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ORIGINAL PAPER

Geographic tools for eradication programs of insular non-native mammals

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Abstract Non-native mammals are major drivers of ecosystem change and biodiversity loss; this is especially apparent on islands. However, techniques exist to remove non-native mammals, providing a powerful conservation tool. Conservation practitioners are now targeting larger islands for restoration. Leveraging existing and developing new techniques and technologies will prove critical to successful eradications on large islands. Using the removal of introduced goats (*Capra hircus*) from Santiago Island, Galápagos as a case study, we present a suite of Geographic Information System (GIS) tools that aid island conservation actions. GIS tools were incorporated into the three phases of the eradication campaign: planning, hunting, and monitoring. Further, these tools were adopted for three eradication techniques: ground-based hunting, aerial hunting by helicopter, and Judas goats. These geographic approaches provide a foundation for statistical, spatial, and economic analyses that should increase the capability and efficiency of removal campaigns. Given limited conservation funds and the dire status of many insular species, efficiently removing non-native mammals from islands is of paramount global conservation importance.

Keywords *Capra hircus* · Eradication · Introduced species · Invasive species · Island conservation · Non-native mammals · *Sus scrofa*

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Introduction

Extinction over the last six centuries has been largely dominated by insular species, with non-native mammals being responsible for the majority (Diamond 1989; Groombridge et al. 1992; MacPhee and Flemming 1999). Introduced predators, such as rats (*Rattus* spp.) and cats (*Felis catus*), have decimated endemic rodent, reptile, and bird populations, and extirpated numerous seabird colonies on islands around the globe (Atkinson 1985; Nogales et al. 2004). Introduced herbivores, such as feral goats (*Capra hircus*) and European rabbits (*Oryctolagus cuniculus*), have caused wholesale changes in insular plant communities, as well as secondary impacts via habitat degradation (Coblentz 1978; Ebenhard 1988; Donlan et al. 2002; Campbell and Donlan 2005). As omnivores, feral pigs (*Sus scrofa*) feed on fruits and plants, prey on vertebrates, and raid nests of birds and reptiles (Coblentz and Baber 1987; Cruz and Cruz 1987; Choquenot et al. 1996). In sum, non-native mammals are major drivers of ecosystem change and biodiversity loss.

In the 1980s, in response to these biodiversity threats, New Zealand conservation practitioners began developing techniques to remove non-native mammals from islands (Taylor and Thomas 1989; Towns et al. 1990; Atkinson 2001; Towns and Broome 2003). Until recently, eradication has been largely limited to small islands, mostly in Australasia. Building on these techniques, conservation biologists and practitioners from around the globe are now tackling large and biologically complex islands (Veitch and Clout 2002; Howald et al. 2005). Removing non-native mammals from islands is now one of our most powerful conservation tools (Donlan et al. 2003). As larger islands are targeted for restoration via introduced mammal eradication, integrating existing and developing new techniques and technology will prove critical for success (Campbell and Donlan 2005).

GIS and GPS technologies are underutilized in eradication campaigns. Although these technologies have been available for nearly two decades and the US Defense Department removed built-in GPS error in May 2000 further increasing accuracy, only in the last few years has this technology begun to be exploited (Hulbert and French 2001; McClelland 2002; Cruz et al. 2005; Howald et al. 2005; Phillips et al. 2005). We know of no published accounts of GIS or GPS methodologies being detailed for non-native mammal eradication programs. In the recently published proceedings of an international invasive species eradications, 27 papers dealt with introduced mammal eradication; none mentioned the use of GIS and seven papers mentioned the use of GPS, four of which provided detailed GPS methodologies (all for helicopter applications, with three being related to aerial baiting of rodents) (Veitch and Clout 2002).

Here, we present a suite of GIS tools that increases the efficiency and capabilities of non-native mammal eradications on islands. These tools are a product of a series of large-scale eradication campaigns on the Galápagos Islands (Donlan et al. 2003; Campbell et al. 2004; Cruz et al. 2005). We integrate GIS and GPS data collection methodologies with existing eradication techniques, including ground-based hunting, aerial hunting by helicopter, and Judas goat techniques. Using an introduced goat eradication campaign on Santiago Island (58,465 ha) as a case study, we present the details of these techniques in an effort to make them available for future island conservation actions.

Background

Santiago Island, located in the center of the Galápagos archipelago, enjoys protected status, and is home to many endemic species. Nonetheless, a number of non-native mammals have been present on the island, including rats, goats, and pigs, which have had devastating impacts on the island. Pigs were recently eradicated and goats are in the final phases of being removed, the largest non-native mammal eradication campaigns to date (Cruz et al. 2005). These conservation actions were accomplished by leveraging three techniques: aerial hunting by helicopter, ground hunting (with and without specialist dogs), and Judas goat techniques. Judas goats, radio-collared individuals that are released and associate with conspecifics, aid in removing remnant goats in the final stages of a removal campaign (Rainbolt and Coblentz 1999).

During the goat eradication campaign on Santiago Island, GIS tools were integrated into each of the three project phases: planning, hunting, and monitoring. GIS tools during the planning phase were critical for all three eradication techniques: aerial hunting, ground hunting, and Judas goat operations. During planning, GIS proved valuable in developing a systematic approach across a large spatial scale. During both aerial and ground hunting, GIS tools were implemented for data collection, which was analyzed daily/weekly and allowed for adaptive management decisions. Lastly, the implementation and efficiency of a large-scale ground monitoring effort and Judas goat operations were vastly improved by using a variety of standard GIS tools.

Methods

Software utilized included ESRI ArcView v3.2/ ArcGIS v8.1, freeware and scripts available from the Internet, and Microsoft Access for database management. Although we describe a detailed methodology utilizing this software, other GIS and database packages could be similarly employed. SPOT images provided the geographic foundation for planning. Hand-held and helicopter mounted GPS units (Garmin 12XL and Garmin GPSII plus respectively) were used to collect hunting and additional geographic data in the field.

Planning and management

Santiago Island was systematically divided into blocks, differing for each phase of eradication: ground hunting, aerial hunting, and Judas goats (Fig. 1). Field knowledge was combined with geographic information to divide the island into blocks. Block boundaries were delineated in ArcMap/ArcView using the combined criteria: vegetation type/cover, trails, topographic features, and the ability to work an entire block over a certain time period. Compare to traditional methods, this approach proved highly effective with respect to the abilities of navigating and systematically covering the block within a given time period.

Santiago Island was divided into 24 blocks for ground hunting, ranging in size from 414 to 4491 ha (Fig. 1a). SPOT satellite imagery was used to assess the island geography; wavelength band combinations were used to highlight vegetated (RGB, bands 4, 3, 2) and volcanic (band Stretch, band 4) areas (Fig. 1b). GPS units were used to mark existing trails throughout the island. Natural topographic features, easily identified by hunters (e.g., ridgelines, hills, etc.), were also identified. Ground hunting blocks were subdivided into sub-blocks (137 total; Fig. 1a) which served two effective purposes: (1) facilitating a specialized ground hunting technique 'rastrillo' (see hunting below), and (2) providing a suitable sized area for a team of 15 hunters to cover in one day. Sub-blocks averaged 384 ha in open areas and 171 ha in heavily vegetated areas.

Blocks for aerial hunting were similar to ground hunting, differing in scale and often covering multiple vegetation types. With experienced pilots and several reconnaissance flights, along with SPOT images, Santiago was broken into ten blocks for aerial hunting ranging from 3547 to 10,109 ha (Fig. 1b). Block size was determined primarily by openness of vegetation and estimated goat density. Individual helicopter flights were limited to two hours, also a factor in block size.

For the deployment of Judas goats, we generated a set of equidistant points with an Avenue script (Nickseigal.CreateTriangularArray.ave, Seigal 2001; Terrace 2002) in which equidistance was based on known home range data for goats, available resources (i.e., number of goat telemetry collars), and distribution of where goats were removed during the hunting phase. Equidistant spacing of 2250 m was adopted, resulting in 111 points. In areas dominated by lava, where few or no goats had been removed, spacing was increased to 3250 m resulting in 12 points. To provide a visual aid to managers and practitioners on the ground, Judas goat blocks were constructed with an ArcScript from Terrace GIS (CreateThiessenPoly.dll) that creates Thiessen polygons around the equidistant points (Fig. 1c).

The equidistant spacing and blocks for Judas goats also aided in the experimental design of research attempting to assess the performance of different types of Judas goats (i.e., males, females, and females with hormone implants, Campbell 2002; Campbell et al. 2005, in press). To randomly assign Judas types across different vege-

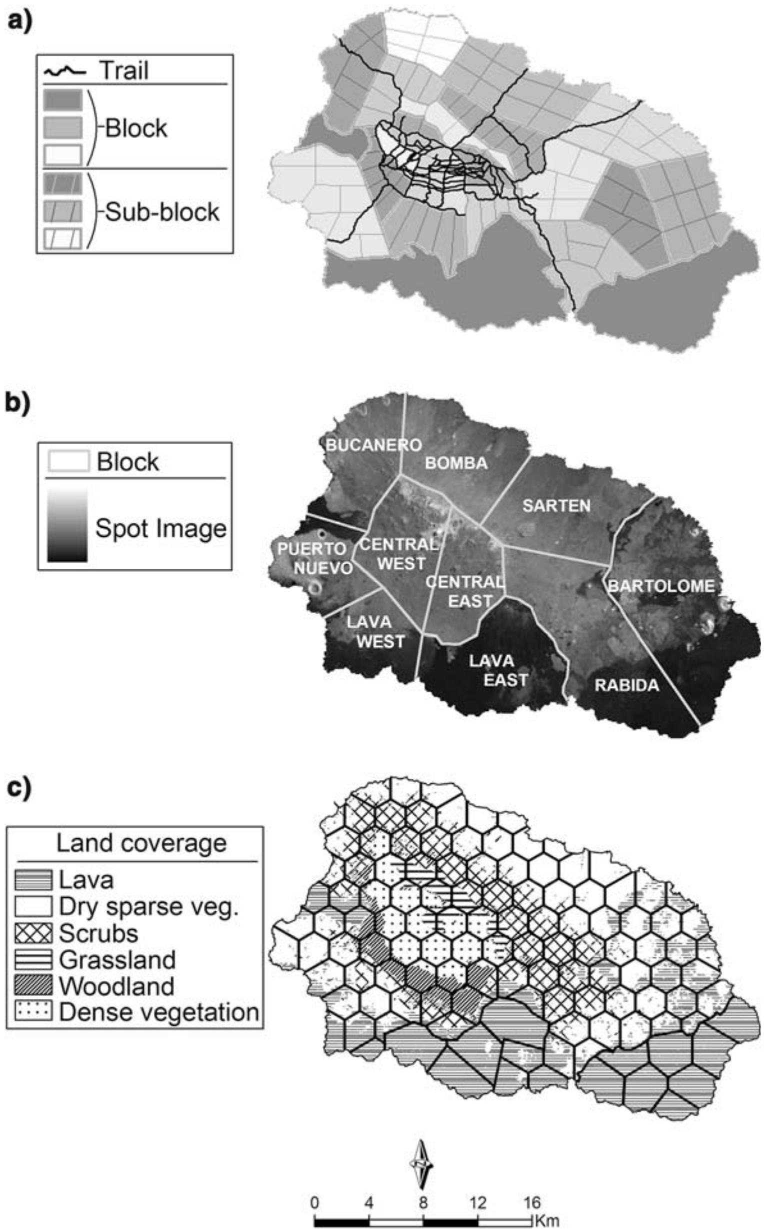

Fig. 1 Geographic planning and management tools used in the removal of non-native goats from Santiago Island. (**a**) Ground hunting blocks and sub-blocks along with established trail systems. (**b**) Aerial hunting blocks and SPOT imaging used to highlight volcanic and vegetated areas of the island, which aided in the sizing of both aerial and ground hunting blocks. (**c**) Judas goat blocks generated as Thiessen polygons from equidistant points, and a vegetation classification generated from SPOT imaging which aided the design of experiments to assess the efficiency of different types of Judas goats (see text)

tation types or lava, we used a non-oriented reclassification with SPOT data to generate six distinct classes: lava, savannah, scrub, grassland, dense vegetation, and woodland (Fig. 1c). Vegetation classes and lava were later validated using digital vegetation maps (data provided by French Research Institute for Development and Cooperation, formerly ORSTOM). Judas blocks were superimposed over the vegetation and lava map, and Judas types were randomly assigned within each lava or vegetation class (Fig. 1c).

Hunting

Three types of ground hunting techniques were used during the Santiago campaign: corrals, free hunting, and ‘rastrillo’. Spatial and non-spatial data were collected during each technique

Table 1 Data architecture of non-native mammal eradications

	Data collected		Geo database planning units
	Non-spatial data (paper forms)	Spatial data (hand-held GPS)	
Ground hunting			
Data description	Individual hunter # Dogs used Effort (hours) # Goats shot & escaped Hunting method Working block Working dates	Shooting event (x, y) Location traveled	Hunting blocks Hunting sub-blocks
1st Level analysis	Statistical & economic analysis Hunter efficiency Method efficiency Cost analysis	Spatial analysis Kills and escapes/block (sub-block) km Traveled/block (sub-block) Time traveled/block (sub-block)	
2nd Level analysis	Geostatistical analysis Hunter efficiency by block type (vegetation, size, etc) Method efficiency by block type (vegetation, size, etc) Cost analysis by block type and hunting method		
Helicopter hunting			
Data description	Pilot & aerial hunter Individual flights Activity (hunting, logistics, etc) Effort (hours) # Goats shot & escaped Working dates	Shooting event (x, y) Location traveled	Hunting blocks
1st Level analysis	Statistical & economic analysis Pilot efficiency Crew or hunter efficiency Cost analysis	Spatial analysis Kills and escapes/block km Traveled/block Time traveled/block	
2nd Level analysis	Geostatistical analysis Cost analysis by block (island, block type, etc.)		
Judas goat monitoring			
Data description	Judas goat (individual traits) Individual Judas goat (ear tag #) Action taken (killed, freed, translocated) Method used # Dogs used Effort (searching time) # & sex-age goats shot & escaped Female goat reproductive data working dates	Deployment, monitoring or translocation event (x,y) Location traveled (GPS collar)	Initial position (x, y)
1st Level analysis	Statistical & economic analysis Judas goat performance Cost analysis	Spatial analysis Linear distance traveled Distance traveled (GPS collar)	
2nd Level analysis	Geostatistical analysis Distance traveled per Judas goat (sex, type, age) Judas goat performance in vegetation type Cost analysis		

Spatial and non-spatial data are combined to facilitate statistical and economic analyses that can be leveraged to increase the efficacy of island conservation actions

(Table 1). Herds of goats were mustered into corrals, which were strategically positioned over the island; this method removed a large number of goats in the early phases of the project. Free hunting with and without specialized dogs was utilized when densities were at medium-low levels. 'Rastrillo' hunting consists of hunters with or without dogs arranged in a line advancing through an area in a systematic fashion; this technique was particularly effective in areas of thick vegetation when goats were at low densities.

In general, hunters are provided custom maps with block and sub-block boundaries, trails, and huts. For 'rastrillo', hunters are assigned a working line, which is uploaded into their GPS units; equidistant points are used and hunters navigate from one point to the next (Fig. 2a). Hunters communicate by radio the distance to their next point, allowing them to maintain straight lines, even in thick vegetation. GPS units are also used for data gathering using the automatic track logger for each hunter, during all free hunting trips (Table 1, Fig. 2b). When a goat(s) is shot, the hunter marks the point applying a 6-digit naming methodology that encompasses hunting method, sex, and number of animals. Data from the GPS units are downloaded using two protocols. First, ArcView shapefiles are created using OziExplorer (Henderson 2002). Second, in order to retrieve encoded information in the 6-digit waypoints, OziExplorer is used to create a delimited text file. A database file (DBF) is then generated which is converted to a shapefile (Newman 2002). Additional information, such as hours worked per hunter, are collected in paper format and entered into the database (Table 1).

Aerial hunting data collection is similar to ground hunting. Helicopters generally hunt in one block per flight. Blocks were uploaded into the inboard GPS, allowing pilots to remain in assigned blocks during hunting trips. OziExplorer converts blocks from ArcView shapefiles to GPS format. The helicopter GPS is programmed to log a position for each track (flight) every 20 s (Fig. 2c); waypoints were marked with every goat(s) shot. Aerial shooters (2 per helicopter) keep track of total number of goats shot per flight with manual

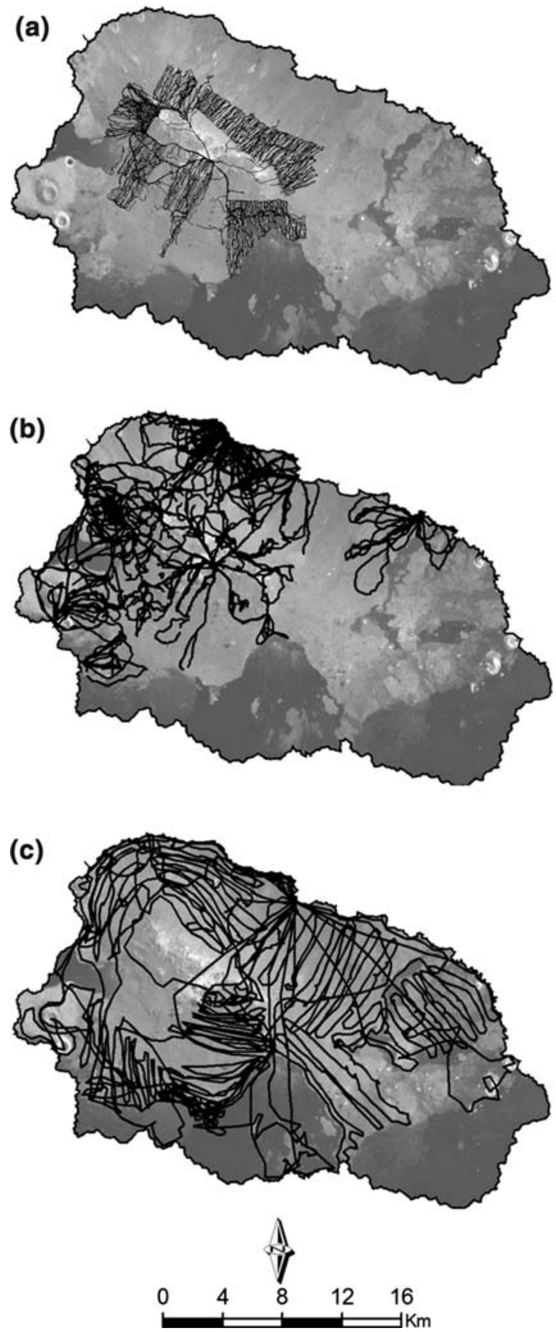

Fig. 2 Tracking island conservation actions spatially using GIS tools. (**a**) Ground hunting using the *rastrillo* technique in a heavily vegetated area. (**b**) Free-hunting using ground-based hunting teams with or without dogs. (**c**) Helicopter flight tracks during aerial hunting events. In all cases, effort and locations of kills and escapes are recorded facilitating spatial, temporal, and economic analyses of introduced mammal removal campaigns (see Table 1)

counters, while the number of waypoints entered in the GPS unit by the pilot (1–5) per shooting event represented number of goats shot depending on goat density (e.g., 1 waypoint entered equals 2 goats shot). Throughout the aerial hunting phase, tracks and waypoints were linked to other relevant data, such as pilot and flight time, all of which were incorporated into the database (Table 1).

Monitoring

Along with hunters with dogs in 'rastrillo', Judas goat operations are the primary monitoring technique used in the eradication campaign on Santiago Island. GIS tools contribute significantly to the efficiency of these operations. Judas goat operations rely on the monitoring of deployed goats with telemetry collars using telemetry antennas and receivers to track the animals either by foot or helicopter. To deploy Judas goats the helicopter's rear seats were removed, allowing up to 12 Judas goats to be deployed per load with a crew member on the pilot's side skid deploying goats numbered as per waypoints. Routes for deploying Judas goats at equidistant deployment points were generated by GIS and uploaded to GPS units to minimize helicopter ferry time. Judas goats are subsequently checked at regular intervals; once Judas goats are located, all associated feral goats are shot. In order to facilitate monitoring activities, on each trip the helicopter crew is provided with maps of the last known position of Judas goats. For each Judas monitoring event, the position is recorded with GPS, and other data are recorded in paper format (Table 1). On a daily basis, data from Judas monitoring events are incorporated into both relational and spatial databases. Data can than be analyzed in an adaptive management fashion. For example, recent events can be queried for selected Judas goats and then linked to the spatial database to generate an updated map of last known positions.

Discussion

The described GIS tools serve three general purposes. First, they allow a large island to be broken into manageable sections that facilitate systematic planning, hunting, and monitoring. Second, they allow critical data to be collected, visualized, and analyzed (e.g., goats shot per hour) on a daily/weekly basis during the eradication campaign; this allows for progress to be monitored and adaptive decisions regarding techniques and strategies to be made in a timely fashion (Fig. 3). Lastly, these GIS tools increase the cost-effectiveness and efficiency of the overall campaign, facilitating economic analysis of eradications and saving both limited conservation dollars and time (Table 1, Fig. 3).

Some or all of these GIS tools should be incorporated into the planning and management of most medium to large-scale non-native mammal eradications, including introduced herbivores (goats, donkeys, sheep, rabbits), pigs, and introduced predators (cats and rats). Most non-native mammal eradications to date have not utilized geographic tools. While this may be a non-issue for campaigns on smaller islands, even medium-sized island eradications have failed or taken decades rather than years due to the lack of incorporating technology and systematic methods (Campbell and Donlan 2005).

A common reason for unsuccessful eradications is the failure to detect the last remaining animals. Integrating GIS tools, such as monitoring programs using equidistant points, holds great potential in detecting remnant animals and subsequently shortening the length of eradication campaigns and their confirmation. On Santiago Island, equidistant points were used for the deployment and monitoring of poisoned bait stations during the successful removal of non-native pigs (see Cruz et al. 2005), as well as for systematic monitoring of invasive plant species. On Pinta Island, equidistant points were used to conduct a systematic search for Galápagos giant tortoises, thought to be extinct on the island (Campbell et al. 2004). This GIS tool was also successfully integrated into a feral cat removal campaign on Baltra Island, both for bait station placement and conducting systematic searches for sign (Phillips et al. 2005). These examples demonstrate the efficacy and potential widespread application of using equidistant points in insular eradication campaigns and other conservation actions.

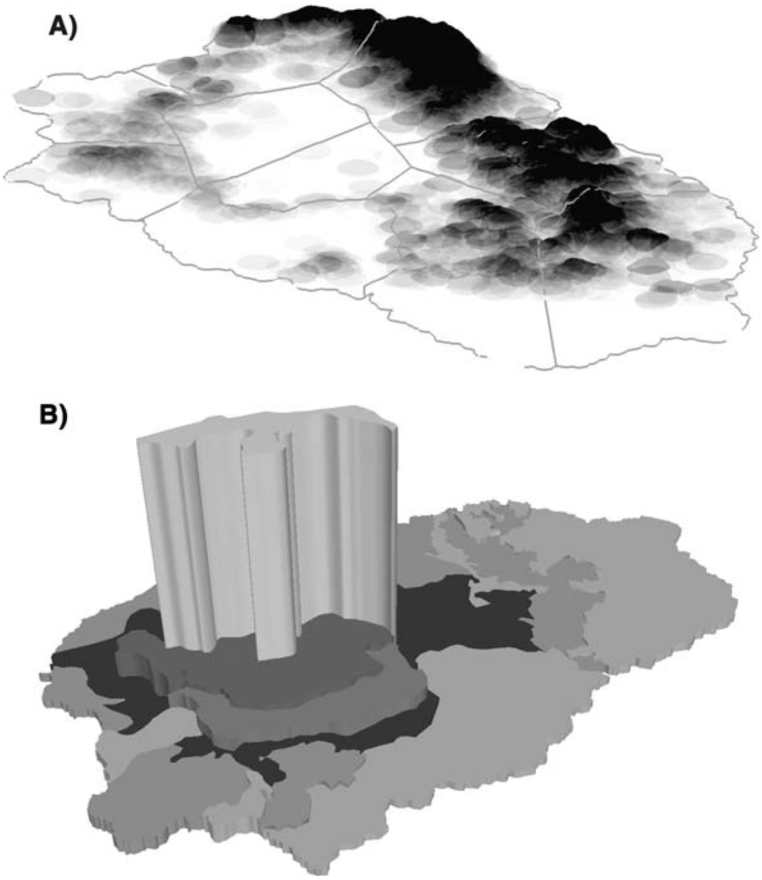

Fig. 3 Combining spatial and non-spatial data to increase the efficiency of non-native mammal eradications. (**A**) Spatial distribution of goat removed via aerial helicopter hunting on Santiago Island (**B**) Cost ($US) per kill in each vegetation type with helicopter hunting

The majority of non-native mammal eradications from islands remain unpublished; this likely inhibits progress in island conservation and contributes to the low level of importance placed on the eradication of invasive species in many conservation circles (Simberloff 2001; Donlan et al. 2003). Further, managers of eradication campaigns rarely collect data (Campbell and Donlan 2005). There are two major problems with a data-less approach. First, assessing progress of an eradication campaign is limited to qualitative and anecdotal observations and this is an inadvisable approach even with small islands and almost surely will lead to failure with larger islands. As important, data-less eradication campaigns make it difficult or impossible to improve on techniques and efficiency for future island conservation actions. By incorporating and leveraging standard geographic tools, the approach outlined here provides a foundation for statistical, spatial, and economic analyses that should improve the capability and efficiency of removal campaigns. Given limited conservation funds and the dire status of many island species, efficiently removing non-native mammals from islands is of paramount global conservation importance.

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