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Estimating the extent of seabird egg depredation by introduced Common Mynas on Ascension Island in the South Atlantic

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Abstract

Common Mynas *Acridotheres tristis* were introduced to the small, isolated barren island of Ascension in the tropical Atlantic Ocean in the 1880s. The founder population of 52 pairs increased at a rate of 2% per annum. Mynas cause egg losses in other species by puncturing and consuming eggs, puncturing eggs with no consumption or displacing incubating birds that then desert viable eggs. The principal target seabirds of Mynas on Ascension Island are Sooty Terns *Onychoprion fuscatus* which number 388,000 birds and constitute 97% of all seabirds on the island. Five censuses of Mynas and 20 of the Sooty Tern population were carried out between 1994 and 2015, and Myna depredation was monitored on 10 occasions between 2000 and 2008. Of all seabird eggs laid annually, we estimated that 19% of them were depredated by c. 1,000 Mynas. In declining severity of impacts of Mynas on all eggs lost, we estimated that 40% was attributable to desertion, 39% to puncturing eggs with no consumption and 21% to puncturing and consumption. As far as we know, our study is the first to estimate the scale of seabird egg depredation by Mynas. Care is needed when applying our findings to other seabird populations. The scarcity of alternative food sources and the ease of locating high densities of Sooty Tern eggs on Ascension Island may have magnified the frequency of egg depredation by Mynas. That said, it is clear that Mynas are major egg predators and the severity of their impacts on native avian populations can be high.

Keywords Non-native species; Population size; Predation rate; Sooty Tern

Introduction

Common Mynas *Acridotheres tristis* (hereafter referred to as 'Mynas') have become established well beyond their native distribution and in many of these areas are known to disrupt the breeding of other avian species. Mynas cause egg losses in other species by puncturing and consuming eggs (Feare and Craig 1998), puncturing eggs with no consumption (Byrd 1979; Hughes et al. 2008) or displacing incubating birds that then desert viable eggs (IUCN 2015a). However, the scale of egg losses directly attributable to Mynas has rarely been quantified (Parkes 2006). In their home range (i.e. India and central and southern Asia), Mynas are regarded as a beneficial species (BirdLife International 2015) because typically more than 80% of food mass comprises insects regarded as pests (e.g. cutworms – larvae of Noctuidae). Sengupta (1976) estimated that a single Myna can consume 10.8 kg of insects in a single year. Thus, Mynas are an important potential biological control agent of agricultural insect pests. In the 19th century it was their effectiveness as biological control agents in their native range that resulted in Mynas being introduced to Australia, New Zealand, Mauritius, South Africa, Fiji and islands in the South Atlantic (Feare and Craig 1998; Yap and Sodhi 2004).

There is little in the literature to suggest that these introductions have resulted in significantly improved local agricultural economies and Mynas are now regarded as a major pest species in Australia, New Zealand and South Africa (ISSG Database 2011). Their presence is now thought to be having significant negative impacts on native avifauna through competition for resources, especially nest sites and food (Rogers and Nesbitt 2007; Blackburn et al. 2009a; Galbraith et al. 2015). Mynas are known to damage fruit crops such as grapes *Vitis* spp., apples *Malus* spp. and figs *Ficus* spp. (Heather and Robertson 2000), but the extent of the damage has not been quantified (IUCN 2015a). Mynas are regarded as a pest species in the cities of Auckland, Canberra, Pretoria and Singapore, in part because they negatively impact human health by carrying mites such as *Ornithonyssus bursa* and *Dermanyssus gallinae* that can infect humans (IUCN 2015a). Furthermore, the rate at which Myna populations increase in cities can be rapid and controlling their populations is problematic (Yap and Sodhi 2004). For example, in Tel Aviv, following a single observation of a bird in 1987, the Myna population reached 100 by 2000 and increased a further four-fold between 2000 and 2003 (Holzapfel et al. 2006).

On tropical islands introduced Mynas depredate eggs of endemic landbirds such as the Tahiti Swiftlet *Collocalia leucophaea* (IUCN 2015a) and the St Helena Plover (or 'Wirebird') *Charadrius sanctaehelenae* (McCulloch 2004). Mynas also prey on the eggs of seabirds such as terns *Sterna* spp. and noddies *Anous* spp. (BirdLife International 2015). In Hawaii, Byrd (1979) estimated that they destroyed 21% of the eggs of Wedge-tailed Shearwaters *Puffinis pacificus cuneatus*. Parkes (2006) completed a feasibility plan to eradicate Mynas on Mangaia Island but found no other studies that gave an objective measure of the effect of Myna depredation on native avian species. Feare et al. (2015) demonstrated that in the Seychelles Mynas had the capacity to inflict heavy predation on Lesser Noddy *Anous tenuirostris* eggs but the extent of depredation was not quantified.

Mynas were introduced to Ascension Island in the South Atlantic Ocean (Fig.1) and Duffey (1964) searched the early records for details. He found that Mynas were introduced in an effort to reduce damage to vegetable crops by Black Cutworms *Lepidoptere noctuidae*. The first 12 pairs of

Mynas arrived from Mauritius in 1879, a second shipment of 24 pairs followed in 1880, 13 birds in 1881 and 10 pairs in 1882. A further 40 pairs were ordered by the Admiralty who controlled the island but their arrival was not recorded (Duffey 1964). The minimum and maximum numbers of Mynas in the founder population were 105 (52 pairs) and 185 birds, respectively, and was sufficient to establish a viable population (Cassey et al. 2005). By 1958 the population size had increased to c. 400 birds (Stonehouse 1962). There are no extant native landbird species on Ascension Island but there are small populations (< 1,200 birds) of non-native Red-necked Francolin *Francolinus afer,* Common Waxbill *Estrilda astrild* and Yellow Canary *Serinus flaviventris* (Hughes 2014). Non-native Black Rats *Rattus rattus* are also found on the island (Ashmole and Ashmole 2000) and they are known to depredate seabird eggs. For example, on Anacapa Island they depredated 50% of Xantua's Murrelet *Synthliboramphus hypoleucus* nests (Mulder et al. 2011). On Ascension Island during breeding seasons between 1994 and 2007 (inclusive), Hughes et al. (2008) estimated that 6% of Sooty Tern eggs were depredated by Black Rats.

In this study we report on Myna depredation of seabird eggs on Ascension Island between 2000 and 2008 (inclusive). Eight seabird species were known to breed on the main island in 2000 (Ashmole and Ashmole 2000). Five of the species bred in very small numbers (i.e. less than 200 individuals of White-tailed Tropicbirds *Phaethon lepturus*, Masked Boobies *Sula dactylatra*, Red-footed Boobies *Sula sula,* Brown Noddies *Anous stolidus* and Red-billed Tropicbirds *Phaethon aethereus* [Ashmole and Ashmole 2000; Sanders 2006]), while there were larger populations of Sooty Terns (388,000) (Hughes et al. 2008), Black Noddies *Anous minutus* (10,000) (Sanders 2006) and White Terns *Gygis alba* (400) (Hughes 2014). Three other seabird species (namely Brown Boobies *Sula leucogaster,* Ascension Frigatebirds *Fregata aquila* and Band-rumped Storm-petrels *Oceanodroma castro*) are found on Ascension Island, but they nest on Boatswainbird Islet (Fig. 1) or off-shore stacks and their eggs are not susceptible to Myna depredation at the present time. The avian population size on the main island is dominated by Sooty Terns and numerically they constitute 97% of all seabirds. Black Noddies form 2.6% and other seabirds just 0.4% of the avian population.

Sooty Tern colonies can be large with a single colony numbering up to one million pairs (Schreiber et al. 2002). Each female lays a single egg with a mean mass of 33.2 ± 3.2 (± 1 SD) g (n = 567 eggs) (BJH unpubl. data). Following egg depredation, Ashmole (1963) estimated that 12.5% of females lay a replacement egg. On Ascension Island Sooty Terns breed every 9.6 months with the breeding season lasting approximately five months (Reynolds et al. 2014) and they migrate away from the island during the non-breeding season. The numbers that return to breed each season are well reported and were relatively constant during the period of this study (Hughes et al. 2008). Black Noddies do not migrate and on Ascension Island their breeding cycle is variable, they breed on exposed cliff ledges and each lays a single egg (Ashmole and Ashmole 2000). In the Hawaiian Islands the mean mass of fresh Black Noddy eggs is 25.2 ± 1.7 (± 1 SD) g (n = 305 eggs) (Gauger 1999).

Grarock et al. (2012) quantified the impact of competition between Mynas and native avian species for nest sites but few data are available on incidents of egg losses of native birds attributable to introduced Mynas (Libsch et al. 2008). Here, we report new findings of the extent of seabird egg depredation by Mynas on Ascension Island.

Methods

Study area and period

Ascension (07º 57´ S, 14º 24´ W, 97 km²) is one of the volcanic islands that make up the UK Overseas Territory (UKOT) of Saint Helena, Ascension and Tristan da Cunha, and is isolated in the tropical South Atlantic Ocean midway between South America and Africa (Fig. 1; Hughes et al. 2010). Its nearest neighbour is the island of Saint Helena some 1,300 km to the SE. The territory is an Important Bird Area (IBA reference number SH001 – Sanders 2006). During the study period there was little or no agriculture on the island and cultivated areas were limited to a few small gardens (BJH pers. obs.). Invertebrate species diversity compared with others islands (e.g. Saint Helena: 1,100 species) are very few in number with only 315 species recorded (Ashmole and Ashmole 2000). With the island having a limited ability to support life, Anderson et al. (1976) described it as a "barren land". The island falls in the Red List habitat category of "shrubland subtropical/tropical dry" (IUCN 2015b). The study area did not include the offshore islet of Boatswainbird (Fig. 1; IBA reference number SH002 – Sanders 2006) where some 30,000 seabirds, but no Mynas, nest. Myna census data were collected on five occasions between 1994 and 2015 (inclusive). Data were collected during fieldwork on the island lasting approximately two weeks every 9.6 months to coincide with the peak in breeding of Sooty Terns (Reynolds et al. 2014). Egg depredation by Mynas was first recorded in 1990 (Hughes 2014) and was systematically monitored every 9.6 months between November 2000 and February 2008 (inclusive). Nests were monitored in two Sooty Tern colonies on the south-west corner of the island at Mars Bay and Waterside (Fig. 1). Each colony contained sub-colonies (defined as spatially separate areas occupied by breeding birds). Typically, the sub-colonies ranged in area between 0.1 and 6 ha, and in number between 3 and 14 in any given breeding season (Fig. 3; Hughes 2014).

Mynas on Ascension Island

Many factors simplify the study of the Myna population size and the rate of egg depredation by Mynas on Ascension Island compared with other locations. The high visibility and ease of access to the vast majority of eggs (i.e. those within the Sooty Tern colonies laid on ground devoid of vegetation; Ashmole 1963) provide a study system where estimating egg loss to Mynas is feasible. The size of the founder population of Mynas on the island is reliably documented and the island is small and isolated enabling absolute abundance of the species to be determined. In this study we used Myna monitoring records collected over 21 years to investigate their ecology on Ascension Island. Standard bird census techniques (Bibby et al. 2000) were used during five field seasons to determine the Myna's population size and trend. From population censuses of Mynas and Sooty Terns, and by monitoring egg depredation for 10 breeding seasons of the latter, we were able to assess the extent of egg depredation on Sooty Terns. Depredation was monitored in >100 quadrats and extrapolated to the whole colony. Our extrapolation of egg depredation in the periphery of the colony is based on Mynas being able to access eggs in all areas of all colonies. Finally, to predict the annual depredation rate for the whole seabird community breeding on the main island of Ascension, we scaled up the Sooty Tern depredation rate to account for their sub-annual breeding cycle and for the relatively smaller numbers of other species in the breeding seabird community on the island. We assumed that the eggs of other species were as accessible and attractive to Mynas as Sooty Tern eggs.

Spatial distribution of Mynas

Mynas are sedentary and, for example in Singapore, may fly only 400 m between roosting and feeding locations (Feare and Craig 1998). On Ascension Island R. Prytherch (pers. comm.) monitored Myna distribution with K. Simmons in January 1996 and produced a map that showed Mynas were widely distributed across the island. We searched the island for Mynas and their roosts, we recorded any Myna nests we found and noted the dates when Mynas were seen carrying food or nest materials. To ascertain if Sooty Tern egg depredation rates were related to Myna foraging range, we measured the distances on a map from Myna night roosts to the furthest and nearest Sooty Tern sub-colony and to their principal foraging site at the One Boat rubbish tip (Fig. 2).

Censuses and Myna population growth rate

There are no detailed ecological studies of Mynas on Ascension Island but it is clear that the population has grown in size since their introduction. Myna population surveys were completed by counting individual birds in 116 1-km grid squares that covered the whole of the island and at the island's two rubbish tips. Squares that contained a tip received additional survey effort and we have categorised the square as a tip. Wherever Mynas have been introduced they are frequently found foraging on rubbish tips (Feare 2010) and hence they have been described as "garbage birds" (University of Melbourne 2007). The counting unit for Mynas was individual birds including juveniles and counts were carried out in 1-km grid squares that were laid over a topographical map of the island to produce a base map. Direct counts of birds seen or heard in each grid square and on the rubbish tips were recorded usually by two observers working together (Bibby et al. 2000). Counts were conducted after Mynas had left their roosts in the morning and before they began to congregate prior to returning to roosts (i.e. between 0800 and 1730hrs UTC). Mynas were counted during one or, more commonly, two transects across each1-km grid square. The duration of each count was approximately 30 minutes. Counts in 1-km grid squares were not carried out simultaneously and did not provide a totally reliable estimate of the Myna population size because some birds were missing and others double counted. Counts of Mynas foraging in the two rubbish tips were conducted from a vehicle by two observers working independently and repeated if count numbers disagreed by more than two birds.

A full census, rather than a count, was needed to calculate the annual growth rate since the introduction of the founder population. Our censuses were obtained from a consolidation of counts in 1994, 2004, 2005, 2006 and 2015 of birds feeding on the two rubbish tips and in grid squares, adjusted by applying a detection probability (*DP*) for individuals present but not detected (Thompson 2002). In 2015 counts were made of Mynas in 1-km grid squares and also entering communal night roosts. Roost counts provide a reliable method of estimating population size (Bibby et al. 2000) and C. Feare (pers. comm.) pointed out that counts of Mynas entering night roosts provide a more reliable estimate of population size than counts in 1-km grid squares. The two counts were used to determine the probability of detecting Mynas during counts in 1-km grid squares earlier in the study. During the breeding season counts at night roosts do not include adult females that are absent incubating eggs (Feare and Craig 1998). An estimate of incubating females was obtained from nest records (i.e. nest locations and breeding activities) collected during nine field seasons of the 21year study period. A detection probability (*DP*) for Mynas in 1-km grid squares (excluding birds on the two rubbish tips) was determined using Equation 1:

$$DP = \frac{M_G}{M_R + M_F - M_T} \qquad \text{(Eqn 1)}$$

where M_G is the total number of Mynas counted in 1-km grid squares (excluding birds on the two rubbish tips), M_R is the total number of Mynas counted entering the roosts, M_F is an estimate of the number of females incubating eggs from the number of active nests found, and M_T is the total number of Mynas foraging on the two rubbish tips.

To determine the annual percentage change in the Myna population size since their introduction, a Compound Annual Growth Rate (CAGR) (as used by Mitchell et al. 2004) was calculated using the online calculator of Investinganswers (2015). Every species when unchecked has an intrinsic rate of natural increase until it reaches the carrying capacity of its habitat (Newton 1998). For example, in the UK Collared Doves *Streptopelia decaocto* have increased by a constant percentage each year (Newton 1998). The annual rate of increase can fluctuate if catastrophic losses occur, however. The Myna population size on Ascension Island in 1959 was 400 birds (Stonehouse 1962) and only one record of Myna population loss prior to 2009 (e.g. 48 Mynas caught in feral Domestic Cat *Felis silvestris catus* traps between 2002 and 2004 [Bell and Boyle 2004]) was found, so we have assumed that population increased by a constant percentage each year. The number of introduced Mynas was taken as 52 pairs and the date of introduction was taken as 1880 (i.e. midway between the putative introduction years of 1879 and 1882).

Sooty Tern egg depredation attributed to Mynas

At the start of the study period telescopes were used to observe Mynas in the tern colony to confirm that it was Mynas (usually in small groups) that were depredating Sooty Tern eggs. Mynas fly to the tern colony from the direction of their night roosts located > 3 km to the north (Fig. 1). Initial observations showed that depredation generally occurred within approximately 7 m of the periphery of sub-colonies. Here, nest density was less than in the core of the colony and Mynas were able to avoid pecks from incubating Sooty Terns. Typically, the mean distance from the core of the sub-colony to the periphery varied between 50 and 150 m (Fig. 3). Depredated eggs were examined and depredation categorised according to egg damage (Fig. 2a). "Consumption" of an egg by Mynas was defined as the opening of a viable egg (assumed as Sooty Terns were incubating on adjacent nests) and feeding on some (usually < 10%; estimated from inspection of > 1,000 depredated eggs) or all of the contents (Fig. 2b). "Puncturing" of an egg was defined as the creation of a single small hole in an egg from a Myna bill tip, thereby destroying its integrity but very little if any egg contents were consumed (Fig. 2c). Sooty Terns were seen incubating recently punctured eggs and may have prevented Mynas from opening eggs. Furthermore, Mynas may have detected an embryo that was close to hatching in the punctured egg and decided not to continue opening it. We studied rates of depredation by recording the number of Mynas in the two colonies, marking focal eggs by nailing numbered plastic tags into the ground 10–20 cm from the eggs (Fig. 2b) and following the fates of eggs for the duration of the field season or until hatching. Focal eggs were selected where space was sufficient between nests to nail markers to the ground to allow their positive identification. Eggs were monitored in sample areas at < 7 m from the periphery or in the core of each colony between 7 m and approximately 50 m from the edge. Eggs were marked in sets of 10–20 with set size determined by the time available for egg monitoring during each field season. The eggs in each set were situated in an area approximately 7 × 10 m and sets were located randomly in well-established and newly settled parts of the two colonies. During each of the 10 field seasons when Myna depredation was monitored, sets were situated in approximately 25% of the sub-colonies, set sampling area was 0.7% of the total colony area and eggs monitored numbered 0.7% of all those laid in the Sooty Tern colony. The fates of focal eggs were recorded as "surviving to hatching", "consumed/punctured", "deserted" or "missing". Focal eggs were not marked on the day of laying. Sooty Terns are synchronous layers and the date of laying was determined from observations of birds laying < 20 m from the focal egg. Sooty Terns defend their eggs intensely close to hatching (i.e. < 3 days pre-hatching) and Mynas probably avoid pipping (i.e. hatching) eggs altogether as consumable egg content is negligible at this stage. Each season 124 (range 74-195) eggs in 10 (range 5-20) sets were marked and fates checked every other day. Missing eggs (i.e. where no evidence of Myna depredation was visible) were attributed to Black Rat depredation. Rats are known to roll eggs from nests (Zarzoso-Lacoste et al. 2011) and rat food caches containing broken eggs were found between rocks in the tern colony (Hughes 2014).

The numbers of Mynas seen foraging in the morning and in the afternoon at Mars Bay and Waterside colonies were recorded. To avoid bias that may result from the over-representation of an individual Myna bird in each season, egg sets were distributed in the two separate colonies situated at Mars Bay and Waterside (Fig. 1) that are 1-3 km apart. During our study concerns were raised by C. Feare (pers. comm.) that the white 5 × 8 cm plastic tags marking focal eggs might attract or repel Mynas. However, this seems to be unfounded since in one season 100 eggs were marked with white plastic tags and 100 with less conspicuous wooden spatula sticks, and five eggs in each set were found depredated by Mynas.

In each Sooty Tern breeding season Myna depredation was measured for approximately seven days (i.e. for 25% of the incubation period of 28.8 days [Ashmole 1963]) and the survival rate was calculated using the Mayfield method (Johnson and Shaffer 1990). Egg depredation was monitored randomly during the incubation period. For each egg set we calculated the number of exposure days (i.e. 24 out of 28.8 days) and the daily survival probability of eggs, resulting in egg failure rate due to consumption/puncturing (F_c) and desertion (F_D) caused by Mynas according to Equations 2 and 3, respectively:

$$F_C = 1 - \left(\frac{1 - E_C}{E_M}\right)^{24} \quad \text{(Eqn 2)}$$

$$F_D = 1 - \left(\frac{1 - E_D}{E_M}\right)^{24} \quad \text{(Eqn 3)}$$

where E_C is the number of monitored eggs consumed and punctured, E_D is the number of monitored eggs deserted and E_M is the number of egg days monitored. Rates of egg desertion (F_D) were pooled for analysis because of their large variance.

Sooty Tern egg desertion attributed to Mynas

Some egg desertion (Fig. 2a) occurred when eggs in neighbouring nests were consumed or punctured and, therefore, it would appear that desertion might be caused by Mynas foraging nearby. To establish its causation, sets of focal eggs that contained deserted eggs were separated into two categories – those containing eggs consumed or punctured by Mynas and those that did not. To reduce the possibility that Mynas were feeding on deserted eggs, we analysed data from egg sets in which consumption or puncturing by Mynas occurred simultaneously with desertion. We tested if the apparent association between these egg fates was significant. To calculate the rate of egg desertion that could be attributed to Mynas, we divided the number of deserted eggs in each of the sample sets that contained Myna-consumed/punctured eggs by the total number of deserted eggs in all egg sets. The mean rate (E_{MD}) of deserted eggs (2000 to 2008 [inclusive]) that could be attributed to Mynas was then calculated.

Total number of Sooty Tern eggs per season

Every 9.6 months we calculated the number of Sooty Tern eggs by measuring the area of the Sooty Tern breeding colony using conventional land survey techniques and determined egg density by counting eggs in circular 10 m^2 quadrats across the whole of the colony (further details in Hughes et al. 2008). To estimate the number of eggs within 7 m of the periphery of each colony where egg depredation by Mynas occurred (E_{PER}), survey data were inputted into ArcMap 9.2 Geographical Information System (ESRI 2010) and the area of the periphery calculated and mean nest density at the periphery and in the core of the two colonies applied (further details in Hughes et al. 2014). The total number of Sooty Tern eggs per season ($E_{SEAS.}$) was calculated from the number of eggs and 12.5% of this total for replacement eggs (Ashmole 1963).

Sub-annual and annual egg depredation rates

The Sooty Tern egg depredation rate ($E_{DEP.}$) on Ascension Island attributable to Mynas was determined each sub-annual breeding season using Equation 4:

$$E_{DEP.} = \frac{(E_{FRC} \times E_{PER}) + (E_{FRD} \times E_{PER-NC} \times E_{MD})}{E_{SEAS.}} \qquad \text{(Eqn 4)}$$

where E_{FRC} is the seasonal egg failure rate due to consumption and puncturing by Mynas in the periphery of the two colonies, E_{PER} is the number of eggs in the periphery of the two colonies, E_{FRD} is the seasonal egg failure rate due to desertion, $E_{PER\text{-}NC}$ is the number of eggs in the periphery that were not consumed or punctured, E_{MD} is the mean rate of egg desertion during the study period attributable to Mynas, and $E_{SEAS.}$ is the number of Sooty Tern eggs on Ascension Island during the season.

The annual Sooty Tern egg depredation rate ($AE_{DEP.}$) on Ascension Island from Mynas was determined each breeding season using Equation 5:

$$AE_{DEP.} = \frac{E_{DEP.} \times 12}{9.6} \qquad \text{(Eqn 5)}$$

Extent of total seabird egg depredation attributed to Mynas

To determine the extent of Myna depredation on eggs of the whole seabird community, we estimated the total number of seabird eggs on Ascension Island, the size of the Myna population and the number of eggs that they depredated. Of the seabirds that breed on Ascension Island, 388,000 (97%) are Sooty Terns (Hughes et al. 2008), 10,000 (2.6%) are Black Noddies (Sanders 2006) and approximately 1,500 (0.4%) are other seabirds (Hughes 2014). To the mean annual number of Sooty Tern eggs we added 3% to account for eggs of Black Noddies and other seabird species. Egg depredation of Black Noddies and of other seabird species was not monitored but we assumed that eggs of other seabird species were as accessible and attractive to Mynas as those of Sooty Terns. Although some of the other species breed annually and clutch size of Masked Boobies, for example, is two (Nelson 1978), the population sizes of these other seabird species are small relative to those of Sooty Terns and Black Noddies. The mean number (E_N) and mass (E_M) of seabird eggs depredated annually on Ascension Island between 2000 and 2008 (inclusive) were determined using Equations 6 and 7, respectively:

$$E_N = \frac{E_{NDep.A} \times 103}{100} \qquad \text{(Eqn 6)}$$

$$E_M = \frac{(E_{N.Dep.A} \times 33.2) + (E_{NDep.A} \times 0.03 \times 25.2)}{1{,}000{,}000} \qquad \text{(Eqn 7)}$$

where $E_{NDep.A}$ is the mean number of Sooty Tern eggs depredated by Mynas annually.

To determine the ratio of consumed:punctured eggs, we counted the number of eggs consumed and punctured in freshly deserted areas of the Sooty Tern colony. We used Chi-square tests with a Yates' correction (for one degree of freedom) to establish if egg desertion was significantly different between egg sets experiencing losses from Myna consumption or puncturing, and those experiencing no such losses. This also allowed us to compare such losses of eggs between the core and at the periphery of tern colonies. We used an alpha threshold of 0.05 and means are presented ± 1 SD.

Results

Between 1994 and 2015 (inclusive) we located five night roosts and recorded Mynas in 85% of 116 1-km grid squares that covered the island. We located 73 Myna nests, of which 30 were found in holes in a bank on the edge of the island's municipal rubbish tip and the majority of the remainder were in buildings. We estimated that first clutches were laid on 2nd February (± 35 days, n = 11 observations of breeding activity). The map distance from night roosts to the prime foraging site at One Boat tip varied between 2.6 and 6.0 km (mean: 3.7 ± 1.5 km, n = 5 night roosts). The distance from night roosts to the nearest Sooty Tern sub-colony varied between 3.4 and 5.1 km (mean: 4.0 ± 0.6 km, n = 5 night roosts) and to the furthest Sooty Tern sub-colony varied between 5.6 and 7.8 km (mean: 6.7 ± 0.9 km, n = 5 night roosts).

Censuses and population growth rate

We completed the first look-see counts of Mynas on Ascension Island in April 1994. Of the 116 1-km grid squares that cover the island, 109 (94%) of them were visited and 363 Mynas detected. Four surveys of Mynas were carried out between 2004 and 2006 (inclusive) and a further one was conducted in April 2015. Five Myna night roosts were identified and simultaneous counts of birds entering each in April 2015 resulted in a total number of 620 birds. We assumed as Mynas are known to be site-faithful that the 73 Myna nests that we had located in the study period all contained a female Myna. Using Equation 1 we calculated the detection probability (*DP*) of Mynas from look-see counts in April 2015 as being 0.59. Population censuses were completed during and after the breeding season and in 2005/2006 the Myna population size ranged between 925 and 1,442 birds (Table 1). The mean density of Mynas on Ascension Island in February 2006 was 9.5 birds/ km^2. The Compound Annual Growth Rate (CAGR) from the introduction of 52 pairs of Mynas in 1880 to February 2006 (i.e. during the pre-fledging census when most Mynas were adults) was 1.75%. The CAGR was calculated from censuses completed prior to the major cull of Mynas in 2009.

Depredation of eggs

Mynas and Ascension Frigatebirds were the only avian species seen foraging in the Sooty Tern colonies. Frigatebirds were only observed depredating chicks while Mynas were only recorded as scavenging, consuming, puncturing eggs and harassing adult terns causing them to desert their eggs. Black Rats were recorded depredating both eggs and chicks. Approximately 50 nests of Brown Noddies were found within the Sooty Tern colony and their eggs may also suffer depredation from Mynas. However, as Brown Noddy eggs were so few, we were unable to quantify their depredation by Mynas. Mynas consumed and punctured eggs that were attended by adult Sooty Terns. Mynas were also seen scavenging on the carcasses of dead adult terns presumably for insects. We found no evidence to suggest that Mynas killed tern chicks. Mynas were recorded every field season in the tern colonies at Mars Bay and Waterside. The maximum number of Mynas foraging together in the Sooty Tern colonies was 21 (mean of 4.38 ± 0.49, n = 72 visits). Mynas were observed in the colonies on 136 (59%) of 229 visits made. Between November 2000 and February 2008 (inclusive) less than 0.5% of the Myna population (range: 925–1,442 birds) was found in the tern colony at any one time. During one full day of observation on 17 February 2004 we recorded the arrival of the first Myna in the colony at 0700hrs UTC a few minutes after dawn and Mynas were still in the colony at 1900hrs UTC 45 minutes before dusk. Depredation from Mynas was not random. Egg sets were either heavily depredated or, more often, not depredated at all. We monitored 1,238 eggs (935 on the periphery and 303 in the core), during 10 Sooty Tern breeding seasons. Of these 88 (7.1%) eggs failed as a result of Mynas consuming or puncturing them during 6.5 days of monitoring. Of the 935 eggs (6,065 egg days) monitored that were situated within 7 m of the perimeter of the colonies, 87 eggs were consumed or punctured by Mynas. Eggs consumed or punctured by Mynas were recorded in both colonies, and the size and location of the colonies in 2005 are shown in Fig. 3. Thirty-eight eggs were consumed or punctured at Mars Bay and 49 at Waterside during the 10 seasons when eggs were monitored. Of the 303 eggs (3,976 egg days) monitored within the colony core, significantly fewer eggs (i.e. only one) succumbed to Mynas in the colony cores (χ^2 = 52.7, df = 1, P < 0.01). The seasonal mean Mayfield egg survival rate during incubation on the periphery of the colony (n = 10 field seasons) due to consumption/puncturing was 0.98 eggs per day and 0.65 eggs over the 24-day period when eggs were prone to depredation. Using Equation 2 we calculated the mean egg failure rate (F_C) at the periphery of the colonies as being 0.35 ± 0.07 eggs per season (n = 10 field seasons) while in the colony cores it was 0.02 ± 0.06 eggs per season (n = 10). The core of the colony appeared largely immune to Myna depredation and was disregarded from further analyses.

Egg desertion attributable to Mynas

Of the 935 eggs we monitored at the colonies' peripheries, 189 (20.2%) were deserted over 6.5 days. Using Equation 3 egg failure rates due to desertion (F_D) by adult Sooty Terns were not random and they were associated with presence of Mynas. There were no signs of desertion or Myna-induced loss of eggs in 54 (52%) of the 103 egg sets we monitored. The 24 egg sets containing deserted eggs (versus 10 egg sets containing no deserted eggs) were significantly associated with incidents of egg consumption or puncturing by Mynas (χ^2 = 4.97, df = 1, P < 0.05). The mean rate of deserted eggs that could be attributed to Mynas (i.e. E_{FRD} in Eqn 4) was 0.75 ± 0.36 eggs per season at the periphery of the colonies (n = 10 field seasons).

Extent of depredation

Using Equations 4 and 5, we calculated the annual rate of egg losses to Myna depredation ($AE_{DEP.}$) as varying between 0.02 and 0.37 eggs per Sooty Tern breeding pair (mean: 0.19 ± 0.11 eggs per pair, n =

10 field seasons; Table 2). The extent of egg depredation varied during the year and was lower during April, May and June (i.e. when Mynas were feeding nestlings) than during the remainder of the year. When depredation was monitored in April, May and June the mean annual rate of eggs depredated was 0.06 eggs per breeding pair but 0.25 eggs per breeding pair during other months. The ratio of consumed:punctured Sooty Tern eggs was calculated as 1:1.83 from > 500 eggs in five sample quadrats across three seasons. In summary, of all Sooty Tern eggs lost to Mynas, 21% were consumed, 39% punctured and 40% deserted. Using Equation 5 to derive annual rate of egg depredation due to Mynas ($AE_{DEP.}$), and assuming Mynas could access all part of the two colonies equally, we calculated that the annual number of Sooty Tern eggs depredated varied between 4,968 and 62,226 (mean: 32,965 ± 20,355 eggs, n = 10 field seasons). The number of eggs depredated on the periphery of the colony where Mynas were known to depredate eggs varied between 3,974 and 49,781 (mean: 26,372 ± 16,284 eggs, n = 10 field seasons).

When the annual number of Sooty Tern eggs depredated was scaled up by 3% to account for other species breeding on the island, using Equation 6 we calculated that the mean number of eggs depredated annually (E_N) was 33,954. Using Equation 7, we calculated the mean mass of eggs depredated annually (E_M) to be 1.1 tonnes of which 0.2 tonnes of eggs were consumed.

Discussion

As far as we are aware, our study is the first to provide a comprehensive estimate of the extent of egg depredation by Mynas on a seabird population anywhere in the world. Assuming Mynas could access all seabird eggs equally, we estimated that annually the mean number of seabird eggs depredated on Ascension Island by a population of approximately 1,000 Mynas was 34,000 eggs from approximately 200,000 seabird nests and that the annual rate of depredation was 0.19 eggs per seabird breeding pair. For every egg that Mynas consumed, they punctured or caused desertion of four others. On average each Myna depredated one egg every 11 days and annually the mass of seabird eggs each Myna depredated was 1.1 kg. On Ascension Island between 2000 and 2008 (inclusive) Mynas depredated three times more eggs than did Black Rats (Hughes et al. 2008). Sooty Terns are not the only seabird species that Mynas depredate. In the Seychelles Mynas were recorded inflicting intense depredation on three seabird species that also breed on Ascension Island (i.e. White Terns, Brown Noddies and Black Noddies [Feare et al. 2015]). However, the only other comparative data for egg depredation by Mynas were those from a study of 350 Wedge-tailed Shearwaters on Hawaii where Mynas punctured 74 (21%) of their eggs (Byrd 1979). However, Byrd (1979) did not report egg desertion caused by Mynas and his definition of "punctured" may differ from ours.

Between 1957 and 1959 when the British Ornithologists' Union (BOU) centenary expedition took place on Ascension Island depredation of seabird eggs by Mynas was considered to have a very minor impact on seabird populations (Ashmole 1963). Our study suggests that the situation is now otherwise. The Myna and seabird populations in 1958 comprised approximately 400 and 800,000 birds, respectively (Stonehouse 1962), while during our study they comprised approximately 1,000 and 400,000 birds, respectively. Thus, over 50 years the Myna population has doubled in size while the seabird population has halved. However, while Myna depredation has undoubtedly contributed to the decline of Sooty Terns, we cannot currently qualify this statement through comparison with other demographic pressures on the Sooty Tern population such as other sources of depredation (e.g. from cats and rats; [Hughes et al. 2008]), food shortage (Hughes 2014), and encroachment onto the breeding grounds by invasive plant species particularly the Mexican Thorn or Mesquite *Prosopis juliflora* (Pickup 1999).

The time of the breeding season of Mynas varies throughout their range (Feare and Craig 1998) and we estimated on Ascension Island that it starts in early February. This is supported by M. Blair (pers. comm.) who saw birds carrying food to nests in February and by S. Saavedra (pers. comm.) who culled 210 juveniles between September and November 2009. As in Australia (Pell and Tidemann 1997), we found that the size of the Myna population on Ascension Island fluctuates widely during the year with peak numbers at the end of their breeding season. These annual fluctuations are reflected in our census data with, for example, five times more Mynas recorded on the rubbish tips at the end of their breeding season compared with at the start. We calculated that during look-see counts in 1-km grid squares 59% of Mynas were detected. As was expected, this detection probability (*DP*) was considerably lower than that of 79% for seven shorebird species (Bart and Earnest 2002). We found that the Myna population size ranged between 925 and 1,442 birds. Feare (2010) estimated that the Myna population size on Ascension Island was between 1,000 and 1,500 birds. Our census data (Table 1) appear to be robust with the estimated population decline of 749 birds between 2006 and 2015 (inclusive) clearly attributable to the culls of 623 birds by S. Saavedra (unpubl. data) and 114 birds by Feare (2010).

We were unable to calculate Myna population growth rates across the entire study period (i.e. to the present day) as censuses of Mynas were conducted at different times of the year and during the study period hundreds of Mynas were culled. However, we calculated it for the period between the introduction of Mynas to the island in 1880 and February 2006 prior to the major culling efforts. Despite the inhospitable habitat on Ascension Island resulting from scarcity of water, vegetation and invertebrates (Ashmole and Ashmole 2000), the founder population of Mynas has increased at a rate of 2% per annum (assuming linear population growth). This growth rate is dramatically lower than the CAGRs of 24% in Canberra (Grarock et al. 2013), of 47% in Tel Aviv, Israel (Holzapfel et al. 2006) and of 37% in Apia, Western Samoa (Gill 1999). However, our estimate of population growth rate is important as it provides evidence that Mynas can cope with novel environments (Blackburn et al. 2009b) and it can assist with predicting the future spread of Mynas in other arid regions (e.g. North Africa and the Middle East) where initial sightings of Mynas have now been reported (Holzapfel et al. 2006).

Mynas are catholic omnivores allowing them to adapt rapidly to foraging conditions where they have been introduced (Feare and Craig 1998). On Ascension Island their main food source is the municipal rubbish tip but they also feed on eggs of Sooty Terns and Green Turtles *Chelonia mydas* (Fig. 2d). While breeding adult Mynas may forage for insects as elsewhere in their range, Myna nestlings are fed for the first 10 days exclusively on invertebrates (ISSG Database 2011). We found no evidence to suggest that a proportion of the Myna population has specialised in the depredation of eggs.

Sooty Tern eggs are available for approximately four months and Mynas will have to forage on other food sources for the remainder of the year.

The depredation rate in the periphery of the colony was 17 times greater than in the core of the colony. It is more likely that higher nest density and more intense egg defence from many terns in the core of the colony rather that Myna foraging range prevented Mynas from foraging in the core. The relative breeding phenologies of Mynas and Sooty Terns strongly influence the extent of egg depredation on the latter. We found that it was lower when Mynas were breeding compared with at other times. The greater the degree of misalignment between peaks in breeding activity of the annually breeding Mynas and the subannually breeding Sooty Terns, the greater the loss of tern eggs to Mynas. The rate of egg depredation was highest when young Mynas had fledged and the population size was thus at its greatest. Whether it is the proportion of juveniles in the Myna population or the overall size of the population that drives the extent of egg depredation needs further investigation. The large variation in the seasonal rate of depredation can also be explained in part by some highly successful Sooty Tern breeding seasons such as in April 2003 and by large variations in the desertion rate. For example, in September 2001 and October 2005 the rates of egg desertion were more than twice the seasonal average.

Why so few Mynas were seen at any one time in the tern colony is uncertain but their detection probability of 0.59 may have played a part. Mynas were seen in the tern colonies at Mars Bay and Waterside both in the morning and in the afternoon during 10 field seasons. However, Mynas were not monitored simultaneously in both colonies and foraging birds may have moved between colonies when they would have avoided detection. On average, group size of Mynas in the tern colonies was four and these were perhaps family groups of birds visiting in rotation; these group sizes were far less than the 100+ birds seen during each visit to the rubbish tips on the island.

Care is needed when applying our estimates of egg losses of Sooty Terns to Mynas to other seabird species because eggs of Sooty Terns on Ascension Island are highly visible, readily accessible and Mynas can approach the egg from many directions (Fig. 2a). Black Noddies on Ascension nest on sheer cliffs and might not offer such straightforward egg foraging opportunities compared with those presented by incubating Sooty Terns. Mynas would find it problematic to approach incubating Black Noddies on narrow ledges compared with the flat plain on which Sooty Terns nest (Deeming and Reynolds 2015). Furthermore, Mynas introduced at other locations may breed in synchrony with other annually breeding native avian species and thus their impact on these native birds may be diminished. The low population growth rate of Mynas on Ascension Island probably reflects food shortage experienced by Mynas at times of the year when Sooty Terns are absent. When Sooty Terns are present on breeding grounds, the super-abundance of their eggs may magnify the egg losses to foraging Mynas. Such a species' dynamic on Ascension Island translates into difficulties of extending our findings elsewhere without equivalent background knowledge of species' interactions.

Empirical evidence of a species' impact is critical for the prioritization of the management of introduced species (Jeschke et al. 2014). Baker et al. (2013) found very little evidence that introduced birds are a major threat to avian biodiversity globally. However, Mynas are an exception (Lowe et al. 2000) because not only can they outcompete native species for nest sites (Grarock et al. 2012), they can also depredate chicks of the native species (ISSG Database 2011). Here, we present strong evidence that Mynas can be major egg predators of seabirds and highlight that their impact on the breeding success and long term population trends of seabirds urgently requires further investigation.

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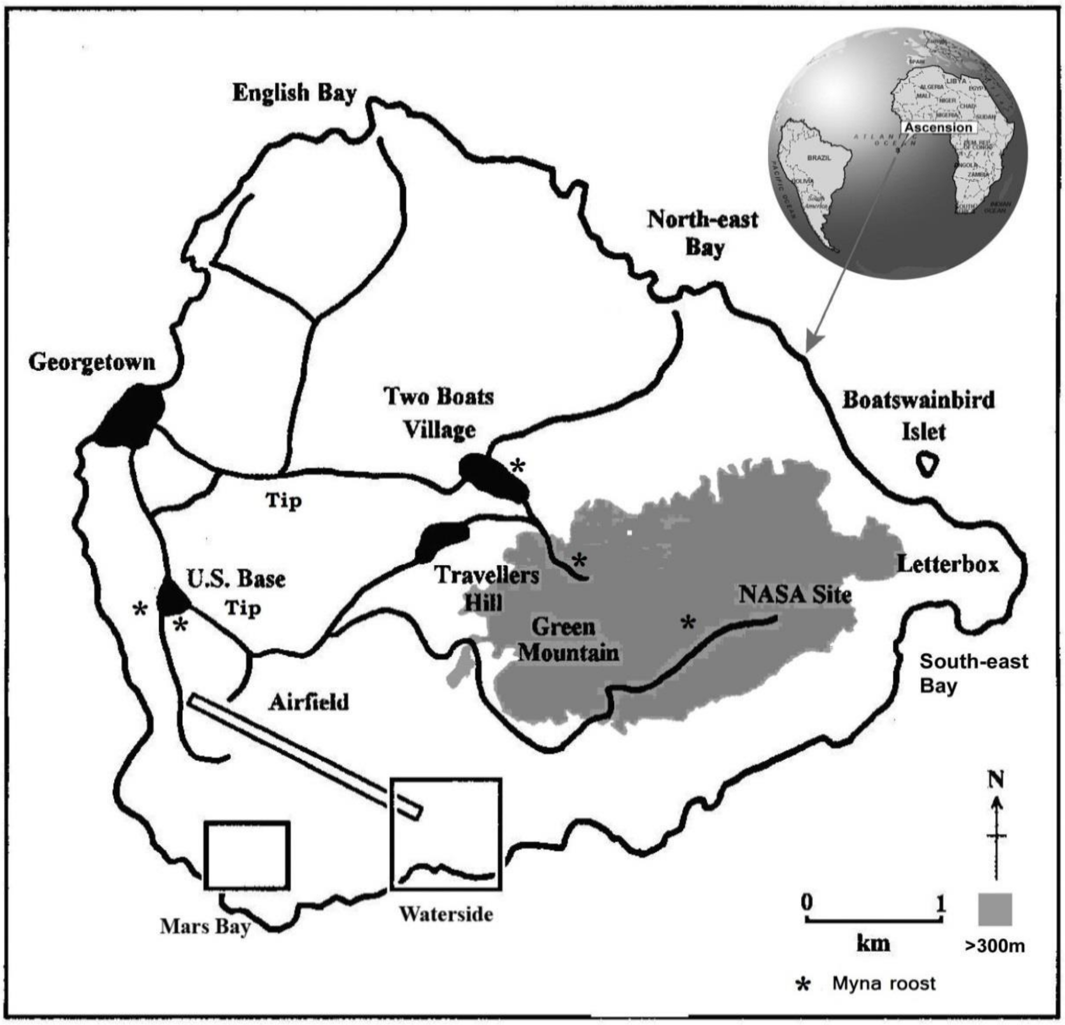
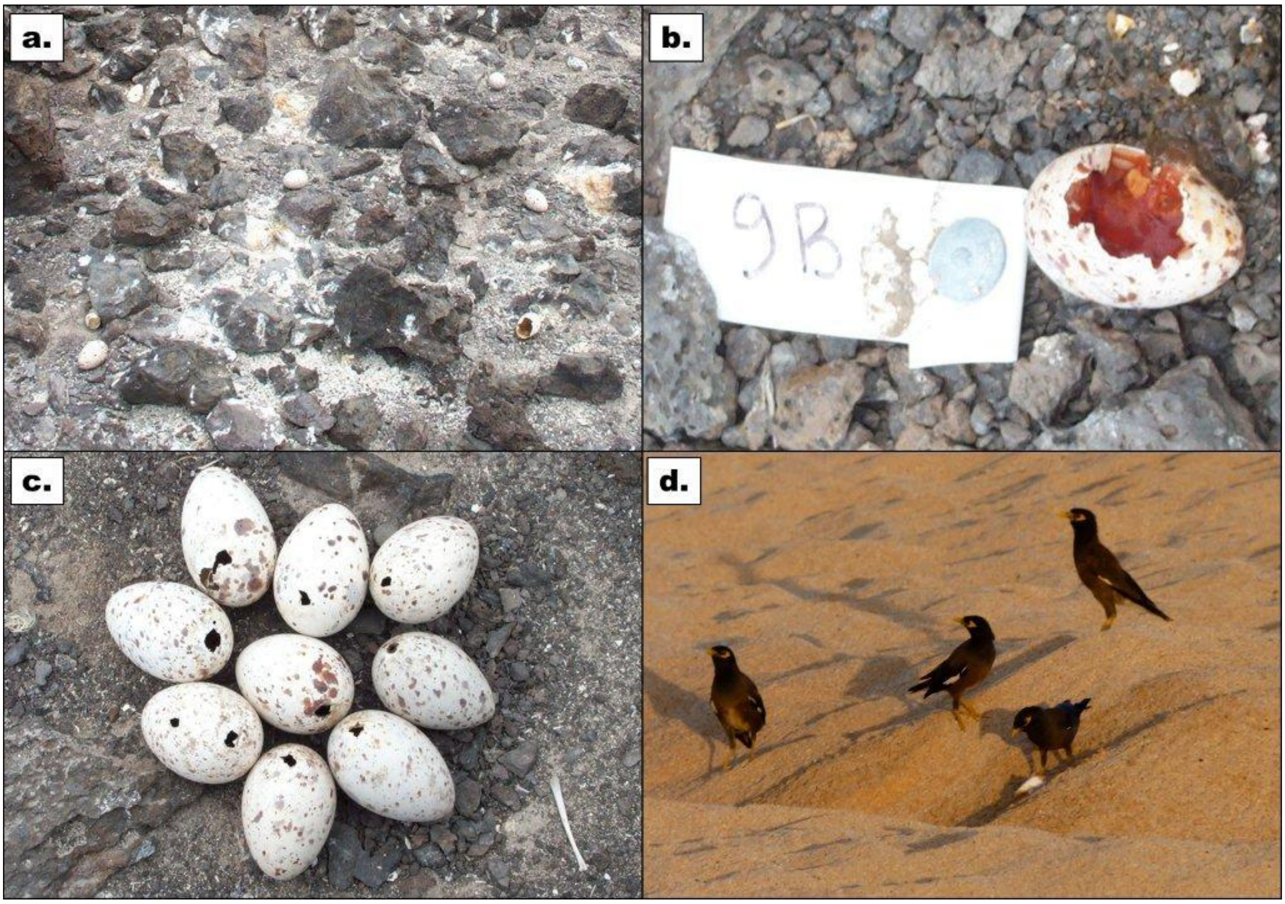
Figure Titles

Fig. 1 Map of Ascension Island in the South Atlantic showing sites of human habitation and ground above 300 m (shaded). The majority of Common Mynas are found at communal roosts (‘*’) at night and in the two rubbish tips (indicated as ‘Tip’) during the day. Sooty Terns nest in the south-west corner of the island in the areas marked as ‘Mars Bay’ and ‘Waterside’.

Fig. 2 Egg depredation by Common Mynas on Ascension Island in the South Atlantic between 1994 and 2015 (inclusive). (a) Egg desertion resulting from Myna displacement of adult terns. (b) Nine Sooty Tern eggs punctured by Mynas. (c) A marked Sooty Tern egg consumed by Mynas. (d) Mynas depredating eggs of Green Turtles *Chelonia mydas* on Long Beach, Ascension Island. (Photos: a, b, c – BJH; and d – R. Moody).

Fig. 3 Map showing (in red) the size and location of Sooty Tern sub-colonies at Mars Bay and Waterside on Ascension Island in the South Atlantic in 2005**.**


English Bay
North-east Bay
Ascension
Georgetown
Two Boats Village
Boatswainbird Islet
Tip
U.S. Base Tip
Travellers Hill
Letterbox
NASA Site
Green Mountain
South-east Bay
Airfield
N
Mars Bay
Waterside
0
1
km
>300m
* Myna roost


a.
b.
9B
c.
d.

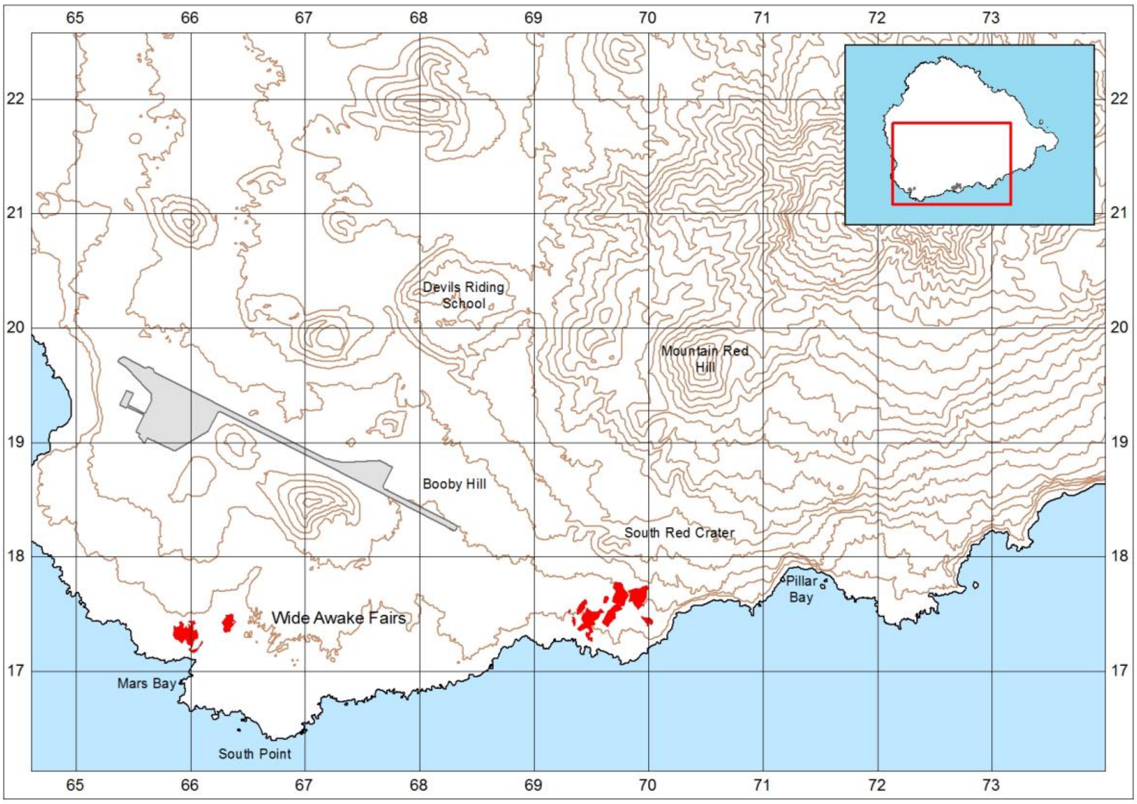

Devils Riding School
Mountain Red Hill
Booby Hill
South Red Crater
Pillar Bay
Wide Awake Fairs
Mars Bay
South Point

Table 1 Details of counts of Common Mynas on Ascension Island in the South Atlantic in April 1994, October 2005 and August 2006 (after their young had fledged), in February 2004 and February 2006 (at the start of their breeding season) and in April 2015 (during their breeding season). Population size was determined from look-see counts of birds in 1-km grid squares, corrected for detection probability and counts of birds on the rubbish tips (see main text for further details).

Count details	**Dates of counts**			
	Apr 1994	**Oct 2005 & Aug 2006**	**Feb 2004 & Feb 2006**	**Apr 2015**
Percentage of 1-km grid squares visited	94	100	100	87
Numbers of birds in1-km grid squares	363	471	471	353
Numbers corrected for detection probability*	610	791	791	593
Mean number of birds on rubbish tips	99	651	134	100
Population size	**709**	**1,442**	**925**	**693**

* A detection probability (*DP*) was determined in 2015 from simultaneous counts of Mynas entering night roosts and look-see counts.

Table 2 Extent of egg depredation on Ascension Island in the South Atlantic by Common Mynas during 10 field seasons between November 2000 and February 2008 (inclusive).

Season	Seasonal egg depredation rate per Sooty Tern breeding pair on colony periphery		Number of Sooty Tern eggs		Total number of Sooty Tern eggs		Annual seabird depredation rate per breeding pair
	consumed or punctured by Mynas (E_{FRC})	deserted by adults terns harassed by Mynas (E_{FRD})	on colony periphery (E_{PER})	on periphery vulnerable to depredation but not taken ($E_{PER\text{-}NC}$)	in the colony ($E_{SEAS.}$)	depredated by Mynas ($E_{DEP.}$)	egg depredation by Mynas ($AE_{DEP.}$)
Nov 2000	0.53	0.31	19,570	9,156	86,625	17,604	0.21
Sept 2001	0.69	0.93	49,248	15,227	173,250	55,795	0.33
Jun 2002	0.11	0.16	52,303	46,717	213,675	13,843	0.07
Apr 2003	0.03	0.03	71,034	68,735	211,365	4,968	0.02
Feb 2004	0.25	0.35	52,353	39,193	202,125	29,478	0.15
Nov 2004	0.28	0.28	47,154	33,980	142,065	25,405	0.18
Oct 2005	0.32	0.84	58,121	39,358	211,365	54,503	0.26
Aug 2006	0.57	0.68	48,246	20,894	228,690	47,622	0.21
May 2007	0.11	0.19	59,940	53,165	242,550	18,204	0.08
Feb 2008	0.38	0.86	70,165	43,740	172,095	62,226	0.37