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A review of mammal eradications on Mediterranean islands

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ABSTRACT

1. Impacts of alien invasive species on island communities and ecosystems may be even more detrimental than on the mainland. Therefore, since the 1950s, hundreds of restoration projects have been implemented worldwide, with the aim of controlling or eradicating alien species from islands. To date, no review has been focused on eradication on Mediterranean islands. To fill the gap, I reviewed the available information concerning mammal eradications so far carried out on Mediterranean islands, examining the details of several aspects of project implementation and monitoring.
2. I obtained data for 139 attempted eradications on 107 Mediterranean islands in eight countries, with Greece, Italy, and Spain accounting for the highest number. Eradication projects targeted 13 mammal species. The black rat *Rattus rattus* was the target of over 75% of the known attempted eradications in the Mediterranean Basin; other species targeted were feral goat *Capra hircus*, house mouse *Mus musculus*, European rabbit *Oryctolagus cuniculus*, and domestic cat *Felis catus*. The most widely adopted technique was poisoning (77% of all eradications), followed by trapping (15%) and hunting (4%). However, techniques were largely target-specific.
3. The average failure rate was about 11%. However, this percentage varied according to the specific mammalian order, and eradications of Carnivora failed more often than those of other mammals. Among rodents, house mouse eradication attained a very high failure rate (75%). Reinvasion occurred after 15% of successful eradications.
4. A better understanding of the motivations of animal rights activists may improve the chance of success when eradicating charismatic or domesticated species. Furthermore, it is crucial to collect data and case studies about re-invasions, in order to strengthen biosecurity programmes following eradication. As in other parts of the world, the next frontier in alien mammal management on Mediterranean islands concerns the eradication of invasive species from inhabited islands.

INTRODUCTION

Biological invasions can lead to alterations of native communities and ecosystem functioning. For instance, alien species are the second most relevant cause of extinctions after habitat alteration and destruction (Bellard et al. 2016b). Island ecosystems are especially prone to the negative consequences of alien species introductions (see, e.g. Bellard et al. 2016a, Holmes et al. 2019), and control or eradication of invasive alien species is widely recommended and undertaken by researchers and conservation organisations to mitigate the impact of introduced invasive species (Russell et al. 2017). Among invasive alien species, mammals have an important role: as an example, 14 out of 100 species considered highly invasive by experts are mammals (Luque et al. 2014). Furthermore, Bellard et al. (2016b) included six mammal species in the top seven invasive alien species threatening terrestrial vertebrates. Invasive mammalian predators such as rats (*Rattus* spp.), cats (*Felis* spp.), mongooses (Herpestidae), and stoats (*Mustela* spp.) have a

pervasive impact on island biodiversity, leading to rarefaction and extinction of endemic species (Doherty et al. 2016).

Due to their natural isolation, islands are ideal places to carry out restoration projects by eradicating invasive alien species. Since the 1950s, many eradications have taken place on islands all over the world, allowing researchers to gain experience through the analysis of successes and failures that have occurred over the years. Benefits deriving to island native ecosystems from the eradication of alien species have also been widely documented (see, e.g. Towns et al. 2006, Jones et al. 2016). However, reviews of these restoration projects on a larger scale (e.g. Nogales et al. 2004, Campbell & Donlan 2005, Howald et al. 2007) have often shown that such actions should be evaluated in their biogeographic context, which, depending on the regions where eradications take place, has specific characteristics and peculiarities. So far, attention has been paid especially to eradications carried out in Australasia and in Tropical regions, in view of the many actions carried out there and the problems shared by them (Burbidge & Morris 2002, Clout & Russell 2006, Keitt et al. 2015, Russell & Holmes 2015).

A summary of available knowledge could be especially helpful when planning restoration projects, to help researchers choose materials and strategies and adopt the appropriate monitoring and biosecurity measures. Eradication projects are funded via different channels, but a major part of them are carried out with public resources. For instance, in the European Union, many projects have been funded by the EU Life Programme (Scalera 2010), but protected areas and regional or central administrations are often willing to finance or co-finance restoration projects in their territory.

To date, islands of the Mediterranean Basin have not been subjected to a comprehensive review, despite their ecological, geographical, and socio-economic contexts differing substantially from those in other biogeographical regions, with relevant implications that influence management strategy (Ruffino et al. 2009, Sposimo et al. 2019).

The Mediterranean Basin is included in three continents, with more than twenty countries sharing its shores, and it is one of the global biodiversity hotspots (Myers et al. 2000). Islands of Mediterranean Basin are characterised by hot, dry summers, and by mild winters. Compared with Oceanic islands, Mediterranean islands are very anthropised: they are very popular with tourists and, in many cases, they are inhabited throughout the year or for part of the year. Many islands host small settlements or villages and are served by regular or seasonal boat services.

In this paper, I reviewed the available information concerning mammal eradications so far carried out on Mediterranean islands. The specific purpose of the study is to examine the available details on several aspects of project implementation: from target species to management techniques, from the analyses of the benefits derived to species and ecosystems to the impact on non-target species, and from causes of failure to biosecurity aspects. My aim is to provide researchers, managers, and conservationists with a synthetic view of the current problems, methods, and trends with regard to eradication of invasive alien mammals in the Mediterranean Basin, thus establishing a firm point in the status of knowledge. The analysis may facilitate better planning of future interventions, mainly by orienting the strategies based on the results and the failures so far recorded. A further aim is to identify the areas in which knowledge should be improved, as well as the problems to be solved in order to increase the chances of conservation goals being achieved in future.

METHODS

It is not always easy to find information on environmental restoration procedures in the scientific literature. Thus, I compiled data from different sources. The primary sources of information were published accounts, such as reviews (e.g. see Campbell & Donlan 2005, Howald et al. 2007, Genovesi & Carnevali 2011, Keitt et al. 2011) and databases on eradication of alien invasive species from islands (DIISE 2019, http://diise.islandconservation.org). Additional data and information about specific actions were collected through consultation of the scientific literature. Since restoration projects often do not result in peer-reviewed publications, to obtain other data I searched for reports of the restoration projects available on the web. In cases of doubtful data, people involved in the projects were contacted to collect the missing information.

RESULTS

I obtained data for a total of 139 attempted mammal eradications from 107 Mediterranean islands. Detailed information about each eradication is given in Appendix S1. For operational reasons (i.e. to avoid quick reinvasion), in some cases mammals were eradicated simultaneously from a number of very close islands. For example, in Corsica, black rats *Rattus rattus* were eradicated from two larger islands and a number of very small islands around each (Lavezzu: main island plus 16 islets; Toro: main island plus three islets). In these cases, I adopted the criterion of DIISE (2019) and Genovesi and Carnevali (2011) by considering the main island as independent and grouping the small islets as a unique eradication.

The number of eradications attempted on the Mediterranean islands has increased over time (Fig. 1); 51 eradications were attempted in the decade 2001–2010. In

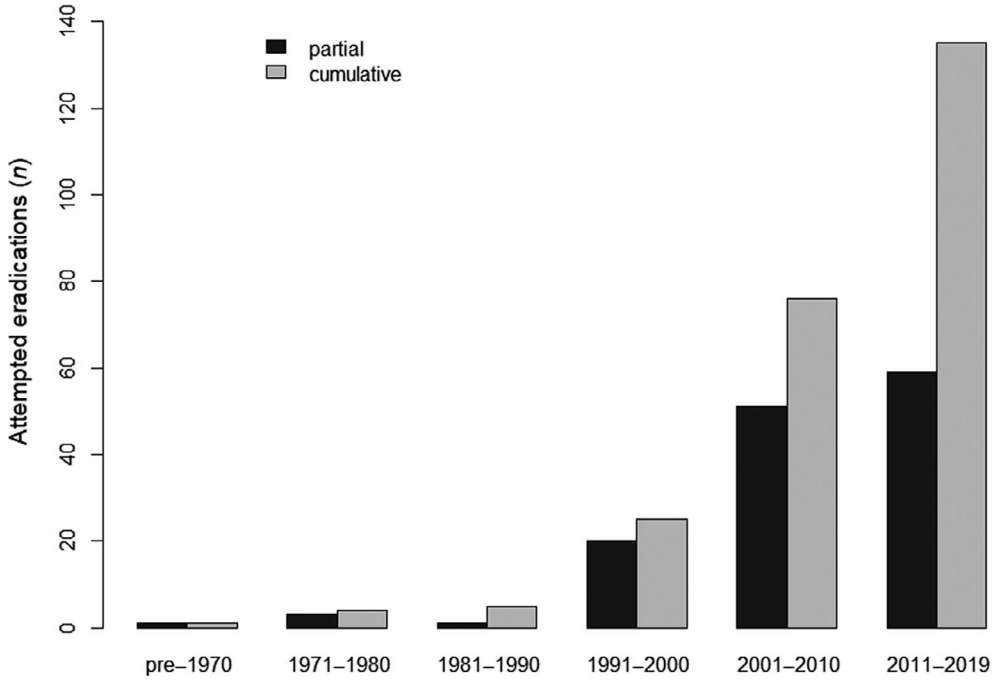

Fig. 1. Number of attempted eradications of invasive mammal species on Mediterranean islands, shown per decade since 1970.

the current decade, from 2011 to 2019, 59 interventions have so far been started, already exceeding the number in the previous decade. It is likely that some interventions that have just started have not yet been evidenced in databases or in publications, and therefore, it is likely that the total number will be even higher than that presented here.

Target species

In Mediterranean islands, eradications of 13 mammal species were recorded (Table 1). Rodents were the target of most eradications (n = 115), followed by Artiodactyla (n = 8), Carnivora, and Lagomorpha (n = 7). Two eradications targeted Erinaceomorpha. The black rat was eradicated from most islands (n = 105) in the Mediterranean Basin and accounts for over 75% of the known attempted eradications. Other species that have been targets of eradications are the feral goat *Capra hircus* (5% of attempted eradications), house mouse *Mus musculus* (4.3%), European rabbit *Orychtolagus cuniculus* (4.3%), and feral cat *Felis catus* (2.9%). More occasional targets were the Norway rat *Rattus norvegicus* (e.g. Canale et al. 2019) and the small Indian mongoose *Herpestes javanicus*, which was eradicated from two Croatian islands (Havar and Čiovo; Barun et al. 2011).

Country of eradication and island area

Mammal eradications took place in eight countries representing all three continents that surround the Mediterranean Basin. Europe had the highest number of projects with Greece (n = 47), Italy (n = 39), Spain (n = 29), and France (n = 16) leading. Eradications were also carried out in Croatia (n = 2) and Cyprus (n = 1). Outside Europe, eradication projects were carried out in Lebanon (n = 1) and Tunisia (n = 2).

Mammal eradications have been attempted on islands as large as 1000 km^2, as in the case of wild boar *Sus scrofa* eradication from the island of Cyprus, an attempt that appeared to be unsuccessful (Hadjisterkoti 2004). The largest islands where a successful eradication was completed were Cabrera Gran (1203 ha), where feral goats were eradicated in the 1940s, and Montecristo (1050 ha), cleared of both black rats and European rabbits in 2012 (Sposimo et al. 2019). Wild cats were eradicated from Pianosa (1025 ha), while the only island so far cleared of house mice was Dragonera (243 ha). Islands where eradication failed (median 145 ha, min: 2 ha; max: 924927 ha) were significantly larger than islands where it was successful (median 3.2 ha, min: 0.1 ha; max: 1203 ha; Kruskal–Wallis test: H = 9.92, d.f. = 1, P < 0.002).

Eradication techniques

Considering the primary eradication technique (i.e. the main method used in any given eradication, see Fig. 2), poisoning was the most widely adopted method (77% of eradications), followed by trapping (15%) and hunting (4.3%). For some eradications (3.6%), I had no data about eradication method. As expected, eradication techniques were largely

Table 1. Number of attempted eradications on Mediterranean islands for the various mammal species in relation to the outcome (successful, successful but reinvaded, failed, incomplete) or the status (in progress, to be confirmed)

		Outcome/status						
Common name	Scientific name	Successful	Successful but reinvaded	Failed	To be confirmed	In progress	Incomplete	Total
Wood mouse	*Apodemus sylvaticus*			1				1
Algerian hedgehog	*Atelerix algirus*			1				1
Feral goat	*Capra hircus*	5		1		1		7
European hedgehog	*Erinaceus europaeus*					1		1
Feral cat	*Felis catus*	2		2				4
Common genet	*Genetta genetta*			1				1
Small Indian mongoose	*Herpestes auropunctatus*					2		2
Brown hare	*Lepus europaeus*						1	1
House mouse	*Mus musculus*	1		3	1	1		6
European rabbit	*Oryctolagus cuniculus*	5		1				6
Brown rat	*Rattus norvegicus*	3						3
Black rat	*Rattus rattus*	73	16	2	7	7		105
Wild boar	*Sus scrofa*			1				1
Total		89	16	13	8	12	1	139

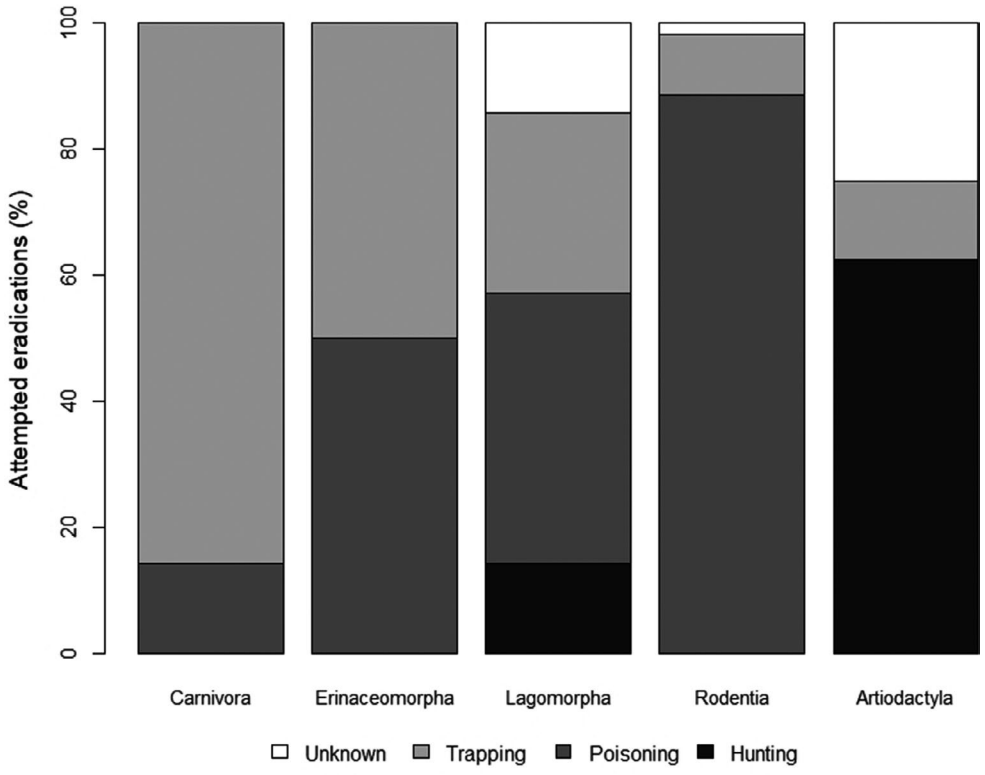

Fig. 2. Percentage of attempted eradication campaigns for each mammalian order, by control technique (Carnivora, *n* = 7, Erinaceomorpha, *n* = 2, Lagomorpha, *n* = 7, Rodentia, *n* = 115, Artiodactyla, *n* = 8, total *n* = 139).

taxon-specific (chi-square test: $P < 0.01$). Hunting has been chosen only for Artiodactyla and Lagomorpha, while poisoning was mainly used against Rodentia, accounting for 89% of rodent eradications. Poisoning was also used against the small Indian mongoose in Croatia, although this technique is reported to be illegal against mongooses (Barun

et al. 2011). Trapping appeared to be a more versatile technique, used against all mammal orders, although with different frequencies. Trapping is not widespread as a main technique against rats, except in France, where it has been widely used (in combination with rodenticides as a secondary technique) for eradicating rats on small islands around Corsica (Lorvelec & Pascal 2005).

Secondary eradication techniques were used in only a small number of eradications (n = 17, 12%), which were mainly rat eradications. In 13 out of 15 rat eradications carried out in France, trapping and poisoning were used in combination, to reduce the amount of poison released into the environment (Lorvelec & Pascal 2005). When considering both primary and secondary eradication methods, poisons were used in 100% of rodent eradications. Other case studies were the feral goat eradication at Lavezzu (France, hunting and trapping), and the attempt to eradicate wild boar from Cyprus (hunting and trapping). This suggests that the simultaneous use of two techniques is not a widespread strategy for invasive species eradication (e.g. see Capizzi et al. 2014), at least on Mediterranean islands.

Poison baiting techniques

Poison was used in almost all rodent eradications. The most used common baiting technique was placing bait stations (containers designed to protect bait from atmospheric agents and non-target species, used in 76% of eradications adopting poisons as primary method), followed by hand broadcast of bait (12%), while aerial baiting was used in only 7.5% of attempted eradications. In a number of cases, the technique was not indicated (4.7%). Aerial baiting was adopted in a limited number of eradications, but it was, so far, 100% successful (Table 2), allowing the removal of black rats and European rabbits from the largest island (Montecristo; see Sposimo et al. 2019), and the only successful action against house mice (Dragonera, see Mayol et al. 2012). On some Italian islands (Zannone, Ventotene and Palmarola), to avoid risks for non-target fauna, biodegradable bait containers were delivered by helicopter in otherwise inaccessible areas (Capizzi et al. 2019).

Active ingredient in bait

When poisoning is the main technique, the choice of the active ingredient should maximise effectiveness by minimising the undesirable effects. Although in several cases (n = 11, 9.6%) the active ingredient was not indicated in the report, the available information showed that in the Mediterranean islands only anticoagulants were used. This is not surprising, since in last 20 years the only rodenticides available on the European market are anticoagulants. The anticoagulants used were always of the second generation (i.e. the most potent ones, active at a single dose), with the sole exception of the first generation (i.e. less potent, much more effective when multiple doses have been consumed) coumatetralyl and chlorophacinone, used in some cases against the black rat. Brodifacoum was the most commonly used poison (in 65% of eradications attempted with poison), being the only poison used against house mice and brown rats, and often chosen also against black rat. Bromadiolone was used in about 15% of the poison-based eradications.

Sometimes, two different anticoagulants were used, and then the most common secondary active ingredient was bromadiolone. Two different anticoagulants were used to reduce risks for non-target species on Linosa and Ventotene (see Capizzi et al. 2019). Specifically, the aim was to reduce the risks to domestic cats: the less toxic bromadiolone was used in the first distributions to reduce the rodent population, reserving brodifacoum for when the presence of rodents was very low, thus greatly reducing the risk of secondary poisoning.

Impacts on non-target species

Very few data are available concerning the impact on non-target species. Capizzi et al. (2016) presented evidence of limited (if any) impacts on several non-target species deriving from eradicating rats from 12 Italian islands, with documented loss of specimens only for gulls *Larus michaellis*, barn owl *Tyto alba*, and feral goats. However, no impact at a population level has been so far documented (Capizzi et al. 2016). Conversely, lizards, geckoes, and snakes showed no impact, in some cases increasing in numbers (Capizzi et al. 2016). Luiselli et al. (2015) hypothesised a possible lowering of average body size of asp viper *Vipera aspis* on Montecristo, due to the lack of mammal prey following black rat eradication. Concerns were raised, despite vipers being introduced to Montecristo by humans, possibly between VIII and III century BC from Sicily (Barbanera et al. 2009, Masseti & Zuffi 2011). Masseti (2016) complained that the goat population of Montecristo has been drastically reduced following the implementation of rat eradication, also claiming damage to the genetic heritage of the same population. However, data from the National Park of Tuscan Archipelago (F. Giannini, personal communication) indicate that goats are now abundant on the island.

Impacts of invasive species and benefits of their removal for species and ecosystems

Showing impacts of alien species and benefits deriving to species and ecosystems from their removal is crucial for

Table 2. Baiting techniques adopted in poison-based mammal eradications so far concluded on Mediterranean islands, in relation to the target species and outcome of the project

	Failed		Successful		
	n	%	*n*	%	Total
Aerial broadcast					
Overall	–	0	7	100	7
Mus musculus	–	0	1	100	1
Oryctolagus cuniculus	–	0	2	100	2
Rattus rattus	–	0	4	100	4
Bait station					
Overall	4	5.3	71	94.7	75
Apodemus sylvaticus	1	100	–	0	1
Atelerix algirus	1	100	–	0	1
Mus musculus	1	100	–	0	1
Oryctolagus cuniculus	–	0	1	100	1
Rattus norvegicus	–	0	3	100	3
Rattus rattus	1	1.5	67	98.5	68
Hand broadcast					
Overall	2	14.3	12	85.7	14
Mus musculus	2	100	–	0	2
Rattus rattus	–	0	12	100	12
Total	6	6.2	90	93.8	96

gaining consensus for eradication actions and to marginalise denialism (e.g. Jones et al. 2016, Russell & Blackburn 2017). Several studies assessed the benefits derived from mammal eradication. Most work was carried out regarding the black rat, but some papers dealt also with feral cats, mainly focusing on the impact of the eradication target species on a single species of conservation interest. The most studied species were Cory's shearwaters *Calonectris diomedea*, yelkouan shearwaters *Puffinus yelkouan*, and storm petrels *Hydrobates pelagicus*. Rat and cat predation on chicks and, in some cases, eggs may have a detrimental impact on reproductive success (for rats: Ruffino et al. 2009, Capizzi et al. 2016; for cats: Bonnaud et al. 2011, Medina et al. 2011, Bonnaud et al. 2012, Ozella et al. 2016). Following predator removal, damage stopped completely, and bird reproductive success immediately settled at physiological levels (Martin et al. 2000, Igual et al. 2006, Bonnaud et al. 2011). Increases in the size of nesting population have also been recorded after eradication (e.g. Bourgeois et al. 2013). On Greek islands, an increase of the reproductive success of the endangered Eleonora's falcon *Falco eleonorae* following rat removal was reported (Hellenic Ornithological Society 2006).

On Tavolara (north-east of Sardinia), the removal of black rats resulted in a sudden increase of the population of the Etruscan shrew *Suncus etruscus* (P. Sposimo, personal communication). Although the shrew is itself an alien species, the increase in shrews demonstrates that removing rats may offer advantages to other species.

A few studies have focused on the impact of invasive species on multiple taxa. Ruffino et al. (2014) investigated the benefits of removing rats together with the invasive ice plants *Carpobrotus* spp. from Bagaud Island (France). Benefits to birds, lizards, insects, and plants were considered, thus focusing the attention on a food web rather than on individual taxa. The authors stressed the importance of long-term monitoring of various native plants and animals. Weber (2014) devoted a strong research effort to birds, invertebrates, and plants, but found few (if any) benefits deriving from the eradication of black rats from eight Greek islands, probably due to the short time elapsed since rat removal.

Successes, reinvasions, and failures

Among completed eradications (n = 118), most were successful (105), but 16 islands were reinvaded (Table 3). Reinvasion occurred only in the case of rodent eradication. Although it is not always easy to establish the causes of the reinvasion, most of the reinvaded islands were close enough to the rat-inhabited mainland or other islands to be accessible by swimming rats. In the case of Molara, reinvaded after a successful black rat eradication, sabotage of the eradication by humans was the most likely hypothesis (Ragionieri et al. 2013).

Of all attempted eradications, 11% ended in failure. Attempted eradications of Carnivora failed (n = 3) more often than expected by chance (χ^2 = 4.615, d.f. = 1, P = 0.03). Attempted eradications of Rodentia failed on six occasions (5.2%). Two failures were recorded for Artiodactyla, one for each of Lagomorpha and Erinaceomorpha; the latter was the only concluded attempted eradication. As regards the Lagomorpha, eradication of the brown hare *Lepus europaeus* from Pianosa (Italy, Tuscan Archipelago) was stopped in the initial phase because genetic analysis showed that the hare population belonged to the autochthonous genotype of the Italian peninsula, now extinct due to the continuous input of

Table 3. Outcome of completed mammal eradications (i.e. not in progress, incomplete, or to be confirmed, n = 118) on Mediterranean islands. For each mammalian order, numbers and percentage of failures, successes, and reinvasions are given

	Failed		Successful		Reinvaded		Total
Order	*n*	%	*n*	%	*n*	%	*n*
Carnivora	3	60.0	2	40.0	–	–	5
Lagomorpha	1	16.7	5	83.3	–	–	6
Rodentia	6	6.1	77	77.8	16	16.2	99
Erinaceomorpha	1	100	–	–	–	–	1
Artiodactyla	2	28.6	5	71.4	–	–	7
Total	13	11.0	89	75.4	16	13.6	118

specimens from other countries or continents (Mengoni et al. 2018).

Biosecurity issues

Biosecurity is critical in preventing alien species invasions on islands, as well as in protecting from reinvasion those islands where they have been eradicated (see, e.g. Russell et al. 2017). However, despite reinvasion often occurring on Mediterranean islands, very little information was available about biosecurity. In 15 cases on Italian islands (P. Sposimo, personal communication) and eight on Greek islands (J. Fric and C. Kassara, personal communication), networks of bait stations containing rodenticide bait were established at the main boat landing points to prevent rat reinvasions. So far, the technique was apparently successful. In Tavolara, a mixed system, based on both bait stations and trapping, has been established (P. Sposimo, personal communication). Apposite regulations for boats providing services between islands and the mainland were also adopted (F. Giannini and P. Sposimo, personal communication).

Communication aspects and public acceptance

Gaining and applying a good understanding of the social and political implications of an eradication strategy is often decisive in the context of environmental restoration projects (e.g. Perry 2004). For instance, the opposite views of animal rights activists and conservation biologists may cause conflicts, thus preventing restoration projects from achieving their goals. On Mediterranean islands, this has happened especially when dealing with large, charismatic, and domesticated species such as goats. In 2016, the protests of animal rights activists forced the eradication of feral goats from Vedrà (Balearic Islands) to stop, and there followed a legal procedure against politicians. In 2017, the eradication of goats from Palmaria (Italy) was stopped because of opposition of animal activists to the shooting of goats. After a revision, the intervention now seems to have been resumed with, instead of shooting, the capture and transport of animals to the mainland. Opposition has sometimes been encountered also towards the eradication of rats. In 2012, the eradication of the black rat from the island of Montecristo through aerial broadcast of rodenticide baits was the subject of protests, with parliamentary questions and appeals in court. However, the eradication was successfully completed in 2014 (Sposimo et al. 2019).

DISCUSSION

Significant results have so far been achieved through the eradication of invasive mammals from islands within the Mediterranean Basin. The techniques and strategies used, although subject to continuous adjustments, have largely proven to be effective, especially for rodents and lagomorphs. Monitoring has shown that eradications have resulted in important benefits for native species, especially marine birds, but also reptiles and other mammals. Although studies focusing on benefits at the ecosystem level are very few, it is reasonable to assume that other species and components may have benefitted from the eradication of invasive alien mammals. An important task for the future is to raise the level of monitoring, by focusing the analyses at an ecosystem level. The EU Life Programme, probably the most important source of funding for this kind of project (Scalera 2010), now requires monitoring of the restoration of ecosystem functions.

In most eradication projects targeting rodents, poison was used. When a toxicant is applied, it is necessary to choose a baiting technique balancing the effectiveness against the target species, the practical feasibility of distribution, and the risks for non-target species. Thus, placing bait stations is considered the most reliable technique, but this technique is suitable only when the island is largely accessible. Otherwise, in the case of large and/or rugged islands, aerial baiting may be more appropriate. A comparison of the percentage of islands where aerial baiting against rodents has been attempted in Europe and in the world (data from Howald et al. 2007) showed that the use of this technique is much less widespread in the Mediterranean (7.5% of attempted eradications) than it is recorded worldwide (22% of attempted eradications). When aerial baiting is used, the risks for non-target species should be carefully evaluated.

In the field of rodent eradication, it is necessary to improve the effectiveness of techniques against the house mouse. Evidence suggests that mice are more difficult to eradicate than rats, in line with the results from Oceanic islands (see MacKay et al. 2007). Given the short range of activity of the house mouse, eradication can only be achieved with capillary bait coverage of an island, either by aerial distribution over the whole island, or with high bait station density (stations spaced 20 m apart, instead of 50 m as is often done in the case of rat eradication). However, applying high bait station density is not always possible on rough, inaccessible islands, and the use of aerial baiting may be constrained by the specifications given on the product labels, which allow their use only in bait containers. In the European Union, aerial baiting requires the release of a derogation, which can be granted pursuant to article 55 of the EU biocidal product regulation no. 528/2012. The competent authorities must be aware of the importance of baiting actions, but this is not always the case: in Italy, for instance, the issue of the derogation for aerial baiting on Tavolara (where the

world's main colony of the Yelkouan shearwater lives, see Bourgeois et al. 2008) has led to a delay of one year in the action (Capizzi et al. 2019). In future, a widening of the available control strategies may offer improved probability of successful eradication of some invasive species, such as small Carnivora (e.g. Barun et al. 2011) and Artiodactyla (Cowan et al. 2020), which so far have been very difficult to eradicate with the means allowed. Combining these techniques with the use of spatially explicit models may make it possible to eradicate Artiodactyla and Carnivora from larger islands (Bertolino et al. 2020).

Although it is not always easy to establish the causes of reinvasion after eradication attempts, most of the reinvaded islands were close to the mainland or to other rat-inhabited islands (see, e.g. Capizzi et al. 2016). The maximum known swimming distances of black rats (750 m) and brown rats (>1000 m) suggest that only islands that are separated by over 2 km of open water are safe from incursion by swimming rats (Russell et al. 2008, Shiels et al 2014, Tabak et al. 2015a, Tabak et al. 2015b). I was not able to compare the reinvasion rate with other contexts, as these data are often lacking or are just included for failures (Howald et al. 2007). In this review, the apparent reinvasion rate of about 18% seems rather high, but reinvasion occurred only in rat eradications in islands close to the mainland or to rat-inhabited islands, with only one case of sabotage (Ragionieri et al. 2013). Therefore, the choice of islands for the implementation of rat eradication appears to be crucial. Molecular techniques should be adopted to establish whether the eradication failed, or the island was reinvaded, as, in the absence of these analyses, it is difficult to support one of the two hypotheses (Abdelkrim et al. 2007). Advances in genetics make it possible to improve the management of alien species by evidencing colonisation pathways, the presence of individuals resistant to anticoagulants, and the origins of reinvasions (Ragionieri et al. 2013, Browett et al. 2020). Significant improvements are expected in the field of biosecurity, at least for rodents, mainly via standardisation of techniques in order to strengthen biosecurity programmes following eradication, which would bring lasting benefits to ecosystems freed from rats. However, successes, failures, and setbacks that have followed over the years can offer important evidence of techniques that can be used successfully and those that need to be calibrated in the frame of adaptive management of alien species (see, e.g. Richardson et al. 2020).

The problem of opposition to eradications by animal rights activists should be faced with greater awareness (Blackburn et al. 2010), by including in eradication projects an accurate preliminary assessment of conservation objectives and risks for non-target species. In order to increase the available case studies, it is essential to publish an overview of each completed project, reporting techniques, objectives achieved, and effects (if any) on non-target species. These data are fundamental so that possible undesirable effects of the projects can be considered, and to allow researchers to reassure people or to take the appropriate countermeasures. Techniques capable of reducing the impact on non-target predators (for example the sequential use of rodenticides with different toxicities) are now available. Interactions with animal rights movements should be carried out in advance, and suitable professional figures (social scientists, ethicists) should be included in eradication project staff (Perry & Perry 2008). This is especially needed when dealing with charismatic, domesticated, or 'cute and furry' animals (Perry 2004). Dealing with protests during the implementation of the project can risk interrupting the actions before reaching the goal, as happened in the case of the eradications of goats in Spain and Italy. Opposition may not only come from activists, since even among researchers there are different opinions on the advisability of eradicating species that have been established on the islands for millennia, as in the case of goats (e.g. Masseti 2009). There are schools of thought contrary to eradications, from people believing that the damage deriving from eradications to local fauna is more serious than the impact that they may mitigate (e.g. Masseti 2016). It has been acknowledged that, over time, eradication action may reveal unforeseen problems. There may be a 'mesopredator release effect' (Courchamp et al. 1999), which predicts that, once a superpredator (e.g. feral cat) is controlled, a mesopredator (e.g. black rat) may show a sudden increase in its population. Another countereffect is the 'competitor release effect', which suggests that control of only one introduced species (e.g. the black rat) may result in an increase in populations of its competitor (e.g. the house mouse). Therefore, the ecological relationships between two or more alien species should be carefully considered when planning eradications on islands. When feasible, simultaneous eradication of two or more competing alien species may be more appropriate. This has been attempted on Pianosa, where cat removal was closely followed by rat and mouse eradication (Sposimo et al. 2019).

Although alternatives to eradication are available, for example containment or *ad libitum* control (see, e.g. Igual et al. 2006), in the medium and long term they may prove too expensive in terms of financial and labour costs and poisons released into the environment. These alternatives should only be adopted in cases in which eradication is not considered feasible (Capizzi et al. 2010, Mill et al. 2020).

The next frontier in alien mammal management on Mediterranean islands concerns eradications from inhabited islands (see, e.g. Oppel et al. 2011, Glen et al. 2013). In this case, the evaluation of the benefits cannot be carried out only at the level of species and ecosystems but must also include socio-economic viewpoints (Reaser et al. 2007).

For example, researchers should consider the reduction of damage to crops, the absence of pest-control activities following eradication (resulting in the use of less rodenticides in the long term), and the lowering of risks of humans and other animals contracting zoonoses (Capizzi et al. 2018, Fratini et al. 2020). Working on islands that host residents and pets requires a lot of caution in choosing the appropriate eradication techniques and materials that nevertheless allow significant results to be obtained, and also consideration of the consensus regarding these restoration projects, as in the case of black rat eradication at Ventotene in Italy (Capizzi et al. 2019). When planning and making decisions about eradications, it is also important to consider uncertainty in different aspects, such as the determination of costs, population size, detectability of invaders, as these aspects are crucial in determining the outcomes of eradications (Ward et al. 2020).

An important future output is a priority list, ranking Mediterranean islands in terms of cost-effectiveness of invasive mammal eradication and comparing benefits to the monetary costs, as has already been done for other contexts on a different scale (e.g. Brooke et al. 2007, Capizzi et al. 2010, Holmes et al. 2019). Prioritising conservation actions can be a strategic tool and a useful guide for managers, conservationists, and politicians, allowing them to convey limited resources to the worthiest restoration projects (Wilson et al. 2006, Helmstedt et al. 2016).

More objective criteria are also needed to define the choice of target species for eradications, so that island ecosystems can be relieved from the pressures of higher alien species diversity. So far, the choice has been made based on local needs and acquired experience, also taking into account public acceptance of the action and the effectiveness of the techniques. This has resulted in the eradication of a few species from many islands, as evidenced by the high percentage of successful black rat eradications. Ideally, multicriteria choices should be made in future, based on the impact and conservation benefits obtained at the level of the entire Mediterranean Basin, and also considering the socio-economic benefits for the resident human populations.

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REFERENCES

Abdelkrim J, Pascal M, Samadi S (2007) Establishing causes of eradication failure based on genetics: case study of ship rat eradication in Ste. Anne archipelago. *Conservation Biology* 21: 719–730.

Barbanera F, Zuffi MAL, Guerrini M, Gentilli A, Tofanelli S, Fasola M, Dini F (2009) Molecular phylogeography of the asp viper *Vipera aspis* (Linnaeus, 1758) in Italy: evidence for introgressive hybridisation and mitochondrial DNA capture. *Molecular Phylogenetics and Evolution* 52: 103–114.

Barun A, Hanson CC, Campbell KJ, Simberloff D (2011) A review of small Indian mongoose management and eradications on islands. In: Veitch CR, Clout MN, Towns DR (eds) *Island Invasives: Eradication and Management*, 17–25. IUCN, Gland, Switzerland.

Bellard C, Cassey P, Blackburn TM (2016a) Alien species as a driver of recent extinctions. *Biology Letters* 12: 20150623.

Bellard C, Genovesi P, Jeschke JM (2016b) Global patterns in threats to vertebrates by biological invasions. *Proceedings of the Royal Society B: Biological Sciences* 283: 2015245.

Bertolino S, Sciandra C, Bosso L, Russo D, Lurz PWW, Di Febbraro M (2020) Spatially explicit models as tools for implementing effective management strategies for invasive alien mammals. *Mammal Review* 50: 187–199.

Blackburn TM, Pettorelli N, Katzner T, Gompper ME, Mock K, Garner TWJ, Altwegg R, Redpath S, Gordon IJ (2010) Dying for conservation: eradicating invasive alien species in the face of opposition. *Animal Conservation* 13: 227–228.

Bonnaud E, Medina FM, Vidal E, Nogales M, Tershy B, Zavaleta E, Donlan CJ, Keitt B, Le Corre M, Horwath SV (2011) The diet of feral cats on islands: a review and a call for more studies. *Biological Invasions* 13: 581–603.

Bonnaud E, Berger G, Bourgeois K, Legrand J, Vidal E (2012) Predation by cats could lead to the extinction of the Mediterranean endemic Yelkouan shearwater *Puffinus yelkouan* at major breeding site. *Ibis* 154: 566–577.

Bourgeois K, Vidal E, Comor V, Legrand J, Dromzee S (2008) Colony-site selection drives management priorities for Yelkouan shearwater populations. *Journal of Wildlife Management* 72: 1188–1193.

Bourgeois K, Ouni R, Pascal M, Dromzée S, Fourcy D, Abiadh A (2013) Dramatic increase in the Zembretta Yelkouan shearwater breeding population following ship rat eradication spurs interest in managing a 1500-year old invasion. *Biological Invasions* 15: 475–482.

Brooke MdL, Hilton GM, Martins TLF (2007) Prioritizing the world's islands for vertebrate-eradication programmes. *Animal Conservation* 10: 380–390.

Browett SS, O'Meara DB, McDevitt AD (2020) Genetic tools in the management of invasive mammals: recent trends and future perspectives. *Mammal Review* 50: 200–210.

Burbidge AA, Morris KD (2002) Introduced mammal eradications for nature conservation on western Australian islands: a review. In: Veitch CR, Clout MN (eds) *Turning the Tide: the Eradication of Invasive Species*, 64–70. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland.

Campbell K, Donlan CJ (2005) Feral goat eradications on islands. *Conservation Biology* 19: 1362–1374.

Canale DE, Di Dio V, Massa B, Mori E (2019) First successful eradication of invasive Norway rats *Rattus norvegicus* from a small Mediterranean island (Isola delle Femmine, Italy). *Folia Zoologica* 68: 29–34.

Capizzi D, Baccetti N, Sposimo P (2010) Prioritizing rat eradication on islands by cost and effectiveness to protect nesting seabirds. *Biological Conservation* 14: 1716–1727.

Capizzi D, Bertolino S, Mortelliti A (2014) Rating the rat: global patterns and research priorities in impacts and management of rodent pests. *Mammal Review* 44: 148–162.

Capizzi D, Baccetti N, Sposimo P (2016) Fifteen years of rat eradication on Italian islands. In: Angelici FM (ed) *Problematic Wildlife*, 205–227. Springer International Publishing, Basel, Switzerland.

Capizzi D, Monaco A, Genovesi P, Scalera R, Carnevali L (2018) Impact of alien mammals on human health. In: Mazza G, Tricarico E (eds) *Invasive Species and Human Health*, 130–150. CABI International Edition, New York, New York, USA.

Capizzi D, Sposimo P, Sozio G, Petrassi F, Gotti C, Raganella Pelliccioni E, Baccetti N (2019) Black rat eradication on Italian islands: planning forward by looking backward. In: Veitch CR, Clout MN, Martin AR, Russell JC, West CJ (eds) *Island Invasives: Scaling up to Meet the Challenge*, 15–20. Occasional Paper SSC no. 62, IUCN, Gland, Switzerland.

Clout MN, Russell JC (2006) The eradication of introduced mammals from New Zealand Islands. In: Koike F, Clout MN, Kawamichi M, De Poorter M, Iwatsuki K (eds) *Assessment and Control of Biological Invasion Risks*, 127–141. Shoukadoh Book Sellers, Kyoto, Japan and IUCN, Gland, Switzerland.

Courchamp F, Langlais M, Sugihara G (1999) Cats protecting birds: modelling the mesopredator release effect. *Journal of Animal Ecology* 68: 282–292.

Cowan DP, van der Waal Z, Pidcock S, Gomm M, Stephens N, Brash M, White PCL, Mair L, Mill AC (2020) Adaptive management of an iconic invasive goat *Capra hircus* population. *Mammal Review* 50: 200–210.

DIISE (2019) *The Database of Island Invasive Species Eradications, Developed by Island Conservation, Coastal Conservation Action Laboratory UCSC, IUCN SSC Invasive Species Specialist Group, University of Auckland and Landcare Research New Zealand*. http://diise.islandconservation.org. Accessed: 9/2/2019.

Doherty TS, Glen AS, Nimmo DG, Ritchie EG, Dickman CR (2016) Invasive predators and global biodiversity loss. *Proceedings of the National Academy of Sciences of the United States of America* 113: 11261–11265.

Fratini S, Natali C, Zanet S, Iannucci A, Capizzi D, Sinibaldi I, Sposimo P, Ciofi C (2020) Assessment of rodenticide resistance, eradication units, and pathogen prevalence in black rat populations from a Mediterranean biodiversity hotspot (Pontine Archipelago). *Biological Invasions*. https://doi.org/10.1007/s10530-019-02189-1

Genovesi P, Carnevali L (2011) Invasive alien species on European islands: eradications and priorities for future work. In: Veitch CR, Clout MN, Towns DR (eds) *Island Invasives: Eradication and Management*, 56–62. IUCN, Gland, Switzerland.

Glen AS, Atkinson R, Campbell KJ, Hagen E, Holmes ND, Keitt BS et al. (2013) Eradicating multiple invasive species on inhabited islands: the next big step in island restoration? *Biological Invasions* 15: 2589–2603.

Hadjisterkoti E (2004) The introduction of wild boar *Sus scrofa* L. on the island of Cyprus. *Galemys* 16: 233–242.

Hellenic Ornithological Society (2006) *Rat Eradication in the National Marine Park of the Northern Sporades*. Project Life Nature 2003 Conservation Measures for Falco eleonorae in Greece. www.ornithologiki.gr. Accessed: 20/03/2019.

Helmstedt KJ, Shaw JD, Bode M, Terauds A, Springer K, Robinson SA, Possingham HP (2016) Prioritizing eradication actions on islands: it's not all or nothing. *Journal of Applied Ecology* 53: 733–741.

Holmes ND, Spatz DR, Oppel S, Tershy B, Croll DA, Keitt B et al. (2019) Globally important islands where eradicating invasive mammals will benefit highly threatened vertebrates. *PLoS ONE* 14: e0212128.

Howald G, Donlan CJ, Galvan JG, Russell JC, Parkes J, Samaniego A et al. (2007) Invasive rodent eradication on islands. *Conservation Biology* 21: 1258–1268.

Igual JM, Forero MG, Gomez T, Orueta JF, Oro D (2006) Rat control and breeding performance in Cory's shearwater (*Calonectris diomedea*): effects of poisoning effort and habitat features. *Animal Conservation* 9: 59–65.

Jones HP, Holmes ND, Butchart SHM, Tershy BR, Kappes PJ, Corkery I et al. (2016) Invasive mammal eradication on islands results in substantial conservation gains. *Proceedings of the National Academy of Sciences of the United States of America* 113: 4033–4038.

Keitt BK, Campbell K, Saunders A, Clout MN, Wang Y, Heinz R et al. (2011) The global islands invasive vertebrate eradication database: a tool to improve and facilitate restoration of island ecosystems. In: Veitch CR, Clout MN, Towns DR (eds) *Island Invasives: Eradication and Management*, 74–77. IUCN, Gland, Switzerland.

Keitt B, Griffiths R, Boudjelas S, Broome K, Cranwell S, Millett J et al. (2015) Best practice guidelines for rat eradication on tropical islands. *Biological Conservation* 185: 17–26.

Lorvelec O, Pascal M (2005) French attempts to eradicate non-indigenous mammals and their consequences for native biota. *Biological Invasions* 7: 135–140.

Luiselli L, Petrozzi F, Mebert K, Zuffi MAL, Amori G (2015) Resource partitioning and dwarfism patterns between sympatric snakes in a micro-insular Mediterranean environment. *Ecological Research* 30: 527–535.

Luque GM, Bellard C, Bertelsmeier C, Bonnaud E, Genovesi P, Simberloff D, Courchamp F (2014) The 100th of the world's worst invasive alien species. *Biological Invasions* 16: 981–985.

MacKay JWB, Russell JC, Murphy EC (2007) Eradicating house mice from islands: successes, failures and the way forward. In: Witmer GW, Pitt WC, Fagerstone KA (eds) *Managing Vertebrate Invasive Species: Proceedings of an International Symposium*, 294–304. USDA, Fort Collins, Colorado, USA.

Martin JL, Thibault JC, Bretagnolle V (2000) Black rats, island characteristics, and colonial nesting birds in the Mediterranean: consequences of an ancient introduction. *Conservation Biology* 14: 1452–1466.

Masseti M (2009) The wild goats *Capra aegagrus* Erxleben, 1777 of the Mediterranean Sea and the Eastern Atlantic Ocean islands. *Mammal Review* 39: 141–157.

Masseti M (2016) The wild goat, *Capra aegagrus* Erxleben, 1777, of the island of Montecristo (Northern Tyrrhenian Sea, Italy): does it still exist? *Mammalia* 80: 125–141.

Masseti M, Zuffi MAL (2011) On the origin of the asp viper *Vipera aspis hugyi* Schinz, 1833, on the island of Montecristo, Northern Tyrrhenian Sea (Tuscan Archipelago, Italy). *Herpetological Bulletin* 117: 1–9.

Mayol J, Oliver J, Mayol M, McMinn M, Rodriguez A, Domenech O (2012) Sa Dragonera, campaña de desratización. *Quercus* 314: 26–33.

Medina FM, Bonnaud E, Vidal E, Tershy BR, Zavaleta ES, Donlan CJ, Keitt BS, Le Corre M, Horwarth SV, Nogales M (2011) A global review of the impacts of invasive cats on island endangered vertebrates. *Global Change Biology* 17: 3503–3510.

Mengoni C, Trocchi V, Mucci N, Gotti C, Giannini F, Mallia E et al. (2018) The secret of Pianosa Island: an Italian native population of European brown hare (*Lepus europaeus meridiei* Hilzheimer, 1906). *Conservation Genetics* 19: 1513–1518.

Mill AC, Crowley SL, Lambin X, McKinney C, Maggs G, Robertson P, Robinson NJ, Ward AI, Marzano M (2020) The challenges of long-term invasive mammal management: lessons from the UK. *Mammal Review* 50: 136–146.

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GA, Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.

Nogales M, Martin A, Tershy BR, Donlan CJ, Veitch D, Puerta N, Wood B, Alonso J (2004) A review of feral cat eradication on islands. *Conservation Biology* 18: 310–319.

Oppel S, Beaven B, Bolton M, Vickery J, Bodey TW (2011) Eradication of invasive mammals on islands inhabited by humans and domestic animals. *Conservation Biology* 25: 232–240.

Ozella L, Cecchetti M, Pessani D (2016) Diet of feral cats during the Scopoli's shearwater breeding season on Linosa Island, Mediterranean Sea. *Italian Journal of Zoology* 83: 589–599.

Perry D (2004) Animal rights and environmental wrongs: the case of the grey squirrel in northern Italy. *Essays in Philosophy* 5: 327–342.

Perry D, Perry G (2008) Improving interactions between animal rights groups and conservation biologists. *Conservation Biology* 22: 27–35.

Ragionieri L, Cutuli G, Sposimo P, Spano G, Navone A, Capizzi D et al. (2013) Establishing the eradication unit of Molara Island: a case of study from Sardinia, Italy. *Biological Invasions* 15: 2731–2742.

Reaser JK, Meyerson LA, Cronk Q, De Poorter M, Eldrege LG, Green E et al. (2007) Ecological and socioeconomic impacts of invasive alien species in island ecosystems. *Environmental Conservation* 34: 98–111.

Richardson S, Mill AC, Davis D, Jam D, Ward AI (2020) A systematic review of adaptive wildlife management for the control of invasive, non-native mammals, and other human-wildlife conflicts. *Mammal Review* 50: 147–156.

Ruffino L, Bourgeois K, Vidal E, Duhem C, Paracuellos M, Escribano F, Sposimo P, Baccetti N, Pascal M, Oro D (2009) Invasive rats and seabirds after 2,000 years of an unwanted coexistence on Mediterranean islands. *Biological Invasions* 11: 1631–1651.

Ruffino L, Krebs E, Passetti A, Aboucaya A, Affre L, Fourcy D et al. (2014) Eradications as scientific experiments: progress in simultaneous eradications of two major invasive taxa from a Mediterranean island. *Pest Management Sciences* 71: 189–198.

Russell JC, Blackburn TM (2017) The rise of invasive species denialism. *Trends in Ecology and Evolution* 32: 3–6.

Russell JC, Holmes ND (2015) Tropical island conservation: rat eradication for species recovery. *Biological Conservation* 185: 1–7.

Russell JC, Towns DR, Clout MN (2008) *Review of Rat Invasion Biology: Implications for Island Biosecurity*. Science for Conservation 286, Department of Conservation, Wellington, New Zealand.

Russell JC, Meyer J-Y, Holmes ND, Pagad S (2017) Invasive alien species on islands: impacts, distribution, interactions

and management. *Environmental Conservation* 44: 359–370.

Scalera R (2010) How much is Europe spending on invasive alien species? *Biological Invasions* 12: 173–177.

Shiels AB, Pitt WC, Sugihara RT, Witmer GW (2014) Biology and impacts of Pacific Island invasive species. 11. *Rattus rattus*, the black rat (Rodentia: Muridae). *USDA National Wildlife Research Center - Staff Publications* 1404: 145–184.

Sposimo P, Capizzi D, Cencetti T, De Pietro F, Giannini F, Gotti C et al. (2019) Rat and lagomorph eradication on two large islands of central Mediterranean: differences in island morphology and consequences on methods, problems and targets. In: Veitch CR, Clout MN, Martin AR, Russell JC, West CJ (eds) *Island Invasives: Scaling up to Meet the Challenge*, 231–235. Occasional Paper SSC no. 62, IUCN, Gland, Switzerland.

Tabak MA, Poncet S, Passfield K, Carling MD, del Rio CM (2015a) The relationship between distance and genetic similarity among invasive rat populations in the Falkland Islands. *Conservation Genetics* 16: 125–135.

Tabak MA, Poncet S, Passfield K, Carling MD, del Rio CM (2015b) Modeling the distribution of Norway rats (*Rattus norvegicus*) on offshore islands in the Falkland Islands. *NeoBiota* 24: 33–48.

Towns DR, Atkinson IAE, Daugherty CH (2006) Have the harmful effects of introduced rats on islands been exaggerated? *Biological Invasions* 8: 863–891.

Ward AI, Richardson S, Macarthur R, Mill AC (2020) Using and communicating uncertainty for the effective control of invasive non-native species. *Mammal Review* 50: 211–220.

Weber C (2014) *Ecological Impacts of Invasive Rat Removal on Mediterranean Sea Islands*. Graduate thesis, University of Michigan, Ann Arbor, Michigan, USA.

Wilson KA, McBride MF, Bode M, Possingham HP (2006) Prioritising global conservation efforts. *Nature* 440: 337–340.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Appendix S1. Summary table of mammal eradications carried out on Mediterranean islands.