records included information collected throughout the rehabilitation process. At admission, the rescue location (resolution to town or county), species, sex, date of admission, estimated age (in days, months or years), intake weight (kg), and the reason for admission (e.g., malnourishment) were recorded. Age was estimated by different rehabilitation/rescue staff using a general aging protocol (Table 1) which enabled age to be estimated in days for the first 10 days for *P. vitulina* and 21 days for *H. grypus*. As accurate age estimations in days become difficult beyond these points, age is then estimated in months, often referencing back to the peak in pupping season for the local area from which the seals were rescued. Additionally, a pupping season variable was derived from the admission date of each seal, which identified individuals that were admitted during their species-specific pupping season (*H. grypus* = September–December; *P. vitulina* = June–July) and those that were not. During rehabilitation, the medications used for treatment were noted throughout, with the most frequently used medication types and their intended effects presented in Table 2 and specific examples shown in Table S1. Finally, on the last day of rehabilitation, the date and the final outcome of rehabilitation (release, transfer, or death) were recorded for each seal.

Similarly to Osinga et al. (2012), all seals that were estimated to be ≤12 months of age were classified as juveniles. Seals above the age of 12 months (i.e., subadults and adults, $n = 29$) were excluded from further analysis to focus on the age category that is most frequently rescued and rehabilitated. In addition, in order to reduce the effect of progressive changes of rescue and rehabilitation protocols on the rehabilitation outcome of the seals, all data for seals rescued between 1966 and 1987 ($n = 445$) were removed from the final data set. Rehabilitation records for all seals had at least one piece of information missing, hence data variables had different sample sizes (Table 3). Seals with missing data values for specific variables were excluded from any multivariate analysis which utilized that specific variable. Due to the incomplete records and the need to exclude certain seals from some analyses, potential bias could not be eliminated from this study. Furthermore, the number of records and admission reasons varied by year (see Table S2), with more records being available for recent years, which may be a result of enhanced record keeping by the rehabilitation centers. The GPS coordinates for all rescue locations reported in the rehabilitation records were extracted from Google Maps (2021) and plotted in Figure 1 to display the geographic range of the present data set. For seals that only had their rescue location recorded at a county level, the GPS coordinates for the central point of the specific county was used.

2.2 | Statistical analysis

2.2.1 | Common causes of seal admission

Data for seal admission dates (month of the year), admission reasons, medication used, and estimated ages were summarized as percentages. Interspecies and sex differences in intake weight and time spent in rehab were then investigated using Mann–Whitney *U* tests, since the data were not normally distributed and data for each subgroup were skewed in the same direction. The median and 95% confidence intervals were all calculated using the percentage bootstrapping method with 1,000 bootstrap replicates. All statistical analysis and map construction was performed in R Studio 1.4.1106 running R version 4.0.2 (R Core Team, 2020; RStudio Team, 2020).

2.2.2 | Factors affecting survival

Weight analysis

Nonparametric local regressions with a locally weighted running line smoother (LOESS) and segmented regressions were carried out to estimate relationships between age and weight for each species. LOESS and segmented linear regressions were used because the rate of weight increases during the preweaning period (*H. grypus* = 15–21 days (Russell et al., 2019), *P. vitulina* = 24 days (Bowen et al., 1992), which involves juveniles suckling on high-fat content

TABLE 1 Protocol for age estimation in days for *H. grypus* and *P. vitulina*.

Age (days)	Indicator/s	Species
0–2	The umbilicus is pink, moist and bloody.	*H. grypus* and *P. vitulina*
3–4	The umbilicus is pink and dry at the tip.	*H. grypus* and *P. vitulina*
5–6	The umbilicus is dry, shrivelled and gray/black in color.	*H. grypus* and *P. vitulina*
7–10	The umbilicus is freshly absent.	*H. grypus* and *P. vitulina*
16–21	White lanugo coat partially shed.	*H. grypus*
>21	Lanugo coat completely shed.	*H. grypus*

TABLE 2 Medication types and their uses in treatment of seals in rehabilitation centers.

Medication type	Intended effect
Analgesics	Relieve mild to severe pain and inflammation derived from injuries and other conditions.
Antibiotic	Prevention and treatment of bacterial infections.
Antiparasitic	Treat infections by parasites, such as helminths, protozoa, and ectoparasites.
Antiseptic	Prevent and treat skin infections in lacerations and wounds.
Antiviral	Treat viral infections and reduce the severity and duration of symptoms.
H2 Blockers	Lower the amount of stomach acid produced to relieve indigestion and acid reflux.
Mucolytics	Reduce production of mucus and aid break down of thick mucus in lungs, enabling easier expulsion.
Ocular lubricants	Keep eyes moist and reduce irritation and discomfort caused by dry eyes.
Other	This category was used for medication that was used less frequently (<2% of all seals). These included rehydration fluids, laxatives, benzodiazepines, antifungal medication and antiemetics.

TABLE 3 Variable sample sizes obtained for *P. vitulina* and *H. grypus*.

Variable	Sample sizes (*P. vitulina*)	Sample sizes (*H. grypus*)
Admission reason/s	934	1,773
Age	701	627
Center	1,435	2,691
Date of admission	1,435	2,691
Date of outcome	1,411	2,540
Final outcome	1,411	2,540
Intake weight	1,184	2,159
Medication	114	321
Pupping season	1,435	2,691
Rescue location	1,411	2,555
Sex	1,073	1,786

milk from their mothers, was expected to be higher than during the postweaning period, where the juvenile seals learn how to hunt for themselves. The regression with the best fit was then used to extract residuals, which represented the difference between the observed weight of a seal of a specific age and the weight predicted by the regression model. Residuals from a LOESS regression (*H. grypus* $n = 571$) and a segmented linear regression (*P. vitulina* $n = 687$) were then used to represent the level of malnourishment exhibited by each seal.

A separate logistic regression was conducted for both *P. vitulina* and *H. grypus* to investigate whether the weight residuals and separate (nonexclusive) admission reasons (Abandonment, Dehydration, Injury, Lethargy, Parasites, Ocular, Oral, or Respiratory conditions) affect the odds of a juvenile seal being reported as malnourished upon admission. The process of model selection involved the construction of all possible variations of a multivariate logistic regression model to predict malnourishment. The models that had the lowest Akaike information criterion (AIC) and was the simplest of all models with ΔAIC < 2 was chosen as the final logistic regression model for each species.

Survival modeling

A binomial mixed effects logistic regression model was built to determine whether any variables from the seal records significantly affected the outcome of rehabilitation. A total of six variables were considered as fixed effect variables for the model. These included species, sex, one variable that indicated the medial treatment used (medication), and one variable that broadly suggested the stage of weaning the seal was in (pupping season). The last two variables considered represented the physical condition of the seals, which included the weight/age regression residuals and the admission reasons variable, which consisted of individual or combinations of specific admission reasons for which each seal was admitted (e.g., Abandoned and Dehydrated).

All six fixed variables were used to construct all possible variations of the mixed effects model. Fixed variables were assessed for multicollinearity using variance inflation factors (VIF), and as no covariates displayed a VIF value above 5, no variables were excluded from model selection. Interaction terms with "Species" were also applied to the fixed variables to determine whether their effect on the outcome is consistent across species. The rehabilitation center and year of admission were included as random effects in order to account for differences in treatment protocols between the five centers and the progressive changes of rescue and rehabilitation protocols over the 32-year period. The random effects were tested in the models as both random slopes and random intercepts. These models were then ranked according to their AIC values and the simplest model with the lowest AIC was selected as the final binomial mixed effect model.

The final model was validated using a K-fold cross validation repeated 10 times to estimate the predictive accuracy of the model as outlined by Colby and Bair (2013). Briefly, the data set was randomly divided into five subsets ($K = 5$) of equal size. Four subsets were combined and used to train the model, and the fifth was used to test the model, yielding a confusion matrix. This was repeated until each subset was used as the test data set. The number of true positives, true negatives, false positives, and false negatives predicted by the model were then extracted from the confusion matrices and the mean percentages for predictive accuracy, sensitivity, and specificity calculated.

Further survival analysis was undertaken using the "Survival" package, that enabled Kaplan–Meier survival plots to be plotted for the "Species" variable and the "Malnourishment" variable for each species using corresponding survival probabilities at each time point of rehabilitation. Seals that were released back into the wild or transferred to a different rehabilitation center were censored, as the true survival time for these seals was unknown. Separate Cox-proportional hazard models were then constructed to calculate hazard ratios for the species and malnourishment variables separately due to different variable sample sizes.

3 | RESULTS

3.1 | Common causes of seal admission

The median percentage of *P. vitulina* admitted to rehabilitation centers was the highest during the summer months, June to August; *H. grypus* admissions were the highest between November and January (Figure 2a). The spring months (March to May) had the lowest overall number of seal admissions.

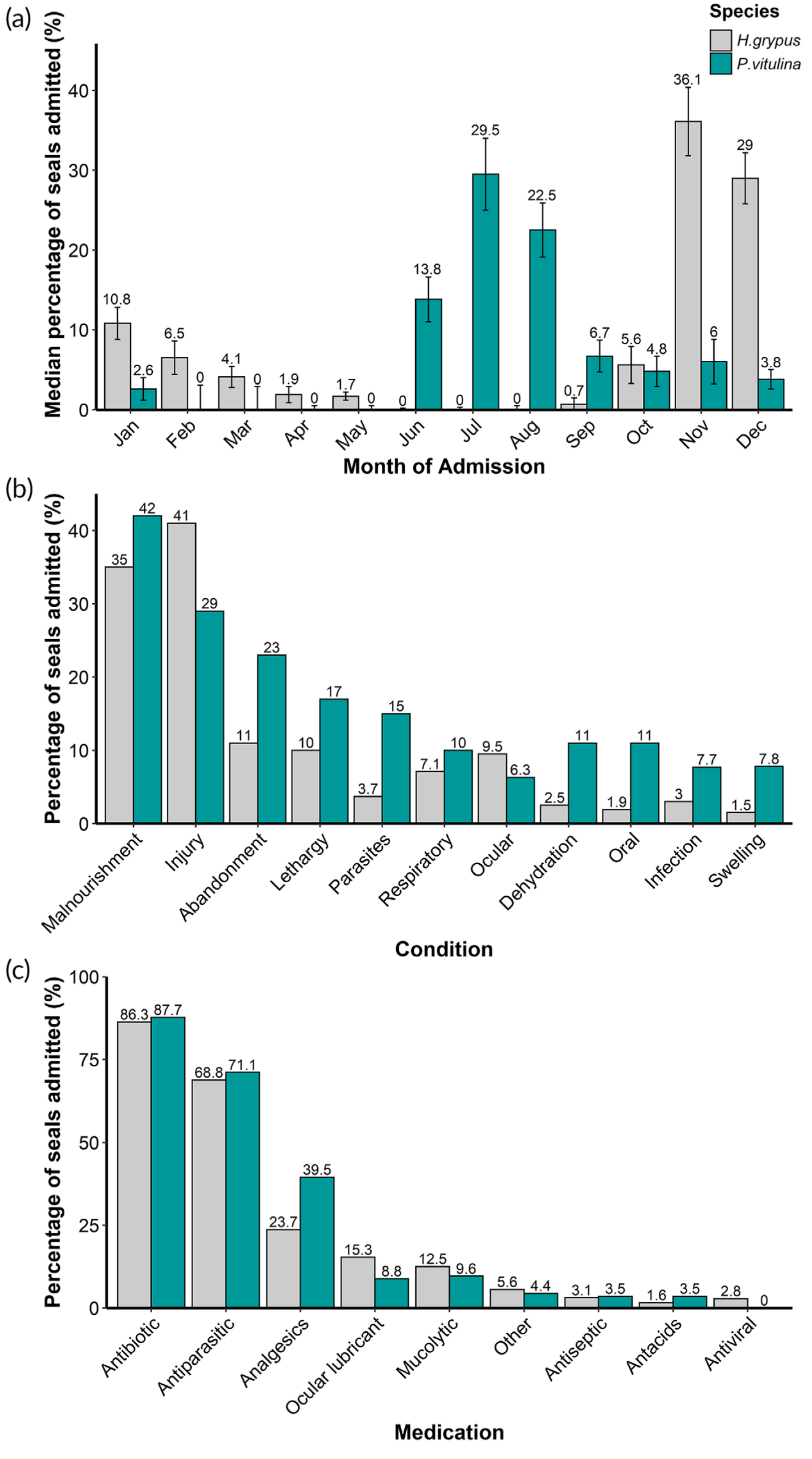

FIGURE 2 Percentage of *P. vitulina* and *H. grypus* admitted to rehabilitation centers; (a) during different months between 1988 and 2020 (*H. grypus n* = 2,691; *P. vitulina n* = 1,435) displaying medians with 95% confidence interval error bars, (b) with a specific/unexclusive condition (*H. grypus n* = 1,773; *P. vitulina n* = 934), and (c) that were treated with different medication types (*H. grypus n* = 321; *P. vitulina n* = 114).

The most common reasons for juvenile *P. vitulina* and *H. grypus* admissions to rehabilitation centers were malnourishment (*H. grypus* = 35%, *P. vitulina* = 42%), injury (*H. grypus* = 41%, *P. vitulina* = 29%), and abandonment (*H. grypus* = 11%, *P. vitulina* = 23%; Figure 2b). Injuries for both species were further subcategorized according to the type of injury reported. In *P. vitulina*, injuries consisted of lacerations (53%), puncture wounds (11%), abrasions (2%), entanglement injuries (1%), skeletal trauma (1%), and 32% of injuries were unspecified. Similarly, injuries obtained by *H. grypus* included lacerations (47%), puncture wounds (4%), abrasions (2%), entanglement injuries (2%), skeletal trauma (1%), and 44% of injuries were unspecified. Parasite cases were comprised of 93% lungworms and 7% unidentified parasites. Of all parasite cases reported in *H. grypus* and *P. vitulina* (n = 273), 74% were confirmed and 26% were suspected due to relevant symptoms (e.g. coughing, breathing difficulties).

The most frequently administered drugs to treat seals in rehabilitation centers were antibiotics, antiparasitic medication, and analgesics (Figure 2c). Data for seals with both medication and admission reasons (n = 387) showed that 68% of the seals did not have parasites (confirmed or suspected) on their records but were treated with anti-parasitic drugs. In addition, 31% of the seals did not have parasites and were not treated and 1% did have parasites and were treated. There were no seals which had parasites reported but did not receive the treatment required.

The majority of seals admitted were estimated to be one month or less in age, with 68.2% of all *H. grypus* and 61.6% of all *P. vitulina* being included in this age bracket (Figure 3a). The median duration of rehabilitation for *H. grypus*, 53 days, 95% CI [51, 55], did not show a significant difference when compared to that of *P. vitulina*, 59 days, 95% CI [54, 66] (Figure 3a, $Z = -1.83$, $p > .05$). For *H. grypus*, the median number of days in rehabilitation for males, 56 days, 95% CI [51, 59] and females, 61 days, 95% CI [56, 65] also showed a lack of statistical significance ($Z = -1.55$, $p > .05$). Similarly, for *P. vitulina* we did not find a significant difference ($Z = -0.23$, $p > .05$) in the median number of days in rehabilitation between males, 67 days, 95% CI [61, 74] and females, 69 days, 95% CI [60, 76]. Sex specific differences in admission weight for *P. vitulina* were significant ($Z = -5.06$, $p < .001$), males weighed 11.6 kg, 95% CI [11.1, 12.2] and females weighed 10.4 kg, 95% CI [10.1, 10.7]. *H. grypus* males were also significantly heavier M = 16.0 kg, 95% CI [15.3, 16.3] than females M = 14.8 kg, 95% CI [14.2, 15.3 ($Z = -5.60$, $p < .001$).

3.2 | Factors affecting survival

3.2.1 | Weight analysis

The age of *P. vitulina* admitted for rehabilitation had a significant effect on their weight (Figure 4a, $F(1,574) = 1,214$, $p < .001$). Using this segmented linear model, the predicted weight of a *P. vitulina* juvenile at birth (±0.5 months) was 9.25 kg and the gain in weight was 2.99 kg/month during the first two months and 0.87 kg/month thereafter. As the LOESS regression comprised of local linear fitting and often results in predictor variables that are temporarily correlated (Mello & Rose, 2005), significance tests were not used. Therefore, the *p*-values and rate of predicted weight increase were not reported, however, the predicted weight of a juvenile *H. grypus* was estimated to be 17.0 kg. The differences between observed and predicted weights (residuals) for both species were extracted to be used as a new variable in further analysis.

A logistic regression model selection for *P. vitulina* (Table S2) showed that the model with the lowest AIC included age/weight residuals, injury, and dehydration variables that all significantly affected the likelihood of *P. vitulina* juveniles being reported as malnourished at admission to rehabilitation centers (Table 4). For every kilogram of weight over the predicted weight of a seal at a specified age, the odds of *P. vitulina* being reported as malnourished were multiplied by 0.77. In addition, the odds of malnourishment were also multiplied by 0.62 when the seal had an injury at admission and by 1.65 if the seal was dehydrated. For *H. grypus*, the logistic regression model that best fit the data (Table S4) included age/weight residuals, injury, and lethargy variables that all significantly affected the likelihood of *H. grypus* being reported as malnourished at admission to rehabilitation centers (Table 5).

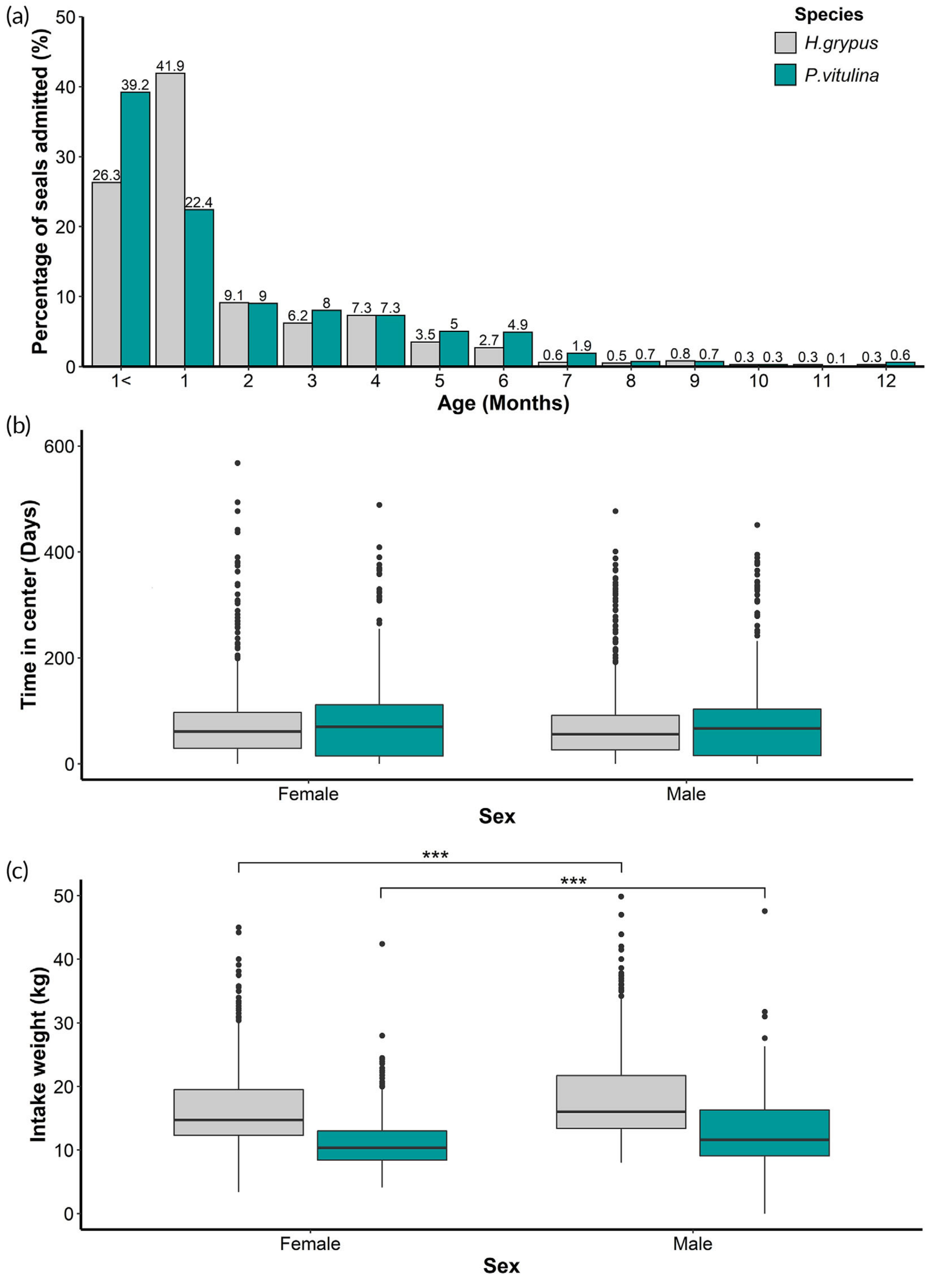

FIGURE 3 (a) Percentage of *P. vitulina* and *H. grypus* admitted to rehabilitation centers at a specific age, (b) boxplots of time spent in the center, and (c) intake weight, which are further subdivided by sex of the seal. Significant sex differences from Mann–Whitney *U* tests are noted as **p* < .05; ***p* < .01; ****p* < .001.

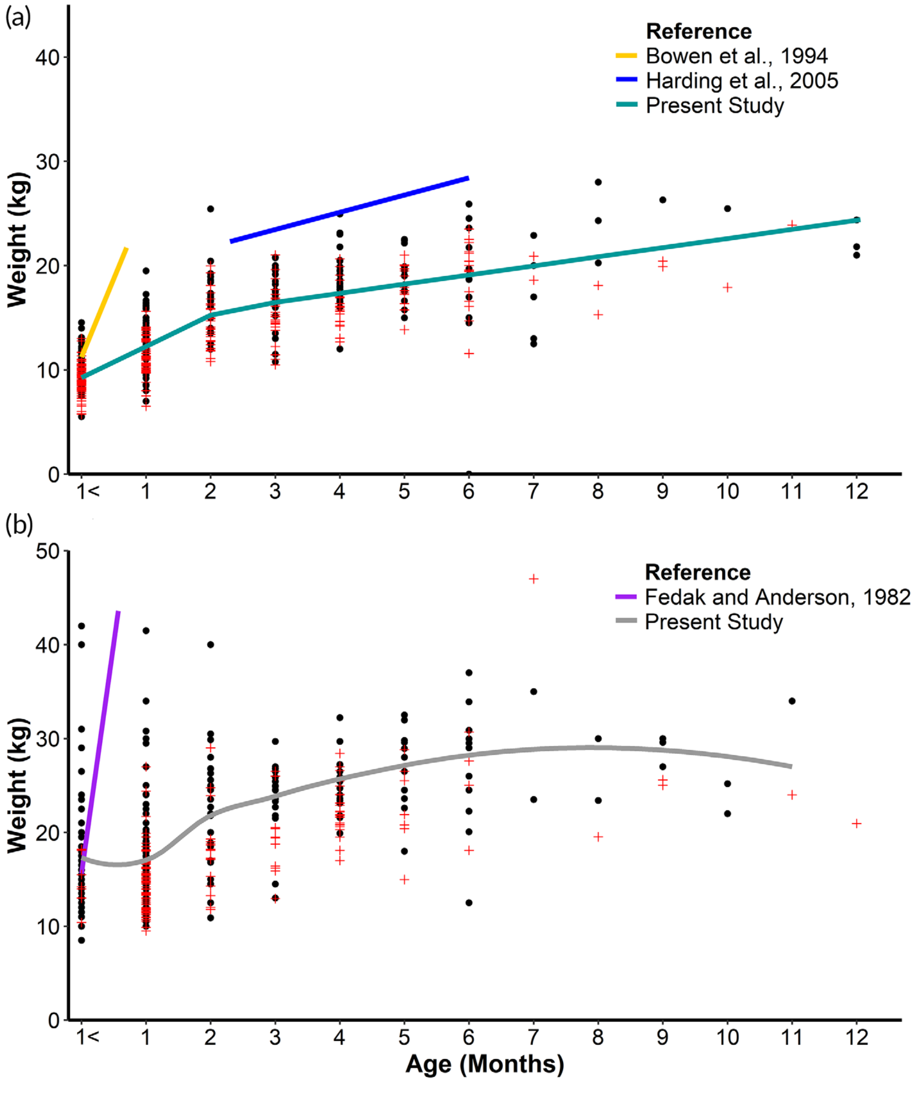

FIGURE 4 Relationships between age estimates (±0.5 months) and weight of (a) *P. vitulina* ($n = 687$) and (b) *H. grypus* ($n = 571$), displayed by segmented and LOESS regressions for seals that were reported as malnourished (+) and those that were not (●) in the present study and published data from other studies.

Specifically, the odds of malnourishment were multiplied by 0.27 when the seal had an injury, by 1.67 when the seal was lethargic and by 0.880 for every kilogram of weight over the predicted weight of a seal at a specified age.

3.2.2 | Survival modeling

Overall, 57% of *P. vitulina* and 68% of *H. grypus* juveniles admitted to rehabilitation centers survived to release. Binomial mixed effect logistic regressions fitted using variables that significantly affected survival showed that the best fitted model to predict juvenile seal rehabilitation outcome included the species, the weight residuals, and species*weight residuals interaction term as fixed effects (Table S5). There was one other model with a delta AIC value

TABLE 4 Variable coefficients, standard errors (*SE*), *z* values, *p* values, and odds ratios (OR) of the final logistic regression for predicting malnourishment in admitted *P. vitulina* ($n = 687$).

	Coefficient	*SE*	*Z*	*p*	OR
Intercept	0.215	0.128	1.678	>.05	—
Injury (TRUE)	−0.482	0.205	−2.349	<.05	0.617
Dehydration (TRUE)	0.502	0.244	2.059	<.05	1.652
Weight.Residuals	−0.256	0.043	−5.921	<.001	0.774

TABLE 5 Variable coefficients, standard errors (*SE*), *z* values, *p* values, and odds ratios (OR) of the final logistic regression for predicting malnourishment in admitted *H. grypus* ($n = 571$).

	Coefficient	SE	*Z*	*p*	OR
Intercept	−0.035	0.150	0.655	>.05	—
Injury (TRUE)	−1.522	0.224	−5.875	<.001	0.268
Lethargy (TRUE)	0.522	0.256	2.039	<.05	1.686
Weight.Residuals	−0.128	0.027	−4.744	<.001	0.880

TABLE 6 Variable coefficients, standard errors (SE), *z* values, *p* values, and odds ratios (OR) for the final binomial mixed effect logistic regression used to predict the rehabilitation outcome of rescued juvenile seals (*P. vitulina* $n = 687$; *H. grypus* $n = 571$).

	Coefficient	*SE*	*Z*	*p*	OR
Intercept	1.315	0.490	2.683	<.01	—
Species (*P. vitulina*)	−1.528	0.185	−8.265	<.001	0.217
Weight.Residuals	0.068	0.023	2.898	<.01	1.071
Species (*P. vitulina*): Weight.Residuals	0.105	0.048	2.182	<.05	1.110

below two, but all other models, including those with fewer variables, had a delta AIC greater than two and were therefore not selected. This final model showed that the odds of *H. grypus* surviving to release were 4.55 times higher than the odds of *P. vitulina* and that the odds of a juvenile surviving to release increased by 1.07 times for every unit of weight (kilograms) over the predicted weight for their age, but when the seal is *P. vitulina* the odds increased by 1.11 times for every kilogram (Table 6). The reason for admission, pupping season, medication used, and the sex of the seal were not found to have a significant effect on the outcome ($p > .05$) and so were not included in the final model selection. The final model had a predictive accuracy of 76%, sensitivity of 97%, and specificity of 23% after K-fold cross validation ($K = 5$, 10 repeats).

Moreover, survival analysis was further used to incorporate the number of months in center for each seal, and Kaplan–Meier estimates were obtained to assess interspecies survival (Figure 5a) and how survival probabilities differ for malnourished and not malnourished *P. vitulina* (Figure 5b) and *H. grypus* (Figure 5c) seals. *H. grypus* again showed significantly higher survival probabilities to release than *P. vitulina* during rehabilitation ($\chi^2_1 = 34.1$, $p < .001$), with a Cox proportional hazard model showing that the hazard of death increased by a factor of 1.44 95% CI [1.29, 1.60] for *P. vitulina* when compared to *H. grypus*. Furthermore, both species also showed a significant difference in survival between malnourished and not malnourished individuals (*P. vitulina* $\chi^2_1 = 9.8$, $p < .01$; *H. grypus* $\chi^2_1 = 35.7$, $p < .001$) as the hazard of death decreased by a factor of 0.72, 95% CI [0.59, 0.89] in malnourished *P. vitulina* and by a factor of 0.54, 95% CI [0.44, 0.66] in malnourished *H. grypus*, when compared to individuals that were not malnourished.

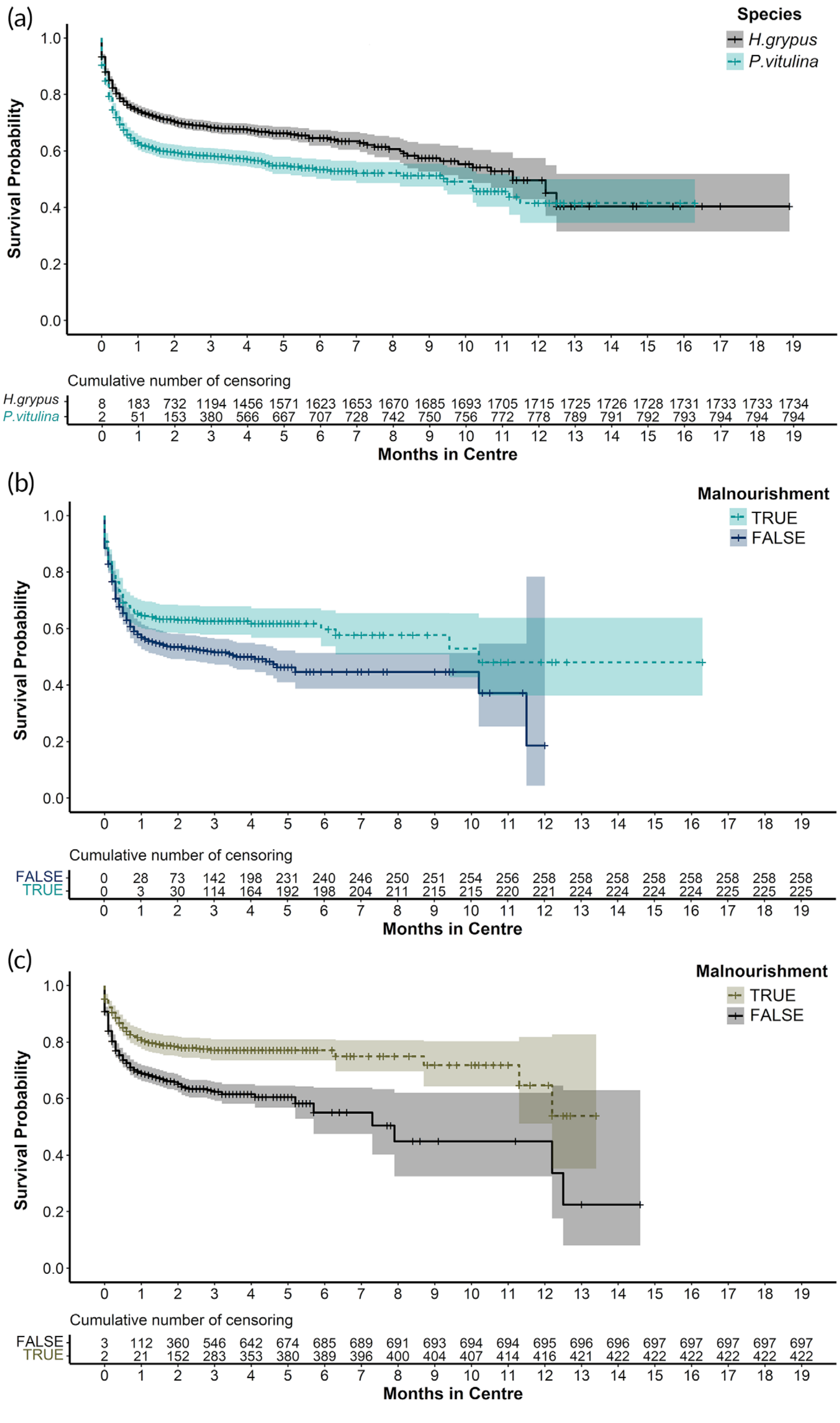

FIGURE 5 Kaplan–Meier plots displaying differences in survival probabilities between (a) juvenile *H. grypus* and *P. vitulina*, (b) *P. vitulina* that were reported malnourished (TRUE) and those that were not (FALSE), and (c) *H. grypus* that were reported malnourished (TRUE) and those that were not (FALSE), all with 95% confidence intervals and the cumulative number of censoring during rehabilitation.

4 | DISCUSSION

Investigating the records data from five different rescue centers over 32 years, has identified that injuries, maternal abandonment, lethargy, and parasite infections are all common causes of *P. vitulina* and *H. grypus* admittance to rescue centers. However, it is the weight of the juvenile seal at admittance that contributes most to the number of seal admissions to rehabilitation centers and has a significant effect on survival.

4.1 | Weight and malnourishment

Malnourishment occurred in over a third of all *P. vitulina* and *H. grypus* juveniles in this study. This high prevalence has also been observed in other studies on the coasts of England, Wales, and Isle of May (Baker et al., 1998; Barnett et al., 2000; Silpa et al., 2015), the Netherlands, and Germany (Osinga & Hart, 2010). Frequent presence of malnourishment among stranded juveniles could be attributed to interruptions in the suckling regime of mother and juvenile pairs (Anderson et al., 1979), postweaning periods of juvenile seal fasting, and inefficient foraging due to inexperience (Muelbert et al., 2003; Nordoy & Blix, 1985). The high prevalence of malnourishment observed is a cause for concern, as survival analysis showed that the odds of a juvenile seal surviving to release increased by 1.07 times for every kilogram over their age predicted weight, or by 1.11 times per kilogram if the seal is a *P. vitulina* juvenile (Table 6). This effect is consistent with that previously reported for both *P. vitulina* (Cole & Fraser, 2021; Harding et al., 2005; MacRae et al., 2011) and *H. grypus* (Hall et al., 2001, 2002), where heavier juveniles had higher survival probabilities. This weight dependent survival can most likely be attributed to the importance of fat (i.e., blubber) in thermoregulation (Harding et al., 2005), maintaining an optimal water balance (Rash & Lillywhite, 2019) and buoyancy especially during foraging (Adachi et al., 2014). Although a clear correlation between weight and survival was displayed (Table 6), there may be further influencing factors affecting both the weight and survival of the seals which were not included in rehabilitation records and hence could not be considered in this analysis.

Furthermore, in both species males weighed more than females, which has previously been observed in both *H. grypus* (Kovacs & Lavigne, 1986) and *P. vitulina* pups (Bowen et al., 1994; Coltman et al., 1998). This weight difference has been suggested to be due to sex-specific maternal investment that favors male offspring and results in higher birth weights and rate of weight increase during suckling in *H. grypus* (Kovacs & Lavigne, 1986). However, as Linderfors et al. (2002) also pointed out, the weight of the mothers was not controlled for in this study and hence the primary reason for weight differences between sexes remains unclear due to age and weight of the mother significantly affecting birth weight (Bowen et al., 1994). Nevertheless, due to the sex-specific differences in weight, it could be hypothesized that male juveniles have a higher survival probability than females. However, Hall et al. (2001) documented the opposite pattern of sex differences in survival to one year for *H. grypus* juveniles, with mortality ranging from 38% in females to 80% in male juveniles in some locations. This sex-specific survival probability was not observed in the present study, which was most likely due to male seals admitted for rehabilitation receiving the same care and treatment as the females.

Age-adjusted weights for *P. vitulina* were lower than was observed in wild seal pups in Canada and Sweden (Bowen et al., 1994; Harding et al., 2005). It should also be noted that the predicted birth weights from the *P. vitulina* and *H. grypus* regressions (Figure 4) were in line with previously reported birth weights in wild seals (Anderson & Fedak, 1987; Shirihai & Jarrett, 2006) and hence prenatal condition and age of mothers could be argued to be an unlikely contributing factor to the observed prevalence of juvenile seal malnourishment.

The odds of a seal being reported as malnourished were, however, affected by the weight residuals and admission reasons, specifically dehydration and injury in *P. vitulina* and lethargy and injury in *H. grypus*. Dehydrated *P. vitulina* were 1.65 times more likely to be reported as malnourished, which could be explained by the importance of diet in hydration, with prolonged periods of fasting potentially leading to dehydration and electrolyte imbalance (Rash & Lillywhite, 2019). Interestingly, although dehydration was observed in 11% of *P. vitulina* and 2.5% of

H. grypus, rehydration fluids were only administered to less than 2% of the seals. Furthermore, although records of age used in this study may have been subject to bias as different veterinarians and rehabilitators carried out the initial assessments upon the rescue or admission of each seal, the age/weight regression residuals obtained significantly affected the odds of a seal juvenile being reported as malnourished, suggesting that the residuals remain a good representation of body condition of juvenile seals in the present study.

4.2 | Other causes of admittance

Presence of injuries was the second most observed condition in admitted seals, presented in 41% of *H. grypus* and 29% of *P. vitulina* juveniles. High prevalence of injuries in *H. grypus* is in line with previous studies finding injuries in 74% (Barnett et al., 2000) and 82% (Silpa et al., 2015) of admitted seals in Cornwall (admitted during different time periods). In addition, using deceased *H. grypus*, Baker et al. (1998) determined that injury caused 24% of deaths in seal juveniles younger than three weeks around England, Wales, and the Isle of Man. By contrast to our results where 7% of all *H. grypus* injuries were puncture wounds and the most common injuries were lacerations (32%), Silpa et al. (2015) observed notably higher prevalence of puncture wounds (69%). The high prevalence of puncture wounds has previously been attributed to intraspecific interactions among *H. grypus* on the same haul out sites (Silpa et al., 2015), with severe cases of cannibalism also reported (Brownlow et al., 2016; van Neer et al., 2019). Although statistical comparisons for *P. vitulina* cannot be made due to the lack of published data, it should be noted that Osinga and Hart (2010) stated that entanglement in ghost nets is a frequent cause of injury along with occasional lesions and fractures inflicted by boat propellers for *P. vitulina* in the Netherlands. Whereas our study found that the most common injury types were lacerations (57%) and puncture wounds (15%), with entanglement injuries (0.5%) and skeletal trauma (1%) only occurring occasionally.

In addition, due to the high rates of injuries observed, which commonly result in infections and/or inflammation, it is not surprising that antibiotics and anti-inflammatories were in the top three most used medications for both *H. grypus* and *P. vitulina*. The high prevalence of antibiotic administration does pose a direct selection pressure on bacteria, which may contribute to the emergence of antibiotic resistant bacteria (ARB) in rehabilitating seals, that could be disseminated to wild seal populations post release (Ramey & Ahlstrom, 2020). The ARBs may also be transmitted to other aquatic animals, domestic animals, and livestock in coastal areas, increasing the spread of ARBs in the environment, and potentially raising significant concerns for human health (Ramey & Ahlstrom, 2020).

Maternal abandonment was also a frequent reason for rescue of *P. vitulina* and *H. grypus* juveniles which is in line with Osinga and Hart (2010) who reported that 40% of *P. vitulina* admitted to a center in the Netherlands were orphaned or abandoned. The common occurrence of abandonment also has an impact on the weight of the seal, as preweaning abandonment results in seal juveniles not achieving their weaning mass which reduces their ability to withstand the initial postweaning period without becoming malnourished, especially in *H. grypus* that undergo an estimated 21-day fasting period (Noren et al., 2008). *H. grypus* in this study had a lower prevalence of abandonment, which may be a consequence of their different lactation strategies where *H. grypus* undergo a fasting period; *P. vitulina* undertake foraging trips to withstand the significant weight loss associated with lactation (Boness et al., 1994, Iverson et al., 1993). Juveniles of both species are at risk of disturbance from neighboring seals, humans, high tides, and storms (Baker, 1984; Burton et al., 1975). These commonly result in mother and juvenile separations and consequent abandonment, but as *P. vitulina* juveniles are left alone more frequently preweaning, they may be at a higher risk of these disturbances leading to their abandonment. Additionally, changes in prey availability also have the potential to increase foraging trip durations (Crocker et al., 2006; Sharples et al., 2012), therefore future changes in prey abundance may contribute to higher prevalence of juvenile abandonment.

The other notable recurring admission reasons were lethargy and parasite infections. Lethargy appeared in 10% of *H. grypus* and 17% of *P. vitulina* juveniles, however, due to lethargy being a side effect of numerous causal factors such as infection (Waltzek et al., 2012), injury (Seguel et al., 2017), toxic poisoning (McHuron et al., 2013), and muscle loss that results from starvation (McCue, 2010), the primary reasons for the observed high prevalence cannot be explained without further examination of individual seal juveniles at admission. Parasite infections were more frequent in *P. vitulina* (15%) than in *H. grypus* (3.7%), which was consistent with the findings of Osinga et al. (2012) where parasitic pneumonia occurred in *P. vitulina* more often than in *H. grypus*. As lungworms were the main parasite with which seals were infected, the higher prevalence in *P. vitulina* is most likely due to *P. vitulina* becoming self-feeding earlier on in life than *H. grypus*, hence *P. vitulina* are more likely to have acquired lungworm before being admitted for rehabilitation through feeding on benthic fish (e.g., flatfish), which are intermediate hosts for lungworms (Ulrich et al., 2015).

Furthermore, it is noteworthy that when drug administration was investigated, 68% of admitted seals (with medication data) were given antiparasitic medication but did not have parasites recorded in their records. Similarly, van Wijngaarden et al. (2021) found that 91.8% of juvenile harbor seals admitted for rehabilitation in the Netherlands were treated with antiparasitic medication but only 35.6% had a confirmed diagnosis. These findings highlight that treatment of juvenile seals commonly involves administration of antiparasitic medication as a precautionary measure when lungworms are suspected, instead of undertaking the more expensive and time-consuming parasitology analysis. This is most likely due to the often-severe parasite induced effects, such as bronchopneumonia which has previously been identified to be a common cause of death among seals that are under a year old (Kroese et al., 2018; Osinga & Hart, 2010). Over-use of antiparasitic drugs should, however, be discouraged, as they are a potential source of environmental contamination and harm (Perkins et al., 2021; Wagil et al., 2015).

4.3 | Species-specific differences

Juvenile seal admission into rehabilitation centers was seasonal, as most *P. vitulina* were admitted between June and August and most *H. grypus* were admitted between October and December. These periods of admission are consistent with that observed in the Netherlands and Germany (Osinga & Hart, 2010) and southwest England (Silpa et al., 2015), and correspond to the species-specific pupping seasons. As *P. vitulina* juveniles are generally born in June and July (Thompson et al., 2002) and *H. grypus* are born between September and December, with pupping usually beginning in the southwest and progressively occurring later in a clockwise manner around the UK (Russell et al., 2019).

In relation to the species effect on survival odds, our study and that of Osinga and Hart (2010) have reported lower survival rates in *P. vitulina* admitted for rehabilitation compared to *H. grypus* juveniles. Therefore, the effect of species on survival could be an indication of the previously observed interspecific advantages *H. grypus* have over *P. vitulina*, specifically the more developed immune system in early life (Hammond et al., 1997) and higher robustness to disturbances (Skeate et al., 2012). However, further studies including both species are required for direct comparisons to be made, to determine the precise reasons why *H. grypus* have better survival probabilities in rehabilitation settings. In addition, the reason for admission and medication used did not influence the odds of survival to release, which could be attributed to effective treatment and care from veterinary and rehabilitation staff, or failure to isolate primary reasons for admission in this study as most seals were admitted due to several reasons/symptoms.

4.4 | Conclusion

While injuries, maternal abandonment, lethargy, and parasite infections were all common causes of seal admittance to rescue centers, the weight of the juveniles at admittance was the most common factor and had a significant effect on survival. Therefore, we recommend that rehabilitation centers should pay special attention to the weight of each admitted juvenile seal during triage and treatment in order to enhance their chance of survival and consequent release to the wild. Finally, there is a need for more consistent record keeping and sharing of best practice guidelines for seal rehabilitation within and between centers, to enable further research into the admission reasons and survival probabilities of admitted seals, that may prove useful in optimizing seal treatment protocols in the future.

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AUTHOR CONTRIBUTIONS

Michal Zatrak: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Sam Brittain:** Data curation; writing – review and editing. **Lauren Himmelreich:** Data curation; writing – review and editing. **Susie Lovick-Earle:** Data curation; writing – review and editing. **Romain Pizzi:** Data curation; writing – review and editing. **Kirsty J Shaw:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Robyn A Grant:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Matthew Geary:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; supervision; validation; visualization; writing – original draft; writing – review and editing.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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