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The risk of rodent introductions from shipwrecks to seabirds on Aleutian and Bering Sea islands

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Abstract Accidental introductions of rodents present one of the greatest threats to indigenous island biota, especially seabirds. On uninhabited remote islands, such introductions are likely to come from shipwrecks. Here we use a comprehensive database of shipwrecks in Western Alaska to model the frequency of shipwrecks per Aleutian and Bering Sea island, taken as a proxy for the threat of rodent introductions, using physical variables, and the intensity of nearby fishing traffic and activity as predictors. Using data spanning from 1950 to 2013, we found that shipwrecks were particularly common in the 1980s to early 2000s, with a major peak in wrecks during the late 1980s. Amount of fishing activity within 5 km of an island was the strongest predictor of shipwrecks, followed by the strength of tidal currents and density of large-vessel traffic. Islands with the highest frequency of shipwrecks are all in the eastern Aleutians, including Unimak, Unalaska, and Akun Islands. By contrast, the largest seabird colonies are in the western Aleutian and Pribilof Islands, including Buldir, Kiska, and Saint George islands. Multiplying the frequency of a shipwreck by the number of seabirds breeding per island provides a measure of risk. The risk of rodent introductions from shipwrecks to seabirds was then greatest for Saint George (Bering Sea), Buldir (Western Aleutians) and Saint Matthew islands (Bering Sea). Keeping these high-risk islands rodent free would maintain their high a conservation value. Most islands with a high predicted frequency of shipwrecks already have established rodent populations and therefore few remaining seabirds. Of those islands

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with established rodent populations, Attu and Kiska Islands would make suitable targets for eradication, given their relatively low expected frequency of shipwrecks for their size. Further improvements in rat prevention on vessels and shipping safety would benefit the economy, human health and safety, and to the long-term conservation of island ecosystems.

Keywords Invasive species · Island conservation · Shipping traffic

Introduction

The introduction of invasive species, especially into island ecosystems, has been the greatest contributor to the documented loss of global biodiversity, being implicated in 51% of all historical extinctions with identifiable causes (Clavero and García-Berthou 2005). Introduced rodents, especially rats (*Rattus* spp.) are of particular concern because they have been associated with declines or extinctions of a large number of indigenous vertebrates, especially seabirds (Towns et al. 2006; Jones et al. 2008). Globally, rats have been implicated in the extinctions of more island bird species than any other non-indigenous species (King 1980).

Once established, the impact of rodents on an island ecosystem can last for millennia (Martin et al. 2000). Until the 1980s, it was deemed impossible to remove rodents, once established on an island (Stolzenburg 2012). However, using advanced rodenticides and broadcast techniques, islands up to a size of 113 km^2 have now been cleared of rats (Campbell Island, New Zealand; McClelland 2011). Although the technical feasibility of rodent eradication has progressed to much larger islands and islands inhabited by humans (Oppel et al. 2011), these actions remain expensive, are not guaranteed to be successful, may result in environmental contamination, and are often controversial (Bremner and Park 2007; Salmon 2010; Buckelew et al. 2011; Veitch et al. 2011; Borell 2011). The identification of locations vulnerable to rodent introductions, along with efforts to prevent introductions at these locations offers a much more cost-effective alternative to eradications, and should be a top priority in island conservation (Sowls 2000).

The Aleutian Archipelago is a chain of volcanic islands, subject to a subarctic climate with seasonal snow-cover down to sea-level (Fig. 1). Native land mammals are absent, except in the easternmost islands, which were connected to the mainland during the last glacial period. By contrast, the islands farther north in the Bering Sea are on a large continental shelf, which was connected to the mainland during the Pleistocene ice-ages (Mandryk et al. 2001). Native populations of small mammals (lemmings, voles) on these islands are thought to be relicts from the Pleistocene (Weksler et al. 2010). Islands in the Aleutian Archipelago and Bering Sea support a rich diversity of seabirds, in numbers unrivaled elsewhere in the Northern Hemisphere (Stephensen and Irons 2003; Byrd et al. 2005).

Hawadax Island, formerly known as Rat Island, is situated in the Rat Island Group of the Aleutian Archipelago and became infested with brown rats (*Rattus norvegicus*) when a Japanese fishing vessel wrecked on the island in 1780 (Ebbert and Byrd 2002). Rats were finally eradicated from the island in 2008, more than two centuries after their original introduction (Borell 2011). Little is known about the circumstances leading to the establishment of invasive rodent populations on other islands in the Aleutian chain, shipwrecks being one out of several causes. Military activities of World War II and the Cold War resulted in

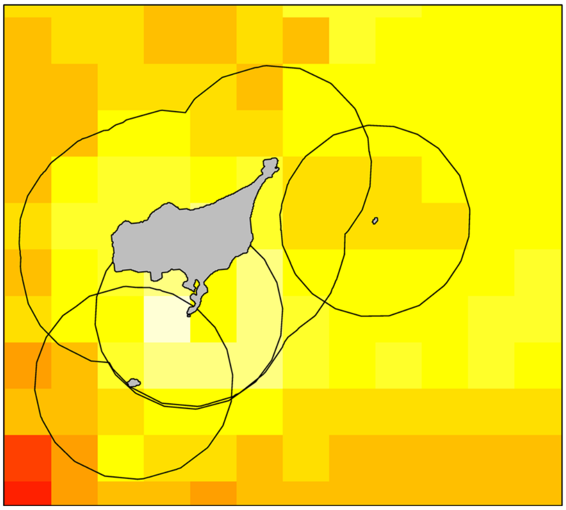

Fig. 1 Saint Paul Island with 10 km buffer, illustrating method of associating raster data with a specific island. The average raster value (here tidal currents) within the buffer was used to link raster layers to islands

numerous shipwrecks, new harbors, and extensive resettlements. Any of these activities were likely factors in the introduction of rodents to numerous islands. Within the Aleutian Archipelago, at least 16 islands have introduced rodent populations (Gotthardt et al. 2016), including every island with a port. Remarkably, the Pribilof Islands of Saint Paul and Saint George, in the Bering Sea, have remained rat-free, despite the presence of port facilities. Rats have been trapped on these islands on several occasions, but evidently no population has yet become established (Sowls 2000).

Seabirds are a dominant feature of the Aleutian ecosystem and perform key ecosystem functions (Croll et al. 2005), vulnerable to invasive mammals, and well surveyed throughout the Aleutian Archipelago. All these factors make seabirds a particularly well suited subject for a risk assessment. Here we quantified the risk from accidental rodent introduction posed to seabirds in the Aleutian Archipelago and Bering Sea islands through shipwrecks. We built a statistical model of the expected frequency of shipwrecks per island. We assigned the greatest risk to islands that harbored a large population of vulnerable seabird species combined with a large expected frequency of shipwrecks, which could lead to the introduction of rodents.

Rats are capable of swimming over considerable distances over open water, with distances of 0.5–2 km documented, depending on the species (Russell and Cloud 2005). An introduction of rodents to an island can therefore affect not only the original island, but also other nearby islands that are within swimming distance, even in cold waters (Tabak et al. 2015).

Our objective was to predict the frequency of shipwrecks per island per 100 years, based on the number of historic shipwrecks and a number of suitable predictive variables, in particular nearby density of small-vessel traffic in the Aleutian Archipelago and Bering Sea islands. We used the concept of “risk” as the likelihood of an incident times the severity of the impact of an incident, measured in the number of birds affected. The greatest risk was then on islands that combined a high expected frequency of shipwrecks that could lead to the introduction of rodents, with a large population of breeding seabirds. This quantitative model of the expected frequency of shipwrecks is also useful when prioritizing islands for eradications of existing rodent populations, by providing a ranking for the probability of reinvasion.

Methods

Data sources

We extracted location and sizes of seabird colonies from the Beringian Seabird Colony Catalog (Stephensen and Irons 2003) with the modifications applied in Byrd et al. (2005). Locations and histories of shipwrecks: we collected and verified data from newspapers, online sources, the Bureau of Ocean Energy Management (BOEM, http://www.boem.gov/Alaska-Coast-Shipwrecks/), as well as collecting and verifying records directly in the field since 1989 by E.N., covering much of the Alaska, while working aboard the U.S. Fish and Wildlife Service vessel M/V Tiĝlax̂. We included shipwrecks from 1950 to 2013, thereby excluding any wrecks associated with World War II, yielding 63 years of exposure.

Predictive variables used to model shipwrecks are summarized in Table 1. These variables fall into three categories: (1) related to the size and shape of the island, (2) physical environment around the island (wind, tides), (3) vessel traffic. We used several different measures of vessel traffic, three being measures of fishing traffic and activity, one being a measure of large vessel traffic. This inevitably led to some overlap, however each of them also has unique properties. Since all of these measures of vessel traffic in the region are quite new, we did not want to make an a priori decision about which might be the most suitable.

We used satellite-based Automatic Identification System (AIS) data purchased from exactEarth for the three-year period extending from 10 July 2010 to 31 August 2013 (see Robards et al. 2016 for discussion of AIS). We created line features—“voyages”—from individual vessel locations, and identified vessel type of each ship from their MMSI (Maritime Mobile Service Identity) number. We used ship registry data from the IHS Fairplay (IHS) maritime master ships database to cross-reference MMSIs in our AIS data with a consistent series of ship classifications. The IHS data broadly includes vessels subject to IMO Resolution A.600(15)—every vessel that is sea-going merchant and of 100 gross tons and above must carry a

Table 1 Data sources and predictor variables used for modeling probability of a ship wreck per island (see text for more details)

Abbreviation	Variable	Radius (km)	Source
AIS_5	AIS vessel traffic of fishing vessels	5	ABSI, USFWS, Anchorage, AK
AIS_10		10	
AIS_20		20	
AIS_50		50	
AIS_100		100	
bathy_10	Bathymetry	10	https://www.afsc.noaa.gov/RACE/groundfish/bathymetry/Aleutians.htm
bathy_20		20	
bathy_50		50	
bathy_100		100	
coastCon	Coastline convolution index		Length coastline/area of island
coastline	Length of coastline		https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html
fishland_5	Observed fish landings	5	NOAA observer program
fishland_10		10	
fishland_20		20	
fishland_50		50	
fishland_100		100	
inhabited	Presence of permanent human habitation		http://www.census.gov/geo/www/gazetteer/gazetteer2010.html
M2tideV_5	Amplitude of M2 tide	5	http://volkov.oce.orst.edu/tides/otis.html
M2tideV_10		10	
M2tideV_100		100	
vms_5	Vessel monitoring system of fishing vessels	5	NOAA
vms_10		10	
vms_20		20	
vos_5	Voluntary observer system, index of large-vessel traffic	5	http://www.vos.noaa.gov
vos_10		10	
vos_20		20	
vos_100		100	
wind_5		5	Climatology of Ocean Winds (SCOW) http://cioss.coas.oregonstate.edu/scow/
wind_50		50	
wind_100		100	

Class-A AIS system. To convert the sometimes widely spaced positions into a high-resolution density grid, we went through the following procedure. We constructed ESRI shapefiles of line features for the primary vessel types and ran these through the Line Density function in ArcGIS 10.1 with an output cell size of 0.5 km and a search radius of 5 km. The algorithm computes the centroid of each pixel, buffers that point with a given radius (5 km), intersects that circular buffer with the lines layer, calculates the length of each of the lines passing through the buffer and sums those lengths and finally divides the summed line lengths value by the area of the circle.

Vessel monitoring systems (VMS) transmit a vessel's location, via satellite, at fixed time intervals. Our dataset includes an average of 418 vessels per year (633 total) in the Bering Sea, Aleutian Islands, and the Gulf of Alaska that transmitted VMS data (typically twice per hour) from 2005 to 2014. Originally implemented to enforce Steller sea lion conservation measures, VMS requirements in Alaska are based on the location and type of permit fished by a vessel, including all vessels targeting walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), Atka mackerel (*Pleurogrammus monopterygius*), and crab (multiple species). Some vessels targeting rockfish and sablefish (*Anoplopoma fimbria*) were also required to maintain a VMS during our study period but virtually all fishing vessels operating in the Aleutian Archipelago had VMS (for details of VMS coverage during 2010, see (www.npfmc.org/wp-content/PDFdocuments/conservation_issues/VMSdiscussionPaper312.pdf). For a more technical description of the VMS data, including transmission errors, see Watson and Haynie (2016).

Groundfish observer data collected by NOAA is available at http://www.afsc.noaa.gov/FMA/spatial_data.htm. Some vessel categories have only partial observer coverage (e.g. less than 46 feet length over all), and confidentiality requirements stipulate that grid-cells with less than 3 hauls be excluded. We used the number of hauls per grid cell, averaged over the a year, as a measure for local fishing effort.

The previous three datasets all concerned fishing vessels. These are the most numerous vessels within the study region, are probably also more likely to be run aground due to operating closer to shore, and we speculate that these may also be more likely to have rats onboard than large tankers, container and similar vessels. Nevertheless, large vessels also have accidents and we therefore wanted to include them in this analysis. To map the distribution and intensity of shipping traffic from large vessels, we used positions from the Voluntary Observing Ship Program (VOS), available from NOAA (http://www.vos.noaa.gov). This program collects meteorological data four or more times a day from participating vessels, to improve marine weather forecasts. The program is designed for large ocean-going vessels, including, but not limited to tankers, bulk carriers, container vessels, tugs, research vessels and ferries. We used all available vessel location data from January 2001 to July 2013. Since vessels made reports at varying intervals, we used linear interpolations of positions of the same vessel to estimate hourly positions, reducing bias from vessels that reported frequently. After cutting out interpolated positions that fall onto land, we used a Gaussian kernel-density estimator with optimized bandwidth to turn positions into a density surface. For more details see Renner and Kuletz (2015).

Physical parameters, like size and shape of an island, strength of tidal currents, and depth may also contribute the likelihood of a shipwreck. We used the high-resolution coastline available from the GSSH project (Wessel and Smith 1996, https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html). To avoid scale-dependence issues with the length of the coastline of individual islands, we calculated the length of convex hulls around each island. An index of the convolution was calculated from the square-root of the area of each island divided by the length of its coastline. Bathymetry information was provided by the Alaska Fisheries Science Center, NOAA. We used the model by Egbert and Erofeeva (2002, http://volkov.oce.orst.edu/tides/region.html) as a measure of the strength of tidal currents. Average wind speeds were taken from a remote-sensing dataset (http://cioss.coas.oregonstate.edu/scow/).

Analysis

We predicted the frequency of shipwrecks per island using a random forest model (Breiman 2001; Cutler et al. 2007; Marmion et al. 2009), using 30 predictive variables at different spatial scales (Table 1). Random forest models are ensembles of regression tree models and as such do not make assumption about an underlying statistical distribution. Initially, we used averages of each spatial variable within 5, 10, 20, 50, and 100 km of the coastline of each island (Fig. 1). For each of these variables, we pre-selected the spatial scales that had the strongest Pearson correlations with the number of shipwrecks. We built a Random Forest model from 10,000 trees. Estimated rates of shipwrecks over 63 years were extrapolated to wrecks per 100 years to have an ecologically meaningful time scale. Confidence-intervals were estimated from the out-of-bag samples.

We follow the common definition of risk as the product of the likelihood and severity of an incident (Michel et al. 2009). Assuming the frequency of rodent introduction to be correlated with the predicted frequency of shipwrecks, we calculated the relative risk to seabirds from rodent introduction per island as the product of the predicted frequency of shipwrecks and the total number of nesting seabirds.

Not all seabird species are equally vulnerable to predation by introduced rodents (Jones et al. 2008). While even large seabird species are preyed upon by rats and mice (Kepler 1967; Wanless et al. 2007), some species are able to persist on islands with rats present. For an alternative assessment, we calculated risk only for the most vulnerable species, those that are unlikely to persist in the presence of rats. As an indicator of which species are able to persist in the presence of introduced rodents, we compared the seabird species breeding on two species-rich islands that have always been free of introduced mammals (Buldir and Chagulak Islands) with the species breeding on two large, nearby islands which have introduced rats and formerly Arctic Fox (*Vulpes lagopus*, Kiska and Adak Islands). These were mostly crevice and burrow nesters, but also a couple of cliff nesters (Table 2). We used species restricted to the pristine islands to calculate risk to the most vulnerable species by summing up the total number of these most vulnerable species per island and multiplying by the expected frequency of shipwrecks. Least (*Aethia pusilla*) and Crested Auklets (*A. cristatella*) persist on Kiska, despite the presence of rats. This is a special situation unique to Kiska (Major et al. 2013). We still consider these two auklets as vulnerable species, because they do not coexist anywhere else with rats.

Gotthardt et al. (2016) recently compiled the available information on existing introduced species in the Aleutian Archipelago and Bering Sea islands. For islands already hosting invasive rodent populations, we calculated the ratio of expected frequency of shipwrecks to island area. All else being equal, this ratio, along with the potential of self-introduction of rats by swimming to an island, would serve as a measure of the suitability of these islands for a rodent eradication program. All calculations were performed in R (R Development Core Team 2016), with package randomForest (Liaw and Wiener 2002) for the modeling.

Results

The frequency of shipwrecks over time within the study area has passed through several phases (Fig. 2). From the 1950s to the 1970s, wrecks occurred at comparatively low rate of 2–4 wrecks per 5-year period, including a remarkable stretch from 1972 to 1979 without any wrecks. This low rate was followed by a spike in wrecks during the 1980s, peaking at 20 wrecks per 5 years in the late 1980s and remained at a high level during the 1990s and early 2000s, compared to the pre-1980 period.

Predictive variables at the smallest small spatial scales, within distances of 5–10 km were most important in the Random Forest model of shipwreck frequency (Fig. 3). The most predictive variable was the average amplitude of the M2 tide within 5 km of an island. Of the different measures of human

Table 2 Most vulnerable seabird species, that are only found on islands free of introduced predators (Buldir and Chagulak Island), but not on nearby islands with established populations of introduced rodents (Kiska, Adak Islands)

Common	Latin	IUCN status
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	Least concern
Leach's storm-petrel	*Oceanodroma leucorhoa*	Least concern
Red-faced Cormorant	*Phalacrocorax urile*	Least concern
Ancient Murrelet	*Synthliboramphus antiquus*	Least concern
Cassin's Auklet	*Ptychoramphus aleuticus*	Least concern
Least Auklet	*Aethia pusilla*	Least concern
Whiskered Auklet	*Aethia pygmaea*	Least concern
Crested Auklet	*Aethia cristatella*	Least concern
Horned Puffin	*Fratercula corniculata*	Least concern
Red-legged Kittiwake	*Rissa brevirostris*	Vulnerable

Crested and Least Auklet also occur on Kiska Island, but are able to persist in spite of introduced rats due to their enormous seasonal population

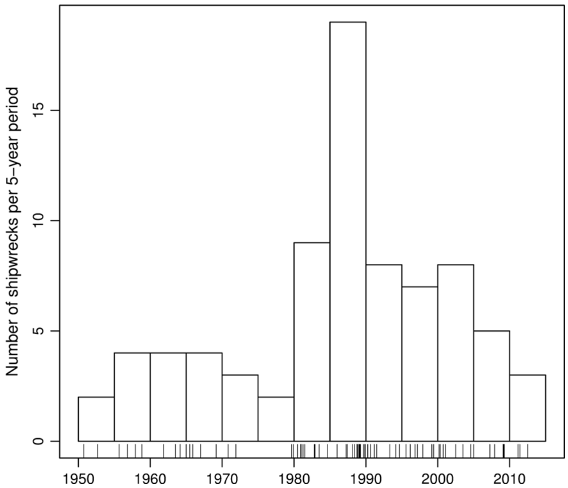

Fig. 2 Frequencies of shipwrecks in the Aleutian/Bering Sea region since 1950 per 5-year period. Note that there is only incomplete coverage for the last period

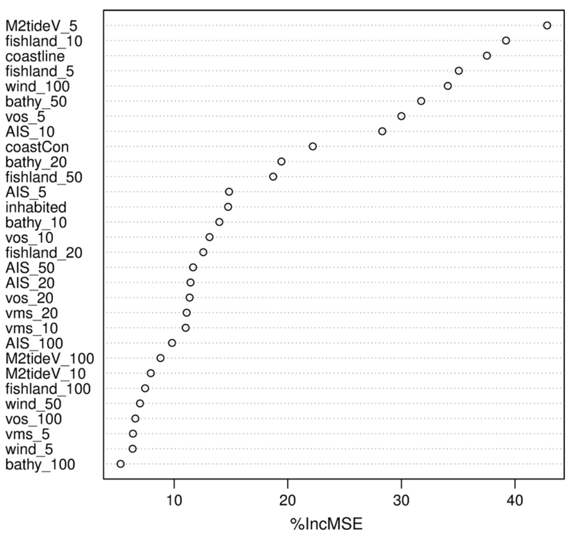

Fig. 3 Variable importance of Random Forest model predicting the expected number of shipwrecks per island. Numbers behind the variable names indicate spatial scales, i.e. distance around and island over which the values of the variable were averaged. Abbreviations used are *M2tideV* amplitude of the M2 tide, *fishland* number of fishing hauls within grid cell, derived from NOAA observer data, *wind* average wind speed, bathy: bathymetry depth. *vos* large-vessel traffic density, *AIS* traffic density of fishing vessels, *CoastCon* convolution index of coastline, *inhabitet* whether or not an island has a permanent human habitation, *vms* vessel monitoring system, a different dataset monitoring distribution of fishing vessels

activities, the number of fishing hauls had the biggest influence (Fig. 3). Length of the coastline (measured as length of the convex hull around the island), average windspeed within 100 km, and average bathymetry depth within 50 km were also important variables.

Predicted frequency of shipwrecks was highest in the eastern Aleutian Islands, whereas highest number of breeding seabirds per island was found in the western Aleutian and Pribilof Islands (Fig. 4). The resultant risk was greatest for Saint George Island in the Pribilofs, an island with high number of individual birds and high number of predicted shipwrecks, followed by Buldir and Saint Matthew Islands (Fig. 5). Many of the islands with a high predicted frequency of shipwrecks had existing rodent populations and therefore did no longer support high numbers of seabirds—with the exception of Kiska Island. Restricting the calculation of risk to only the most vulnerable seabird species, Buldir Island had far greater risk than any other island (Table 3). The random forest model used to predict the frequency of shipwrecks had an estimated $r^2 = 0.34$, and wide confidence intervals indicate moderate uncertainty in the predicted number of shipwrecks.

Comparing the size of islands with established rodent populations to the predicted number of shipwrecks (Table 4), we found that the islands of Attu, Kiska, and Unalaska had a comparatively low expected frequency of shipwrecks in relation to their size. Attu and Kiska have both been uninhabited and therefore appeared particularly suitable for eradication under this scenario. Sedanka and Kagalaska Islands had even greater area to shipwreck ratios, but were within a swimming distance of rats from inhabited islands harboring rat populations.

Discussion

We created a model of the risk of accidental introductions of rodents from shipwrecks to Alaskan island ecosystems, based on existing shipwrecks, physical characteristics of the islands, intensity of fishing and vessel activities nearby, and the natural seabird resources present on the island. Risk was calculated as an index, presumed to be positively correlated to actual risk. We can predict the frequency of shipwrecks, but know little about the process of rodents becoming established on an island in the event of a shipwreck. We do not know the proportion of vessels carrying rodents, or differences in rodent

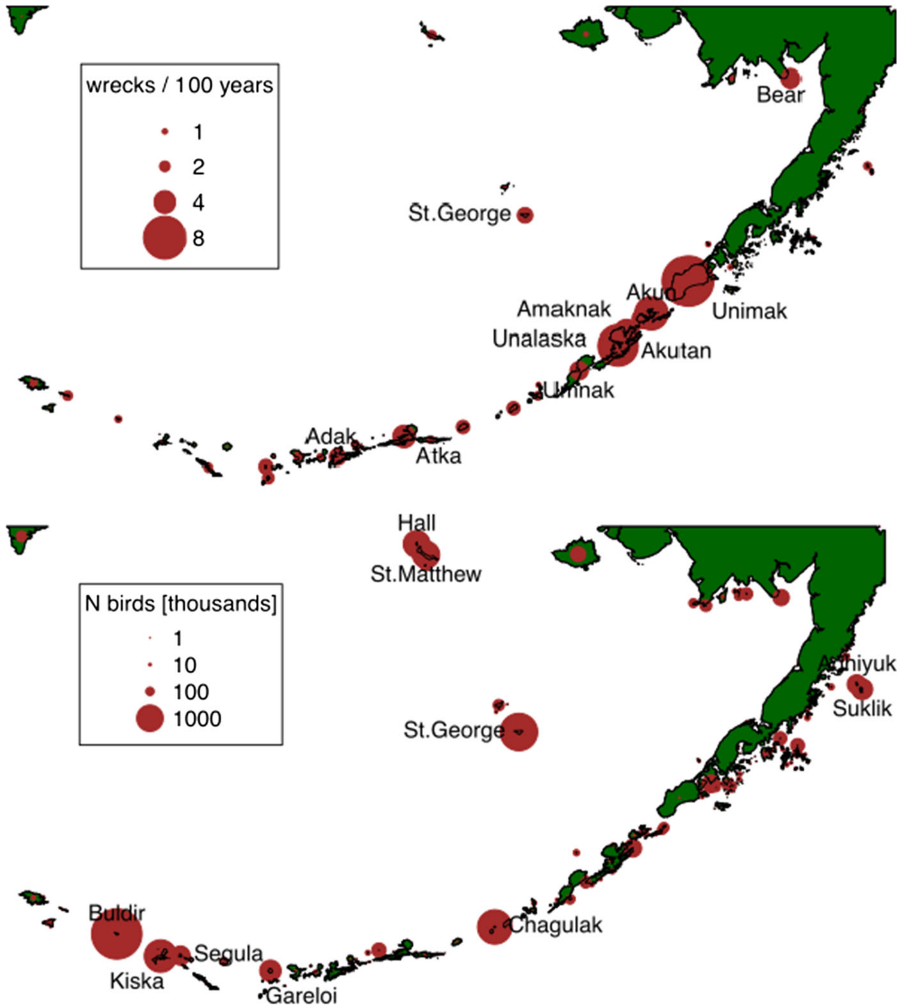

Fig. 4 Modeled frequency of shipwrecks per island (top) and the distribution and size of seabird colonies, according to the Beringian Seabird colony catalog. The islands with the ten highest values are labeled. Note that shipwrecks per island is on a linear, seabirds per island on a quadratic scale

occupancy between different types of vessels. Neither do we know how likely rodents are to make it ashore alive in the event of a wreck, or how likely they are to become established on an Alaskan island once ashore. In New Zealand it has been shown that even from only two founders, a house mouse (*Mus musculus*) population can invade an entire island and reach carrying capacity within less than six months (Nathan et al. 2015).

Still, a remarkably large number of islands have remained free of introduced rodents, despite being located along a major shipping route and fox-farming attempts on virtually all large islands (Bailey and Kaiser 1990). Current and future climate change is likely to affect the impact and likelihood of eradications of introduced species on indigenous island ecosystems (McCreless et al. 2016). Over the recent past, winter temperatures and snow-cover on Aleutian and Bering Sea islands may be near the limit of what rodents can survive away from the protection of human settlements. If that is the case, a warmer climate scenario in the region would increase the chances of survival for a small population of rodents over the winter, making accidental introductions of rodents to the region more likely and eradications more difficult.

The frequency of shipwrecks in the Aleutian Archipelago has declined since its peak in the 1980s. On the other hand, incident rates are still higher than pre 1980s. Whether the effects of improvements in

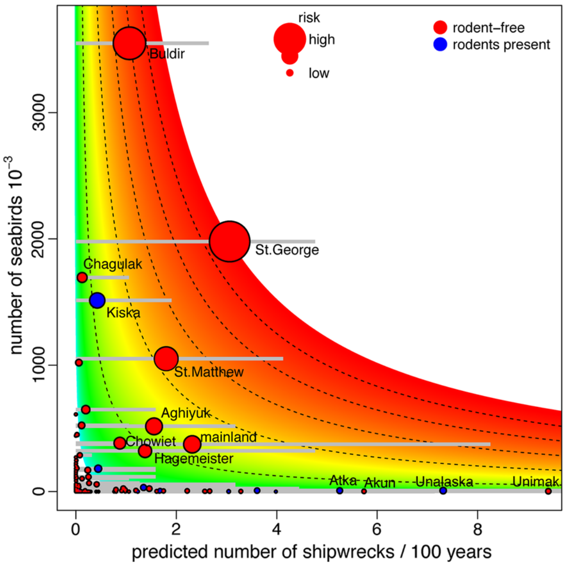

Fig. 5 Risk diagram of rat-spills for islands in the Aleutian/Bering Sea region to seabirds. Risk is the product of the likelihood of an incident × the severity an incident (here number of seabirds affected). The area of the circles is proportional to the risk. Rodent-free islands are shown in red, others in blue. We assume that the likelihood of accidental introductions of rodents is proportional to the frequency of shipwrecks. The gray lines represent 90% confidence intervals for the predicted frequency of shipwrecks. The dashed lines are iso-risk lines. Labeled are the islands with highest risk

shipping technology, fishing regulations, and safety systems will lead to further reductions in shipwrecks, or whether increases in traffic will outweigh those improvements, remains to be seen.

Every shipwreck is different and the causes leading to a wreck are numerous. It is therefore not surprising that with wrecks being relatively rare events on a per-island basis, confidence intervals of the predicted number of wrecks per island are fairly wide. Nevertheless, strong spatial pattern emerged. The islands with the highest predicted frequency of shipwrecks are all in the eastern Aleutian Islands, where vessel traffic is at its densest (Renner and Kuletz 2015; Robards et al. 2016), especially where fishing activities are most intense.

Accidental introductions of rodents, or "rat spills", have a number of similarities and important differences compared to oil spills. The most striking difference may be that oil spills make international news headlines and provide graphic images of dying birds. Rat spills cause less easily observed, long-term damage. Depending on water temperature, most of the immediate effects of an oil spill can last for weeks or months, while some effects may linger on for decades (Rice 2009; Bodkin et al. 2012). The risk of an oil spill to seabirds is therefore greater during seasons of high seabird densities, when large number of birds may be affected, but is less at other times of the year when seabird densities are lower due to the timing of their breeding cycle or migration. The effects of rat spills, on the other hand, are likely to affect breeding seabirds regardless of what time of year the spill occurred, and are likely to persist for centuries, until the unlikely event of a natural extinction or an eradication program is successfully implemented. The case of Hawadax (Rat) Island illustrates that even on an island without human presence and few nesting seabirds, rats can persist for hundreds of years (Ebbert and Byrd 2002). It is also likely that seasonal variation affects the probability of initial invasive species establishment on islands; however, we are unaware of any studies on this matter.

Arguably, the establishment of an invasive rodent population constitutes one of the most serious, long-lasting ecological disasters that can befall an island ecosystem. Fortunately, most islands in the Aleutian Archipelago and Bering Sea remain free of introduced rodents, even though within the Aleutian Islands, every island with a port has now established populations of rats or mice (Ebbert and Byrd 2002). We hope that this work will help raise the awareness for the risk from rat-spills in the Aleutian Archipelago and on Bering Sea islands. We encourage any efforts that will improve biosecurity on vessel, bringing benefits both the economy, human health, and island conservation. Likewise, efforts to further improve shipping safety will convey both economical and ecological benefits. As so often, prevention is more cost-effective than treatment (Ebbert et al. 2007). Our analysis allows prioritization of prevention efforts, e.g., in the form of preplanning responses and local rapid response networks, to allow for an immediate response in the event of a ship-wreck. Finally, our analyses are useful for making recommendations regarding priorities for eradication programs.

Conclusions

The density of near-shore fishing activities was the best predictor of the expected frequency of

Table 3 Frequency of observed and predicted shipwrecks, number of seabirds, and number of most vulnerable seabirds, as well as resultant risk per island

Observed Island	Region	Wrecks	Shipwrecks (N/100 years)	N birds (10^3)	Vul. birds (10^3)	Risk	Risk vul.
St. George	Bering Sea	3	2.92	198	24	5,770,000	694,000
Buldir	Western AI	1	1.31	355	307	4,640,000	4,010,000
St. Matthew	Bering Sea	1	1.49	105	15	1,570,000	227,000
Bear	Bering Sea	0	3.53	38	1	1,330,000	40,600
Kiska	Western AI	0	0.52	151	2	789,000	10,100
Aghiyuk	Bering Sea	1	1.51	52	5	781,000	70,700
Chowiet	Bering Sea	1	0.87	38	15	332,000	126,000
Chagulak	Central AI	0	0.17	170	166	293,000	286,000
Arwirnuk Rock	Bering Sea	0	0.87	32	1	281,000	9690
Gareloi	Western AI	0	0.33	65	6	213,000	19,300
St.Paul	Bering Sea	0	0.62	18	4	113,000	25,300
Unalaska	Eastern AI	5	7.56	1	1	61,800	42,700
Attu	Western AI	1	1.46	3	1	47,800	18,000
Segula	Western AI	0	0.08	52	0	39,400	205
unnamed	Bering Sea	0	0.19	17	13	33,000	24,300
Atka	Central AI	2	4.25	1	1	32,800	27,700
Akutan	Eastern AI	2	3.76	1	0	31,800	14,600
Unimak	Eastern AI	9	9.41	0	0	30,800	339
Koniuji	Central AI	0	0.11	29	28	30,800	30,000
Akun	Eastern AI	5	6.3	0	0	13,000	5330
Delarof	Western AI	2	2.21	1	1	12,800	11,500
Seguam	Central AI	2	2.53	0	0	10,300	3670
Tanaga	Central AI	1	1.7	1	0	8790	7070
Umnak	Eastern AI	3	3.42	0	0	7210	7070
Yunaska	Eastern AI	2	2.5	0	0	7110	6500
Hall	Bering Sea	0	0.01	102	24	6460	1510
Unalga	Western AI	3	2.6	0	0	4250	2160
Adak	Central AI	2	3.13	0	0	4110	0
Amagat	Eastern AI	0	0.01	45	44	3480	3400
Shemya	Western AI	2	1.83	0	0	1890	165
Egg	Eastern AI	0	0	44	44	897	892
Suklik	Bering Sea	0	0	61	54	233	206
Amaknak	Eastern AI	4	4.73	0	0	184	94.6

Of 1376 islands, we only show the highest 1% for shipwreck frequency, seabird numbers, and relative risk: *shipwrecks* × *birds*. Risk was rounded to three significant digits

shipwrecks. Combining this model with seabird colony counts on rodent-free islands, we find that the islands of Saint George and Buldir, with their large seabird colonies and large volume of nearby shipping traffic, are at greatest risk from accidental rodent introductions. Preventative management action would represent an efficient conservation action.

Table 4 Suitability of islands hosting invasive rodent species for eradication, based on area and predicted frequency of shipwrecks over 100 years

Island	Area (km^2)	Shipwrecks	Area:shipwrecks	Inhabited
Sedanka	110.1	0.03	3339	No
Kagalaska	120.2	0.05	2649	No
Little Kiska	8.8	0.01	758	No
Attu	901.4	1.46	616	No
Kiska	285.7	0.52	548	No
Unalaska	2790.6	7.56	369	yes
Atka	1060.2	4.25	249	Yes
Adak	732.3	3.13	234	Yes
Amchitka	311.1	1.6	194	No
St.Paul	110.1	0.62	178	Yes
Great Sitkin	157.5	1.41	112	No
Akutan	333.9	3.76	89	Yes
Shemya	15.5	1.83	8	Yes
Amaknak	10.7	4.73	2	No

Inhabited islands pose additional challenges to eradication programs. Sedanka and Kagalaska Islands are all in close proximity to larger, inhabited islands harboring rats (Unalaska and Adak, respectively), leaving Little Kiska, Attu, and Kiska islands as the islands with the biggest area to shipwreck ratio that are not inhabited by people

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