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Improving the breeding success of a colonial seabird: a cost-benefit comparison of the eradication and control of its rat predator

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ABSTRACT: Breeding success of 5 Cory's shearwater *Calonectris diomedea* sub-colonies of Lavezzu Island (Lavezzi Archipelago, Corsica) was checked annually for 25 consecutive years from 1979 to 2004. Between 1989 and 1994, 4 ship rat *Rattus rattus* controls were performed in several sub-colonies. In November 2000, rats were eradicated from Lavezzu Island and its 16 peripheral islets (85 ha) using traps then toxic baits. We compare cost (number of person-hours required in the field) and benefit (Cory's shearwater breeding success) of control and eradication. The average breeding success doubled when rats were controlled or eradicated (0.82) compared to the situation without rat management (0.45). Moreover, the average breeding success after eradication (0.86) was significantly (11%) higher than after rat controls (0.75). Furthermore, the great variation in breeding success recorded among sub-colonies both with and without rat control declined dramatically after eradication, suggesting that rats had a major impact on breeding success. The estimated effort needed to perform eradication and checking of the permanent bait-station system during the year following eradication was 1360 person-hours. In contrast, rat control was estimated to require 240 or 1440 person-hours per year when implemented by trained and untrained staff, respectively. Within 6 yr, eradication cost is lower than control cost performed by untrained staff and confers several ecological advantages on more ecosystem components than Cory's shearwater alone. Improved eradication tools such as hand or aerial broadcasting of toxic baits instead of the fairly labour-intensive eradication strategy we used would dramatically increase the economic advantage of eradication vs. control. Therefore, when feasible, we recommend eradication rather than control of non-native rat populations. Nevertheless, control remains a useful management tool when eradication is not practicable.

KEY WORDS: Biological invasion · Eradication · Control · Seabirds · *Rattus rattus* · *Calonectris diomedea*

INTRODUCTION

Since the 1992 Rio Summit, studies devoted to biological invasions have confirmed the initial conclusion of the summit that such invasions induce major economic costs (OTA 1993, Perrings et al. 2000, Pimentel et al. 2000, 2005, Pimentel 2002), have a strong impact on human and veterinary health (MacMichael & Bouma 2000, Ruiz et al. 2000, Audouin-Rouzeau 2003), and are one of the major sources of global biodiversity loss (Diamond 1989, Wilson 1993, Vitousek et al. 1997, Veitch & Clout 2002, Hulme 2003; but see Gurevitch & Padilla 2004, Clavero & García-Berthou 2005). Moreover, in the last half century dramatic increases in the number

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of biological invasions (e.g. Wilson 1993, Pascal et al. 2006), related to a dramatic increase in trading activity (Cariton 1987, Cariton & Geller 1993, Ruiz et al. 1997), led Mooney & Hobbs (2000) to consider biological invasion as one of the major processes of current global changes. The latter authors ranked biological invasions at the same level as climate change.

Biological invasions affect most ecosystems (e.g. Mooney & Hobbs 2000), but are particularly damaging on oceanic islands. There are 2 main ecological explanations for this: insular trophic webs are simple compared to continental ones (Towns & Ballantine 1993, Courchamp et al. 2002), and islands host a higher proportion of endemic species than continents (Nunn 1994, Whittaker 1998). Consequently, the extinction rate of native species owing to the effects of invasive species has been notoriously higher on islands than in continental ecosystems (Diamond & Veitch 1981, Honegger 1981, King 1985, Ceballos & Brown 1995, BirdLife International 2000).

Although island invaders may belong to any taxon (Towns & Ballantine 1993, Lever 1994, Courchamp et al. 1999), those that have induced documented species extinctions mainly belong to higher trophic levels (predators and herbivores), and are predominantly mammals. Mammal introductions have been so numerous that very few islands are not affected (Atkinson 1985,1989, Ebenhard 1988, Flux 1994, Vitousek et al. 1997). Rats (*Rattus* spp.) alone have been introduced to more than 80% of island groups worldwide (Atkinson 1985) and, although the introductions were mostly accidental, have extirpated many animal and plant species (e.g. Bell 1978, Groombridge 1992). Mediterranean islands provide a good illustration of this phenomenon: more than 2000 yr ago, humans introduced the ship rat *Rattus rattus* to most islands in the region (Audouin-Rouzeau & Vigne 1994). Subsequently, this rodent has strongly affected insects (Palmer & Pons 1996), vascular plants (Palmer & Pons 2001), birds (Martin et al. 2000), and endemic mammals (Vigne 1999, Pascal et al. 2006). Mediterranean colonial nesting seabirds have been among the most vulnerable in terms of both distribution and abundance, the level of impact being affected by bird body size, island area and island substrate (Penloup et al. 1997, Martin et al. 2000).

Many islands are sufficiently small and isolated for management of invasive species to be more easily implemented there than on the mainland (Chapuis et al. 1995, Atkinson, 2001, Courchamp et al. 2002). Such management actions must be considered as experiments (Pascal & Chapuis 2000), but have nonetheless often produced strikingly unexpected results (Simberloff 2001, Pascal et al. 2005), and have enlightened several aspects of evolutionary biology (Sax et al. 2007) that may be of major interest for management.

Two different management options have been used against alien mammals: (1) control (also known as maintenance management), and (2) eradication. All management of invasive rat populations was restricted to population control prior to the first known insular rat eradication in 1952 (Lorvelec & Pascal 2005). Towns & Broome (2003) quoted more than 250 insular rat eradications in their 2003 synthesis. A recent review increased this number to 318 out of a total of 332 actions aimed at eradicating rats and mice (Howald et al. 2007). Moreover, the increasing effectiveness of eradication techniques (Taylor & Thomas 1993, Taylor et al. 2000, Towns & Broome 2003) has enlarged the extent of eradications in continental (Simberloff, 2002) and insular settings, reaching 12000 ha on Campbell Island, New Zealand (McClelland & Tyree 2002).

Therefore, rat eradication presently appears to be more limited by finance than by technology. Nevertheless, control continues to be performed in many instances, including situations where eradication is possible. Thus, costs and benefits of both options have to be considered, keeping in mind that control requires continuous action (Hodges & Nagata 2001), whereas eradication, if successful, is a permanent solution if new introductions are prevented.

Here we undertake a cost-benefit analysis, using as a case study, Lavezzu Island, where the ship rat was recorded in the fifteenth century (Vigne et al. 1994a,b) and was very abundant until recently (Thibault et al. 1987a,b). This rodent strongly affects breeding success of the colonial seabird Cory's shearwater *Calonectris diomedea*. On Lavezzu Island, like other Mediterranean islands, rat predation on adults or eggs has never been recorded, the rodents apparently affecting 4 to 6 d old chicks until fledgling (Daycard & Thibault 1990, Thibault 1995). These effects were recently confirmed by Igual et al. (2006). Howald et al. (2007) briefly discussed the economic aspects of eradication and shared the views expressed by Donlan & Wilcox (2007) who underlined the difficulties that must be overcome to comprehensively cover the subject. We suggest a way to avoid covering all economic aspects, while allowing rational comparisons by using one simple parameter: time spent in the field to perform management actions. The Lavezzu Cory's shearwater population size and breeding success have been recorded annually since 1979. In past years, rodent control was performed sporadically, but rodents were eradicated from the island during October 2000. This situation provides a unique opportunity to contrast these 2 management strategies and to compare respective cost (time spent in the field to perform control or eradication) and benefit (Cory's shearwater breeding success).

MATERIALS AND METHODS

Study site. Lavezzu Island (73 ha) and its 16 peripheral islets (total area 12 ha) is a Nature Reserve and a part of the International Bonifacio Strait Marine Park within the Lavezzi Archipelago (Corsica) in the Bonifacio Strait, between Corsica and Sardinia (Fig. 1). Lavezzu Island has no cliffs and is flat though punctuated with bare granite eroded masses reaching a maximum height of less than 40 m. Typical dry Mediterranean flora covers the thin sandy soil between the rocky masses. Domestic pigs, goats, sheep, cattle, donkeys and cats, feral rabbits, and synanthropic ship rats were present during the 20th century, and possibly for a long time previously. All but rats were extirpated before the end of the 1990s.

Cory's shearwater. Cory's shearwater (order: Procellariiformes) breeds on northeastern Atlantic Ocean (Macaronesian) and Mediterranean islands (Thibault et al. 1997). The estimated 50 000 to 65 000 pairs of the Mediterranean population breed at fewer than 150 sites (Thibault et al. 1997), and most of the population is concentrated in a small number of colonies in the Sicily Channel and the western part of the Mediterranean Basin (Zotier et al. 1999). The Lavezzu Island Cory's shearwater population was estimated at 395 to 450 pairs in 1995. These pairs are scattered among 8 permanent distinct sub-colonies. All colonies are located in crevices, many of which are deeply cut into the base of granite masses. Each year between 1979 and 2004, breeding success from laying to fledging was recorded in 5 to 6 of these sub-colonies (Fig. 1). A single egg is laid per burrow each year (Warham 1996). Egg-laying is synchronised within sub-colonies and between years (Thibault et al. 1997). Incubating birds were therefore checked each year by a single observer on 2 consecutive days between 2 and 26 June. Fledging occurs in October (Thibault et al. 1997), and thus fledging success was recorded over 3 or 4 d between 20 September and 6 October. We used the presence of a fledgling in a burrow as a proxy of breeding success. On average, 107 Cory's shearwater nests (range: 93 to 181) were checked each year.

Rat management. During all the 1989, 1992, 1993 and 1994 breeding seasons, rat control was performed within 1 to 4 of the Cory's shearwater sub-colonies using toxic pellets (coumatetralyl) inserted in PVC tubes that were checked daily. The number of person-hours allocated to these field operations was recorded daily.

Strategies used to eradicate ship rats were based on those described in Pascal & Chapuis (2000) for successful eradication of insular Norway rat *Rattus norvegicus* populations that shared islands with other small native mammal species (Pascal et al. 1996, Lorvelec et Pascal 2005). This method involves the successive use of trapping and toxic baiting. By trapping more than 90% of the individuals of the target species, samples can be obtained for other analyses such as population genetics (Calmet et al. 2001, Abdelkrim et al. 2005a,b, 2007). In November 2000, 540 trapping-baiting devices were distributed over a 25 × 25 m square grid on Lavezzu Island and its 16 peripheral islets. Each device included a live-trap (Manufrance©) and a PVC tube. Traps, baited with a mixture of oat-flakes, peanut butter and sardine oil (Buckner 1957), were checked daily. Rats were euthanized and non-target species released. When the number of trapped rats dropped to zero per day, toxic baits made of wheat covered by an oily bromadiolone concentrate (50 ppm) were inserted in the PVC tubes and checked each 2 to 4 d. Baits and tubes were removed at the end of the operation.

In order to equally share effort between teams during the eradication operation, the total area was split into 6 units (A, B, C1, C2, D and I), 5 for Lavezzu Island, the sixth encompassing all other islets. We assessed time in the field allocated to each unit as 40 person-hours for setting the trapping-baiting devices, 12 person-hours for each trap daily control, and 8 person-hours for each daily simple toxic-bait control.

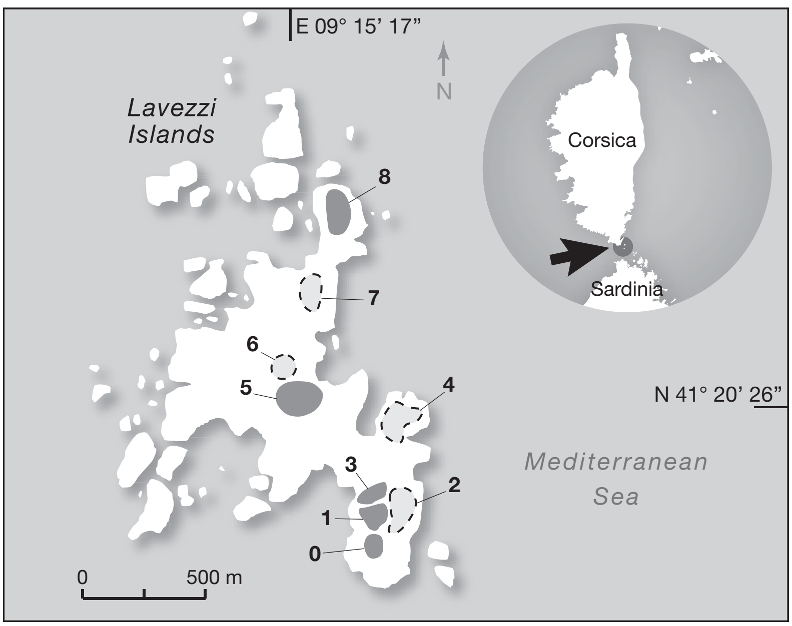

Fig. 1. Lavezzu Island and its peripheral islets. Grey numbered areas show Cory's shearwater sub-colonies. Darker areas indicate investigated and analysed sub-colonies

After eradication, a permanent bait-station system (maintenance system) was set in order to detect eradication failure or newcomer arrival. Checking this system took 4 person-hours. If this maintenance system was routinely checked only every 2 or 4 mo as soon as eradication was considered successful, it was checked monthly during the year following the eradication attempt.

Statistical analyses. As some burrows were out of reach, checking breeding success was restricted to reachable breeding pairs. However, we used burrow rather than pair as the statistical unit in analysis because (1) pair identity can change from year to year, as mate fidelity, although high, is not 100% (Warham 1996), and (2) burrow number changed from year to year, only the ones that hosted an egg being taken into consideration. We used Generalised Linear Models with binomial error distribution and a logit link function in order to model effect on breeding success (0 = no fledged chick; 1 = chick fledged) by independent variables such as rat management (3 classes: no rat management, rat control and rat eradication), year and sub-colony. We checked model over-dispersion, and corrected deviance if necessary using a scaling factor. Because our focus was on the effects of rats on breeding success, only second-order interactions involving rat management were modelled. Two models were compared: before 2000, when rat management only included rat control, and between 1978 and 2004, for comparison between the 2 rat management options. All statistical tests were performed using the SAS 8.0 statistical package.

Table 1. Estimation (person-hours) of effort devoted to rat management operations: eradication (year: 2000) and control. For details of the sub-areas see 'Materials and methods'; for 'sub-colonies' see Fig. 1

Eradication			
Sub-area	No. stations	No. trap controls	No. toxic bait controls
A	102	15	1
B	99	12	2
C1	81	15	2
C2	85	15	2
D	74	12	1
I	87	13	3
Total	540	82	11
No. person-hours	240	984	88
Rat control operations			
Year	Colonies	No. bait stations	No. person-hours
Apr–Sep 1989	8	31	180
Jul–Aug 1992	5	30	60
Jul–Aug 1993	1,3,5	38	120
Jul–Sep 1994	0,1,3,5,8	65	150

RESULTS

Rat management

During the eradication trapping stage (18 October to 6 November 2000), 1338 ship rats were trapped, all during the first 12 trapping days (6480 trap-nights). No evidence of rats was found at the end of the toxic baiting stage. In October 2001, no rats were caught in the 106 traps that were set for 4 nights (5 d) in the area where the highest rat density was recorded during the eradication process. Checks for signs of rats were also unsuccessful, thus confirming eradication success. Since November 2000, neither rats nor signs of rat activity have been recorded either on the main island or on islets, and none of the baits in the permanent bait stations have been touched.

A total effort of 510 person-hours was invested in control during 4 yr over the 25 yr period (Table 1). The number of person-hours per sub-colony decreased from 180 to 30 between 1989 and 1994, but stabilised during the 2 last operations. This variation was linked to increasing ranger experience in rat management. Consequently, we estimated effort, first for untrained staff based on the 1989 value, and second for trained staff based on the 1994 figure, and showed that 240 or 1440 person-hours (trained and untrained staff, respectively) would be required annually in order to control rats in the 8 Cory's shearwater sub-colonies.

The total number of person-hours required to eradicate rats by trained staff was 1312 (Table 1), to which must be added a year of effort for the monthly checking of the permanent bait-station system (48 person-hours yr^{-1}), for a total of 1360.

Cory's shearwater

The number of nests checked per year and per colony is given in Table 2. Breeding success varied greatly among years, and to lesser extent, sub-colonies, presumably in relation to interannual and local variations in rat density and behaviour (Fig. 2). Breeding success before eradication varied significantly among years and sub-colonies (year effect: χ^2 = 363, df = 21, p < 0.001; sub-colony effect: χ^2 = 168, df = 4, p < 0.001; interaction: χ^2 = 376, df = 84, p < 0.001). This result was the same if data collected after eradication were added. Although the year effect was the most important after eradication, all sub-colonies reached the same level of very high breeding success (Fig. 2).

Table 2. *Calonectris diomedea*. Number of Lavezzu Island Cory's shearwater nests checked per year and per sub-colony (sub-colony numbers as in Fig. 1). Bold: values under rat control; bold and italic: values after rat eradication

Year	Sub-colony 0	1	3	5	8	Total
1978	21	25	10	33	20	109
1979	24	29	13	53	34	153
1980	26	27	11	52	33	149
1981	28	28	13	55	37	161
1982	24	26	13	57	34	154
1983	28	29	15	58	35	165
1984	30	27	15	55	26	153
1985	31	27	16	59	34	167
1986	32	30	16	55	30	163
1987	34	31	18	57	29	169
1988	34	35	20	56	36	181
1989	33	33	20	54	**38**	178
1990	32	32	18	54	37	173
1991	7	34	19	49	35	144
1992	30	35	20	**52**	34	171
1993	9	**36**	**18**	**56**	32	151
1994	**15**	**40**	**14**	**51**	**26**	**146**
1995	16	38	15	42	27	138
1996	14	41	12	48	22	137
1997	15	44	15	46	22	142
1998	13	33	15	41	19	121
1999	15	37	16	51	21	140
2000	13	30	9	26	15	93
2001	***15***	***40***	***15***	***49***	***18***	***137***
2002	***21***	***55***	***17***	***50***	***25***	***168***
2003	***22***	***50***	***21***	***53***	***19***	***165***
2004	***23***	***58***	***22***	***50***	***27***	***180***
Total	605	950	426	1362	765	4108

Significant differences in breeding success were detected when we compared breeding success before eradication, between sub-colonies where rats were controlled and those where they were not (Table 3). We found a strong significant effect of rat management (Table 3), and a significant interaction between years and rat management, suggesting that rat impact differed according to year, presumably again in relation to rat density. After eradication (hence including the years 2001 to 2004), the model changed slightly, showing a significant interaction between rat management and sub-colony. This underlined the fact that all sub-colonies achieved higher (and more or less equal) breeding success, irrespective of year (after 2000) and sub-colony (Fig. 2). On average, breeding success doubled when rats were controlled or eradicated when compared to breeding success without rat management (0.82 ± 0.10 SD compared to 0.45 ± 0.27 SD). Moreover, rat eradication significantly improved breeding success of Cory's shearwater beyond the breeding success recorded when rats were only controlled (0.75 ± 0.15 SD for control versus 0.86 ± 0.05 SD for eradication; $\chi^2 = 385$, df = 2, $p < 0.001$) (Fig. 2).

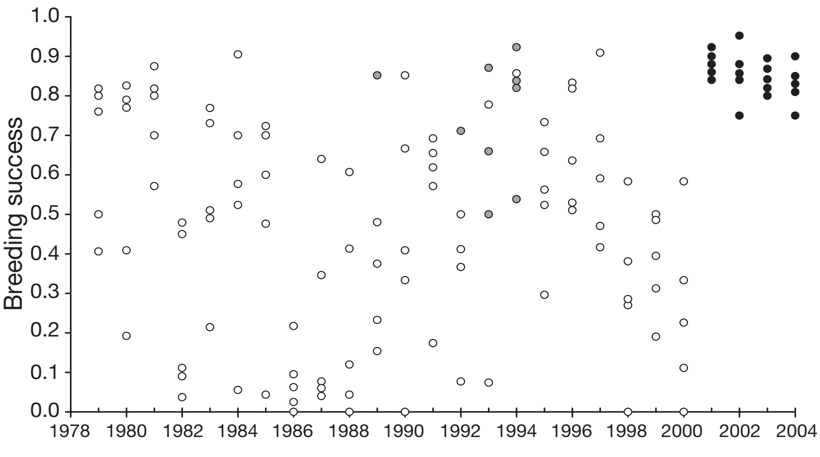

Fig. 2. *Calonectris diomedea*. Cory's shearwater breeding success in the 5 sub-colonies under study according to year and rat management options showing breeding success at sub-colony level without rat management (○), with rat control (●) and after rat eradication (●)

DISCUSSION AND CONCLUSIONS

Comparing rat eradication and rat control costs

Rat eradication on the main island and its peripheral islets, and monthly checking of permanent bait-stations during the year following eradication required 1360 person-hours (trained staff). Once eradication was achieved, 8 to 16 person-hours of yearly effort (depending on whether checks were made 2 or 4 times a year) must be added for maintaining and monitoring the system. By comparison, the yearly effort needed to control the 8 sub-colonies (i.e. the whole breeding Cory's shearwater population) would vary from 1440 to 240 person-hours, depending on whether the work was performed by untrained or trained staff, respectively. The better performance of trained compared to untrained staff may seem to be a trivial result. However, many current control or eradication projects employ untrained operators. The magnitude of difference that we observed between the 2 situations should encourage managers to use only trained staff. Depending on staff experience, full eradication followed by post-eradication monitoring equates to between 1 and 5 or 6 yr of annual control. If only economic cost is taken into account, the ship rat eradication program on Lavezzu Island was more economical than the control

Table 3. Results of Generalized Linear Models for Cory's shearwater breeding success under 2 different rat management options. ns: not significant

Factor	Before eradication (1978–1999)			Including eradication (1978–2004)		
	df	χ^2	p-value	df	χ^2	p-value
Rat management	1	26.9	<0.001	1	29.7	<0.001
Sub-colony	4	132.1	<0.001	4	137.2	<0.001
Year	21	457.7	<0.001	24	480.4	<0.001
Sub-colony × Rat management	2	1.1	0.6 (ns)	6	60.8	<0.001
Year × Rat management	3	13.8	<0.01	2	13.7	<0.01

program after only 6 yr. Once again, such a result may appear trivial *a posteriori*, but gives an idea of the return on investment for both strategies. Moreover, the eradication strategy we used for the reasons outlined in 'Materials and methods' is fairly labour intensive compared to the improved strategy consisting of hand or aerial broadcasting of toxic baits for example (Towns & Broome 2003). No doubt using these methods would greatly increase the economic advantages of eradication if compared to control.

Comparing the ecological benefits of eradication and control

Comparison of Cory's shearwater breeding success with (0.82) and without (0.45; see also Thibault 1995) rat control demonstrates the detrimental effect of these rodents. A similar increase in breeding success after rat control or eradication was previously recorded for Cory's shearwater in Cabrera Island (Balearics Archipelago; Amengual & Aguilar 1998) and in Congreso Island (Chafarinas Islands; Igual et al. 2006). Such a result was also obtained for Audubon's shearwater *Puffinus lherminieri* in the Sainte-Anne islets (Martinique Island, French West Indies) where breeding success increased from 0 before eradication to 85–90% after eradication (Pascal et al. 2003). During the 4 yr following Lavezzu ship rat eradication, breeding success was not only higher, but also more homogeneous among sub-colonies and years compared to previous years without rat management (coefficient of variation, CV = 6.8 vs. 63.9%). Moreover, breeding success was significantly (11%) higher when rats were eradicated than when rats were only controlled, suggesting that control did not totally prevent the detrimental effects of rats. Igual et al. (2006) observed similar variation of Cory's shearwater breeding success among sub-colonies of the Chafarinas Islands despite rat control. They suggested that rat impact differed among the 2 investigated habitats, being higher in vegetated than in rocky habitats. As all of the Cory's shearwater sub-colonies of Lavezzu Island are located in rocky habitats, the explanation given for Chafarinas Islands is inconsistent with our results for Lavezzu. Nevertheless, variations in rat density or in rat predation behaviour identified by Igual et al. (2006) were attributed to variations in breeding site anti-predation quality. Igual et al. (2007) explained these variations in their 'evolutionary trap' theory, which may explain variation of Cory's shearwater breeding success among Lavezzu Island sub-colonies. The great variation of breeding success among years and sub-colonies without rat control suggests that measuring rat impact on reproductive success of seabird colonies in such situations requires several years of data. Data collected during 1 yr alone may lead to the wrong conclusion, for example that rats have no impact.

In the medium term, additional positive effects are expected from rat eradication. Examples include an indirect effect of increasing breeding success on mate fidelity, as found by Thibault (1994) for Cory's shearwater and Bried & Jouventin (1999) for white-chinned petrel *Procellaria aequinoctialis*, or an increase in the number of breeding pairs through either immigration or better local recruitment. However, the last scenario would require about 10 yr, given the fledglings' long delayed sexual maturation (Thibault et al. 1997). It is also likely that pairs prevented from breeding early in the season because of disturbance by rats, will now be able to breed on the rat-free island, and that further nesting places which were previously unsuitable because of the presence of rats will now be available.

Long-term strategy: balancing costs and benefits

Many Cory's shearwater colonies are currently under pressure from ship rats or other alien mammals (Martin et al. 2000). Published breeding success assessments are thus usually rather low (but see Bayle & Fernandez (1992) for Frioul Island off Marseilles, with a value of 0.85, n = 321). Breeding success on the mammal-free Selvagem Islands (Madeira Archipelago, Atlantic Ocean) is also low (0.59, n = 3289; Mougin et al. 1993), but here the low rates are related to predation by yellow-legged gulls *Larus cachinnans*. Although ship rats have been present on Lavezzu for a long time, the Cory's shearwater breeding population has survived and remained stable during the last 25 yr (Thibault & Bonaccorsi 1999). Although they reduced breeding success, rats did not induce local extinction of the species. Until recently, the great auk *Pinguinus impennis* was the only western Palaearctic seabird known to have become extinct in the past 1000 yr (Fuller 2000) and to have disappeared from western Europe since the Bronze Age (Lehnebach 2003, Pascal et al. 2006). Since, despite the long-standing and widespread introduction of rats (Alcover et al. 1992, Milberg & Tiberg 1993, Vigne et al. 1997, Zotier et al. 1999), no western Palaearctic seabird has been recorded as extinct. But very recently, Rando & Alcover (2007) showed that the Lava shearwater *Puffinus olsoni*, which was endemic to the Canary Islands, was still present between 1240 and 1475 AD and became extinct after Europeans reached the archipelago in the early 14th century. Rando & Alcover (2007) strongly suggest that Europeans and species they introduced, such as rats, cats and mice, accelerated initial declines induced by earlier inhabitants who arrived before 2000 BC. However, there are many Mediterranean islands that are currently inhabited by both rats and Cory's shearwaters (see references in Martin et al. 2000), thus suggesting that Cory's shearwater is an atypical and interesting model. However, the Lava shearwater example shows that extinction may be induced by the sum of several aggressive events distributed along time, the last one being often the only one documented. As Mediterranean islands are currently under increasing pressure from various human activities, such a scenario may occur within a brief period of time, and any management operations that improve population health must be promoted.

Our cost–benefit comparison strongly suggests that eradication is preferable to control. Moreover, eradication provides additional advantages, since it affects other organisms such as ground-nesting birds, reptiles, insects, snails, and plants, which unlike Cory's shearwater, are actually eliminated by rats. It thus provides a new island for colonisation by locally extinct or endangered species that cannot sustain their populations if rats are present. For example, although founding new populations could be a long process for long-lived colonial birds, several Mediterranean species, such as pallid swift *Apus pallidus*, storm petrel *Hydrobates pelagicus* or Mediterranean shearwater *Puffinus yelkouan* may be candidates for increasing or establishing populations in Lavezzu Island. Furthermore, eradication requires only one, admittedly major, ecosystem disturbance, whereas partial control produces detrimental effects annually. Finally, eradication requires a single effort, in contrast to the perennial financial support required to perform yearly control operations.

Another issue that must be considered when weighing up the benefits of eradication and control is the potential emergence of rodenticide resistance during long-term control campaigns. Such resistance appeared 11 yr (1958) after the first use of warfarin, the first anticoagulant rodenticide (Lund 1964, Greaves 1971, Jackson et al. 1975). Moreover, resistance appeared again when the second-generation anticoagulants were used (Lund 1984, Greaves 1994). Relationships have been documented between resistance and genetics (Greaves et al. 1977), resistance and reproduction (Bishop et al. 1977, Partridge 1979), and resistance and an increase in the need for vitamin K in resistant rodents (Greaves 1994). These relationships suggest that resistance is potentially present in every rodent population, thanks to the coevolution between plants that produce anticoagulants such as coumarin and rodent consumers. This resistance can nullify the benefits of control and limits options to plan for future eradication.

One final issue to be considered is the risk that rats may recolonise after eradication. On Lavezzu Island, this risk may be high, owing to the disembarkation of ca. 150 000 tourists per year, and the anchoring of ca. 4000 ships in summer. To deal with this, we suggested establishing a rat-proof wharf and a permanent bait-station system. The recolonisation issue also means that choosing between control and eradication must take into account the risk of reintroduction by humans, and we advise that eradication in areas where human pressure is high (i.e. many small and medium-sized Mediterranean islands) should be chosen only for protected and actively managed areas. Indeed, when eradication is not feasible, control remains a useful management tool.

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