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Eradication of Feral Swine from a Barrier Island in Florida, USA: An Examination of Effort and Multi-method, Multi-species Population Indexing

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Research Article

Eradication of feral swine from a barrier island in Florida, USA: an examination of effort and multi-method, multi-species population indexing

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Abstract

Feral swine were targeted for and successfully eradicated from Saint Vincent Island (SVI), a National Wildlife Refuge (NWR) along the coast of Florida's panhandle to protect its habitats and uncharacteristically high diversity of wildlife species for barrier islands in the region, including federal and state-listed threatened and endangered species. The eradication effort was initiated in early 2015 and concluded in 2019. A total of 438 feral swine were removed from the Island, 417 by federal control experts and 21 by recreational hunters. In general, the amount of effort needed to eradicate each feral swine slowly increased as the eradication effort progressed; however, effort increased by an order of magnitude in the final six months. The last three feral swine took 77 days of effort to remove. The eradication effort provided an opportunity for evaluating and comparing methods for indexing feral swine population abundance and their abilities to describe population trends and to detect animals at low population abundance. The feral swine population was monitored from 2015–2019 using a passive tracking index (PTI) twice each year and using camera traps. Camera and track plot data were used to calculate abundance indices based on a well-documented indexing paradigm applied to feral swine populations. In addition, we simultaneously monitored relative abundance of other mammalian species crucial to management for the Island. The PTI and camera index both well-tracked population abundance simultaneously for the large ungulates inhabiting the Island (feral swine, white-tailed deer, sambar deer). However, the sensitivity for the PTI to capture animal observations was much greater than for the camera stations. This held true even over 5-day observation sessions by cameras versus 3-day observation sessions for track plots. Additionally, the PTI was sensitive for simultaneously capturing data for smaller animals, raccoons and armadillos, whereas the camera stations were ineffective for the smaller species, likely due to camera positions being optimised to capture feral swine. Our 100-m track plots outperformed the camera stations in many regards, but the camera stations required less labour in the field and were less fragile in the field, especially from weather or access issues. In 2018, Hurricane Michael, a category 5 hurricane, struck SVI. Its habitat damage may have adversely impacted white-tailed deer and sambar deer populations, but not armadillos or raccoons. Both the swine eradication and hurricane impacts provided valuable means for validating indexing procedures.

Key words: animal damage, camera trap, conservation, deer, feral hog, Florida, hunter take, invasive species, passive track index, population monitoring, *Sus scrofa*

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Introduction

Globally, feral swine (*Sus scrofa*) have a broad native range and an even broader range as an exotic invasive (non-native, alien) species (Massei et al. 2018; VerCauteren et al. 2020). Feral swine are globally infamous for damaging native plant species, animal species, habitats, ecosystem processes and archaeological sites, as well as spreading disease to livestock, wildlife and humans (Singer et al. 1984; Choquenot et al. 1996; Seward et al. 2004; Engeman et al. 2007a, 2013a, 2017; USDA 2015). Of all large wild mammals in North America and possibly the world, feral swine possess the greatest reproductive potential (Bieber and Ruf 2005).

The many significant forms of damage caused by feral swine make them a highly desirable invasive species to eradicate. Yet, their reproductive capacity, mobility and the often-challenging habitats in which they live typically make eradication practical only for incipient populations, insular populations or other populations similarly constrained geographically. Even under these circumstances, complete eradication typically takes years of intensive control, with the elimination of the final animals particularly challenging. For example, an incipient, low-density population inhabiting mixed agricultural and forested land in Fulton County, Illinois required eight years of intensive integrated pest management methods application to eradicate (Engeman et al. 2019b). Similarly, the eradication of feral swine from North Island, South Carolina that had for years destroyed sea turtle nesting, required seven years of intensive control on this 1800 ha barrier island, with the final 11 swine requiring three years to remove (Engeman et al. 2019a). Other significant insular feral swine eradication efforts have included Santa Cruz Island, California, USA (Ramsey et al. 2009) and Santiago Island in the Galapagos Islands, Ecuador (Cruz et al. 2005).

Knowledge of local abundance of feral swine is often required when managing feral swine populations or mitigating their impacts. Hence, monitoring of population changes and trends is a key performance metric for evaluating the need for and efficacy of management actions (Engeman et al. 2013b). Rarely is it possible to have available the absolute numbers of free-ranging animal populations, which would be ideal for validating and evaluating abundance measures (Allen and Engeman 2015). However, it is possible to assess abundance indices through induced population changes and corroboration amongst multiple methods (Allen and Engeman 2015).

Here, we document multiple methods applied to the monitoring of feral swine removal until elimination from a multi-year feral swine eradication effort on Saint Vincent Island National Wildlife Refuge, Florida, USA (SVI). Other priority mammalian species for refuge management were simultaneously monitored. Both monitoring scenarios provided an excellent opportunity to assess how well the methods reflected changes in population abundance, how well they demonstrated agreement for each species and how well they described population trends (including management-expected population fluctuations). As SVI is an island, the potential bias from immigration and emigration during our investigation was essentially eliminated.

This was a long-term, multifaceted research effort with multiple fundamental objectives:

1. Describe the feral swine decline to zero over time through the eradication effort using multiple monitoring methods.

2. As recreational hunting for white-tailed deer (*Odocoileus virginianus*) and sambar deer (*Cervus unicolor*) is a high priority for the refuge, simultaneously monitor populations of the deer species for information on population health.
3. To improve overall refuge management, simultaneously monitor populations of two known sea turtle nest predators: raccoons (*Procyon lotor*) and armadillos (*Dasypus novemcinctus*).
4. Evaluate individually, compare and validate the different monitoring methods for their abilities to track population changes and their practicality for use in continuing refuge operations.

Methods

Saint Vincent Island

SVI is a nearly 5000 ha undeveloped barrier island along Florida's panhandle coast at the west end of Apalachicola Bay (Fig. 1). The Island comprises about 98% of the Saint Vincent National Wildlife Refuge and is managed to conserve SVI in a natural state. This triangular-shaped Island is about 14.5 km long, 6.5 km wide at its east end and tapers to a point on its west end. SVI exhibits ridge and swale topography with upland habitats and salt- and freshwater wetlands. SVI supports an uncharacteristically high diversity of wildlife species for barrier islands in the region. This diversity includes a variety of federal and state-listed threatened and endangered species such as sea turtles (*Caretta caretta*, *Chelonia mydas*, *Dermochelys coriacea*) and shorebird species (e.g. *Haematopus palliates*, *Charadrius nivosus*, *Sternula antillarum*) that use the Island for nesting. SVI also has served since 1990 as an island propagation site for the red wolf (*Canis rufus*) recovery programme.

Three large ungulates were present on the Island at the outset of this project: white-tailed deer (*Odocoileus virginianus*), sambar deer (*Cervus unicolor*) and feral swine (US FWS 2006). SVI, like all National Wildlife Refuges in the US, has a legal requirement to allow public hunts when compatible with a refuge's mission. Moreover, SVI had a further requirement to specifically allow hunts for sambar deer. Recreational hunting for the deer species is a key management priority for the refuge, while feral swine were an ancillary species taken by deer hunters. White-tailed deer are native to the Island. Sambar deer, originally imported to SVI in 1908, are a relic from when the Island was used as a private hunting reserve stocked with exotic species (USFWS 2012). Feral swine initially served as a sport hunting species, but ultimately were regarded as a destructive invasive species meriting eradication due to their damage to the Island's sensitive habitats, state-listed plants and to nesting by sea turtles and ground-nesting seabirds that use SVI's beaches and a threat to SVI's archaeological sites spanning millennia as documented elsewhere in Florida (Engeman et al. 2013a; 2017).

Feral swine removal by federal control experts

Removal of feral swine as part of eradication operations was conducted by government experts in an agreement with USDA Wildlife Services (WS), the Federal agency responsible for managing conflicts with wildlife Only approved and humane methods to euthanise animals conforming to guidelines in the 2013 Report of the American Veterinary Medical Association Panel on Euthanasia (American Veterinary Medical Association 2013) and set forth as agency policy in USDA/APHIS/WS Directive 2.505 were used.

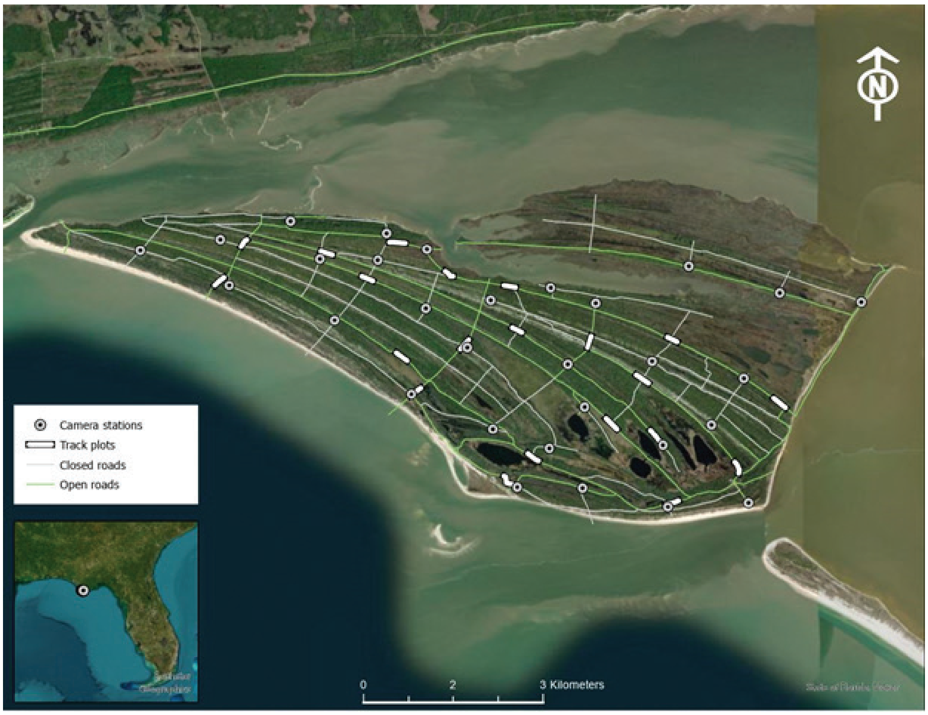

Figure 1. Location of track plots and camera stations for calculating passive abundance indices to monitor feral swine and sympatric species at Saint Vincent Island in Florida, USA, 2015-2020.

Feral swine were primarily removed by capture in pen traps and sharpshooting. After identification of the most favourable locations to carry out trapping activities, pen traps were constructed and baited with soured corn to condition the feral swine to feeding at trap sites. After feral swine were consistently entering the pen trap to feed, the trap would be set and triggered remotely. During the times when control experts were on the Island to conduct trapping activities, they also were opportunistically removing feral swine by sharpshooting, including a small number of animals removed by sharpshooting from a helicopter. All feral swine were lethally removed by USDA/APHIS/Wildlife Services personnel during the regular course of their official duties. Control personnel were not permanently stationed on the Island, but carried out control activities there according to budget cycles, when their efforts would have maximal impact and demand for their services elsewhere in Florida. The methods for lethal removal in addition to ethical considerations regarding lethal take were fully considered in accordance with the National Environmental Policy Act (USDA 2015). All other components of the study received agency approval by way of the USDA/APHIS/Wildlife Services/National Wildlife Research Center Quality Assurance (QA) procedure: QA1394.

Indexing methodologies based on data collected from observation stations

General observation station concepts

The goal for placement of observation stations is not so much to observe the geography of an area, but rather the animal population(s) inhabiting the area (Engeman 2005). Animals rarely use the landscape uniformly and data collection for calculating an abundance index is made highly efficient if observation stations can be placed to intercept predicted daily activity of the target animals (Engeman 2005; Bengsen et al. 2011; Engeman et al. 2013b). As demonstrated for many species around the world, roads or tracks through native terrain provide many animal species with convenient travel routes, thereby making them prime locations to place observation stations. This has proven especially true for monitoring feral swine in various places in the world, especially Florida (e.g. Jiang et al. (2006); Engeman et al. (2007a); Theuerkauf and Rouys (2008); Elledge (2011); Boughton et al. (2019)). In fact, feral swine in Florida have been well-documented to travel primitive roads, even when the off-road habitat offers little hindrance to travel, such as in pasturelands (Boughton et al. 2019). Thus, observation stations on SVI were deployed on the approximately 129 km network of primitive roads on the Island remaining from the island's days as a private hunting reserve and which are now used for visitor hiking trails, refuge management and public hunts (Davis and Mokray 2000). Areas holding refuge infrastructure and buildings were unlikely locations to observe animals and were excluded from station placement.

Two forms of observation stations were designed to accommodate two distinctively different forms of data collection (described below): track plots and camera traps. To reduce variability and increase compatibility amongst sampling occasions, we used the same track plot and camera trap observation station locations throughout the multi-year course of study (Ryan and Heyward 2003; Engeman 2005). Observations obtained for analysis from both types of observation stations were "passive" because they did not involve the use of attractants or drives to bring animals to the stations. The animals arrived, based on their normal daily routines of movement. One of the benefits from using attractant-free, passive observation stations to intercept the daily activities of animals is that it offers the opportunity to simultaneously monitor a variety of animal species without preference based on an attractant (Engeman 2005). Thus, the species of interest for our population monitoring objectives (feral swine, sambar deer, white-tailed deer) could simultaneously be readily monitored. Moreover, two species that can be significant sea turtle nest predators, a native meso-predator species, raccoons (*Procyon lotor*) and an invasive species, armadillos (*Dasypus novemcinctus*), could also be monitored (e.g. Engeman et al. (2003, 2005, 2010, 2012)).

Passive track index (PTI)

We applied passive tracking index (PTI) methodology in a fashion similar to the methods successfully used to monitor feral swine in a variety of properties throughout the State of Florida and globally (Engeman et al. 2007a, 2013b). Beginning spring 2015, track data were collected from 21 permanent plot locations twice per year in spring and autumn (Suppl. material 1: table S1). The first track plot data collection was conducted in March 2015 at the same time as the first round of control by federal experts was underway (Suppl. material 1: table S1). The track plots were 100 m in length and located along the primitive road system on SVI. Track plots were randomly located along the road system with the restriction for all plots to be at least 900 m apart from each other as measured along the roads, not as the crow flies (Fig. 1). The surfaces of the plots were smoothed for reading tracks and the number of track intrusions by feral swine and other wildlife species were counted and recorded at each plot the following day (Fig. 2; Engeman et al. (2007b)). Feral swine and other animal tracks were easily detected in the freshly

Figure 2. Track plot preparation using a tractor (top left photo); smoothing the track plot surface using a chain drag (bottom left photo); and reading the track plot (right photo)

smoothed, sandy soil. The procedure of preparing the tracking surfaces and recording the number of track intrusions for each species was repeated for three consecutive days for all sampling events, except autumn 2019 when we were unable to collect data on day 3 due to heavy overnight rain that washed away the tracks.

Camera trap index

Camera traps were placed similarly to the track plots along the system of primitive roads to capture images of wildlife travelling the roads, where camera stations were randomly located along the road system with the restriction for all cameras to be at least 500 m apart from each other as measured along the roads, not as the crow flies (Fig. 1). Camera data were collected from 30 permanent camera trap locations four times per year, including similar spring and autumn timeframes as for track plots and also in winter and summer (Suppl. material 1: table S1). Pre-control camera trap data were collected in January 2015 just before control by federal experts was initiated (Suppl. material 1: table S1). To avoid introducing bias or decreasing precision, all cameras were the same make and model to ensure consistency in detection and camera response time (Reconyx PC800, Holmen, WI, USA) and the same functioning setup including equipment mounting and field of view was used throughout. For each trigger of a camera, there was a burst of three photos per trigger (1 second delay between photos) and a 30 second delay between trigger events. Each image incorporated a date and time stamp.

Photos of each burst were inspected to determine the number of individuals of each species captured. The minimum of a 30 sec delay between camera trigger events usually meant the photographed animals had cleared the view. However, following Massei et al. (2018) and Palmer et al. (2018), we defined one visit as one or more photographs of a given species until there is a lapse of at least 10 minutes between consecutive photographs. We counted photos > 10 min apart as new independent visits. Exceptions were made for consecutive photos of morphologically distinct individuals of the same species. That is, individuals that were significantly different in size or pelage, to a point where there was no question whether they were different individuals, were counted separately, regardless of the time elapsed between photos. Thus, for a given 3-photo trigger or sequence of triggers less than 10 minutes apart, we recorded the number of the individuals of a given species pictured. The total number of individuals was accumulated through each 24-hr period and considered to be the maximal number of individuals photographed on that day by that camera. Indices were calculated from 5 consecutive days of these camera data for each species (Suppl. material 1: table S1).

Index calculations for data collected from observation stations

Camera trap and track plot data were used to calculate abundance indices using a well-documented indexing paradigm that has been applied to many wildlife species populations in many places, including feral swine and deer (Engeman 2005; Engeman et al. 2013b). The indexing paradigm calculations described in Engeman (2005) were used to calculate the PTI and camera trap index values for feral swine and the other species for each sampling occasion. In short, for each sampling occasion, the mean measurement across observation stations was calculated for each day and the index values were the means of the daily means (Engeman 2005):

$$PTI = \frac{1}{d}\sum_{j=1}^{d}\frac{1}{s_j}\sum_{i=1}^{s_j}x_{ij}$$

where x_{ij} represents the number of feral swine intrusions at the i^{th} track plot on the j^{th} day, d is the number of days of observation and s_j is the number of plots contributing data on the j^{th} day. (See Engeman (2005) and Shulman et al. (2016) for supporting statistical theory and background). Amongst the benefits of this paradigm's methodology are that independence amongst observation stations or amongst days is not required for these calculations and unequal numbers of station observations across days do not invalidate calculations (Engeman 2005). In other words, if on some days a camera fails or a track plot is obliterated by weather or machinery, the theory behind the calculations and subsequent analyses are not impacted.

Take-rate indices

Take-rate index for feral swine by control experts

Federal control experts targeted feral swine, but not deer, making feral swine the only species to have a take index by control experts. Index values were calculated similar to those calculated for other animal control operations where the control experts simultaneously applied multiple control methods at varying intensities (Avery et al. 2014). The dynamic integration of control strategies when operational personnel were working on the Island made the standard working day of 8 hours the only practical definition for unit of control effort. Thus, we expressed efficacy of the control effort as the number of feral swine removed per person-day during each control period. In order to compare the expert control index values to values derived from the other methods, we defined the control periods using the quarterly camera data collection events, such that a control period covered approximately a three-month time frame starting at the end of one camera collection event and including data through the end of the following camera collection event (Table 1). While the indexing was broken into three-month intervals, it would be deceptive to consider the total take per three-month interval to be accurate for indexing abundance, because the control effort put forth during each three-month period was not equal. Only the take-per-effort provides a reliable assessment from each three-month interval.

Take-rate indices for feral swine and deer by recreational hunters

We also considered three other types of take-rate indices, based on removals by recreational hunters during three types of hunting seasons. Hunter take (catch per effort) is widely applied for assessing relative abundance of wildlife, including wild/feral swine (Boitani et al. 1994; Fernandez-Llario et al. 2003). Catch per effort is often formulated as animals per hunter-day. SVI is a relatively large, controlled area with a long history of public hunting, with three hunts (archery, sambar, muzzleloader) per year in late-autumn/winter timeframe (Table 1). Deer are the primary species of interest and feral swine and raccoons are also encouraged to be taken. Recreational hunters entering SVI must check in upon arrival, upon leaving and when their take is recorded. Thus, reliable data were available on hunter take and the corresponding number of hunter-days for each hunt each year. A take-per-effort index was calculated for each hunt and standardised as take per hunter-day.

Table 1. Indexing results for feral swine by six methods on Saint Vincent Island, Florida, USA from 2015 to 2020. Feral swine were eradicated 1 Oct 2019, which was before the fall track plots and fall camera data collection were initiated in 2019.

Year	Season	Feral swine abundance indices									
		Track plot data			Camera data			Expert take	Hunter take (take/hunter-day) for each hunt season type		
		Index val.(track intrusions/plot/day)	% plots detecting swine day 1	% plots detecting swine over 3 days	Index val. (visits/camera/day)	% cameras detecting swine day 1	% cameras detecting swine over 5 days	Index value (take/person/day)	Muzzle-loader	Archery	SambarDeer
2015	Winter				0.938	38.5	84.6	3.692	0.016		
	Spring	2.433	30.0	47.6	0.379	20.7	41.4	1.960			
	Summer							0.771			
	Autumn	0.511	16.7	52.6	0.307	10.0	36.7	1.061		0.026	0.006
2016	Winter				0.467	20.0	50.0	1.203	0.008		
	Spring	0.444	33.3	38.1	0.221	6.9	34.5	1.345			
	Summer				0.138	13.8	34.5	1.226			
	Autumn	0.829	28.6	61.9	0.187	6.7	26.7	0.997		0.021	0.008
2017	Winter				0.186	6.9	37.9	0.972	0.000		
	Spring	too dry	too dry	too dry	0.179	10.3	17.2	0.793			
	Summer				0.069	0	10.3	0.512			
	Autumn	0.746	42.9	61.9	0.080	0	20.0	0.473		0.000	0.000
2018	Winter				0.152	3.4	31.0	0.948	0.006		
	Spring	0.365	19.0	38.1	0.100	3.3	10.0	0.884			
	Summer				0.034	6.9	6.9	0.458			
	Autumn	hurricane	hurricane	hurricane	hurricane	hurricane	hurricane	0.000		hurricane	hurricane
2019	Winter				hurricane	hurricane	hurricane	0.207	hurricane		
	Spring	hurricane	hurricane	hurricane	0.000	0	0	0.068			
	Summer				0.000	0	0	0.037			
	Autumn	0.000	0	0	0.000	0	0	0.000		0.000	0.000
2020	Winter				0.000	0	0		0.000		

Analytical assessment and comparison of indexing methodologies

We first examined index values over time from each method individually for each species to make sure the results were reasonable relative to what was known to be taking place on SVI through time, a key component to evaluating performance of abundance indices (Allen and Engeman 2015). Feral swine were being removed by control experts throughout the course of this study and at all times of the year, but control operations were only taking place within budget and logistics constraints and, therefore, not continuously ongoing non-stop. Recreational hunting only took place during refuge-set hunting seasons.

We assessed the relationship amongst methods using correlation analyses for each monitored species, with feral swine data providing the most meaningful results due to consistent direct population manipulation (Allen et al. 2014, 2017). As species alter activities (and numbers) through the seasons of the year, only time points in common between each pair of monitoring methods could be analysed. For example, correlations between indices derived from camera trap data versus track plot data could only be analysed from spring and autumn seasons when data collection was coincidental between both of the methods. Suppl. material 1: table S1 indicates how the different monitoring methods were classified into a given season. We tested for correlations between index values within a given season (i.e. row) in the Table 1.

We also wanted to compare sensitivities of each method to detect animals and index abundance as the population decreased to low numbers for feral swine. This is crucial for many types of wildlife monitoring situations from opposite ends of the management spectrum. When doing an eradication, it is essential to know if the population has been removed. In contrast, when attempting to conserve a rare species, it is essential to know if a population exists in an area and its relative size. Thus, the methods were examined pairwise using their assessment time points in common. We also did this for the other species as well, realising their populations should be detectable year-round each year, although hunter take-rate indices were only available once per year for each of the three types of hunts for deer.

Uncontrollable data gaps

Unfortunately, there were some gaps beyond our control where data collection did not occur. The first occurred for summer 2015 due to financial constraints preventing expenditure on this research. Later in the study, the collection of track plot data was not feasible for spring 2017, which was during an abnormally dry weather period. This made the soft sand substrate unstable for maintaining track details and, therefore, distinguishing tracks amongst species impossible. Our data collection and indexing results for all species and all methods are summarised in Table 1 and Suppl. material 1: tables S2–S5; these tables also indicate gaps where data collection did not occur.

In October 2018, Hurricane Michael, a devastating Category 5 hurricane, struck Florida's panhandle coast (Byrne 2019) including SVI and the destruction severely affected our ability to collect indexing data (Suppl. material 1: table S1). Data collection using camera traps in autumn 2018 and winter 2019 could not be made when we could not access and sample the Island (data collection opportunities lost). For the same reason, the autumn 2018 track plot sampling was lost. Further, no data were collected for track plots in spring 2019 because damage and debris were still too severe to implement the 100 m plots.

Assessing Hurricane Michael's impacts to SVI wildlife populations

Prior to Category 5 Hurricane Michael reaching the Florida panhandle, a series of hypotheses were formulated around impacts on vertebrate populations. These considerations were based on how directly the hurricane would hit and the magnitude and timing of high tide and, therefore, whether a storm surge might over-wash the entire Island (possibly as deep as 2 m). We expected that a substantial over-wash might cause an acute reduction in numbers of some animals, especially armadillos. It also could hasten the elimination of an already-reduced feral swine population. The deer and racoons were expected to mostly survive the storm. Besides the acute threat to animal numbers from a potential island over-wash, the environmental destruction from such a powerful storm could have longer term population impacts through such impacts as destruction of food sources. Depending on island access and destruction levels post-hurricane, our population indexing methods were well-suited for assessing hurricane impacts to SVI's wildlife populations.

Results

Feral swine eradication

Between January 2015 and October 2019, WS experts invested a total of 559 person-days to remove a total of 417 feral swine. During that same time, 21 feral swine were removed by hunters during 15 refuge hunts (3863 hunter-days), for a combined total of 438 feral swine removed by both methods. As is often the case (see Engeman et al. (2019a, b)), the last few feral swine individuals to be removed in this eradication effort involved the greatest effort/time per individual (see Expert Take and Recreational Hunter Take in Suppl. material 1: table S2; Fig. 3). During the first year of eradication efforts, expert take was 3.692, 1.960, 0.771 and 1.061 swine per person-day of effort for winter, spring, summer and autumn, respectively (Fig. 3). By 2019 when the eradication was completed, the expert take per person-day of effort had dwindled to 0.207, 0.068, 0.037 and 0.000 swine per person-day of effort (Fig. 3). It took 77 person-days to remove the last three animals.

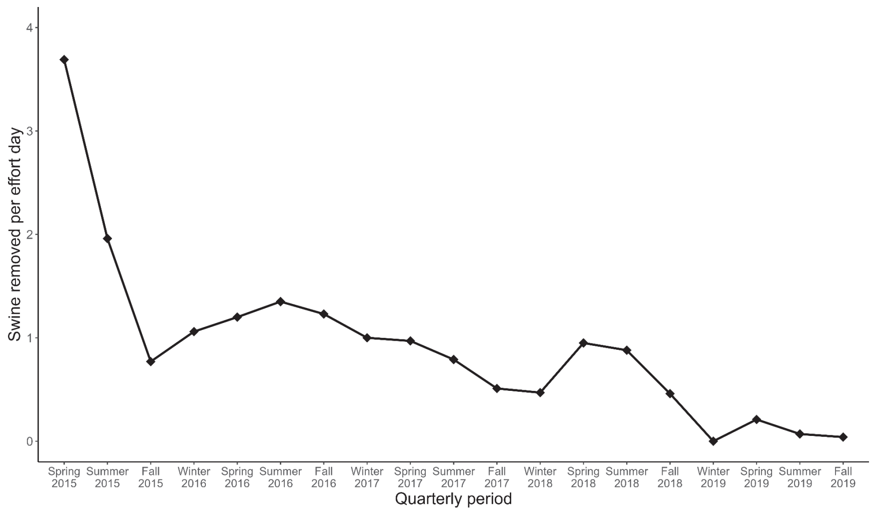

Figure 3. Feral swine take by federal experts in relation to person/hunt days (take per hunt day) on Saint Vincent Island, Florida, USA, 2015-2019.

Similarly, for recreational hunter muzzleloader season, take per hunter day numbers decreased over years from a high in 2015 at 0.016 swine per hunter day to 0.008, 0.000, 0.006 and 0.000 for 2016, 2017, 2018 and 2020, respectively (there was no muzzleloader hunting season in winter 2019 due to hurricane damage). The archery season followed the same pattern with 0.026 swine taken per hunter day in 2015, then declining to 0.021, 0.000 and 0.000 for years 2016, 2017 and 2019, respectively (no archery season was held in late autumn 2018 due to hurricane damage). Lastly, the number of feral swine taken per hunter day during the sambar deer season was never high and quickly dropped to zero with the takes per hunter day in 2015, 2016, 2017, 2020 of 0.006, 0.008, 0.000 and 0.000, respectively (no sambar season was held in autumn 2018 due to hurricane damage).

Indexing results

Feral swine indexing

The indexing results for feral swine (Table 1) provide valuable insights across the six indexing methodologies considered. The initial powerful impacts of control by WS can be readily seen (Fig. 3). The initial camera data were collected in winter 2015, just before expert control was implemented. WS control was ongoing during the initial track plot session in spring 2015, the second camera session was in spring 2015 and partially overlapped with the muzzleloader season in winter 2015. The decline in index value seen in the camera index in spring 2015 from the index value from winter 2015 was the greatest change in camera index values during the 5-year course of this study (Fig. 4). The greatest decline in index values for expert take occurred between the initial value in winter 2015 and the second in spring 2015. Similarly, the largest decline in the track plot index occurred between its initial session in spring 2015 and the one in autumn 2015 (Fig. 4). The muzzleloader hunt index, taken once per year in the winter, showed its greatest drop from 2015 to 2016 after WS control had been in place for a year. These results point to the immediate impact of control on a population where the greatest number removed, as expected, occurred early in the process.

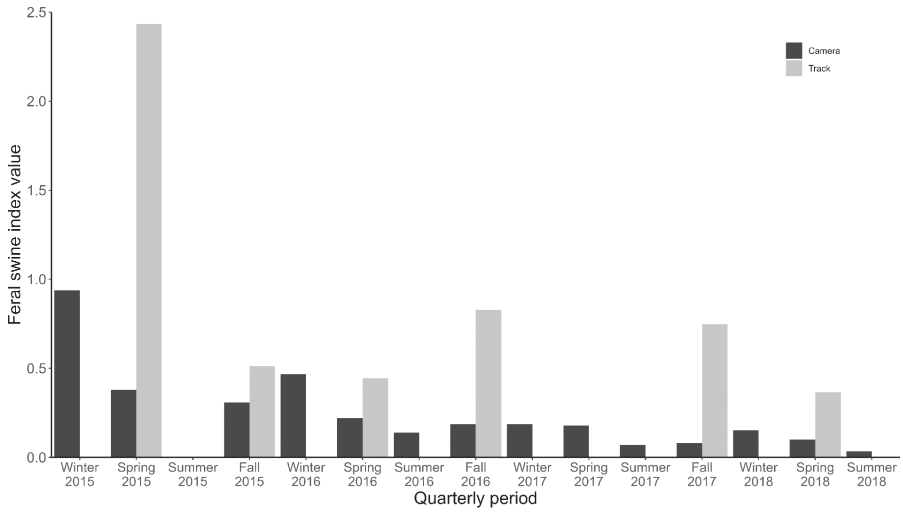

Figure 4. Feral swine track and camera index on Saint Vincent Island, Florida, USA, 2015-2018. Quarterly periods after Summer 2018 not shown as all indices were zero.

All indexing methods reflected the feral swine population decline to zero. The population decline for feral swine was especially well-documented by track plot, camera, and expert take indices, although it should be noted that the expert take results were not completely independent of those other two indices since the control experts had access to track plot and camera information to aid in their control efforts. However, the indices, based on recreational hunters targeting deer, were not very sensitive to detecting swine as their population became low. This would be expected for an ancillary species taken by hunters while targeting deer, thus receiving less opportunistic attention as their numbers became scarce.

Sensitivity of indices for monitoring the diminishing feral swine population

While both track plot and camera indices followed the feral swine population decline, another primary question to consider is which index method is most sensitive to the presence of low numbers of animals. A higher percentage of stations detecting the target species for a monitoring method reduces the number of such stations that would be needed to monitor the population, especially important if resources, logistics or labour are at a premium. Although the indices based on track plot and camera data each well-documented the decline and removal of the feral swine population, it is not surprising that a higher percentage of track plots detected feral swine than camera stations on the first day during an observation session, because track plots were 100 m in length, whereas camera views were about a tenth of that (Table 1). The difference in station size between track plots and cameras would be expected to be mitigated somewhat by field logistics where cameras were operating for a greater number of days (5 days) without effort, while the labour involved in reading and smoothing tracking plots placed practical limits on the number of days (3 days) track plots were maintained in the field.

Looking at the percentage of track plots versus the percentage of camera stations that recorded feral swine on the first day shows a much greater likelihood at each common observation session that the track plots would detect feral swine (Table 1). At least 1.5 to 6 times as many stations recorded feral swine activity on the first day of observations (noting that, at the autumn 2017 session, 42.9% of track plots recorded feral swine, but no cameras recorded swine on the first day). One could argue that this is due strictly to the track plots being 100 m in length, whereas a camera station's view would be a fraction of that (~ 10%). However, the cameras were recording observations for 5 days, while the track plots were only recording for 3 (except for the autumn 2019 session which only had 2 days of observations). Having a 67% longer observation period for cameras brought the detection percentages over an entire observation session for cameras closer to that for track plots through the spring 2016 sampling sessions, (within 70–91% of track plot detection rates, Table 1). However, after the feral swine population had been decreased substantially, the proportion of track plots recording swine during 3 days of sampling was ~ 2–3 times higher than for 5 days of camera observations (see the results in Table 1 from autumn 2016 through spring 2018). Thus, having more camera observation days at each session did not make up for the greater size of the track plots.

Levels of agreement amongst indexing methods for feral swine

The levels of agreement amongst the primary indexing methods for feral swine are reflected in the pairwise correlation coefficients amongst the methods (the results for the take results from the three hunting seasons are not considered since feral swine were not the target species). All indexing approaches indicated the declining feral swine populations. Of particular interest, the track plot index was reasonably well-correlated with the camera index with r = 0.73 (n = 7; Fig. 5). Similarly, the index, based on expert take, was also reasonably well-correlated with the track plot index, with r = 0.78 (n = 7; Fig. 5). However, the camera index and the index based on expert take were highly correlated at r = 0.94 (n = 17; Fig. 5). To explain the implications from these correlation results, we again must consider the relative sensitivities of the methods. A high correlation between two of the three methods does not imply that either of those methods is of higher quality than the third method. For expert take, there is not an analogous measure for detection on the first day of observation, nor an analogue for the percent of stations detecting feral swine during an observation session. This is due to multiple control methods being used simultaneously with those methods applied at differing and changing locations through the course of a control session. While the sensitivity of cameras compared to track plots was apparently limited by its smaller area sampled at each station, the magnitude of control by experts would also be expected to be limited by the manpower and trapping resources available, resulting in lower potential for large take numbers. These limitations for breadth of camera data and take by experts undoubtedly contributed to correlations with track plot indices not being higher.

Figure 5. Heat-map of Pearson's correlation coefficients for feral swine indexing methodologies, Saint Vincent Island, Florida, USA, 2015-2019.

White-tailed deer population monitoring and sensitivity of indices

While white-tailed deer were not the subject of population removal, they appeared to exhibit an overall population decline over the course of the study (Suppl. material 1: table S2). The correlation between track plot and camera indices for white-tailed deer was nearly the same as for feral swine, with r = 0.72 (n = 7). As the camera data were obtained quarterly, some interesting patterns emerged that could not be detected with the track plot data obtained twice per year. Going from each winter to spring assessment, the camera index showed a similar drop through the course of the study. A further, but smaller drop was then observed going from each spring to summer. Yet, by the ensuing winter, the index values returned to a similar level as seen in the previous winter. These patterns hold true throughout the course of our study, although with diminished numbers after Hurricane Michael (see Wildlife impacts from Hurricane Michael Subsection). As a result of data not being obtained for track plots due to Hurricane Michael for autumn 2018 and spring 2019, coupled with tracking observations not being feasible in spring 2017, similar seasonal patterns could not be elucidated from the track index values, but the index values within the available seasons appear supportive of the camera results indicating a stable population.

As observed for feral swine, track plots were much more likely than camera stations to record white-tailed deer on the first day of observation (Suppl. material 1: table S2). Similar to the feral swine results, the percentage of stations recording white-tailed deer over the three observation days for track plots exceeded the percentage of stations recording white-tailed deer over the five observation days for cameras (Suppl. material 1: table S2).

Sambar deer population monitoring and sensitivity of indices

Unlike for white-tailed deer, neither the camera index nor the track plot index revealed a consistent annual pattern in sambar deer abundance across years (Suppl. material 1: table S3). The two indices were moderately correlated, with r = 0.62 (n = 7) and both seemed to indicate a relatively stable population prior to Hurricane Michael (see Wildlife impacts from Hurricane Michael Subsection) or more on the hurricane's effects). As with the other ungulate species, the percent of track plots recording sambar deer on the first day and the percentage of track plots recording sambar deer during an observation session were each higher than for the camera stations, although the discrepancies for this species tended to be less than for white-tailed deer and especially feral swine.

Raccoon and armadillo population monitoring and sensitivity of indices

Track plot and camera indices for raccoons did not correlate well (r = -0.15, n = 7) and only to a limited degree for armadillos (r = 0.47, n = 7). The lack of correlation is easily understood when examining the proportion of stations recording either species on the first day or for the duration of the sampling event (Suppl. material 1: tables S4, S5). Track stations were much more likely to record presence of both raccoons and armadillos (Suppl. material 1: tables S4, S5). First day detections across track stations for armadillos ranged from 28.6% to 71.4%, whereas only 0% to 6.9% of camera stations recorded armadillo on the first day, with 0% observing the most common result over all observation sessions. Detections of armadillos across track stations over the course of an observation session ranged from 66.7% to 100% of stations, whereas the percentage of camera stations recording armadillo ranged from 3.4% to 26.7%.

Wildlife impacts from Hurricane Michael

During Category 5 Hurricane Michael, the Island experienced a storm surge, but only portions of the Island were over-washed. Swine survival following the hurricane was readily documented through animal signs and ultimately in the take by experts in spring 2019.

Both species of deer were documented by track plots and cameras to have survived the hurricane, as expected. Nevertheless, the white-tailed deer track plot index (Suppl. material 1: table S2) after the hurricane in autumn 2019 was only roughly half what it was in the previous autumn assessments in 2015, 2016 and 2017 with an observed 50.27% decrease when comparing pre-hurricane autumn seasons (2015–2017) and post-hurricane autumn seasons (2019; Fig. 6). The spring and summer 2019 camera index values for white-tailed deer were very close to the spring and summer values prior to the hurricane. However, the autumn 2019 and winter 2020 white-tailed deer camera index values were much smaller than the autumn and winter values before the hurricane, which also was reflected by the autumn 2019 track plot index. A 64.06% decrease was observed when comparing pre-hurricane (2015–2017) and post-hurricane autumn season camera index values (2019; Fig. 6).

Sambar deer track plot and camera index values followed patterns pre- and post-hurricane (Suppl. material 1: table S3) similar to the patterns for white-tailed deer. The autumn 2019 track plot index after the hurricane was only a fraction (61.03% decrease) of the autumn index values in preceding years, as was the case for white-tailed deer (Fig. 6). The spring 2019 camera index for sambar deer was similar to spring results in preceding years. The summer 2019 camera index was lower than all previous summer results, except for 2018 when an exceptionally low index resulted. As for white-tailed deer, the autumn 2019 and winter 2020 camera index values were much less than all previous index values from 2015–2018. A 75.70% decrease was observed when comparing pre-hurricane and post-hurricane autumn season camera index values (2019; Fig. 6).

Raccoons did not appear to have their abundance strongly affected by the hurricane (Suppl. material 1: table S4). When comparing autumn seasons pre- and post-hurricane, a 73.08% decrease in raccoon camera index values was observed, whereas a 16.28% increase in raccoon track plot index values was observed (Fig. 6). Armadillos also did not appear to have their abundance severely diminished by the hurricane (Suppl. material 1: table S5). The opposite pattern was observed when comparing autumn seasons pre- and post-hurricane for armadillos; there was a 41.67% increase in camera index and a 12.59% decrease in track plot index values (Fig. 6). The track plot index values for both species after the hurricane were similar to their values before the hurricane.

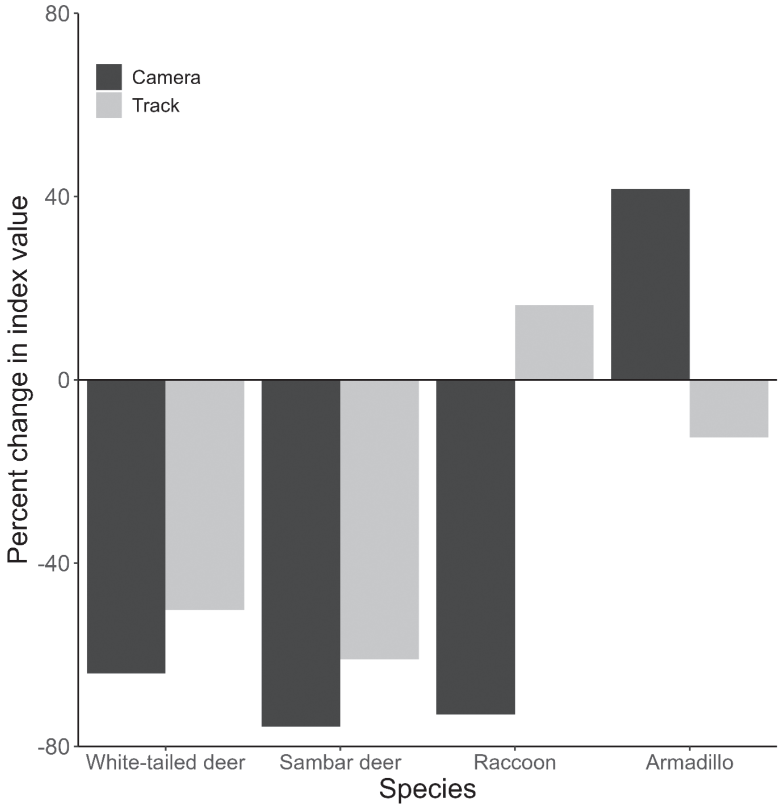

Figure 6. Percentage change in camera and track plot index values between pre- and post-hurricane sampling periods. Camera and track plot index values were compared between pre- (2015-2017) and post-hurricane autumn seasons (2019). No data were collected in autumn 2018.

Discussion

Feral swine eradication

Control by experts targets all population demographics while typically being cost-effective (Engeman et al. 2003, 2004, 2007b, 2010), yet it requires consistent application to be effective. For an insular population where immigration is a negligible or even a non-existent threat, consistent effective control by experts can eventually lead to eradication. In the case of SVI, control by experts through numerous (typically) week-long operational visits each year resulted in the final swine being eliminated from this 5000-ha Island in just under 5 years, primarily by trapping, but also sharpshooting (including four occasions from a helicopter).

In most places where feral swine are found, re-immigration after control operations is a concern. Effective control has substantially reduced feral swine populations on mainland Florida in a variety of places, including across even very large areas (e.g. Engeman et al. (2007a, 2013b)). Nevertheless, feral swine are ubiquitous in Florida, making re-immigration into an area a persistent threat. Re-immigration, coupled with feral swine possessing the greatest reproductive potential of any large mammal in North America (Wood and Barrett 1979; Hellgren 1999), means the beneficial effects of feral swine population reduction can be quickly undone. Thus, in areas where re-immigration can occur, control efforts must be re-administered consistently over time to maintain the beneficial effects of the initial control efforts.

In general, recreational hunting can inflict a source of mortality on a population of feral swine, but hunters generally do not equally target all population segments, thereby potentially limiting the severity of population reduction (Festa-Bianchet 2007; Braga et al. 2010; Plhal et al. 2011; Keuling et al. 2013). Moreover, recreational hunters on SVI were focused on the two deer species, with feral swine being an ancillary target. This further diminished the potential for recreational hunting to serve as a significant factor for eradicating the species from the Island. Luckily, SVI is surrounded by a barrier of water, although the distance to the mainland does not make it impossible for feral swine to cross, especially at low tide and especially in winter. Yet, it is sufficient to make such crossings unlikely and infrequent without human assistance.

Seasonal monitoring

The importance of making comparisons over years from the same timeframe within years was highlighted by our results. Many, if not most, animal species go through seasonal changes in activities. This would influence the animal intercept rate at indexing observation stations, thereby influencing observation rates for calculating population abundance estimates. Be it observations or captures, the probability of intercepting an animal at any given location is influenced both by that species' abundance and by its activity level. Activity levels vary through the year according to various lifecycle factors including mating, rearing of young and dispersal of young. For example, the increased camera index values for white-tailed deer in the winter each year likely reflects increased activity during the rut, which would increase the number of white-tailed deer interceptions at observation stations. Importantly and as professed in various seminal papers on indexing (e.g. Engeman (2005)), this demonstrates the necessity of comparing index values from the same timeframe each year when looking at trends over years. Otherwise, indexing results between years would be confounded with seasonal results within years. Use of a valid sampling design that incorporated observations seasonally each year also resulted in our indexing data appearing to indicate that white-tailed deer harvest by hunting was in a stable balance with population recruitment, as the within-season indexing results did not have substantial changes across years. While most species likely show seasonal fluctuations in activity, it is not always the case. For example, no consistent within-year pattern in sambar deer abundance was revealed across years by either the camera index or the track plot index (see Sanbar deer population monitoring and sensitivity of indices Subsection). This is probably because sambar deer do not have a distinct rutting season and males can be in rut nearly any time of year. Yet, seasonal sampling each year would still be crucial for showing if there was an unexpected impact on the population from a hunting season or other event.

Thus, to avoid confounding between differences amongst years with differences amongst seasons, comparisons amongst years are only valid when examining the same season across years. Such seasonal activity changes and the impact on abundance measures were clearly borne out in our camera indexing results for white-tailed deer. Making appropriate seasonal comparisons is a well-known design facet for long-term abundance monitoring (Engeman 2005). However, it is not always well-applied, as with the studies described by Allen et al. (2011) that led to invalid inferences and questionable policy recommendations. Even for species where patterns are not as easily discernible as those for white-tailed deer, it is still essential to make comparisons from the same within-year timeframes to avert potential confounding in inferences across years.

Considerations for selecting an indexing method

To monitor the decline and confirm the eradication of the feral swine population on SVI, we considered: (1) two station-based indices, (2) a track plot index and a camera index, (3) take indices by control experts and (4) take indices by recreational hunters during three types of annual recreational hunting seasons. As indicated already, the recreational hunters on SVI were there to target white-tailed deer or sambar deer, with feral swine only taken opportunistically as an ancillary species, as reflected in only low numbers of hunter take for feral swine (only 21 over the course of this study). Thus, for indexing purposes in situations similar to SVI, recreational hunt indices where feral swine are not the primary target should not be used as the population index for feral swine or to provide information for feral swine management. Unlike hunter take, control by WS aimed to target all population demographics. Even when simultaneously integrating multiple control methods with effort for each unfeasible to define, an adequate index can be formed using take per person-day as the take measure. We saw this in our results and it was previously applied successfully by Avery et al. (2014). Control in general and especially for eradication, very typically targets a particular species, making the simultaneous acquisition of indexing measures on multiple species highly unlikely.

Both track plots and cameras provided data simultaneously for multiple sympatric species (five species) from which abundance indices could be calculated. This study raised a variety of factors to consider if a choice had to be made between these two methods. When considering comparisons or trade-offs between track plots or trail cameras as tools for collecting monitoring data, we must realise that the track plot and camera methods we applied represent one of many possible configurations for each. Cameras, in particular, have myriad settings that can be employed to meet the field circumstances and in-office examination/sorting of photos. Similarly, track plots have been deployed in a wide range of sizes for many species. For example, besides the 100 m length we used in the present study, successful monitoring of feral swine and sympatric species in Florida has been conducted using track plots 3 m in length (Engeman et al. 2003), 0.8 km in length (Engeman et al. 2013a) and 1.6 km in length (Engeman et al. 2007b).

That being said, our results offer considerable insight into the performance of the two substantially different station-based observation methods. First, when we only considered what the amount of data collected would have been if the stations were only set out on one day, we found that a much higher percentage of track plots than cameras recorded the presence of an animal. The size of each track plot was much greater than the area viewed by a camera, which led us to consider the percentage of track plots and the percentage of cameras that recorded the presence of each species during their respective deployment of 5 days for cameras and only 3 days for track plots. Still, the track plots had a higher percentage for recording presence of each species than cameras. The discrepancy in recording presence of a species was much greater when looking at the data for the two species of smaller stature: raccoons and armadillos. Our primary focus was to monitor the eradication of feral swine, along with the concurrent interest to monitor the populations of the two important sport hunting species: white-tailed and sambar deer. The positioning of cameras for recording the high priority ungulates might have resulted in decreased detection of the smaller species. As camera height at the observation stations was optimised for feral swine, the species of lesser physical stature (raccoons and armadillos) may have been too low to the ground to trigger the cameras in much of the area of camera view where a larger animal would trigger the camera. In contrast, the sandy substrate made the track plots very sensitive to the deposition of spoor by all species, making the presence of all species that entered the plot detectable as long as tracks could be identified. Thus, it was not a surprise that a method (cameras) that had difficulty recording the presence of these species did not correlate well with a method that is much more sensitive to their presence (track plots).

Considering that if track plot dimensions were similar to the areas within camera views, similar sensitivities for recording animals might have resulted. If the number of camera stations were doubled or tripled to better match the areas surveyed with track plots, the individual probability that a particular camera could detect a target animal would remain the same, but the probability that a target animal could be detected by the full accumulation of cameras would increase. However, the trade-off for such an increase in cameras (especially for an entity with a limited budget) might be fiscally impractical. In contrast, as we can see from the gaps in our data and the reasons for those gaps, track plots are more vulnerable to environmental conditions and vehicle or foot traffic (e.g. by livestock or humans) destroying data or preventing data collection than cameras. Cameras, on the other hand, especially in areas with fewer limits on public access, can be highly vulnerable to vandalism or theft.

Labour and cost are amongst other determining factors when considering an indexing method to apply. For track plots, the size of the plot, the soil substrate and the means for smoothing the plot surface determine the amount of labour and cost. Short plots (e.g. 3 m in length) would typically be prepared and smoothed by hand using a rake or broom. Longer plots, such as the 100 m plots used in this study, would be prepared and smoothed by mechanical means, such as a pickup truck or all-terrain vehicle with an attached or towed device. This may or may not be a significant cost. For example, the 1.6 km track plots used by Engeman et al. (2007b) were made simply by dragging a section of weighted chain link fencing behind a pickup truck along well-maintained fire lines. Thus, no extra cost or labour was incurred from observing the plots. Track plots do require an observer to "read" and resurface the plots (erase tracks) each day. Camera stations, on the other hand, require less preparation and maintenance. When using permanent station locations as we did, occasional vegetation maintenance may be required to maintain consistency in the field of view across sampling events. Beyond that, however, cameras only need to be set out at their stations at the start of the observation session and then retrieved at the end. The ease in the field with which cameras can collect data (while recognising the concomitant strain in lab or office of managing the photos) can provide continuous data collection for extended periods of time, offering more detailed assessments of seasonal effects. Monitoring with cameras may require a considerable upfront cost to purchase the cameras if they are not already on hand. Ideally, all cameras would be the same make and model, but at the minimum, they should all be capable of having the identical settings for time lags between photos, burst ability and burst size etc. In addition, unlike for track plot data, the resource intensive portion for camera data occurs in the office or lab where potentially thousands of photos must be sorted through to create the indexing dataset.

Index validation

Whether an index can detect known or expected changes in a population and whether multiple methods show agreement on population changes are essential components to index validation. Fully enumerated, known populations virtually never exist in nature, but would be ideal for testing and validating relative abundance indices (Engeman 2005; Allen and Engeman 2015). In the absence of known wild populations that a method can be tested on, guidance has been developed for evaluating and validating the use of an index for monitoring population abundance (Allen and Engeman 2015). Multiple different monitoring tools simultaneously applied provide the greatest assurances that population trends can be detected (Allen and Engeman 2015). Moreover, validation methods for indexing procedures include evaluating concurrence amongst different methods when assessing abundance amongst changing populations and whether those results line up with expected changes in abundance.

Agreement amongst multiple different monitoring methods provides strong assurance that the observed population trend is true. We observed that track plots, camera stations and take by experts obtained observations well-suited for calculating indices that documented the demise of the feral swine population on SVI with varying levels of sensitivity. This was a crucial first step to evaluating the efficacy of the indexing procedures.

Another key to validating monitoring procedures is whether they can detect known or strongly expected changes in a population. Concomitantly, that the monitoring methods tracked the decrease in the feral swine population as it was being removed was one means of addressing this second validation point. Besides the diminishing population of feral swine, the impacts of Hurricane Michael provided further validation opportunity to assess indexing procedures relative to expected population changes.

The possibility of a severe hurricane causing an island to be over-washed with its storm surge would naturally be expected to negatively impact wildlife populations on the island. On SVI, the storm surge did not completely inundate the Island, yet it apparently impacted some of the wildlife populations. Its effect on feral swine was indeterminate because the population was already very low through control efforts and the monitoring efforts that could have possibly detected the storm's immediate impacts could not be applied immediately prior to the storm or immediately afterwards. By the time the camera stations were able to be re-implemented after the hurricane and the track plots later after that, the final feral swine had been removed. Although at the time that the final animal was eliminated, it was not certain that it was the final animal. Yet, we know feral swine survived the storm because the eradication was completed after the storm. Even with a complete over-wash, a proportion of the terrestrial species can survive a storm surge. For example, during the eradication effort for Gambian giant pouched rats on Grassy Key, Florida, the storm surge from Hurricane Wilma over-washed much of the island with over a 1 m of water. While there was hope that the population might have been eliminated, the monitoring methods in place quickly showed survival of the population (Engeman et al. 2007b). Track plot index values and camera index values both indicated concurrence that Hurricane Michael had an impact on the populations of both species of deer, thus, satisfying the above two validation points of concurrence amongst different methods when assessing abundance amongst changing populations and whether those results line up with expected changes in abundance. Moreover, both the track plot index and the camera index showed concurrence in an ultimate decline by autumn 2019 in white-tailed and sambar deer populations. Our results suggest that a portion of the white-tailed deer population may not have been directly eliminated by the hurricane, but rather succumbed due to lasting effects on their health or environmental resources necessary for survival. Similarly, sambar deer also appeared to, at least initially, survive the hurricane, but subsequently showed a population reduction perhaps due to health or environmental resource deficiencies. Thus, while cameras did not reveal an immediate decline after the hurricane, an eventual decline was, nevertheless, a reasonable expectation due to the landscape destruction from a Category 5 storm, with both indices fulfilling that expectation.

Conclusions

While this study was primarily focused on documenting a feral swine eradication, it has provided a variety of additional insights for managing vertebrate populations on small islands. First, the work has demonstrated a successful insular feral swine eradication effort, while reinforcing that these eradications are difficult to accomplish, even in insular situations. This eradication effort required consistent swine control over five years using multiple methods including trapping, shooting, even aerial gunning and augmented by three deer hunting seasons where swine were also taken as ancillary species. Such effort to reach a complete insular eradication should likely be expected, especially since a similar effort on North Island, South Carolina required nine years of expert control using the same combination of methods as used on SVI (Engeman et al. 2019a). Second, expert take expressed as animals taken per person-day of effort where effort is inclusive of all control methods applied is reliable in tracking the decline in population abundance, although its relative accuracy can be limited during high population levels by the amount of labour and resources available to carry out control. Often population monitoring is not incorporated into control efforts for many species. Using take per person-day of effort offers a means to document efficacy of control in the absence of other population monitoring methods (see Avery et al. (2014)). Third, the PTI and camera index both well-tracked population abundance simultaneously for the large ungulates inhabiting the Island (feral swine, white-tailed deer, sambar deer). However, the sensitivity for our 100 m track plots to capture animal observations was much greater than for the camera stations. This held true even over 5-day observation sessions by cameras versus only 3-day observation sessions for track plots. Fourth, the track plots were also sensitive for simultaneously capturing data for smaller animals, raccoons and armadillos, but the camera stations were ineffective for the smaller species. This was likely due to the camera positions being optimised to capture feral swine observations, yet it would extend as a cautionary note to other studies where observations across different-sized species are desired. Fifth, both camera stations and track plots are valuable methods for obtaining data from which population abundance indices can be calculated. Many configurations of each are possible to address in-field, resource and labour circumstances. Here, we saw that our large track plot configuration probably outperformed the camera stations in many regards, but the camera stations required less labour in the field (but considerable in-office effort) and were less fragile in the field than track plots, especially from weather or access issues.

Ideally, when there is a need to monitor population abundance, especially for multiple species simultaneously, multiple monitoring methods are advised (Allen and Engeman 2015). Lastly, to ensure early detection of re-immigration and efficient removal after a successful eradication effort, follow-up monitoring is worth implementing occasionally, even without visual observations of the species. This would also likely require the method(s) to be practical in terms of economics and labour. While the track plots required more labour in the field than cameras, they also were more sensitive to detecting a small population. Thus, we recommend monitoring at SVI and other barrier islands with risk of feral swine establishment by way of PTI once per year. Concomitantly or alternatively, a large number of cameras, if available, could also be deployed to increase detection probabilities.

Other options for detecting re-invasion might include testing environmental DNA (eDNA) for swine. Due to feral swine affinity for water, testing water samples might be the most efficient means to sample for eDNA testing, as was developed for Burmese pythons (*Python bivittatus*) in Florida (Piaggio et al. 2014). For an area like that of SVI, a composite water sample from all fresh water sources might be used to answer the yes-no question of whether a feral swine exist anywhere on the Island.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary information

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Data type: docx

Explanation note: **table S1.** Dates during which data was collected by six methods on Saint Vincent Island, Florida, USA from 2015 to 2020 and the seasons to which they were assigned for correlation analyses. In October 2018, Hurricane Michael struck the area resulting in disruptions to track plot and camera data collection and the cancellation of NWR scheduled hunts. **table S2.** Track plot and camera station index values for white-tailed deer on Saint Vincent Island, Florida, USA, from 2015 to 2020. **table S3.** Track plot and camera station index values for sambar deer on Saint Vincent Island, Florida, USA, from 2015 to 2020. **table S4.** Track plot and camera station index values for raccoon on Saint Vincent Island, Florida, USA, from 2015 to 2020. **table S5.** Track plot and camera station index values for armadillo on Saint Vincent Island, Florida, USA, from 2015 to 2020.

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Supplemental Table 1. Dates during which data was collected by six methods on Saint Vincent Island, Florida, USA from 2015 to 2020 and the seasons to which they were assigned for correlation analyses. In October 2018, Hurricane Michael struck the area resulting in disruptions to track plot and camera data collection and the cancellation of NWR scheduled hunts.

		Data collection intervals					
Year	**Season**	**Track plots**	**Cameras**	**Expert take**	**Muzzleloader**	**NWR Hunt Archery**	**Sambar**
2015	**Winter**		Jan 10-14	Jan 15 - Apr 15	Jan 22-24		
	Spring	Mar 17-19	Apr 11-15	Apr 16 - Jul 17			
	Summer		None	Jul 18 - Oct 18			
	Autumn	Sept 23-25	Oct 14-18	Oct 19 - Feb 2		Nov 19-21	Dec 3-5
2016	**Winter**		Jan 29-2	Feb 3 - May 2	Jan 21-23		
	Spring	Apr 26-28	Apr 28-2	May 3 - Jul 17			
	Summer		Jul 13-17	Jul 18 - Oct 18			
	Autumn	Oct 4-6	Oct 14-18	Oct 19 - Jan 15		Nov 17-19	Dec 1-3
2017	**Winter**		Jan 11-15	Jan 16 - Apr 17	Jan 19-21		
	Spring	too dry	Apr 13-17	Apr 18 - Jul 18			
	Summer		Jul 14-18	Jul 19 - Oct 18			
	Autumn	Oct 4-6	Oct 14-18	Oct 19 - Jan 15		Nov 16-18	Nov 30-Dec 2
2018	**Winter**		Jan 11-15	Jan 16 - Apr 17	Jan 25-27		
	Spring	Apr 25-27	Apr 13-17	Apr 18 - Jul 17			
	Summer		Jul 13-17	Jul 18 - Oct 18			
	Autumn	hurricane	hurricane	Oct 19 - Jan 15		hurricane	hurricane
2019	**Winter**		hurricane	Jan 16 - Apr 17	hurricane		
	Spring	hurricane	Apr 13-17	Apr 18 - Jul 17			
	Summer		Jul 13-17	Jul 18 - Nov 13			
	Autumn	Nov 11-12	Nov 9-13	Nov 14 - Jan 14		Oct 31-Nov 2	Nov 21-23
2020	**Winter**		Jan 10-14		Jan 16-18		

Supplemental Table 2. Track plot and camera station index values for white-tailed deer on Saint Vincent Island, Florida, USA, from 2015 to 2020.

		White-tailed deer (WTD) index values					
		Track plot data			**Camera data**		
Year	**Season**	**Index value (track intrusions/ plot/day)**	**% plots detecting WTD, day 1**	**% plots detecting WTD, all days (3)**	**Index value (visits / camera/ day)**	**% cameras detecting WTD, day 1**	**% cameras detecting WTD, all days (5)**
2015	Winter				2.438	84.6	100
	Spring	3.2	50	90.5	0.593	44.8	69
	Summer						
	Autumn	2.903	94.4	100	1.593	63.3	96.7
2016	Winter				2.453	63.3	86.7
	Spring	1.444	61.9	85.7	0.448	24.1	65.5
	Summer				0.359	31	69
	Autumn	3.042	90.4	100	1.453	46.7	90
2017	Winter				2.724	79.3	100
	Spring	too dry	too dry	too dry	0.724	51.7	86.2
	Summer				0.324	27.6	65.5
	Autumn	3.556	95.2	100	2.02	66.7	86.7
2018	Winter				2.283	72.4	93.1
	Spring	2.619	76.2	95.2	0.78	36.7	86.7
	Summer				0.448	34.5	72.4
	Autumn	hurricane	hurricane	hurricane	hurricane	hurricane	hurricane
2019	Winter				hurricane	hurricane	hurricane
	Spring	hurricane	hurricane	hurricane	0.762	34.6	69.2
	Summer				0.526	33.3	59.3
	Autumn	1.575	72.2	75	0.607	43.3	80
2020	Winter				1.653	83.3	90

Supplemental Table 3. Track plot and camera station index values for sambar deer on Saint Vincent Island, Florida, USA, from 2015 to 2020.

		Sambar deer index values					
		Track plot data			**Camera data**		
Year	**Season**	**Index value (track intrusions/ plot/day)**	**% plots detecting sambar, day 1**	**% plots detecting sambar, all days (3)**	**Index value (visits / camera/ day)**	**% cameras detecting sambar, day 1**	**% cameras detecting sambar, all days (5)**
2015	Winter				0.292	26.9	42.3
	Spring	0.7	40	71.4	0.214	13.8	58.6
	Summer						
	Autumn	0.674	27.8	73.7	0.247	16.7	60
2016	Winter				0.22	13.3	40
	Spring	0.54	14.3	52.4	0.359	17.2	58.6
	Summer				0.172	6.9	31
	Autumn	1.048	33.3	80.1	0.22	16.7	40
2017	Winter				0.566	24.1	75.9
	Spring	too dry	too dry	too dry	0.234	17.2	51.7
	Summer				0.221	6.9	24.1
	Autumn	1.079	47.6	76.2	0.607	36.7	60
2018	Winter				0.303	17.2	55.2
	Spring	0.825	33.3	61.9	0.36	16.7	50
	Summer				0.028	0	13.8
	Autumn	hurricane	hurricane	hurricane	hurricane	hurricane	hurricane
2019	Winter				hurricane	hurricane	hurricane
	Spring	hurricane	hurricane	hurricane	0.292	23.1	57.7
	Summer				0.133	11.1	33.3
	Autumn	0.364	27.8	40	0.087	13.3	23.3
2020	Winter				0.14	20	43.3

Supplemental Table 4. Track plot and camera station index values for raccoon on Saint Vincent Island, Florida, USA, from 2015 to 2020.

		Raccoon index values					
		Track plot data			**Camera data**		
Year	**Season**	**Index value (track intrusions/ plot/day)**	**% plots detecting Raccoon, day 1**	**% plots detecting Raccoon, all days (3)**	**Index value (visits / camera/ day)**	**% cameras detecting Raccoon, day 1**	**% cameras detecting Raccoon, all days (5)**
2015	Winter				0.138	19.2	23.1
	Spring	1.483	45	66.7	0.007	0	3.4
	Summer						
	Autumn	0.674	38.9	57.9	0.127	13.3	16.7
2016	Winter				0.113	10	33.3
	Spring	1.968	61.9	85.7	0.069	3.4	17.2
	Summer				0.021	0	10.3
	Autumn	1.383	76.2	85.7	0.047	6.7	13.3
2017	Winter				0.069	3.4	17.2
	Spring	too dry	too dry	too dry	0.048	3.4	17.2
	Summer				0.007	3.4	3.4
	Autumn	0.429	19	42.9	0.06	3.3	13.3
2018	Winter				0.028	3.4	10.3
	Spring	0.587	28.6	57.1	0.02	0	10
	Summer				0.014	3.4	6.9
	Autumn	hurricane	hurricane	hurricane	hurricane	hurricane	hurricane
2019	Winter				hurricane	hurricane	hurricane
	Spring	hurricane	hurricane	hurricane	0.069	0	19.2
	Summer				0.067	3.7	3.7
	Autumn	0.964	44.4	65.0	0.021	3.4	10
2020	Winter				0.021	0	6.7

Supplemental Table 5. Track plot and camera station index values for armadillo on Saint Vincent Island, Florida, USA, from 2015 to 2020.

		Armadillo index values					
		Track plot data			Camera data		
Year	**Season**	**Index value (track intrusions/ plot/day)**	**% plots detecting Armadillo, day 1**	**% plots detecting Armadillo, all days (3)**	**Index value (visits / camera/ day)**	**% cameras detecting Armadillo, day 1**	**% cameras detecting Armadillo, all days (5)**
2015	Winter				0.038	3.8	11.5
	Spring	0.65	35	66.7	0.007	0	3.4
	Summer						
	Autumn	0.663	44.4	73.7	0.02	3.3	10
2016	Winter				0.067	6.7	26.7
	Spring	1.27	28.6	95.2	0.048	0	13.8
	Summer				0.028	6.9	10.3
	Autumn	1.538	71.4	95.2	0.02	6.7	6.7
2017	Winter				0.014	0	6.9
	Spring	too dry	too dry	too dry	0.021	0	10.3
	Summer				0.007	0	3.4
	Autumn	1.111	52.4	76.2	0.033	0	10
2018	Winter				0.048	6.9	17.2
	Spring	0.905	47.6	100	0.013	0	6.7
	Summer				0.021	6.9	6.9
	Autumn	hurricane	hurricane	hurricane	hurricane	hurricane	hurricane
2019	Winter				hurricane	hurricane	hurricane
	Spring	hurricane	hurricane	hurricane	0.008	0	3.8
	Summer				0	0	0
	Autumn	0.925	61.1	75.0	0.034	3.4	10
2020	Winter				0.028	3.4	13.3