Research Article

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Eradications as scientific experiments: progress in simultaneous eradications of two major invasive taxa from a Mediterranean island[†]

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Abstract

BACKGROUND: Black rats, *Rattus rattus*, and mat-forming iceplants, *Carpobrotus* aff. *acinaciformis* and *Carpobrotus edulis*, are pervasive pests on Mediterranean islands. Their cumulative impacts on native biotas alter the functioning of island ecosystems and threaten biodiversity. A report is given here of the first attempt to eradicate both taxa from a protected nature reserve in south-eastern France (Bagaud Island). In order to minimise unwanted hazardous outcomes and produce scientific knowledge, the operations were embedded in a four-step strategy including initial site assessment, planning, restoration and monitoring.

RESULTS: Trapping, which resulted in the removal of 1923 rats in 21 045 trap-nights, made it possible to eliminate a substantial proportion of the resident rat population and to reduce the amount of rodenticide delivered in the second stage of the operation. Forty tons of *Carpobrotus* spp. were manually uprooted from a total area of 18 000 m^2; yet careful monitoring over a decade is still required to prevent germinations from the seed bank.

CONCLUSION: Two years after the beginning of the interventions, both eradication operations are still ongoing. Biosecurity measures have been implemented to reduce reinvasion risks of both taxa. With the long-term monitoring of various native plants and animals, Bagaud Island will become a reference study site for scientific purposes.

Supporting information may be found in the online version of this article.

Keywords: biological invasions; biosecurity; ecosystem engineers; pest management; restoration; species interactions

1 INTRODUCTION

Biological invasions are a pervasive component of environmental global change,[1−3] challenging mitigation measures for the conservation of biodiversity in the most sensitive ecosystems. On islands that host disharmonic and simple food webs with high rates of endemism, the introduction of non-native species by humans has led to disproportionately devastating ecological impacts compared with continental areas.[3−5] While direct effects via predation can cause rapid local extinctions,[6,7] the disruption of species interactions following the deletion (e.g. by predation or competition) of keystone native species can unleash sudden bottom-up and top-down forces that can deeply alter the functioning of island ecosystems, from above- to below-ground processes.[8−10] Furthermore, the impacts on native communities are amplified and diversified in multi-invaded systems, where synergism in invasive impacts can precipitate 'invasional meltdown', i.e. ecological mutualism between several invasive taxa, leading to accelerated impacts on native ecosystems.[11]

The eradication of non-native species, i.e. the complete removal of all individuals of a distinct population not contiguous with

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other populations,[12] has become an efficient conservation tool to prevent extinctions and restore native insular communities. Eradications of non-native rodents have provided the most numerous examples of broad ecological benefits. Positive effects of rat removal include the regeneration of native forest,[13] the enhancement of breeding performance in native birds,[14] the increase in abundance of native invertebrates,[15,16] lizards[17,18] and small mammals[19] and the re-establishment of seabird colonies previously extirpated. Similarly, the removal of non-native plants can have broad ecological outcomes, from the re-establishment of native plant species[20] to the recovery of soil properties[21–23] and the restoration of ecosystem-level processes.[22,24] However, successful control of invasive plants often requires a commitment to long-term management and monitoring, as well as a human-assisted restoration of native plant communities (e.g. transplantation, seed sowing and nutrient addition to soils).

With the development of new technologies and instructive lessons learnt from cases of success and failure, non-native mammals, especially rodents, have been successfully removed from larger and more biologically complex islands, ranging from tropical to subantarctic and temperate ecosystems.[25] On the other hand, attempts to eradicate invasive plants have resulted in very few clear victories,[26] yet better chances of success hold for small islands or when the target plant species are restricted to small- to medium-sized patches that can be easily located and treated.[26,27] The next challenges for island conservation science are now to target broad ecological restoration by removing multiple introduced species, including plants, and to build long-term projects that integrate both conservation and science.[28,29] Eradications offer unique opportunities for large-scale ecological experiments that conservation researchers and practitioners should more routinely exploit in order to produce scientific knowledge.[29]

In spite of the ecological benefits induced by the removal of non-native mammals and plants, significant technical and ecological challenges still need to be addressed. Firstly, on islands where several introduced species interact, eradications can have unexpected and unwanted outcomes, such as the release of mesopredators or competitors with cascading deleterious impacts on native species.[30–32] Undesired ecological effects can be avoided by gathering sufficient knowledge on the ecological interactions between introduced species, which is essential to determine the order in which they should be eradicated.[31,33,34] Simultaneous eradications usually increase the overall benefit–cost ratio of the intervention, as there are few operational costs per extra species eradicated, but large biodiversity benefits.[35] Secondly, failure to maintain adequate island biosecurity regimes can lead to reinvasion, which is difficult to detect and mount a response against. However, the risk of reinvasion is reduced on uninhabited islands or islands owned and managed by only one stakeholder aiming at the conservation of biodiversity. Thirdly, eradication campaigns can face objections from individuals or organisations sceptical about the chance of success or concerned about animal rights and toxicity issues.[36] The reduction in potential non-target impacts and the amount of toxin released into the environment increases social acceptance and is of primary importance in protected nature reserves, which concentrate a large proportion of vulnerable native species. Integration of eradications into a holistic process of assessment, planning, restoration and monitoring will help to safeguard against adverse effects on native communities.

The authors report here on progress in the first attempt to eradicate two major island-invasive taxa, the black rat, *Rattus rattus*, and iceplants, *Carpobrotus* aff. *acinaciformis* and *Carpobotus edulis*, in the Mediterranean region. The small island of Bagaud (58 ha), a protected nature reserve off the French Mediterranean coast, was selected to launch a long-term research and conservation project, with the aim of attempting the complete eradication of the resident black rat population using both trapping and baiting, and achieving, within 10 years of perseverant monitoring and control, the eradication of *Carpobrotus* spp. The nature reserve status of the island and its small size are vital for the success of the operations; land managers are committed in the long term, and reinvasion risks are reduced owing to access restrictions. The technical strategy used to treat each target taxa was defined on the basis of initial site assessment, including biodiversity surveys and studies of the phenology of the target populations and their interactions with native species. The strategies were developed to minimise non-target hazards and the amount of rodenticide used. A report is given here of the four-step management strategy that was developed on the island from 2002 to 2013, and that will continue until 2019: assessment, planning, interventions and monitoring.

2 EXPERIMENTAL METHODS

2.1 Island description

Bagaud Island (43° 00′ 42″ N, 6° 21′ 45″ E; 58 ha, 1.48 km long, 0.59 km wide) is an uninhabited and protected nature reserve lying within Port-Cros National Park, in the Mediterranean Sea (Fig. 1). It is located 7.5 km off the south-eastern coast of France and ∼1 km (0.45–1.6 km from nearest to furthest points) from the main Port-Cros Island. Bagaud Island is composed of acid rock substrate, has a rather smooth topography and reaches 63 m above sea level. Mean monthly temperatures range from 9.5 to 24.7 °C, and total yearly rainfall averages 625 ± 147 mm. During the dry season (June–August), maximum daily temperatures often reach >30 °C (Levant Island Meteorological Office, period 1998–2009). Bagaud Island is mainly covered by a native dry Mediterranean mattoral, dominated by *Pinus halepensis*, *Erica arborea*, *Myrtus communis*, *Arbutus unedo*, *Phillyrea* spp., *Pistacia lentiscus* and *Juniperus phoenicea*, and supports rich native plant communities.[37,38]

Carpobrotus aff. *acinaciformis* and *C. edulis* were voluntarily introduced on Bagaud Island in the middle of the nineteenth century to stabilise embankments created during small fort construction by the army, and have now colonised the coastal halophile belt of the island (Fig. 1). The genus *Carpobrotus* (Aizoaceae) includes mat-forming succulent plants that are aggressive and invasive in many Mediterranean areas, especially in open areas such as dunes and rocky coasts on western Mediterranean islands.[21,39–41] The mats of *Carpobrotus* spp. can reach 50 cm in depth, and their clones 10 m in diameter. The two *Carpobrotus* taxa produce large fleshy indehiscent fruits containing on average 1331 seeds fruit^{-1} for *C. edulis* and 367 seeds fruit^{-1} for *C.* aff. *acinaciformis*[40] that are preserved in the thick litter and soil seed bank.[42] Fruits are produced in large numbers (ca 25–55 fruits m^{-2}) and have high energetic (310 kJ 100 g^{-1} dry mass) and water (79%) contents.[43] The flowering season extends from March to May; fruits are produced in May–June and ripen in June–July. The impacts of *Carpobrotus* spp. on Bagaud Island[44,45] encompass (i) very high competitive capacities that result in a decrease in species richness and diversity, leading to the extirpation of plant functional groups and life forms, (ii) changes in soil composition (i.e. pH, carbon and nitrogen contents and C/N ratio) and (iii) a decrease in pollinator visits of the co-flowering native plants.

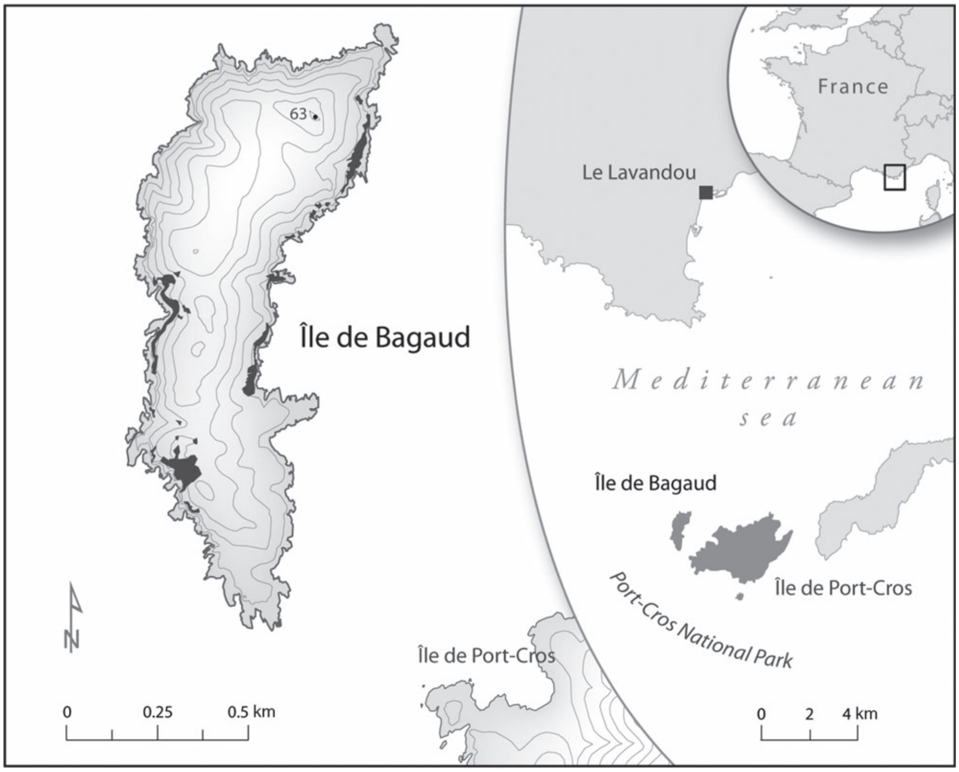

Figure 1. Map of Bagaud Island, with contour lines of elevation and areas invaded by *Carpobrotus* spp. (in dark grey), and location of Port-Cros National Park, south-east France, in the Mediterranean Sea.

The black rat is the only non-flying mammal living on the island and was probably introduced during the Roman period.[46] On Bagaud Island, rats prey on a large array of plants and animals.[47] Possible impacts of rats include predation on seeds, beetles, geckos, terrestrial breeding birds and shearwaters, as has been observed on other Mediterranean islands.[48–51] *Carpobrotus* fruits were identified as one of the most common items in rat diet all year round (28 and 58% in assimilated diet[47]), especially in summer, when the availability of natural resources and fresh water is low. The dispersion of *Carpobrotus* spp. seeds via rat faeces, with increasing germination rates through gut passage,[52] heightens the need to coordinate the eradications of both species. Rat eradication should be carried out before the eradication of *Carpobrotus* spp. in order to prevent rats from dispersing the seeds while the plants are being removed.

Baseline biodiversity surveys[53,54] conducted before the eradications revealed the presence of 216 species of native plants, a minimum of 223 species of terrestrial arthropods, four species of reptiles, 14 species of terrestrial breeding birds and four species of marine birds. Among them, key species for recovery are, for plants, *Romulea florentii* (endemic from the Îles d'Hyères archipelago), *Orobancha sanguinea*, *Limonium pseudominutum* (endemic from the Provence region), *Senecio leucanthemifolius* subsp. *crassifolius*, *Asplenium obovatum* subsp. *obovatum* and *Galium minutulum*, and, for animals, the European leaf-toed gecko *Euleptes europaea* ('NT' IUCN status, with restricted distribution in the Mediterranean, i.e. France, Italy and Tunisia) and the yelkouan shearwater *Puffinus yelkouan* ('VU' IUCN status). Apart from *Carpobrotus* spp., no introduced plants or arthropods with high invasive potential (e.g. ants) were documented on the island. Moreover, no endemic animal species susceptible to non-target poisoning occurred on Bagaud Island.

2.2 Eradications

2.2.1 Planning the eradications

In order to increase the cost effectiveness of rat eradication, managers should be able to outpace rat reproduction and maximise detection probabilities. Chances of success are therefore high if the operation is conducted when rats are relatively deprived of food by seasonal decline in resources. Pre-eradication live trapping of the resident rat population conducted from June 2007 to January 2009[55] indicated that breeding activity fluctuated over time, dropping to substantial low levels at the end of the summer (September–October) drought season. Detection probabilities also varied with seasons, but were consistently higher in autumn (October) and winter (December–January) compared with June–July (see supporting information Table S1).

The eradication of rats should be timed to minimise the disturbance of non-target native species. Five species of terrestrial birds (i.e. *Sylvia melanocephala*, *Cyanistes caeruleus*, *Parus major*, *Erithacus rubecula* and *Fringilla coelebs*) were at risk of being caught in traps during the first eradication stage. Among them, three seed-eaters (i.e. *C. caeruleus*, *P. major* and *F. coelebs*) were susceptible to ingesting toxic bait, and two insect-eaters (i.e. *E. rubecula* and *S. melanocephala*) were at risk of being exposed to secondary poisoning. In addition, yelkouan shearwaters are highly sensitive to the disturbance caused by human presence, and yellow-legged gulls *Larus michahellis* might disturb trapping within the colony located at the southern tip of the island or ingest toxic baits. For most birds, spring and summer were the periods of the year when they were reproductively active on Bagaud Island (Table 1). Based on the above data, it was decided to start rat eradication in early September 2011. This period of the year, following the summer drought season, also has low levels of natural resources, which increases bait attractiveness to rats.

Table 1. Compilation of information used to define the timing of black rat and *Carpobrotus* spp. eradications on Bagaud Island. Black areas represent the optimum period for the operations

Seasons	Winter			Spring			Summer			Autumn		
Months	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
CARPOBROTUS ERADICATION												
Phenology of rare and protected plants												
Crepis leontodontoides												
Gallium minutum												
Limonium pseudominutum												
Orobanche sanguinea												
Romulea florentii												
Senecio leucanthemifolius												
Teucrium marum marum												
***Carpobrotus* spp.**												
Flowering/fructification												
RAT ERADICATION												
Biology and population dynamics of rats												
Low population size												
Low reproductive rates												
Low detection probability												
Breeding of vulnerable birds												
Puffinus yelkouan (mating-fledging)												
Sylvia melanocephala												
Cyanistes caeruleus												
Parus major												
Erithacus rubecula												
Fringilla coelebs												
Yellow-legged gulls												
Presence on the island												

The eradication of *Carpobrotus* spp. was timed to minimise disturbance of the native flora and the risk of re-establishment of *Carpobrotus* seeds from the seed bank. The eradication had therefore to be conducted outside the period of flowering and fructification seasons of *Carporbrotus* spp. and vulnerable plants. An exhaustive inventory of the native plant species considered to be sensitive to human intervention revealed the presence of seven rare and protected species, with a moderate to high percentage of occurrence (7–60%) in *Carprobrotus*-invaded sectors[53] (Table 1). Based on the phenology of those native plants and that of *Carpobrotus* spp., the most appropriate period for *Carpobrotus* eradication appeared to be October–February (Table 1). Previous studies showed that the *Carpobrotus* spp. seed bank can persist for 5 years after eradication,[56] and massive germination can occur 3 years after the initial intervention, with evidence of sprouting observed even after 8 years of control.[57] Regular control of the treated areas will therefore have to be conducted over a 10 year period before the success of the eradication can be assessed.

2.2.2 Rat eradication

The strategy used for the eradication combined trapping and rodenticide delivery in two successive steps.[53] A total of 886 trapping stations were set every 25 m along eight concentric lines (21 km of lines separated by 20 m) (Fig. 2a). Such a dense trapping grid has been commonly used in the Mediterranean and in north-western France;[14,19,58] it allows maximum detection during the first stage of the eradication and increases the rate of eradication. Each station had one live trap (BTT-Mécanique, Besançon, France) and one protective PVC tube containing the rodenticide, which was deployed during the second stage of the eradication. Traps were baited with a mixture of peanut butter, oats and sardine oil, checked daily and rebaited when necessary. All rats captured were euthanised by spinal dislocation and then brought to the lab for further analyses. Trapping success was calculated as the number of rats caught per 100 trap-nights, corrected by the number of traps sprung by any causes.[59]

Toxic baiting was initiated 13 days after trapping started, when trapping success had reached 1–2% for three consecutive days. Rodenticide wax–cereal blocks (50 g each) containing 0.005% bromadiolone (second-generation anticoagulant, RAKIL BLOC; SOFAR® France) were used. One bait block was fixed into each of the 886 protective PVC tubes (diameter 10 cm, length 30 cm), reducing bait uptake by non-target bird species and degradation by rain or UV light. The bait was secured in the PVC tube so that it could not be dragged away. Some extra 29 bait stations were set along maritime cliffs (Fig. 2a). When the bait stations were checked, it was noted whether the bait block was intact, missing or chewed (with degrees of consumption assigned to four categories: 25, 50, 75 and 100%). Bait consumption by rats was evidenced by incisor marks. Bait stations were checked daily until the 16th poisoning day, and then at a 1–8 week interval until June 2012, where 74% ($n = 652$) of the bait stations were removed. All the excess bait that was not consumed by rats by June 2012

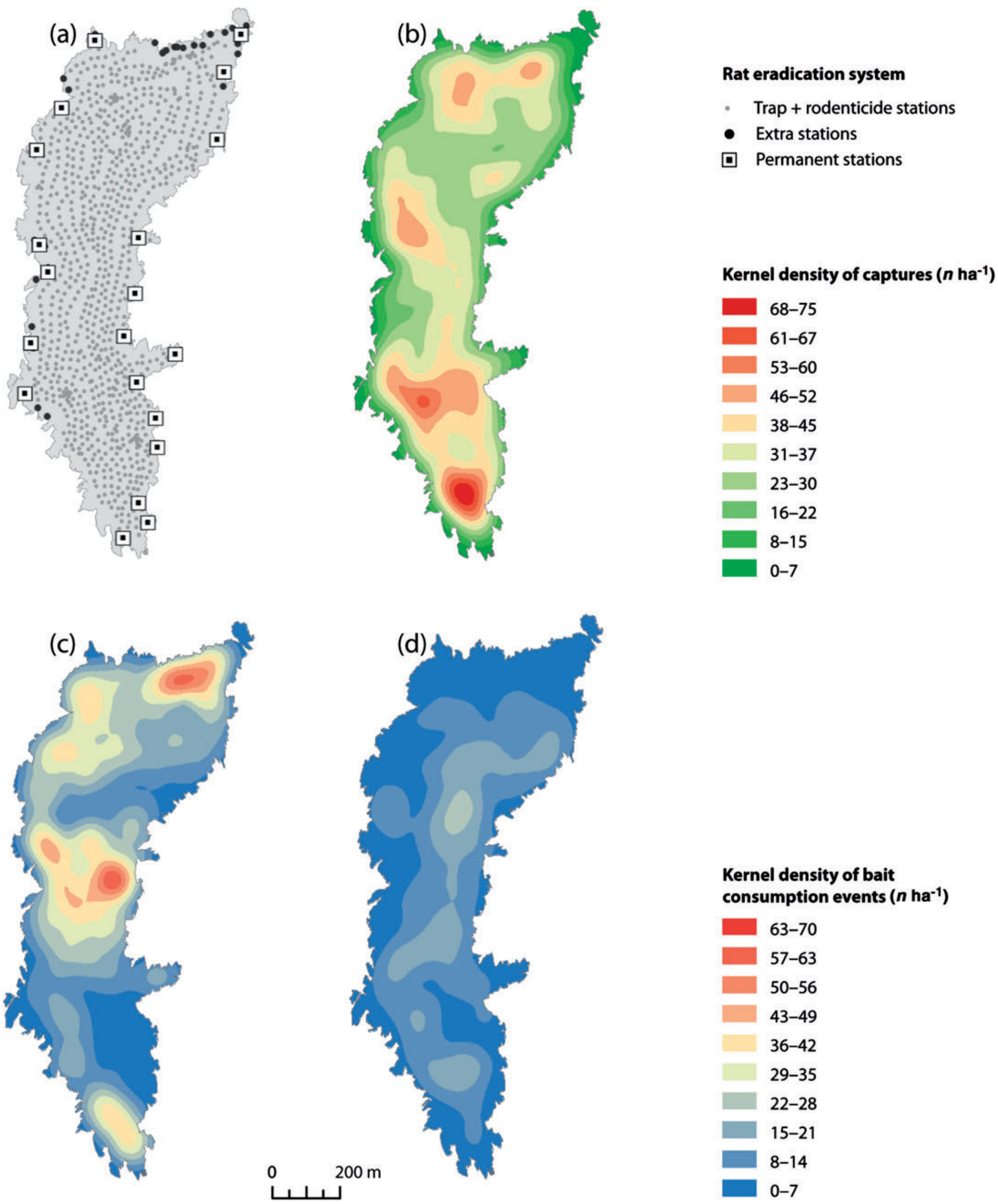

Figure 2. (a) Map of the 886 and 29 extra trap and bait stations set from 6 September 2011 to the end of June 2012, and the 20 permanent stations set along the coast as part of biosecurity measures; (b) kernel density of black rat captures from 7 September 2011 to 1 October 2011; (c) kernel density of bait consumption events by rats from 19 September 2011 to 4 October 2011; (d) kernel density of bait consumption events by rats from 5 October to the end of June 2012. All the kernel densities were calculated with ESRI Spatial Analyst, with a 100 m radius around each station. Data source: Aurélie Passetti.

was removed from the island. In order to maximise the chance of success of rat eradication and prevent any rat incursion during the summer, 234 toxic bait stations, set every 25 m, were left along the external mattoral edge of the island from June 2012 to December 2012, and checked for bait consumption every month.

2.2.3 *Carpobrotus spp. eradication*

A complete survey of the island was conducted in 2009 to locate and map the sectors invaded by either or both *Carpobrotus* taxa, and to determine the size of the patches as well as their accessibility for human intervention.[53] A total of 35 sectors (total area = 18 000 m^2) were identified as invaded by either one or both *Carpobrotus* taxa (Fig. 1). Manual uprooting was considered to be the most effective management option for the complete removal of *Carpobrotus* spp. from Bagaud Island. The use of herbicides, while proven to be effective on other islands, was not allowed by the legislation owing to their potential lethal effects on native plants. The technical eradication strategy of *Carpobrotus* spp. was designed on the basis of pilot studies[42,53] aiming at assessing the nature of the seed bank occurring in the litter and soil and the consequences of removing live *Carpobrotus* and/or its litter for soil erosion. Those studies showed that *Carpobrotus* spp. produced a large quantity of litter containing up to 77.6% of its own seeds, but also that removing both live *Carpobrotus* material and its litter increased soil erosion. The litter was therefore removed at the same time as live *Carpobrotus* rhizomes and shoots to prevent a great amount of seeds from reinvading the treated areas and to favour the re-establishment of native plant communities.

2.3 Biosecurity measures

Biosecurity against rat incursion includes a series of measures to achieve maximum detection: (i) 20 toxic bait stations were set permanently along the coast from May 2012; they were checked monthly until December 2012 and then every two months to ensure surveillance of areas of high reinvasion risk (Fig. 2a); (ii) a request for a mooring ban along the entire coastline was made to the national park authorities; (iii) genetic samples from rats present on neighbouring islands and islets ($n = 153$ from various places on nearby Port-Cros Island, and $n = 13$ and 15 on two small nearby islets) were collected in order to assess the origin (i.e. survivors or re-invaders) of any potential rats captured on Bagaud Island and hence help island managers to guide their strategy of actions.[60] Other measures to prevent the reintroduction of both rats and *Carpobrotus* spp. include the prohibition of boat landing on the island, as well as public education.

3 RESULTS

3.1 Rat eradication

Trapping lasted 25 days and yielded a total of 1923 captures (33 rats ha^{-1}) in 21 045 trap-nights (i.e. 23 trapping days, 915 traps). Trapping success was >57% on the first two trapping days (Fig. 3a), but declined below 15% after day 5 and then fluctuated between 3 and 0% from day 9 to day 25. Rodenticide delivery started after 13 days of trapping, when 97% of the trappable population had been removed. Evidence of bait consumption by rats was documented in 17–20% of the bait stations on days 17 and 21 (Fig. 3b), indicating that some rats escaped trapping and were still present on the island. From late November 2011 (59 days after baiting started) to early March 2012 (168 days after baiting started), only 1–3% of the stations showed signs of bait consumption by rats. No evidence of bait consumption by rats was documented from March to the end of June 2012. In summer 2012, the bimonthly control of bait stations revealed a few suspicious signs of bait consumption that could not be strictly attributed to rats owing to high bait degradation in the summer. However, in spite of an intensive trapping regime deployed around the stations, no rat was captured. Trapping involved 21 traps set 31 m apart (on average) in September, and 34 traps set 16 m apart (on average) in October, and checked for four consecutive days.

By the end of June 2012, a total of 1837 bait blocks had shown signs of consumption by rats. The total amount of bait blocks consumed by rats was estimated to be, at that date, 48 kg (0.83 kg ha^{-1}). Evidence of bait consumption by ground arthropods (i.e. ants and beetles) was frequently observed throughout the poisoning period, but bait uptake was always very low. Distribution of rat captures was higher in coastal areas, where vegetation is more

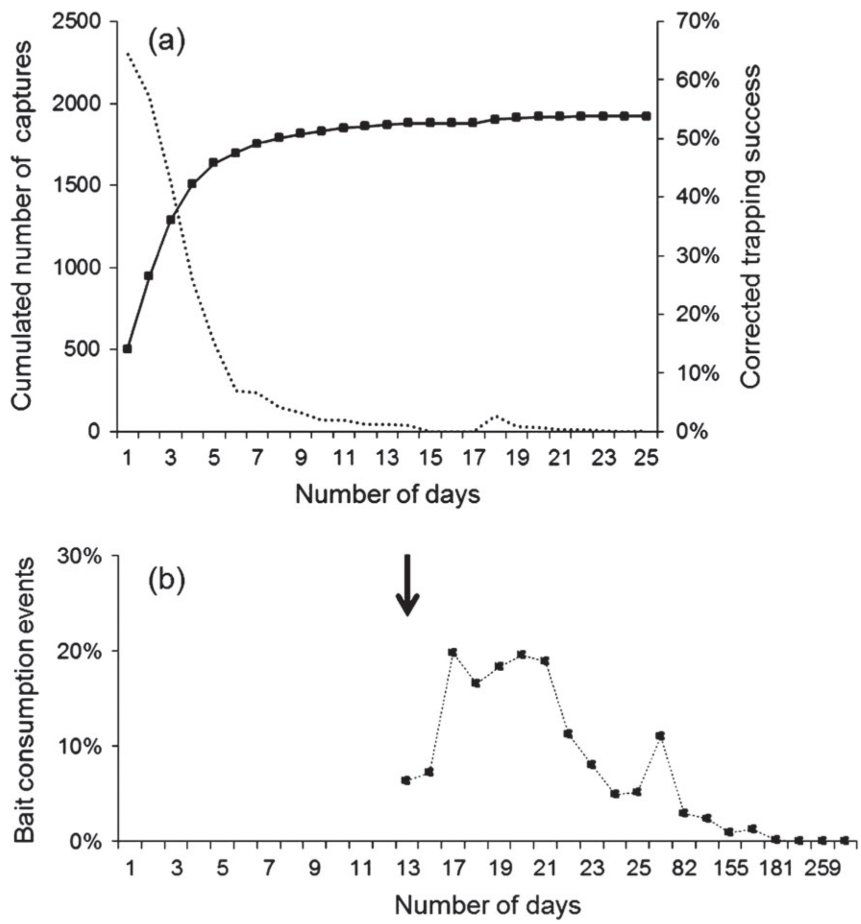

Figure 3. (a) Cumulative number of black rat captures (squares) and trap success (dotted line) from 7 September 2011 to 4 October 2011; (b) proportion of stations showing bait consumption from 19 September 2011 (day 13) to the end of June 2012 (day 294). The arrow indicates the beginning of rodenticide delivery (day 13).

open and diverse, and at the southern tip of the island, hosting a gull colony (Fig. 2b). Bait consumption events showed some ‘hot spots’ of rat activity in some open coastal areas and at the southern tip of the island (Figs 2c and d). During the 23 trapping days, five *E. rubecula*, one *S. melanocephala* and one *Coturnix coturnix* were accidentally captured, but released without injuries. Dead birds were never found on the island following rodenticide delivery. Searches for carcasses were done opportunistically as part of maintaining the bait stations.

Two years after rat eradication started, in September 2013, an island-wide live-trapping session was conducted (1280 trap-nights) to control the outcome of the rat eradication campaign. This session led to the capture of one rat in the southern part of the island, in the vicinity of the only boat-mooring area along the island coastline. A few bait stations also showed evidence of rat consumption in the same area from September to December 2013. Whether these events were related to a biosecurity breach, a failure in eradicating the resident rat population or advanced disintegration of the bait ingredients over time is not known, but they clearly call for vigilance and perseverant ongoing control.

3.2 *Carpobrotus* spp. eradication

Carpobrotus-invaded areas accessible by foot (11 000 m^2) were eradicated in 13 working days (i.e. 52 man-days) in November–December 2011, while cliff areas that were only accessible by boat (8000 m^2) were treated in October–November 2012 and January 2013. A total of 40 t of *Carpobrotus* material was uprooted and left in piles on Bagaud Island to reduce disturbances linked with moving this biomass on the island and the risk of dispersing seeds. To achieve the complete eradication of *Carpobrotus* spp., regular controls of the treated areas, with systematic uprooting of new sprouts and shoots over a decade, have been implemented in the eradication strategy. In September 2012, 5 days of work (i.e. 90 man-days) were necessary to remove all the *Carpobrotus* sprouts in areas accessible by foot. This operation was repeated in October 2013. Another control will occur in 2014, followed by a control every 2 years until no more *Carpobrotus* seedlings are detected in those areas. Cliff areas were controlled in November 2013–January 2014, and further controls will occur every 2 years.

3.3 Costs

The total cost of the operations, including rat and *Carpobrotus* spp. eradications, biodiversity surveys and operating costs, was €252 831 (€4359 ha^{-1}) and €187 806 (€3238 ha^{-1}) for 2011 and 2012 respectively. Costs per item are described in Table 2.

4 DISCUSSION

The authors report here on progress in the first attempt simultaneously to eradicate two major invasive pests, the black rat and *Carpobrotus* spp., from a Mediterranean island. More particularly, emphasis is placed on the importance of embedding the operations in a holistic process of assessment, planning, restoration and monitoring to minimise unwanted hazardous effects on the native ecosystem and to produce scientific knowledge. Two years after the beginning of the interventions, both eradication operations are still ongoing, and the authors are confident that, with careful planning and sufficient effort, the complete eradication of both taxa can be achieved. The project meets predetermined conditions of success, including (i) a small island size, (ii) the long-term commitment of managers, (iii) the involvement of experts who can adapt the technical strategy over the course of the interventions and (iv) limited reinvasion risks owing to access regulations and adapted biosecurity measures. Moreover, the absence of other introduced plants or animals with high invasion potential is an asset to guaranteeing the recovery of native wildlife. Finally, given the access restrictions implied by the creation of an ‘island sanctuary’, it is crucial that the operations are accepted by the public, especially the inhabitants of the nearby Port-Cros Island. To maximise social adhesion, a large effort has been made to communicate the actions to local people and to use the media to reach a larger audience.

Given the capture of one rat in September 2013, further control is required before being able to declare Bagaud Island as rat free. Island managers and experts have adapted their strategy of actions to increase the efficiency of the operation. Firstly, a series of toxicity tests will be conducted on the bait blocks acquired at the beginning of the interventions to ensure that the anticoagulant molecule is still active. The persistence of one (or more) rat(s) on the island, in spite of 2 years of intensive baiting, may result from a decrease in the level of bait toxicity through natural degradation. Secondly, an intensive chemical control was implemented in January–February 2014, covering the whole island. Bait stations were set every 25 m along the coastline and in areas where evidence of bait consumption was observed in 2012 and 2013, and every 50 m elsewhere. Thirdly, a mooring ban within a minimum of 100 m from the southern coast is currently being discussed with the national park authorities and will considerably limit reinvasion risks from boats anchored offshore. Biosecurity actions also target individuals that could re-invade by swimming from nearby islands (most probably from the main Port-Cros Island, but these events are considered to be rare). Fourthly, an island-wide trapping session is scheduled for September 2015 to assess the success of the eradication.

According to expectations, regular controls of all *Carpobrotus*-removal areas, with systematic uprooting of new sprouts and shoots over a decade, are still needed before being able to

Table 2. Details of costs per item for the operations related to the eradications of black rats and *Carpobrotus* spp. and the biodiversity surveys on Bagaud Island (58 ha) for 2011 and 2012 (costs are in euros)[a]

	Year	
	2011	2012
***Rattus rattus* eradication/biosecurity**		
Material (including baits)	50 602	2615
Boat expenses	7528	
Staff	47 610	1760
Opening vegetation paths	29 571	
***Carpobrotus* eradication**		
Material	946	4622
Staff	11 372	101 161
Biodiversity surveys	**7000**	**2500**
Operating costs		
Scientific coordination (including travel expenses)	40 000	55 000
Port-Cros National Park staff	58 202	20 148
Total	252 831	187 806

[a] Pre-eradication biodiversity surveys and scientific supervision of students are not included in the costs listed.

conclude the operation. The achievement of successful plant eradications commonly includes a perseverant control of the treated areas for at least a decade.[26] Rigorous controlling efforts are motivated by the persistence of *Carpobotus* seeds in the soil[42,56] and by the capabilities of *Carpobrotus* spp. to regenerate and reinvade quickly with only low recruitment rates, owing to their high genetic diversity,[56,61] and to reinvade via seed transportation by birds. However, the chance of reinvasion by non-native plant species and their spread further inland is expected to be low as soon as native plants, including species forming the dense Mediterranean mattoral, have re-established.

Eradicating non-native rodents by combining live trapping and baiting in two successive steps has proven to be successful on a large number of small- to medium-sized islands (i.e. <75 ha).[62,63] Trapping was regarded as efficient on Bagaud Island, with a relatively high catching rate during the first 5 days, and allowed the removal of a substantial proportion of the resident population. However, the use of rodenticide was necessary in order to knock down the population because of declining catching rates at low densities and the presence of trap-shy individuals. By the end of June 2012, when no signs of bait consumption had been detected for 3 months, approximately 0.83 kg of toxic bait blocks was consumed by rats per hectare. Such low amounts could be achieved by using bait stations that were checked daily, and by systematically removing decaying baits and the excess bait not taken by rats at the end of the operation. This is ecologically sensible given the common delivery of 10–20 kg ha^{-1} via aerial or hand broadcast baiting with no prior trapping to reduce the target rat population size.[33,64,65] This strategy also made it possible to collect unique biological and genetic data on the resident rat population that are crucial for understanding the structure and dynamics of the populations in a meta-population context.[66] However, this approach is restricted to islands that are fully accessible and where disturbance from months of setting and maintaining traps and bait stations is not an issue. On larger islands, or on islands with a steep and rough terrain, this approach may not be feasible, and other, more traditional approaches, such as broadcast of bait, may be required.

If one way to diagnose eradication success relies on the absence of detection of the target species after repeated controls, another indicator is the recovery of native animal and plant communities. Biotic communities are expected to respond in three ways to the removal of introduced rats:[67] recovery of resident species that have been affected, recolonisation by species that had disappeared locally and the appearance of species previously unrecorded. While an increase in recruitment rates and abundance of native species has typically been documented in response to predation or competition release,[14,16,68] more subtle, and unexpected, behavioural shifts can be observed in response to relaxed predation[69,70] owing to complex interactions between native and introduced species, especially in cases of long-standing introductions. For instance, in New Zealand, endemic tree wetas (Orthoptera) adjusted their behaviour to the removal of introduced Pacific rats by increasing activity and using less concealed cavities,[69] while Duvaucel's geckos responded to the eradication by shifting habitat use.[70] This aspect highlights the need for caution while monitoring the recovery of long-lived reptiles on Bagaud Island, i.e. European leaf-toed geckos and common wall lizards, as an apparent increase in catching rate after eradication might not reveal an actual increase in recruitment rates, but instead a relaxation of their activity rhythms. The re-establishment of seabird colonies following rat eradication depends on the ability of particular species to colonise from source populations. In cases of yelkouan shearwaters, which have low reproductive rates and show strong philopatry and site fidelity, a recovery programme via active management actions (i.e. artificial burrows and playbacks) has been launched on Bagaud Island. Source populations of large numbers of immigrating yelkouan shearwaters may be found in the vicinity of Bagaud Island, i.e. Le Levant Island (~3 km; 800–1300 pairs[71,72]), and further away, in the Maltese and Sardinian archipelagos, which support some of the world's largest populations of this species.[71]

Some invasive plants, such as *Carpobrotus* spp., can deeply disturb ecosystem functions, acting as 'ecological engineers'.[73] *Carpobrotus* spp. do not only interact with native biotas by suppressing the growth of mature native shrubs and the establishment of native seedlings, but also alter soil chemistry and properties.[21,45,74] Such complexity in the nature of impacts implies different recolonisation pathways. The recovery rate of *Carpobrotus* spp.-treated areas depends on life forms, growth forms, longevity and dispersal abilities;[42] it is expected to be rapid for native pioneer species, especially in the surroundings of the dense native mattoral, which is an important source for new propagules. In addition, the increases in light, soil temperature and resource availability created by the removal have been shown to favour the germination of native annual plants from the seed bank,[20,75] while the recovery of species that do not tolerate low pH levels and high organic content in soils will take longer.[76] In the latter case, soil conditions would need to be ameliorated to allow restoration, either via human assistance or indirectly via the re-establishment of first succession plants.

5 CONCLUSIONS AND FUTURE PROSPECTS

Biological invasions are a pervasive component of global change, and their impacts can have far-reaching economic consequences in various fields of human activities, including forestry, agriculture and human health. The removal of introduced plants and animals is a common and effective conservation tool to restore island systems and reverse the current rate of biodiversity loss. However, it has to be borne in mind that eradications are not minor operations; removing one component of the ecosystem, even of exogenous origin, can potentially lead to hazardous unexpected consequences. With this study, the authors wish to highlight the importance of integrating pest management actions into a holistic process of 'research–action–monitoring' to ensure coherence and efficiency of actions, and to draw attention to the considerable source of scientific knowledge represented by these operations. The authors also believe that, given their limited size and relatively simple food webs, small islands offer unique opportunities to target multipest removal, including plants, as well as broad ecological restoration. The next important scientific challenges in pest management science include increasing the cost effectiveness of eradications by, for example, applying modelling approaches to management operations in order to predict the effort required to meet a target probability of success immediately following an operation.[65,76] Finally, in Europe, science-based prioritisation programmes built on integrated data analysis of islands, native species and key invasive species at regional scales (Mediterranean, Atlantic, tropical overseas territories and sub-Antarctic overseas territories) are still very much needed.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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