IBIS
BOU international journal of avian science
Ibis (2018), **160**, 846–854 doi: 10.1111/ibi.12594

Factors influencing Manx Shearwater grounding on the west coast of Scotland

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Grounding of thousands of newly fledged petrels and shearwaters (family Procellariidae) in built-up areas due to artificial light is a global problem. Due to their anatomy these grounded birds find it difficult to take off from built-up areas and many fall victim to predation, cars, dehydration or starvation. This research investigated a combination of several factors that may influence the number of Manx Shearwater *Puffinus puffinus* groundings in a coastal village of Scotland located close to a nesting site for this species. A model was developed that used meteorological variables and moon cycle to predict the daily quantity of birds that were recovered on the ground. The model, explaining 46.32% of the variance of the data, revealed how new moon and strong onshore winds influence grounding. To a lesser extent, visibility conditions can also have an effect on grounding probabilities. The analysis presented in this study can improve rescue campaigns of not only Manx Shearwaters but also other species attracted to the light pollution by predicting conditions leading to an increase in the number of groundings. It could also inform local authorities when artificial light intensity needs to be reduced.

Keywords: light pollution, moon, probability model, *Puffinus puffinus*, random forest classification, Scotland, seabirds, weather condition.

Worldwide, many different species of animals are disturbed by artificial light pollution (Gaston *et al.* 2013). It can increase activity during the night (Dominoni *et al.* 2014), restrict or change patterns of movement of light-avoiding species (Frank 1988, Kuijper *et al.* 2008), influence reproductive phenology (Dominoni *et al.* 2014), disturb circadian patterns (Reiter *et al.* 2009) and cause fatal disorientation or attraction to the source of light (Verheijen 1960, Le Corre *et al.* 2002). One major group influenced by artificial light pollution comprises birds that show nocturnal activity, such as petrels and shearwaters (family Procellariidae; Rodríguez *et al.* 2017). Recent studies have found that seabirds are more likely to be encountered in locations with high light intensity (Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009, Rodrigues *et al.* 2012, Troy *et al.* 2013, Rodríguez *et al.* 2015). Fledglings on their first flight are often found to crash-land in the cities and towns near their nest-sites; this phenomenon can be termed 'grounding' (Le Corre *et al.* 2002, Rodríguez *et al.* 2014) or 'fallout' (Ainley *et al.* 2001, Troy *et al.* 2011). Seabirds that land on the ground are often unable to take off from these urban locations due to their specialized anatomy, exemplified by legs set far back on the body to facilitate diving. However, this 'forward heavy' anatomy requires a slope or a gust of wind to be able to take off. Thus, if a grounded bird is not helped, it may fall victim to predation, dehydration, starvation or being hit by a vehicle (Telfer *et al.* 1987).

Even though the biological bases causing seabirds to ground are not fully understood, several patterns have been described across the family Procellariidae. Adverse weather conditions and

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moonless nights were reported to increase seabird fallout (Phillips & Lee 1966, Imber 1975, Reed *et al.* 1985, Telfer *et al.* 1987, Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009, Miles *et al.* 2010, Rodríguez *et al.* 2014). A study by Rodríguez *et al.* (2014) also showed that strong winds blowing in the direction of areas of light pollution caused more seabirds to ground.

Like other birds from the family Procellariidae, Manx Shearwaters *Puffinus puffinus* encounter problems with light pollution (Brooke 1990, Rodríguez *et al.* 2008, Rodríguez & Rodríguez 2009, Miles *et al.* 2010). Manx Shearwaters are listed as least concerned by IUCN with an estimated population of more than 1 million individuals, but the majority of birds breed only on three islands – Skomer, Skokholm and Rum (Brooke 1990). In the current study we report grounding data collected during 6 years and investigate what factors influenced the number of Manx Shearwater groundings in the Scottish coastal village of Mallaig located close to the second largest colony of Manx Shearwaters (the Isle of Rum). A random forest model was developed that used meteorological variables and moon cycle to predict the daily quantity of birds that were encountered on the ground. Young petrels and shearwaters are inexperienced in flying and may be blown in the direction of a source of light, e.g. a village (Rodríguez *et al.* 2014). Therefore, we predict that the wind direction coming from Rum (westerly), as well as strong winds, causes the highest fallout. Similar patterns may be found due to visibility conditions; we predict that higher visibility would result in higher fallout, as the village of Mallaig might be seen by Manx Shearwaters from further away, causing more birds to be attracted to the light pollution. We further predict that the full moon results in a small number of grounded birds, due to the fact that the greater ambient light from the moon may cause a diminution of attraction to the artificial light (Reed *et al.* 1985). The random forest model presented allows exploration of each environmental variable and answers which of these has the greatest influence on the number of grounded Manx Shearwaters.

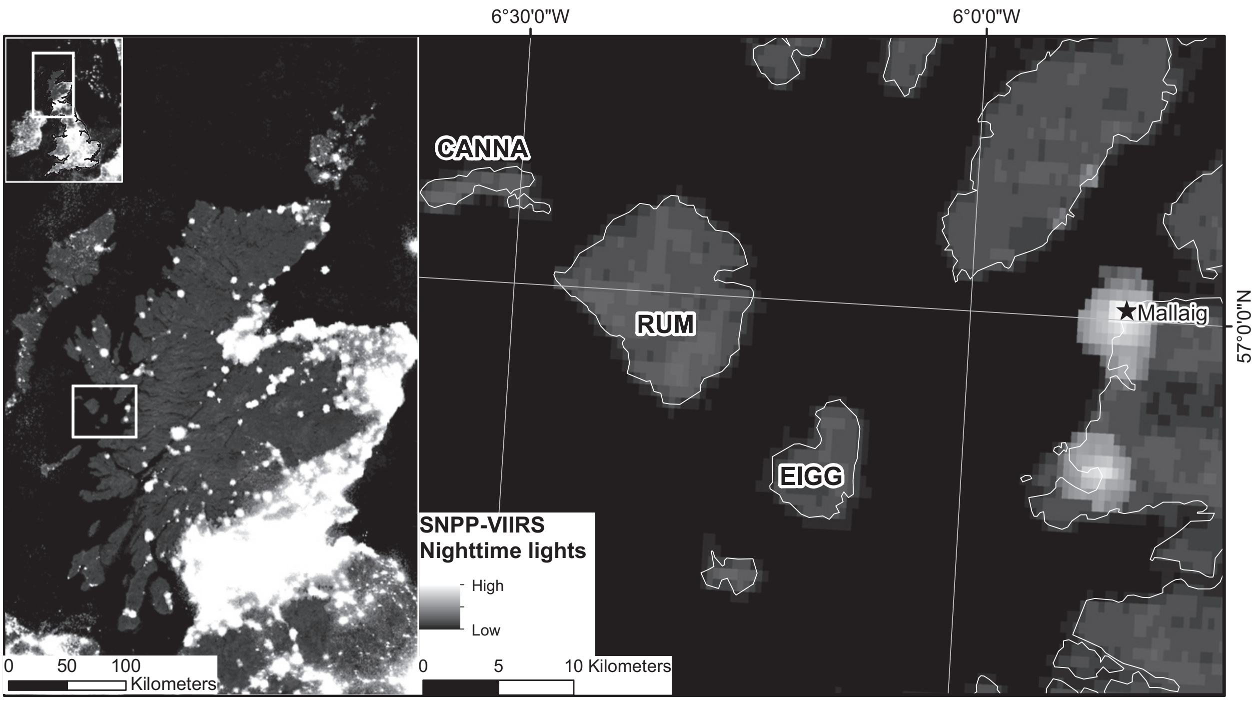

Figure 1. Artificial lights in the British Isles, the Isle of Rum and Mallaig. The left overview represents a night-time light map over the British Isles and Scotland in particular with the extent of the main map on the right (white box). The main map locates the village of Mallaig in relation to the Isle of Rum and how it accounts for a significant source of artificial light for the region. The night light is based on the Visible Infrared Imaging Radiometer Suite (Earth Observatory, 2012, Elvidge *et al.* 2013).

METHODS

Study site and Manx Shearwater grounding data collection

Mallaig (57°0′14.57″N, 5°49′52.36″W) is located on the west coast of the Scottish Highlands, 27 km east of the Isle of Rum (Fig. 1). The Isle of Rum harbours the second largest nesting site of Manx Shearwaters in the world with an estimated 76 000 pairs (Murray *et al.* 2003). Small numbers are reported to breed on the nearby island of Canna, in the region of 12–15 pairs (B. Swann, unpubl. data), and Eigg, with an estimated population of 50–150 breeding pairs (J. Chester, pers. comm.).

Manx Shearwaters from Rum leave the colony in late August and September (Brooke 1990). A volunteer-based project in Mallaig collected data between 2009 and 2014. Every day in September, at 22:00 h, at least one volunteer systematically checked Mallaig's harbour, going from Moorings Guest House to the outer harbour and back by foot (*c.* 2 km, Fig. 2) mainly in the harbour area (indicated by the black line). Additionally, the local community as well as other volunteers were involved in searches in other parts of the village. The local community is informed and reminded every year by posters and advertisements in the local paper about the possibility of grounded Manx Shearwaters.

When a bird was found, it was placed in a bird bag, then transferred to a suitable box and stored safely until the morning. The following day at 10:00 h, rescued birds were ringed and weighed. Manx Shearwaters were then taken on a ferry and released halfway between Mallaig and the Isle of Skye. The birds were released far from land, to avoid predation from Great Black-backed Gulls *Larus marinus* and European Herring Gulls *Larus argentatus*.

Predicting the number of grounded birds per day

To evaluate the influence of different environmental conditions on the number of birds grounded each night, a predictive model was developed using moon illumination, wind conditions and visibility. The total number of grounded birds reported across all of the surveyed area in Mallaig for a specific night was used in this analysis.

The wind, cloud cover and visibility variables for the period in which the birds are susceptible to grounding (month of September) were gathered for the years 2009–14 from the Met Office weather station located in Skye/Lusa (57°15′25.2″N, 5°48′32.4″W, 27.4 km north of Mallaig; Met Office 2006). The hourly data between 22:00 and 01:00 h BST was downloaded, as most of the rescue effort was during those hours. The wind direction was categorized based on the 16 compass directions. For each night, the weather was aggregated to calculate the average wind speed and visibility; for the wind direction, the mode for each night was extracted. In addition to the weather data from the Met Office, we also calculated the hourly moon illumination from the moon percentage derived from the oce R package (Analysis of Oceanographic Data, Kelley & Richards 2016). The value when the moon was below the horizon for the given time period was then set to 0, and when above the horizon, weighted by the cloud cover by multiplying the percentage of visible moon with factor proportional to the cloud coverage (in oktas between 1 for clear sky with no cloud cover and 0.5 for full cloud cover). This hourly weighted moon illumination variable was averaged for the time period and added to the weather data.

To predict the number of grounded birds during the month of September 2009 to 2014, a random forest algorithm was developed as a regression model, using the randomForest package in R (4800 trees; Liaw & Wiener 2002). The number of grounded birds for each night was predicted based on the aggregated weather data, the moon phase and the year. A random variable was also added as a 'noise' term representing the effects of influences not included in the model. By comparing the relative importance of the other variables in the model with this predictor, we could assess how they 'performed' in contrast to the 'noise' term. The accuracy of the model was estimated through a correlation between the observed and the predicted number of grounded birds. The latter was estimated from a random subset of the data that was excluded during the tree building iteration of the random forest ('out of the bag' prediction, Breiman 2001). This process, embedded in the algorithm, allowed us to discard the selection of training and test sets.

RESULTS

The number of grounded Manx Shearwaters varied from year to year and fluctuated within the month

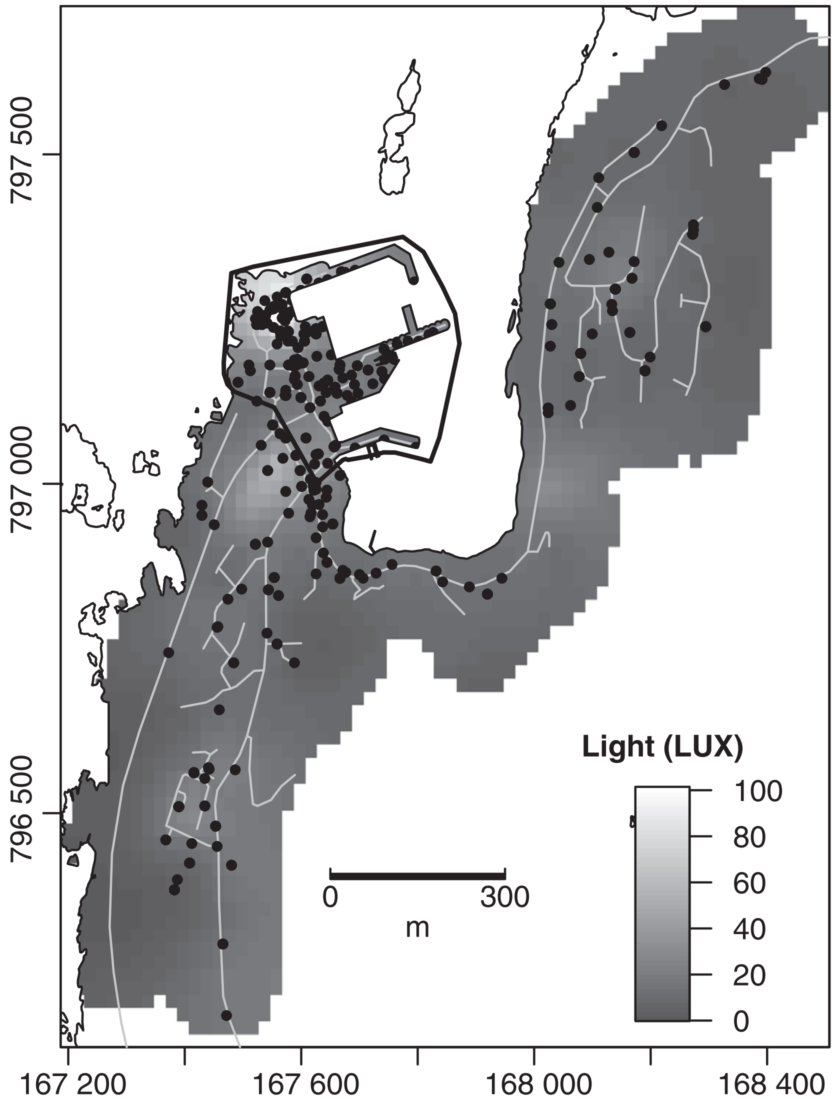

Figure 2. Spatial distribution of the grounded birds in relation to measured and estimated light intensities. The harbour area (delimited by a black line) contained most of the recovered birds. The road network is represented in light grey. The coordinates are in British National Grid panel easting and northing (metres).

(Table 1, Fig. 3a). Of the 1646 birds recorded between 2009 and 2014 included in the model, 45.0% were grounded during September 2012. The lowest fallout happened in 2011 with 4.6% of the total number of observed birds. The other years contained between 11.0% (2014) and 17.4% (2009) of the records. Most of the birds were found alive (92.2%) and were released successfully. Of the 1127 birds with known locations, 69.2% were found in the harbour area (Fig. 2, area indicated by black line), indicating a strong aggregation in that zone.

Predicting the number of grounded birds per day

When predicting the number of grounded birds in relation to the weather and moon cycle, the random forest algorithm explained 46.32% of the variance (with a mean squared residual = 197.71). Figure 4a represents the contribution of the different variables to the model; the year, the weighted moon percentage, the wind direction and the visibility all contributed more to the model compared

Table 1. Summary of numbers of grounded Manx Shearwaters each year between 2009 and 2014, showing the total number of birds ('Total') and birds that were found dead or that died before release due to an injury ('Dead'). 'Retraps' indicate the number of birds that were attracted to the light twice – they were ringed in Mallaig and came back after release.

Year	Total	Dead	Retraps
2009	287	29	0
2010	173	21	0
2011	75	9	0
2012	741	37	3
2013	189	20	0
2014	181	12	2
All years	1646	128	5

with the random noise variable. Other climatic variables were tested (temperature, rainfall, atmospheric pressure) but they did not lead to an increase in model performance or made lower contributions compared with the random variable. Figure 4b represents the significant relation between the observed and the predicted number of groundings ($F_{1,178} = 192.1$, $P < 0.01$), although the model tended to underestimate the number of groundings. Figure 5 represents the partial dependence plots for the different variables. These plots confirmed the exceptional number of groundings for 2012 and how low moon illumination and strong westerly winds increased the probability of groundings. To a lesser extent, both low and high visibility conditions contributed to a higher probability of groundings.

DISCUSSION

Difference between years, caused by the exceptionally high number of groundings in 2012, was the most important correlate of the variation in number of Manx Shearwater groundings in Mallaig. We also showed that the new moon and strong onshore winds were associated with an increase in probability of groundings. To a lesser extent, visibility conditions were also related to grounding probabilities. Our model, however, predicted just under half of the variance (46.32%) in the data, which might be due to other factors influencing grounding probabilities that were considered in our model or, more likely, to the coarse time resolution of the data.

We found that the grounding probability of Manx Shearwaters in Mallaig is best explained by differences between years, with a higher number of groundings in 2012 than in other years. Unfortunately, the population of Manx Shearwater on Rum and other nearby islands lacks yearly data on demography. However, the average productivity from colonies in Rum did not show statistically significant variations between 1986 and 2015 (JNCC 2016). The colony of Manx Shearwaters on Rum is 27 km away from Mallaig, and light pollution does not affect a high proportion of fledglings (maximum 741 grounded fledglings out of up to 76 000 fledglings, Murray *et al.* 2003, Table 1). Therefore, small variations in the number of fledged Manx Shearwaters on Rum are unlikely to have a strong influence on the numbers of grounded birds in Mallaig. Although during the fallout in 2012, moon phase and weather conditions tended to increase groundings (see below), the exceptionally high number of groundings that year is not completely explained by these environmental variables alone, as demonstrated by the high contribution of year in the model. This indicates that in addition to possible effects from population fluctuations, there may be other factors that were not included in the study, such as the concentration of food in the waters around Mallaig or attraction by sound (as suggested in Miles *et al.* 2010), or other factors not measured.

This study also found that variation in the number of grounded fledglings in Mallaig was related to the moon phase; in moonlit nights the number of grounded birds decreased. The same pattern has been observed by several other studies focusing on shearwaters and petrels (Imber 1975, Reed *et al.* 1985, Telfer *et al.* 1987, Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009, Miles *et al.* 2010, Rodríguez *et al.* 2014). The reason for the moon influence was explained by the fact that a greater ambient light from the moon may cause a diminution of attraction to artificial light (Reed *et al.* 1985). Nevertheless, Le Corre *et al.* (2002) observed that grounded seabirds had longer wingspans and were lighter when the fledging period coincided with the full moon. This suggested the young seabirds stayed longer in their burrows because the full moon inhibits them from fledging. It is possible that both factors, the decreased activity of fledging, as well as the reduced attraction to the light, causes fewer groundings during the full moon. Further studies are needed to quantify the influence of each of these factors.

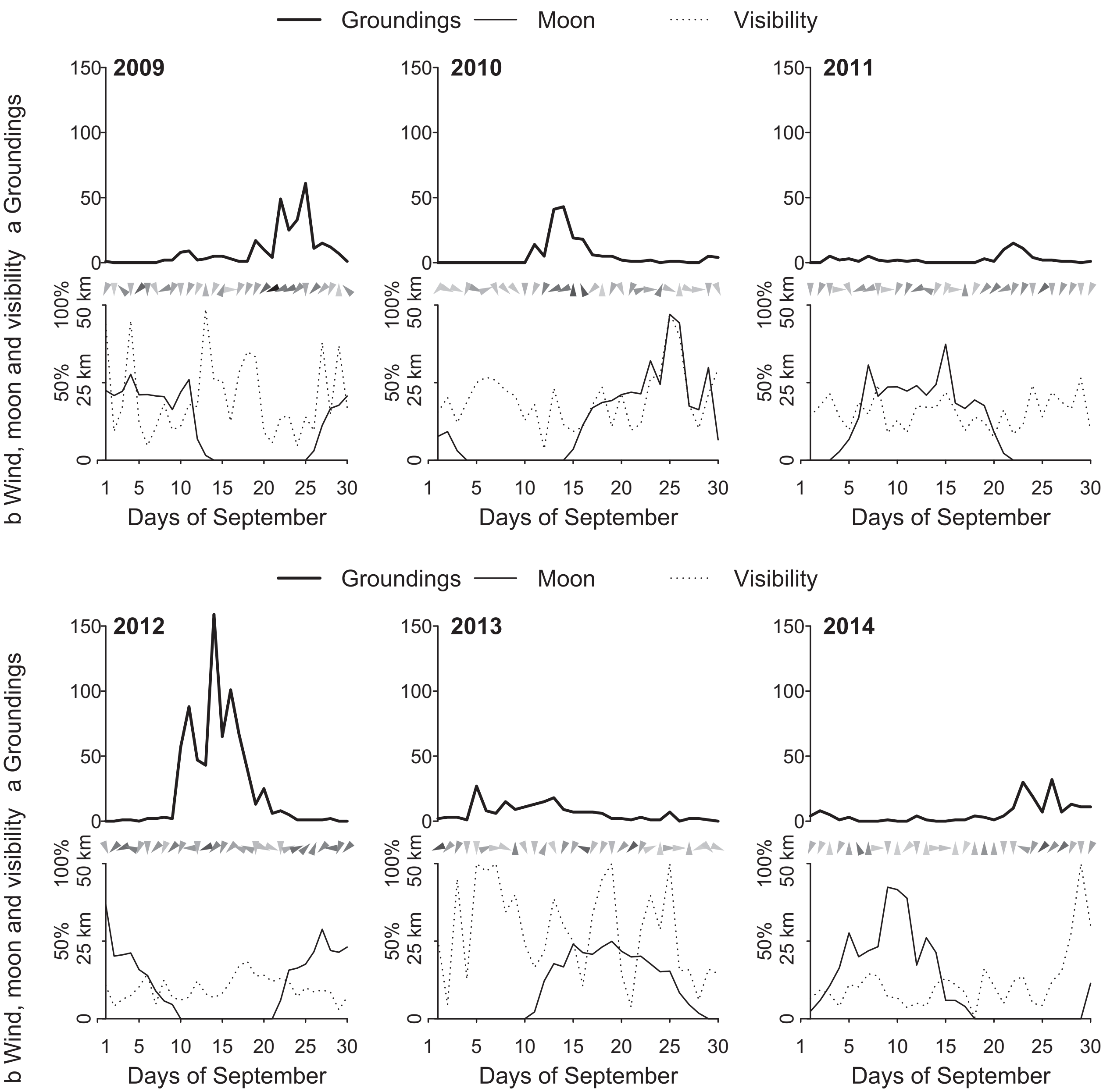

Figure 3. Daily distribution of the number of grounded birds (a, thick black line), wind (arrows), weighted moon illumination (b, thin black line) and visibility conditions (b, dotted line) between 2009 and 2014. The arrows represent the direction of the wind and darker arrows indicate stronger winds.

In addition to the influence of the moon and an important year effect, other climatic variables showed a strong effect when predicting the number of groundings. Onshore winds and strong winds contributed to higher probabilities of bird grounding. Extremes in visibility (high and low) also moderately increased the risk of grounding. Weather conditions can change very quickly during the 4-h window considered in this study. Aggregating the weather variables over the night means that some of the fine temporal scale changes were lost. In addition, it is difficult to match some short-term weather patterns with a specific bird grounding, as there may be a delay of several hours to even a few days between the moment when a bird was grounded and when it

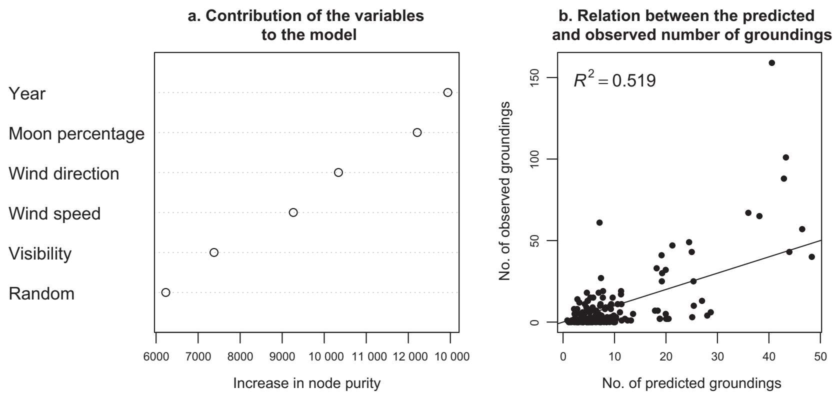

Figure 4. (a) Ranked importance of the different variables in the contribution of the prediction model for the number of bird groundings. (b) Correlation between the observed and predicted number of groundings.

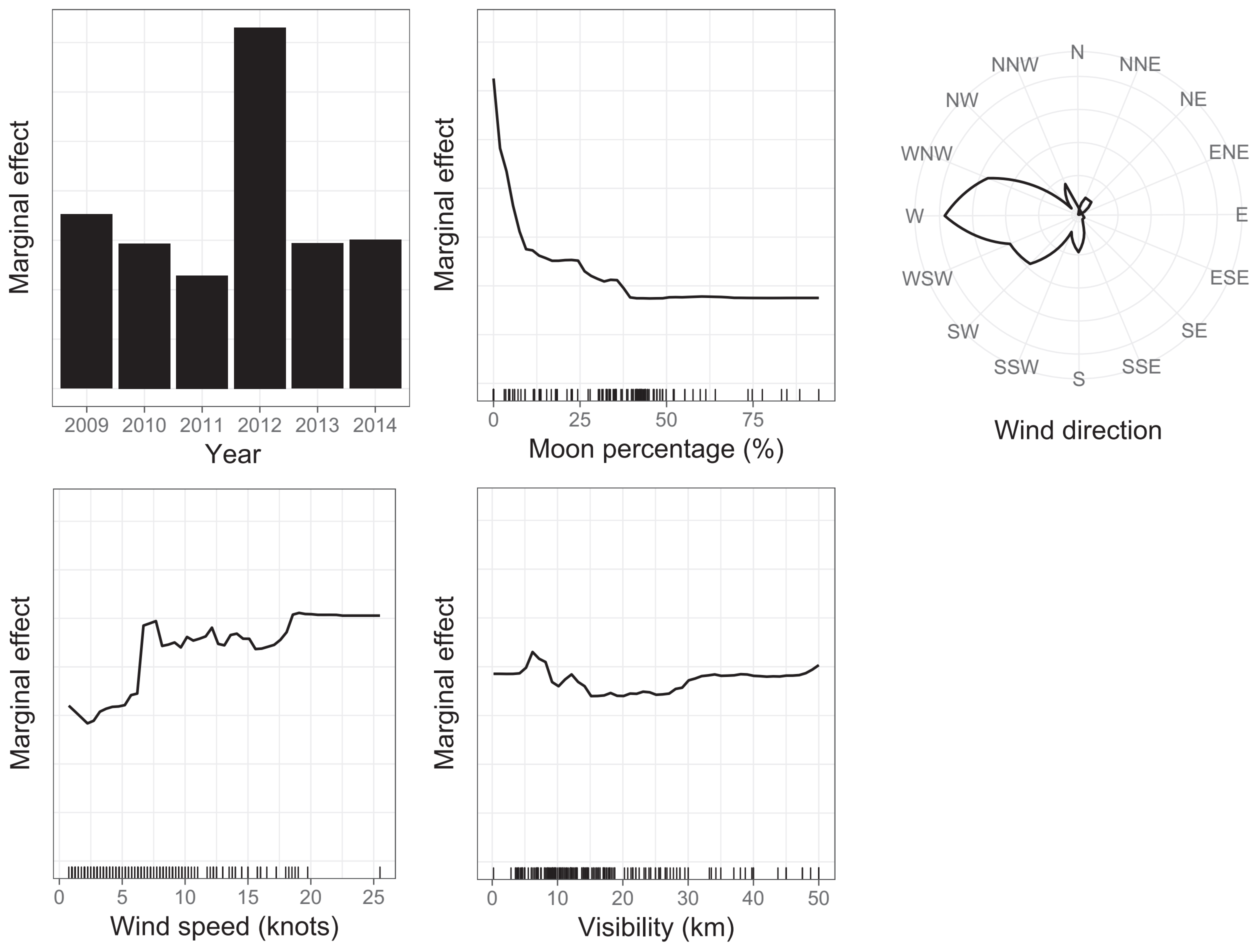

Figure 5. Partial dependence plots for the main variables contributing to the model illustrating the effect of the predictor variables on the fluctuations of the probability of bird grounding. On the polar plot for the wind direction (top right), the delimited area indicates the contribution of each wind direction to grounding probability.

was spotted and recovered (Rodríguez *et al.* 2012b, 2015). Similarly, there may be some delays between a change in weather pattern and a peak in groundings; these delayed effects are difficult to include in the model. The quantity of grounded birds is also influenced by the number of fledging birds and therefore more favourable weather conditions for fledging can cause higher numbers of groundings. The other main limitation of the model is related to multicollinearity, where some weather variables might be correlated, causing us to underestimate their individual effects.

The current study found a similar association between wind direction and grounding as the study of Rodríguez *et al.* (2014); the number of grounded Short-tailed Shearwaters *Ardenna tenuirostris* in that study was higher, with winds blowing from the colony to the artificial light pollution. It was suggested that birds might be blown away from the colony onto the roads. In other studies the breeding colonies were situated all around the coast or inland (Le Corre *et al.* 2002, Troy *et al.* 2011, Rodríguez *et al.* 2012a) and in these conditions it would be hard to test the effect that the wind direction has on groundings. The location of the Manx Shearwaters colony in Rum is to the west of Mallaig and the current finding confirms that strong winds blowing towards the source of light pollution causes the largest number of groundings. Rodríguez *et al.* (2014) found that the wind speed also had a positive influence on the risk of grounding, possibly because Short-tailed Shearwaters on flat Phillip Island, southern Australia, needed a gust of wind to facilitate their first flight. In our study area, westerly winds tended to be stronger than winds from other directions (average of 9.2 vs. 4.6 knots), indicating that low pressure weather systems might combine wind speed and direction effects leading to a higher risk of grounding. The burrows of Manx Shearwaters are situated on steep mountains (Mitchell *et al.* 2004) that allow birds an easier take-off. Thus, it is likely that the higher number of grounded birds during a strong westerly wind can be explained by inexperienced fledglings being blown in the direction of the light pollution in Mallaig.

An increase in the number of groundings can be expected when there are adverse weather conditions and cloudy, rainy nights (Phillips & Lee 1966, Telfer *et al.* 1987). This is possibly caused by increased light pollution due to rain, mist and clouds (Day *et al.* 2003). Nevertheless, a recent study by Wilhelm *et al.* (2013) did not detect any evidence for visibility influencing the fallout of Atlantic Puffin *Fratercula arctica*. This can be explained by the fact that more birds start their migration with clear sky conditions (Hüppop & Hilgerloh 2012). Our study confirmed both these trends presented in research by Phillips and Lee (1966) and Hüppop and Hilgerloh (2012), with slight increases in predicted grounding when the visibility was either low or high. Poor visibility was associated with strong westerly winds that were likely to disorientate and push the birds toward Mallaig. This is consistent with data obtained in this research, as it was found that visibility did not strongly contribute to the predictive model of the Manx Shearwater groundings.

Our study confirmed that more birds were grounded in nights with less moonlight (Reed *et al.* 1985, Telfer *et al.* 1987, Le Corre *et al.* 2002, Rodríguez & Rodríguez 2009, Miles *et al.* 2010, Rodríguez *et al.* 2014) and in nights with strong westerly winds (Rodríguez *et al.* 2014), showing that birds may be blown from their colony in the direction of the light pollution. Low and high visibility conditions also contributed to higher grounding probabilities. Thanks to these findings, rescue campaigns could focus their efforts on nights when the risk of groundings is highest or could inform local authorities under which conditions light intensity needs to be reduced.

We are deeply thankful to the communities of Mallaig, Morar and Arisaig, who kindly helped rescue Manx Shearwaters, and especially Victor Cruden, Sandy Maclaren, the local police and Steve MacDonald and family. We would also like to acknowledge Marine Harvest for their support, and the ferry company, Caladonian MacBrayne, who allowed us to release Manx Shearwaters from their ferry. We thank N. Harrison, P. Brown and S. Mowles for constructive comments on the manuscript and Anglia Ruskin University for its support.

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Received 13 April 2017;
revision accepted 20 February 2018.
Associate Editor: Lorien Pichegru.