Facing the dilemma at eradication's end: uncertainty of absence and the Lazarus effect

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Feral ungulates, such as pigs, are highly destructive to island ecosystems and are therefore often the target of eradication efforts. To succeed in eradication, however, managers must address a question made formidable by the great difficulty of detecting animals at very low levels of abundance: how will we know when elimination has been achieved? We developed and tested a framework to address this problem in a program to remove feral pigs from Santa Cruz Island, California. In an unprecedented timeframe for an island of this size, the program has progressed to a point at which pigs can no longer be detected. We describe seven key attributes of our approach, and how they have increased the likelihood that our inability to detect additional pigs indicates successful eradication, rather than the pigs having become better at escaping detection. This approach represents an important advance in the practice of eradication that can serve as a model for increasing the pace and scale of island restoration around the world.

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Non-native vertebrates threaten island biodiversity throughout the world and eradication is often necessary to prevent extinctions of native biota (Myers *et al.* 2000; IUCN 2002). Eradication efforts, however, can represent high-risk investments of scarce conservation resources: millions of dollars may be spent on eradication, but if just one pregnant individual survives, the program can fail.

Perhaps the greatest challenge confronting managers of eradication programs is knowing when elimination has been achieved. This is because animals at very low abundance can be exceedingly difficult to detect (eg Russell *et al.* 2005). Even when massive efforts have been made to remove a population, uncertainty as to the success of the program can linger for years (eg Carey 1991). The reappearance of biota thought to be extinct – the "Lazarus effect" (Flessa and Jablonski 1983) – underscores why such caution is required (Whitten 2006). Campbell and Donlan (2005), reviewing efforts to eradicate goats from islands, cite many that failed due to inadequate intensity of effort and the difficulty of detecting and dispatching the last remaining individuals.

In a nutshell:

- It is difficult to detect animals at very low numbers, so it is especially difficult to determine when they have been completely removed – and that exacerbates the risk of failure in eradication programs
- Hunters specialized in not "educating" the target population can reduce much of the risk inherent in eradication
- Applied as a model, the approach used on Santa Cruz Island can allow for the attainment of ambitious island restoration goals, and accelerate the conservation of imperiled island biota

Because absolute certainty as to the absence of a species can only be attained by passage of time without detection (Perkins 1989), eradication managers invariably face a dilemma: the decision regarding when to dismantle an eradication program must be made despite the lack of certainty that elimination has been achieved. It would be a mistake to disband an eradication team too soon, because any remaining animals would likely require the greatest skill to detect and dispatch. Yet, given the scarcity of conservation resources and the expense of maintaining eradication teams, sustaining capacity to hunt animals that do not exist would waste limited funds. At what point, then, should an eradication be declared "done"?

Surprisingly, the eradication literature has rarely explicitly addressed the fundamental question of how to design and conduct an eradication program so that, at its end, there can be confidence that the population has been driven extinct. There are numerous case studies of monitoring protocols that have been used to increase certainty of absence following a program's hunting effort (eg IUCN 2002), as well as analytical guidance on estimating probabilities of extinction (eg Reed 1996), evaluating trade-offs between risk and cost (eg Regan *et al.* 2006), and so on. What is lacking is a discussion about the relationship of the day-to-day conduct of hunters with the ability to reach a goal of absence with certainty.

Here, we discuss how a program to eradicate feral pigs (*Sus scrofa*) from Santa Cruz Island, California, was designed to increase not only the likelihood of achieving eradication but also the ability to determine when eradication had been achieved. Although our example concerns pigs, we suggest that the principles can be applied generally. All vertebrate eradication programs face a

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Figure 1. *Pig-infested islands of the world. Area of islands < 10 500 km² where pig presence has been reported; islands where eradication has occurred are noted above the corresponding bar (IUCN 2005). Note that these data probably underestimate the occupied range of pigs, because "pigs are sometimes considered too commonplace to be remarked upon" (IUCN 2005). Island names below the axis are provided for size reference only.*

range of challenges; some are specific to the target species and/or the particular island system, others are more general. The approach used on Santa Cruz can be generalized as a framework for eradication because it spans many current challenges facing island managers, including the need to deliver effective conservation at increasingly larger scales (Santa Cruz is relatively large among those islands that are currently the focus of eradication projects) and within decreasing time frames (the viability of highly imperiled native species, such as the many endangered species on Santa Cruz, may depend upon eradication of invasives within the very near term). Delivering better results faster also requires that managers address the specific challenges posed by the adaptive biological and behavioral traits of the invader. A framework that can address these three issues would have broad application.

■ A world of pigs

Feral pigs rank among the "World's 100 Worst Invaders", due in part to their destructive impact on diverse island ecosystems (IUCN 2005). Through eradication, some of the threats posed by pigs have been abated, but pigs do remain widely distributed on the world's islands (Figure 1). Most reported eradications have been on smaller islands, but there are some notable exceptions. A 30-year eradication campaign has recently been declared complete on 58 465-ha Santiago Island in Ecuador (Cruz *et al.* 2005). A 15-year eradication program on California's 19 400-ha Santa Catalina Island is reportedly in its final stages (Garcelon *et al.* 2005). Eradication was achieved on 21 450-ha Santa Rosa Island, also in California, in considerably less time (approximately 3 years; Lombardo and Faulkner 2000). That shorter timeframe may in part be attributed to Santa Rosa's mostly low-stature vegetation being conducive to hunting and monitoring. It is also worth noting, however, that the Santa Rosa project was initiated as an eradication program, whereas the Santa Catalina and Santiago projects began as pig population control operations that only later segued to full island eradication. As discussed below, hunting with control as the desired outcome differs in important ways from hunting with eradication as the goal. Indeed, beginning with a control phase may affect the characteristics of the remaining animals, the duration of the effort, and even the likelihood of success of the program.

Eradication accomplishments are especially noteworthy given the predisposition of pigs to survive an eradication attempt. In favorable conditions, pigs can breed throughout the year and may have as many as 10 offspring per litter (IUCN 2005). They can recover rapidly from reductions in population, perhaps better adapted to survive in an increasingly hostile eradication environment. Through selection, conditioning, and/or learning, the pigs that survive the early phases of an eradication campaign will have traits that make them more difficult to encounter later. Even though it is expected that pigs will become increasingly elusive, it is hard to predict how that elusiveness will manifest itself. These factors heighten the risk of failure of the program.

Recent advances in aerial, GIS, GPS, and telemetry technologies provide tools that can help reduce the risk of failure, but the extent to which they do so depends on how they are deployed. Reducing risk requires an explicit focus, in planning and implementation, on basic aspects of biological systems that may undermine the likelihood of success: reproduction, selection, and uncertainty. Without this focus, it would be difficult to drive the population to non-detectable levels, much less to be confident that the lack of detection indicates success.

■ What does "lack of detection" mean?

At the apparent end of an eradication program, an inability to detect more animals may mean either that there are no remaining individuals or that those still present went undetected. The latter might be assumed for two reasons. The first is that the probability of detecting animals may vary among individuals and among detection techniques. No one technique can successfully detect all pigs, for example. If bait stations are used to detect pigs, only a subset of the overall population will come into contact with the station, and fewer still may take the bait (Fleming *et al.* 2000). Other techniques may be similarly limited. Dispatch rates of pigs using aerial hunting tend to follow a Type III functional response (Choquenot *et al.* 1999), whereby the ability to detect the pigs drops effectively to zero below a certain level of abundance. Consequently, if that were the only technique employed, pigs would have a refuge below that threshold, and the population could be sustained despite continued allocation of effort. Multiple techniques used in concert can reduce the likelihood that tactical refugia remain, but it is usually impossible to know if these refugia have been eliminated completely.

Courtesy of L Laughrin

Figure 2. *Feral pig rooting damage on Santa Cruz Island. The endangerment of at least nine plants and one endemic canid has been attributed to the presence of feral pigs on the island (NPS 2002).*

Compounding the difficulty of detecting a population at low levels of abundance is the potential effect of the means by which that population was reduced; if the animals are low in number because of persecution, the remaining animals will probably possess traits that render them even more difficult to detect, as a result of selection and/or learning. So the second reason for assuming that individuals are present but have been missed is that the mean detection probability of the population at the end of the project is likely lower than at the beginning. In the end, the usefulness of indicators of absence will be largely dependent upon how the hunt was designed and conducted.

■ Test case for a new approach: Santa Cruz Island

The largest pig eradication program currently underway is on Santa Cruz Island, approximately 40 km offshore of Santa Barbara, California. The Nature Conservancy (TNC) owns 76% of the 24 900-ha island; the United States National Park Service (NPS) owns the remainder. Pigs were introduced to the island in the mid-19th century and have since caused extensive damage to the island's natural and cultural resources (NPS 2002; Figure 2). In response, various alternatives for abating this threat were analyzed; the preferred alternative was eradication by dividing the island into management zones with pig-proof fencing and then hunting within the zones to eventually eliminate pigs island-wide (NPS 2002). It was estimated that the "hunting" phase would take 6 years, with an additional 5 years for the "final hunting and monitoring" phase. Fifteen months after the start of the hunt, we dispatched what seems to be the last pig, for an island total of 5036. In over 11 subsequent months of searching, no additional pigs have been detected.

So, is the eradication of pigs from Santa Cruz Island complete? The description of (1) the techniques used to reach this point and (2) the analyses that identify the probability of Number 5037 still being out there will be presented elsewhere. Here, we focus on the approach we took to minimize the likelihood that a pig would remain undetected at this stage of the program.

■ Achieving absence with greater certainty

It has long been recognized that success in an eradication program depends upon a number of conditions (eg Parkes 1990). Of those, most emphasis is generally placed on two. The first condition is that all individuals in the target population must be at risk; there can be no spatial, temporal, or tactical refuge for the animals to exploit. Because no single eradication technique will work for all individuals, a suite of techniques must be strategically deployed. Our program, for example, progressed from trapping to helicopter hunting to ground hunting to monitoring. The second condition is that eradication must outpace replacement. If hunting pressure is relaxed, the population can recover or reinvade areas previously cleared.

We build from those foundational principles, emphasizing the importance of designing a program that provides managers with greater certainty that zero detection does in fact indicate absence. After all, the goal of an eradication program is not apparent absence, but the highest possible degree of certainty of absence. Apparent absence alone provides minimal assurance to a manager deciding whether to disband the eradication team. An informed decision requires an understanding of how the hunt was conducted and to what degree animals were precluded from becoming more difficult to detect. Thus, our singular focus as we proceeded through the eradication on Santa Cruz Island was to avoid educating the remaining

Figure 3. *The seven attributes of highly effective eradication. Arrows indicate the biological challenge expected to be most reduced by the individual attribute. The key attributes also act synergistically, as a framework to enhance the likelihood that eradication will be achieved, and to reduce variation in (and so enhance the information value of) data from the project. Systematic, intensive, and disciplined implementation, for example, also helps reduce uncertainty concerning whether pigs remain following a given allocation of effort.*

pigs to the fact that they were being hunted. To enhance our ability to achieve eradication, and to ascertain when this occurred, we designed a program with the following key attributes: implementation that was *strategic, systematic, intensive, skilled, disciplined, measured,* and *analyzed* (Figure 3).

The strategic, systematic, and intensive aspects can be seen in the way the program was structured and adaptively implemented. To create a field of operation of a size that would enable maximal effect, the island was divided into fenced zones, each representing an independent eradication unit. Nested within those zones were non-fenced operational units, defined largely by topographic features. Aggressively but methodically, we progressed through the units and across the island, deploying an array of techniques in a wave of increasing intensity. Hunters worked as a coordinated team, focused on overall outcomes rather than who among them dispatched a given pig. Moving in formation provided comprehensive ground coverage that left little chance of escape (Figure 4). A helicopter serviced all aspects of the program, so extensive areas could be worked rapidly, using a variety of techniques. Nearly 80% of the pigs were dispatched using the helicopter as a hunting platform. With comprehensive helicopter support for transport of personnel and supplies, all energies could remain focused on the hunt (the team could be positioned in minutes, for example, and only needed to hunt downslope). As a result, field effort remained consistent and intense, education and replacement of pigs was minimized, and the resulting data were better standardized to support analyses that provided ongoing guidance for the program.

To further minimize selection of the population toward greater wariness, we assembled skilled and disciplined hunters committed not only to the aforementioned team ethic, but also to the standard that every engagement with a pig must be lethal. Not every encounter of a pig is an engagement; "engagement" is when the hunter attempts to dispatch an individual pig. If, for example, a hunter in an aerial hunting sortie is not confident that all the pigs in an encountered group (Figure 5) can be dispatched, perhaps because some are too near protective cover, no shots will be fired. This is because any pig that survives would likely learn from the experience to avoid the helicopter, and so become harder to engage again. The need to forego engagement rather than risk escape distinguishes an eradication from a sport hunt or control operation. An eradication team must ultimately dispatch every animal, so maintaining the naïveté of the hunted population is strategically paramount. For this standard to be met, the team must possess superior technical ability (eg to shoot with precision in suboptimal conditions), field intuition (eg to determine whether animals encountered should be engaged), and discipline (eg to refrain from engaging if conditions are not conducive). It is worth noting that such attributes provide other programmatic benefits. For example, precision shooting by skilled hunters reduces wounding and escape, and therefore minimizes animal stress and suffering (AVMA 2001). An intensive program not only accelerates the attainment of the conservation benefits of eradication, but also limits reproduction and reduces the total number of animals that ultimately need to be dispatched.

While the above attributes help to reduce uncertainty concerning the status of the remaining population, to reduce that uncertainty in a rigorous manner, implementation must be measured and analyzed. Throughout our program, we collected comprehensive data on all effort (eg Figure 4) and outcomes (eg dispatches) to permit managers and independent auditors to estimate the statistical confidence that should be ascribed to indicators of absence. Can such spatial and statistical analyses resolve the eradicator's dilemma? Not alone, but they are essential to responsible and transparent decision making. We suggest that another input is confidence that the hunting team conducted the hunt in a manner that reduced the confounding effects of learning and selection on detection probability.

Figure 4. *Sample of effort data collected from the pig eradication project on Santa Cruz Island. The island was divided into five pig management zones, using approximately 45 km of pig-proof fencing. All hunting effort and outcomes were logged using portable GPS units. Depicted are cumulative (a) daily ground hunting tracks, with each color representing a different day's activity by hunters and (b) aerial hunting flight paths, for May–July 2005, in the westernmost zone. Insets show (a, inset) the subject zone and property ownership, and (b, inset) location of the island within the State of California.*

■ Finding Lazarus

While eradication of non-native vertebrates is widely appreciated as an essential tool for conserving island biodiversity, there has been little discussion about how its implementation affects the ability to ascertain when eradication has been achieved. The relationship between field methodology and subsequent certainty of absence needs greater research attention, especially as eradication efforts are directed to larger and more complex island systems. In our program, we set out to design and test an approach to maximize certainty of absence within the time frame needed to make major management decisions (eg when to disband the eradication team). We collected comprehensive data during the hunt, and conducted the hunt in a manner that supported meaningful analysis and interpretation of those data. Well before we dispatched the first pig, we were focused on how we would detect the last – an approach that has significantly reduced the program's duration, from an initial estimate of 6–11 years (NPS 2002) to approximately 2 years.

This approach represents an important advance in the tools available for restoration of island ecosystems. Applied as a model, it can increase the scale and pace of future eradication programs, while decreasing their inherent investment risk. It can therefore greatly accelerate accrual of the biodiversity conservation returns so urgently needed on islands, and allow ambitious restoration goals for islands to be set.

Each day in the course of an eradication program, basic aspects of biological systems – reproduction, selection, uncertainty – conspire against the program's success. Fortunately, over the past decades, great advances have been made in leveraging other aspects of biology and behavior to the eradicator's advantage; the "Judas animal" represents the classic example. Judas animals are

Courtesy of O Pollak/TNC

Figure 5. *Feral pigs on Santa Cruz Island. Early in the eradication program, encounters with groups of pigs like this one were commonplace. The program's success depends upon the cumulative outcomes of daily decisions made by hunters facing such encounters, regarding whether or not to engage (ie attempt to dispatch) the animals. If the hunters were not confident that all of the encountered animals could be dispatched, they needed to demonstrate the discipline not to engage any, since any individuals that escape may become considerably harder to engage later.*

radiotelemetered, usually sterilized, and released back into the wild; hunters then need only locate the Judas animal and dispatch any associates it may have assembled. The use of Judas pigs, for example, can be an effective tactic in eradication (McIlroy and Gifford 1997). Of more fundamental *strategic* concern, however, is what we refer to as the "Lazarus pig", the last animal of the project, perhaps that pregnant individual whose fate may determine the success of the program. The characteristics of that animal, and the ability to detect it, will be shaped by events unfolding from the first day of the hunt. Through adherence to the key attributes outlined above, eradication teams can reduce the likelihood of creating an animal that is effectively undetectable and leaving behind the individual that can restore a population. The continuing challenge for the science and practice of eradication is to hone field and analytical methods so that, with each subsequent program, we are increasing the likelihood and efficiency of finding the Lazarus animal – and decreasing the time it takes us to recognize it once we have done so.

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