Title Page

UNIVERSITY OF CALIFORNIA
Santa Barbara

Wild Pig Management at the Jack and Laura Dangermond Preserve

A Group Project Final Report submitted in partial satisfaction of the requirements for the degree of the
Master of Environmental Science and Management
for the
Bren School of Environmental Science & Management

By

Peter Omasta
Shuhan Song
Benson Truong
AJ Zekanoski

Committee in charge:
Kelly Caylor
Chris Costello

Spring 2021

Title Page	**1**
Executive Summary	**3**
Project Objectives	**4**
I. Background	**4**
i. The Nature Conservancy and The Jack and Laura Dangermond Preserve	4
ii. History of the Land	7
iii. Wild Pig History in the United States	8
iv. Damage from Wild Pigs	9
v. Wild Pig Management Strategies	11
Exclusion Fencing:	11
Lethal Control (hunting,trapping, toxicants):	12
Monitoring:	13
Camera Trap Analysis:	14
Mark Recapture Technique:	14
Eradication:	15
II. Methods	**16**
i. Literature review and interviews with experts	16
ii. Population estimation from photo data analysis	16
Megadetector to Timelapse2 workflow	16
Feral pig population estimate	17
N-mixture model	17
Justification of using N-mixture model for this project	17
Estimate the number of groups of wild pigs	18
Transform estimated number of groups to number of individuals	18
Assessing spatial abundance of feral pigs on the Dangermond Preserve	19
iii. Potential Wild Pig Management Strategies	21
Exclusion Fencing:	21
Hunting:	23
Trapping:	23
iv. Cost benefit analysis of three levels of Pig Management	24
Reduction of damage (fencing priority areas)	24
Active management of pig population	25
Total eradication of wild pigs from the Jack and Laura Dangermond Preserve	28
III. Results	**29**
i. Occurrences of feral pigs over time	29
ii. Estimate of abundance from N-mixture modelling	31
iii. Spatial distribution on the preserve	32
iv. Results of cost benefit analysis for three conservation scenarios.	33
Reduction of damage (Fencing Priority Areas)	33
Monitoring Results	36
Total Eradication Results	38
IV. Discussion	**42**
i. N-Mixture Model	42
ii. Cost Analysis	43
iii. Spatial Analysis	45
V. Conclusions and Recommendations	**45**
Acknowledgments	**47**
References	**47**
Appendix	**51**

Executive Summary

The expansion of wild pigs (*Sus scrofa*) into nearly every region in California presents a difficult conservation problem for land managers. Native ecosystems in both coastal and inland areas have struggled to adapt to the destructive foraging behavior of wild pigs. Pig populations continue to grow with no signs of slowing and it has fallen onto land managers to find ways to reduce their negative impacts. This challenge is made more difficult by the limited amount of resources that conservation organizations typically have to use on invasive species management. The management of wild pigs on the Jack and Laura Dangermond Preserve (henceforth referred to as 'the Preserve' or 'Dangermond') by The Nature Conservancy (TNC) exemplifies the issue well. TNC's vision for Dangermond is grounded in conservation of the land's natural resources. It has become apparent that the abundance of wild pigs has the potential to threaten this vision. The purpose of this report is to assist TNC in the selection of a specific wild pig management approach that achieves their conservation goals on the Preserve with the most efficient use of resources.

There were two primary objectives for The Nature Conservancy's pig management at the Preserve with this project. The first objective was to analyze a historical dataset of camera trap photos to generate a population estimate of wild pigs at the Preserve. Although feral pigs have been known to inhabit areas of the Preserve, this objective was necessary because the true abundance of wild pigs at Dangermond had not yet been estimated. Our second objective was to provide TNC with three cost analysis models illustrating different possible management approaches and the tradeoffs between them. We then use the results of our analysis to make a management recommendation that is most appropriate to counter the wild pig threat at Dangermond.

Our approach to the first objective was driven by data collected during a previous wildlife camera trap survey at the Preserve. From 2013 to 2014, 38 camera stations collected about 400,000 photos from different locations across the preserve. Our team then used Microsoft's `MegaDetector` machine learning software to isolate photos that contained likely images of humans, animals, and vehicles. The photos were then pared down to find those that only contained images of pigs using `Timelapse2`. From the remaining photos, N-mixture analysis allowed us to generate a population estimate of wild pigs at the Preserve.

The second objective was to provide TNC with quasi cost benefit analyses (CBA) of three different conservation strategies for wild pig management. The three strategies were defined by the following:

1. Fencing of various high-priority areas around the Preserve to exclude pigs from sensitive habitat.
2. Active management/reduction of the wild pig population through limited fencing of high-priority areas and the implementation of a hunting/trapping program.
3. Total eradication of wild pigs at the Preserve by total perimeter and zone fencing followed by lethal control by hunting, trapping, and other removal methods.

Early on we recognized that the 'benefit' portion of the CBA was hard to quantify with an actual number, so the benefit in these scenarios is marked as area conserved. The analysis is referred to as a cost analysis at times because the benefits are only defined through the area protected. These CBAs were informed by our pig population estimate, interviews with local experts, the Dangermond Integrated Resource Management Plan, and literature reviews of prior pig management activities. We expect the results of our cost analysis to call for a management scheme that combines aspects of strategies 1 and 2 because of the likely prohibitive costs associated with total eradication.

Project Objectives

1) Generate a population estimate of wild pigs at the Dangermond Preserve preserve using historical camera trap data.
2) Create three cost-benefit analyses of different conservation strategies for the management of wild pigs at the Dangermond preserve.

I. Background

i. The Nature Conservancy and The Jack and Laura Dangermond Preserve

The Nature Conservancy was founded in 1951 and has grown into the largest environmental nonprofit by assets and revenue in the Americas. Globally, they have over one million members and have protected 125 million acres of land as well as thousands of miles of rivers. In 2017 TNC received their largest philanthropic donation to date, a gift of $165 million from ESRI founders Jack and Laura Dangermond. The funds were used for purchasing the 24,000 acre Bixby Ranch (a combination of the Cojo and Jalama Ranches) on the California coast at Point Conception where the cold waters of the North Pacific mix with the warmer waters of the Santa Barbara Channel. The land was renamed Jack and Laura Dangermond Preserve (**Figure 1**). TNC's vision for the Preserve is for it to serve as a global platform for applied conservation research and education to inspire the next generation of conservation leadership. The mean to achieve this vision through the pursuit of four major goals (JLDP IRMP, 2020):

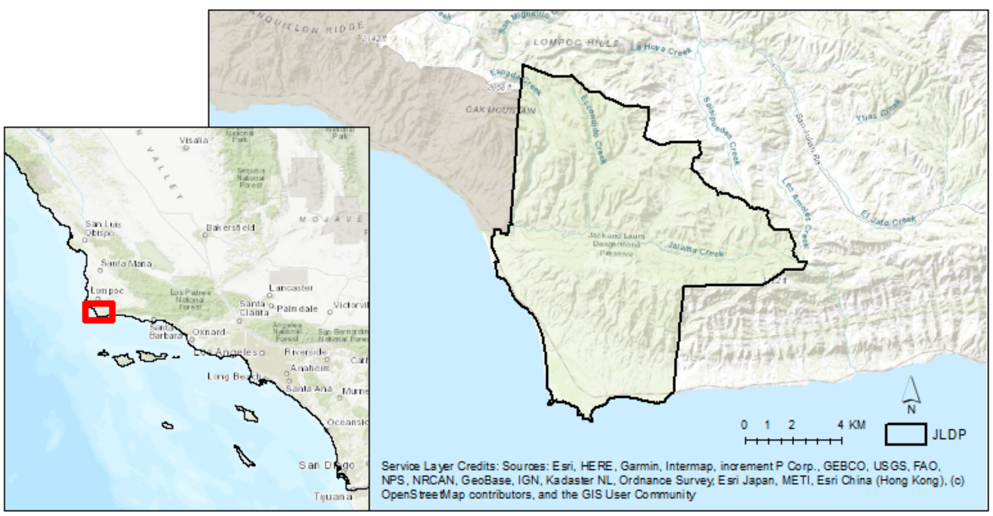

Figure 1. The Jack and Laura Dangermond Preserve location and boundary.

Goal 1: Protection, restoration, and management of natural resources.

TNC's management of the Preserve will promote and restore natural communities, ecosystems, and biodiversity so that they are resilient to environmental change and catastrophic events by using the best available science, state-of-the-art technology, best management practices, and a learning and adaptive management philosophy that demonstrates how to deal with uncertainty, risk, conflicting objectives, and diverse values.

Goal 2: Conservation and protection of cultural resources.
TNC's management will protect and conserve cultural resources, which provide a rich history of human land use and lifeways, through the stewardship of archaeological, ethnographic, and historical resources; partnerships with local communities; and the use of the best available science, technology, and management practices.

Goal 3: Promotion and support of scientific research and technology.
TNC will promote and support scientific research to understand and advance protection, restoration and management of native species and ecosystems through research partnerships and by leveraging state-of-the-art technology and data-intensive science.

Goal 4: Public Engagement.
TNC will engage the public in the vision of the Preserve by supporting K-12 and community education programs, through which current and future generations of Californians will explore the landscape and deepen their knowledge of the ecological and cultural significance of this extraordinary area.

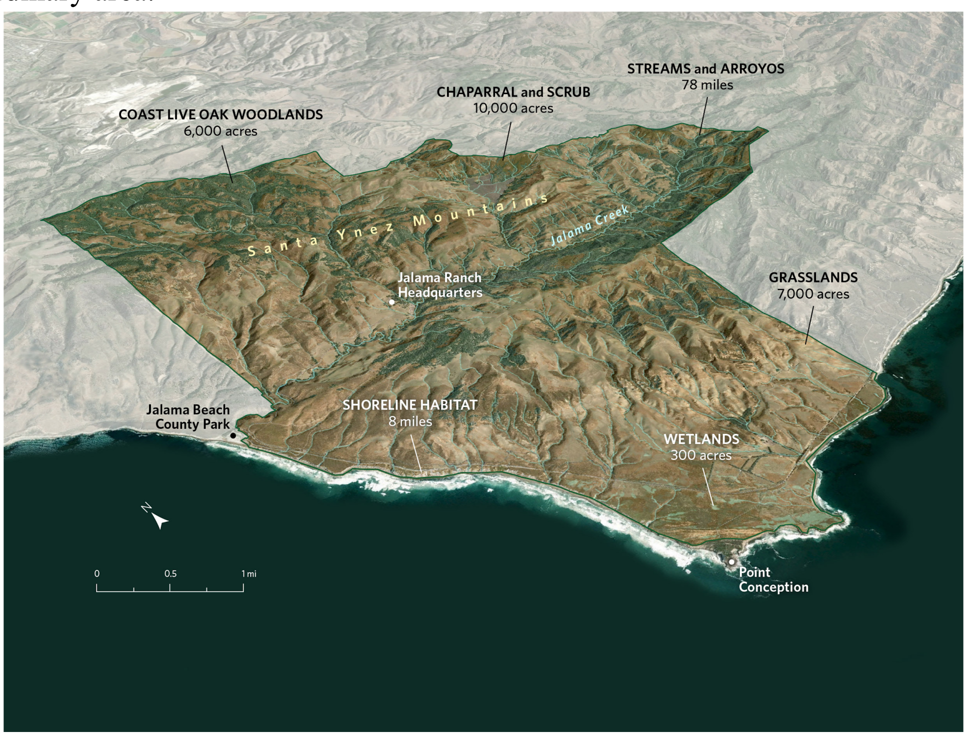

Figure 2. The Preserve with dominant habitat types shown.

Prior to TNC's establishment of the Preserve, the land was owned and operated by the Cojo and Jalama Ranches, collectively known as Bixby Ranch. Bixby Ranch was in operation for over 100 years primarily as a beef cattle operation. The property is home to diverse habitats such as oak woodlands, shrublands, grasslands, and coastal prairies. These varied environments provide habitat for over 50 rare and endangered species. The Preserve is also one of the last large, undeveloped coastal properties in southern California, making it known as the "last perfect place" to protect from anthropogenic effects (Herold et al. 2007). The Nature Conservancy's establishment of the Dangermond Preserve in December 2017 offers opportunities for conservation planning, scientific research, education outreach, and historical understanding, all while protecting the land.

There are over 20 special status plants on the preserve, including the Gaviota tarplant, Lompoc yerba santa, La Purisima manzanita, surf thistle, and four others which are all listed as a 1B classification in the State of California's Rare Plant Rank. The rank of 1B indicates that the plant is now rare throughout the historical range and has declined significantly in the last decade. There are several other rank 4 species on the list as well which are species that indicate they have limited distribution throughout the state of California. In addition, there are 34 documented special status species on the preserve, with 21 of them being birds, 5 mammals, and 3 reptiles. Four species are federally endangered including the Southwestern willow flycatcher, Least Bell's vireo, the tidewater Goby, and the black abalone. A fifth species, the steelhead salmon (*Osncorhybhuc mykiss)* may be present but is currently not due to migration barriers in Jalama Creek.

ii. History of the Land

The Jack and Laura Dangermond Preserve is located on the coast of Santa Barbara county in a region that has been historically occupied by the Chumash people. Indigenous people have lived along the California coast for roughly 11,000 years and the abundant marine and terrestrial resources made the Santa Barbara Channel region a prosperous home for the Chumash (Dartt-Newton 2006). The anthropological term Chumash captures a broad group within which there was much diversity (Hudson and Blackburn 1982). Chumash people were sociopolitically organized at the village level and their group identity was more associated with their village than the greater region (Mclendon and Johnson 1999).

Figure 3. Chumash Stone Bowl (Image by Jack Elliot)

Within the modern boundary of the Dangermond Preserve, there were at least two villages identified and mapped by the ethnologist John Harrington (King 1991). One of these was the major trading port of Shisholop located at Canada del Cojo Creek east of Point Conception. From there, Chumash people would launch specialized plank canoes called tomols into the Santa Barbara Channel to fish (TNC IRMP 2020). The other was the village of Shilimaqshtush located on the northern edge of the Preserve's coast, which is now the Jalama Beach County Park. Shilimaqshtush's more surf-swept location likely prevented it from being a trading hub as widely used as Shisholop. Along the coast between these village sites are numerous shell middens where Chumash people harvested and processed various marine organisms.

Point Conception is also a very sacred parcel of land for the Chumash people; it is known as the "Western Gate", or the place where the souls of the deceased pass on to the afterlife. Although, it should be noted that there are other similar places for different Chumash villages. In 1978, the Chumash people protested the development of a pipeline at the point in 1978, which was ultimately not constructed. In 1787, Spanish missionaries founded the La Purisima Conception mission with the intention of stamping out local Chumash culture and language with the intent of converting the peoples to Christianity (Sandos 1985). The Mission also began ceding land grants to soldiers with the first coming in 1837 of six leagues to Anastasio José Carrillo, and these lands would eventually become the Cojo and Jalama Ranch (Crespí, Brower, and Bolton 1927). The lands were never given to the Spanish and Mexican parties by the Chumash, and their ownership was recognized in treaties with the United States. TNC recently signed a memorandum of understanding with the Santa Ynez band that this is unceded land and continue to have a beneficial working relationship with their indigenous partners although there is more work to be done. TNC has been working on incorporating more environmental justice actions and working more with native communities in land management decisions.

Figure 4. Map of Chumash villages created by Chester King with Dangermond Preserve boundary overlaid.

iii. Wild Pig History in the United States

Pigs were first brought to North America in the 1500s as a food source for colonists and have been expanding their range and numbers ever since. Some of the domestic pigs escaped from enclosures, thus establishing the first feral pig population. Four hundred years later in the 1900s, the Eurasian wild boar arrived for sport hunting in the United States. They interbred with existing feral pigs and spread to other counties in the 1950s (Hoehne 1994). Their strong adaptability boosted by climate variation, human relocation, and lack of natural predators has allowed them to expand to at least 35 states today. Spatially, feral pig populations began clustered in the south and expanded northward and westward. Eastern states have higher population density than the west although populations are still expanding in several western states. The abundance of feral pigs in the US has increased from 2.4 million in 1982 to 6.9 million in 2016, and could expand to approximately 21.4 million if all available habitat was occupied (Lewis et al. 2019).

During the 1700s in California, feral pigs foraged on acorns in oak woodlands in coastal regions during the early Spanish settlements. In 1925, Eurasian wild boars introduced for sport hunting were first released in Monterey County. The animal was designated as a game mammal in 1956 during which time approximately 30,000 individuals were harvested by hunters each year (Waithman et al. 1999). By the mid 1980s, the wild pig population in California reached about 70,000 to 80,000 based on estimates from harvest surveys (Waithman et al. 1999). The population expanded (**Figure 5**) from around 10 coastal counties in the 1960s, to 33 counties in the 1980s, 49 counties by 1996, and 56 out of 58 counties by 2020 with an estimated population of 133,106 (CDFW 2020, Frederick 1998, Waithman et al. 1999).

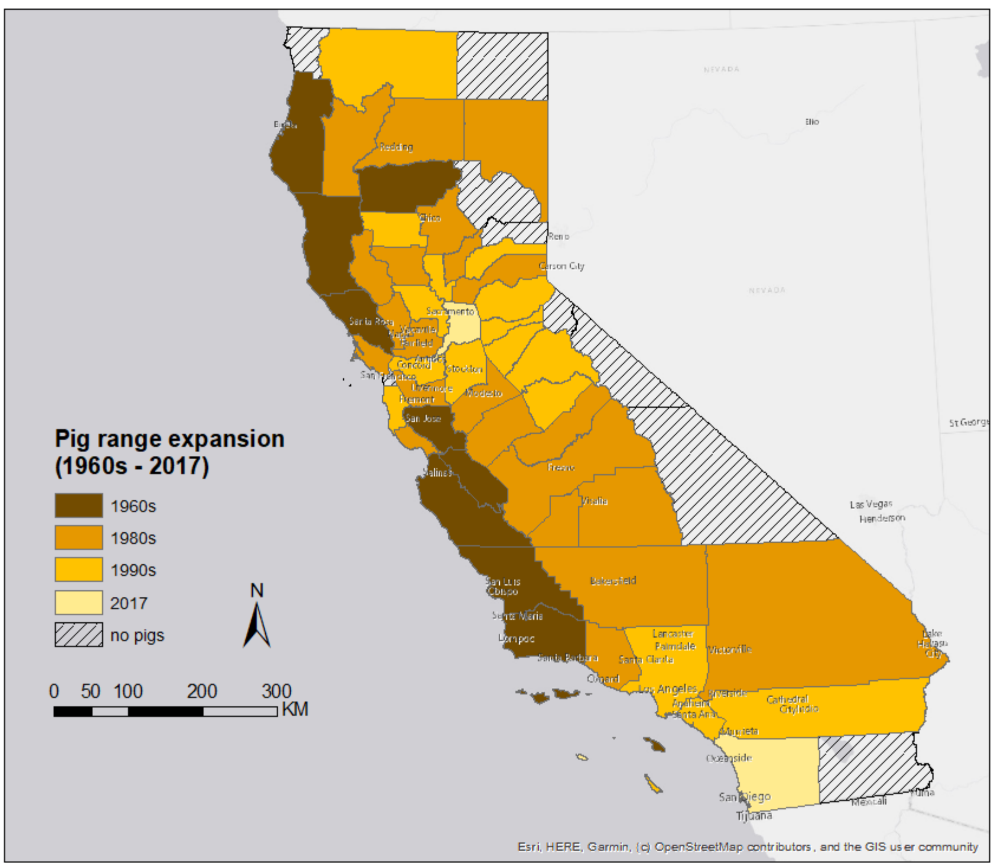

Figure 5. Historical range expansion of wild pigs in California (1960s - 2017).

Despite the ecological damage they wreak, wild pigs in California are classified as a game species by the CDFW. Hawaii, West Virginia, and Tennessee also classify wild pigs as game species while the rest of the United States rightly designate them as pests (Wood and Barrett 1979). Game species have unique requirements to take, or only allow for a certain number of permitted hunting licenses to be allocated annually. It also limits the methods that can be employed to curtail the populations; poisons, castration, and other methods are often prohibited (Wood and Barrett 1979). In other states where feral pigs are considered pests, there are no limits on taking pigs and hunting permits are not required. However, employing traps requires permits as it can affect other species.

iv. Damage from Wild Pigs

Wild pigs (*Sus scrofa)* are a serious concern for land managers across the United States and throughout many regions globally. The population of wild pigs that threaten California ecosystems are a hybrid of the European wild boar introduced to the Americas and domestic pigs that have escaped from farms and become feral (USDA APHIS 2020). Their foraging strategy of rooting through the top layer of soil with their snouts can be incredibly destructive to native plants that haven't evolved to co-exist with such destructive omnivores (Sweitzer and Van Vuren 2001). Feral pigs and signs of their presence have been frequently observed at the Jack and Laura Dangermond Preserve (Katkowski 2020).

Wild pigs are considered a pest throughout the world chiefly because of the harm they do to agricultural operations (Frederick 1998). Damage to corn, peanuts, orchards, avocados, and various other crops has been observed by researchers studying wild pig herbivory (Frederick 1998, Bengsen et al. 2014, Boyce et. al 2020). Additionally through rooting activities, wild pigs can damage drip irrigation systems, increase erosion near streams, and flood/erosion control fencing with these activities (Kreith, n.d.). Wild Pigs in California have an adverse effect on cattle operations, such as spreading *E. coli* to cattle as well as damage cattle fencing which allows for cattle to escape and predators to come in (Kreith, n.d.).

The Nature Conservancy is concerned about the wild pig population on the Jack and Laura Dangermond Preserve for a number of reasons. There are 14 threatened or endangered species that inhabit the coastal ecosystems along the 8 mile stretch of coastline on the Preserve including the threatened western snowy plover (IRMP). TNC also has inherited a settlement with the California Coastal Commission to restore 200 acres of oak woodlands on the property. Those restoration projects are threatened by the propensity of pigs to target acorns while foraging (Baber et al. 1987). There are also concerns regarding the health of riparian corridor plant species which provide much needed shade and bank stabilization to the streams and creeks at Dangermond. As the weather gets warmer, pigs spend more time resting and foraging in these corridors (Baber et al. 1987), likely damaging those plant species and disrupting the riparian ecosystem.

It is well documented that wild pigs are capable of serving the role of an ecosystem engineer in changing the habitat of Oak Woodlands in California (Kotanen 1995; Wilcox and van Vuren 2009; Crooks 2002). The pigs act as an agent of disruption in these areas through rooting and foraging of acorn mast, which reduces the regeneration of oaks in this habitat (Kotanen 1995). The rooting also creates a disturbed patch of soil which allows for increased recruitment of non-native grasses and forbs (Tierney and Cushman 2006). Exotic species may not be able to be consumed by native species which have not adapted to consuming it, which is why in areas that pigs have disturbed the percent cover of vegetation that is exotic grasses and forbs increased after pig disturbance and remained constant until pigs were removed (Tierney and Cushman 2006). Pigs can function as ecosystem engineers that reduce the recruitment of native oak woodlands and allow for increased recruitment of exotic species potentially altering the successional pathways of these areas following disturbances.

If The Nature Conservancy is to achieve its goal of conservation and stewardship of natural resources, the threat posed by feral pigs must be quantified so that effective management strategies can be developed and implemented. TNC is not the first organization to grapple with this issue and there are many case studies to draw knowledge from across California. However, the unique qualities that make the Jack and Laura Dangermond Preserve such a valuable scientific resource also means that no previous land owner has had to contend with the same set of factors. This is why characterizing the population dynamics of pigs at Dangermond and creating cost benefit analyses of management scenarios is a priority for TNC. The results of this project will also add to the body of knowledge regarding invasive species management and aid future land managers in their pursuit of natural resource protection and ecosystem resilience.

v. Wild Pig Management Strategies

Exclusion Fencing:

Fencing is an expensive endeavor upfront with continued costs associated with maintaining and monitoring the fenceline. Initial installation costs can be as much as $140,000/km if a helicopter is required to bring in materials to remote locations (Massei, 2011). While fencing off areas on the preserve can stress the pig population, it alone does not lead to mortality of pigs. However, it can be a useful tool for protecting high priority areas such as vegetation restoration projects and critical habitats of endangered species. TNC has already constructed 26,340 feet of fencing around 5 areas on the preserve designated for oak restoration. This was done at a cost of $8.95 per foot ($29,356/km).

Fencing also requires ongoing maintenance and monitoring to ensure that there are no breaks or gaps in the fenceline that need to be replaced. Pinnacles National Park employed an extensive perimeter fencing operation to exclude wild pigs from entering the park during a total eradication program. The fencing that was installed by the team at Pinnacles requires monthly monitoring to ensure that any gaps created either through biotic (falling tree branches, burrowing, human activities) or abiotic (erosion, rock falls, floods) are repaired. This does require experienced personnel to undertake as the repairs need to be done properly to ensure that the area does not continue to serve as a gap in the perimeter. Monitoring and maintenance of the fenceline can be determining by a number of factors; the terrain the fence passes through (grassland vs. dense brush), stream crossings (require a specialized fence), and the prominence of the ground (for traversing) can all delay the time that it takes for monitoring activities and also increase the potential maintenance costs as these areas are prone to disturbances that create gaps in the fenceline.

Fencing can also prevent migration of pigs from coming back into the area after eradication efforts. Oftentimes it will be used in conjunction with hunting activities to ensure a total eradication of the feral pigs on the property. This was the case during the eradication of pigs in Pinnacles National Park and on Santa Cruz Island. This does require additional costs in the form of monitoring the fenceline as well. Naturally occurring events and human activities can damage fences which may mitigate the effectiveness of the fencing. To prevent this, ongoing monitoring and maintenance needs to occur periodically.

One potential drawback of using widespread exclusion fencing is the unintended effects on non-target animal species. Although no longer its primary purpose, the Preserve is still home to a cattle ranching population. While a sufficiently well designed pig exclusion fence can still be travelled over by deer populations (Rattan et. al 2010), cattle will almost certainly be unable to do so. Most pig fence designs also call for mesh openings of sufficient size for smaller rodents and mammals to be able to pass through (VerCauteren et. al 2019). The ability of wild mammals of more similar size to pigs (ie. coyotes, mountain lions) to cross these fences is unknown. In order to mitigate potential negative effects on these non-target species, it's advisable to avoid fencing around resources like water sources that are used by many different mammals at the Preserve. If fencing is deemed appropriate for the purpose of resource exclusion to pigs, monitoring efforts at those sites should be implemented to observe any negative effects on non-target species.

Lethal Control (hunting,trapping, toxicants):

Wild pig removal operations can take many forms, each with its own advantages and disadvantages. Citizen hunting programs have the advantage of being much cheaper than other management actions aimed at lowering pig populations though their effectiveness is doubtful. Private landowners have the potential ability to generate revenue in the process of achieving population control in the form of the sale of hunting permission (Zivin et al. 2000). However these citizen hunting programs are unlikely to achieve eradication unless efforts are sustained, systematic, and immigration from surrounding areas is curtailed (Stone and Anderson, 1988). In fact, recreational hunting alone hasn't been observed to be an effective method of long term population control (VerCauteren et al. 2019). Hunting to reduce the population needs to be greater than 70% of the population in a given year (Hiroyasu, 2020) while it has been reported that recreational hunting removes on average only 23% of pigs (Mayer 2014).

Using hired professional hunters can achieve desired results faster but is far costlier than citizen hunting programs. The National Park Service employed hunters in Hawaii Volcanoes National Park who were able to remove pigs with the use of hunting dogs at the approximate cost of $95/pig. At Fort Benning Georgia, researchers tested the effect of different levels of pig harvest on two populations. They found that a heavily harvested population (hunting and aggressive trapping) would see a reduction in survival compared to a moderately hunted population (just hunting). Despite the increased mortality of the heavily harvested population, there was no significant difference in density between the two populations due to a compensatory recruitment effect. Whether by increased reproduction or immigration, the heavily harvested population maintained its abundance relative to the moderately harvested population (Hanson et al 2009). This indicates that increasing hunting pressure alone is not likely to produce the desired reduction in population.

A different study at Fort Benning found that a bounty program to encourage hunting of pigs actually led to an increase in population. This was because hunters were taking large trophy pigs which had an effect on the age-structure of the population. The focus on taking larger pigs allowed younger reproductive pigs to take advantage of the increased food via bait and reproduce at a greater rate (Ditchkoff et al 2017). This led to an increase in both sounder size and litter size during the course of the bounty program.

While hunting dogs have proven to be quite successful in capturing or cornering solitary pigs, they are only effective when the sounder size is less than or equal to the number of dogs in the hunting party (one dog can only take one pig). Hunting with dogs is efficient only after other controls have reduced population density to the point where solitary pigs are likely to be encountered or if you have large parties of hunters with multiple dogs per hunter (Caley and Ottley 1995).

Traps have been used to capture wild pigs in North America since the 17th century and the technology has been mostly unchanged with some notable exceptions. At the most inexpensive level, traps used today are still simple constructions of walls and a door with an optional mechanism for shutting the door. The cost effectiveness of trapping as a means of population reduction has proven highly variable across geographic and temporal scales. A corral trapping program in Australia was able to reduce the pig population by 80-90% in only two weeks but efforts in North America have proven less successful (Choquenot et al. 1993). A review of trapping programs in Texas in 2014 found that the average cost of pig removal by traps was $46.95 per animal for a total of 585 pigs (Bodenchuk, 2014). This review however does not report on the previous abundance of pigs at the sites so it's unclear whether that cost effectiveness would hold true in other regions.

While there are a great variety of designs for different box traps and corral traps with gates, the proper location of traps is just as important as design. Rather than placing them at the site of damage, locating traps in travelled areas between damage sites and bedding locations tends to be more effective (VerCauteren et al. 2019). Trapping at water sites during droughts or in arid habitats has also shown effectiveness. Trapping as a population reduction tool can have diminishing returns. Sows that are exposed to traps and uncaptured have the potential to replace captured individuals due to their recognition of the threat.

<u>Monitoring:</u>

There are a variety of methods that have been used to monitor/estimate wild pig populations in the United States. These can range from empirical countings of pigs from a slowly moving vehicle to aerial thermal imaging. A survey of many of these methods was conducted by Engeman et al. in 2013. The necessary measurement tools, potential measurements, and potential metrics of abundance of some of the more widely used survey types are displayed below in **Table 1**.

Table 1. Necessary components and potential outputs of several types of wild pig surveys (from Engeman et. al 2013).

Type of survey	Measurement tool(s)	Potential measurements	Potential metrics of abundance
Dung	Defined areas for Pellet counts	Number of pellet groups	Index
	DNA analysis	Number individuals and "recaptures"	Known to be alive
Road counts (counts from vehicles)	Human observers	Counts	Index

	Spotlight	Distance to animals observed	Density estimate
	Night vision		
	Thermal imaging		
Animal marking	Trap and mark	Resight/recapture	Density estimate
	Bait markers	Capture and check for mark	Known to be alive index
Take rates	Hunter survey	Hunter take	Take index
		Hunter effort	Take/effort index
Camera	Camera traps	Number photographed	Index
		Resight (recapture)	Known to be alive index
			Density estimate

While each of these different monitoring methods for wild pig abundance has their strengths and weaknesses, their cost effectiveness for any one management unit will depend on the circumstances and goals for that project area. Based on the management goals of our client for both this project and the Preserve generally, our team is focusing on wild pig monitoring techniques involving camera trap analysis, mark recapture methods, and VHF radio collaring. We chose these methods because of their ubiquity in the literature and the impression that they are most applicable to the wild pig management problem at Dangermond Preserve.

Camera Trap Analysis:

Camera trap image analysis is widely used for pig abundance estimation in the United States for several reasons. First the cost-effectiveness of wildlife camera traps for monitoring makes it an attractive option. Researchers comparing the costs and quality of different wild pig density estimators found that wildlife cameras placed at ~1.3 cameras/km² yielded density results similar to those of a parallel fecal DNA analysis at 59% of the cost (Davis. et al 2020). The authors noted that the largest proportion of costs related to camera trapping is the labor associated with reviewing the photos and tagging pigs. Due to continual advances in machine learning object detection (such as Microsoft's `MegaDetector`), it is likely that the cost of processing large amounts of images will decrease in the future. This would make wildlife camera trapping a more viable option for managers seeking to estimate wild pig density. It should be noted however that Davis and their team was able to identify individual pigs in images based on distinctive pelage patterns. This allowed the use of a spatially explicit capture recapture (SECR) model to calculate pig density. In areas where individuals cannot be so easily distinguished, camera trapping can still yield useful density estimates but with lower precision than with SECR.

Another reason for the ubiquity of camera trapping for wild pig monitoring is the simple fact that they can also be used for monitoring other species as well. Land managers concerned with wild pig density on their properties are also likely to be interested in other wildlife. Cameras are becoming the preferred monitoring method for many organizations because they are non-obtrusive, have low observer error, are comparable across sites, and the data collected has a multitude of uses (Easterday 2021). The potential for such cross functionality is a reason that increased camera trapping operations at the Jack and Laura Dangermond Preserve is a near certainty regardless of our recommendations for this project.

Mark Recapture Technique:

The second potential wild pig monitoring technique that can be implemented at the Preserve are mark recapture methods. These widely practiced methods are used to monitor wildlife population abundances and densities. The traditional mark recapture method involves capturing a sample of the desired population, marking the captured individuals, releasing the marked individuals back into the wild, and finally recapturing the marked individuals along with unmarked individuals. Assuming the number of marked individuals within the second sample is representative to the whole population, an estimation of the total population size can be obtained by dividing the total number of marked individuals by the portion of marked individuals in the second sample. Although the traditional mark recapture method is simple and commonly used, this method is time-, cost-, and labor-intensive and highly prone to capture heterogeneity among age and sex classes (Baber and Coblentz 1986; Sweitzer et al. 2000). Feral pigs have different capture probabilities which weakens population estimates, and if the population is also not closed, density estimates by this method becomes more uncertain (Engeman et al. 2013).

An alternative marking approach to monitor feral pigs involves the use of baits containing marker agents. Marker agents include a variety of substances including dyes, radioactive and stable isotopes, and systemically absorbed chemicals (Savarie et al. 1992; Fry and Dunbar 2007). A study was conducted to test the usage of an ingestible antibiotic called tetracycline hydro as a marking agent to monitor feral pig populations (Reidy et al. 2011). The researchers found the antibiotic to be a suitable marker for mark-recapture estimates of feral pigs. Unlike the traditional method, this approach alleviates the cost and effort because it does not require the initial and physical capture of pigs. In addition, this method may also reduce possible biasing effects, where the probability of initial capture of pigs differs from the probabilities of recapture. This type of monitoring would be highly attractive if trap and bait stations were to be implemented as lethal controls on the Preserve in the future.

Mark recapture methods are commonly used to monitor wildlife and estimate populations but have data requirements that make them difficult to use at Dangermond. Pre-baited camera traps have been used in mark-recapture methods to estimate population density (Holtfreter et al. 2008, Rowcliffe et al. 2008). This method requires identification of individuals and keeps track of individuals throughout all the camera stations. The amount of work limits the sampling time to several days or a few weeks, which limits the possibility to analyze population seasonality with one set up. Besides, additional information on the setup needs to be measured during the installation of cameras to account for the limited scope of view (Rowcliffe et al. 2008). In addition, it can improve the results of individual identification by placing multiple camera traps along frequently used paths to capture animal photos at varying body orientation (Jackson et al. 2006, Karanth 1995). Therefore, using camera traps and mark-recapture methods for abundance estimation can be challenging if the goal is to cost-effectively survey the preserve and develop an effective management strategy (Schlichting et al. 2020).

Eradication:

At Pinnacles National Park, then Pinnacles National Monument, a program for the entire removal of pigs began in 1985. The construction of an exclusion fence cost $2M dollars and was completed in 2003. There was 42 km of fencing on the monument, enclosing 52 square kilometers of area (Mccann & Garcelon, 2008). Upon completion of the fencing construction, a hunting approach was carried out using dogs, ground hunters, and the occasional Judas pig. It took 13,489 staff hours to complete the eradication of over 200 pigs from the preserve at an additional cost of $626,601. This was a complete eradication as no pigs have been observed on the property since that time.

On Santa Cruz Island, The Nature Conservancy and the National Park Service constructed 42.6km of fencing at a cost of $42,000 per km, totaling $1.8M. It took 1,111 hunter days of ground hunting to eliminate 261 pigs from the Island, which constituted about 5% of the overall elimination. There were no recorded costs associated with this part of the program, but it took TNC and the NPS 411 days to eliminate close to 6000 pigs from the island using this method (Barrios-Garcia & Ballari, 2012).

This approach has high costs associated with the construction and maintenance of fencing, as well as additional labor hours to have hunters and dogs root out the remaining portion of the pig population. But when effectively enacted, as seen with the Pinnacles and Santa Cruz Island case studies, it leads to total eradication of pigs on the preserve.

II. Methods

i. Literature review and interviews with experts

Over the course of the summer and throughout the fall, the team conducted literature reviews and interviewed experts in the field of wild pig management. To establish a comprehensive understanding of the problem, an exhaustive literature review was performed, focusing on topics related to pig demography, wild pig management techniques, and the Preserve itself. In order to conduct a cost benefit analysis on the different management techniques, the team pulled data from other published studies and brought values up to 2020 costs. The review was also used to obtain crucial information for the background data for the N-Mixture Model like the average home range of feral pigs.

Furthermore, the team spoke with a variety of experts on wild pigs and the preserve. These included interviews with Dr. Elizabeth Hiroyasu, who is a population ecologist with The Nature Conservancy and wrote her dissertation on wild pig management. Interviews were also conducted with members of nearby properties like Vandenberg Air Force Base and Hollister Ranch with land managers to see what their management approaches are. Interviews were conducted with Dr. Bruce Kendall to establish the N-Mixture Model methodology and to format the data necessary for the analysis. Attempts were made to interview members of the local Chumash tribe to get their perspective on the local land management and history of the preserve.

In order to determine the impact that wild pigs were having on the coastal parts of the preserve, three team members did a survey along the Northern part of the Preserve coastline. To track where pigs are accessing the beach, the team did a ground survey, took images, and documented signs of pig activity. The locations were mapped in Avenza Maps to show the exact location of higher abundance areas. These locations were then used to examine possible additional camera trap placement on the preserve and to inform of other management implications and scenarios that could be undertaken.

ii. Population estimation from photo data analysis

1. Megadetector to Timelapse2 workflow

We used `MegaDetector` and `Timelapse2` to process around 400,000 raw camera trap images into less than 10,000 pig photos which were transformed into tangible feral pig species occurrence data. `MegaDetector` is a camera trap photo analysis tool developed by Microsoft AI for Earth program. It detects moving objects in the photos, draws a bounding box around each object, and groups them into animal, vehicle, or human with confidence scores. The output of `MegaDetector` is a JSON file that includes the group of the detected moving object, location of each bounding box, confidence score of the grouping, image file path, and metadata of the image set (e.g. date, time, temperature).

After using `MegaDetector` to filter images with animals, humans, and vehicles, `Timelapse2` was used to further filter this image pool by manually tagging images that contained feral pigs. `Timelapse2` is an image analyser tool for camera trap photos with handle options to customize and accelerate the tagging process. We first used the `Timelapse2TemplateEditor` to define parameters, data type, default value, labels in `Timelapse2`, labels in exported CVS, and whether the parameters were copyable or not. In `Timelapse2`, the value of a copyable variable was automatically recorded by copying the value in the previous image to the current one, which was handy for variables like species name and number of individuals. Timelapse2 also allowed us to populate metadata of images to designated fields, which was efficient to record date, time and temperature. Besides, with the JSON file generated by `MegaDetector`, it narrowed down photos to animal-only by filtering photos with a confidence score above a threshold. In our analysis, we chose a threshold of 0.70, which was higher than the default 0.80 to avoid undercounting pigs. In addition, `Timelapse2` grouped images into episodes according to the time difference between two successive images to allow us to skip uninterested episodes. We chose the default time threshold of 5 minutes and 30 seconds which successfully separated different groups as we manually went through the camera trap photos.

2. Feral pig population estimate

N-mixture model

The N-mixture model allows for the estimation of detectability and population size from count data instead of individually marked data. It was developed to accommodate zero-inflated data by using zero-inflated count models (Joseph et al. 2009). The N-mixture model combined with proper camera trap placement and statistical analysis can result in similar estimations of relative abundance of wild pigs in some systems at a lower cost (Schlichting et al. 2020). The N-mixture model assumes observed counts from a Binomial(N,p) distribution, independent observation, constant population abundance (N), constant detection probability (p), constant temporal and spatial detection error, and a closed population over the survey period (Joseph et al. 2009, Royle 2004). The model is very sensitive if violation of assumptions are made such as double counting, unmodeled variation in population size over time, and unmodeled variation in detectability over time (Massei et al. 2018). It is also not useful when the count data collected are not randomly distributed, over-inflated by zeros, or not made from independent observations (Joseph et al. 2009).

Justification of using N-mixture model for this project

The N-mixture model is suitable for our project given it's capability for unmarked animals, incomplete sampling, and zero inflated data. The camera trap images collected from 2013-2014 did not contain captured or individually marked pigs. Going through camera trap photos to identify individuals is theoretically possible based on their unique and natural markings, but most pigs in the photos were indistinguishable based on natural markings. Therefore, manually going through pig photos in our data would be extremely time-consuming and inefficient. Training machine learning models to process massive image sets can accelerate this process and benefit future monitoring on the preserve. However, we are limited by our programming experience and the timeline. In this way, using a reliable population model that works with unmarked individuals is more efficient and effective for the current situation of TNC.

In addition, the N-mixture model can estimate detection probability and abundance simultaneously to account for incomplete sampling. Camera trap stations have limited scope of view that can result in incomplete sampling. Besides, some camera trap stations had many days without observations of pigs, which resulted in zeros in our data. N-mixture can tolerate zero inflated data by employing zero‑inflated count models, such as zero‑inflated Poisson and zero‑inflated negative binomial (Joseph et al. 2009). In this project, we used the `unmarked` package in R to fit the model for April check and September check (see Appendix for code).

Estimate the number of groups of wild pigs

Daily group counts of feral pigs from the 38 camera stations were used to estimate pig abundance in the N-mixture model. Group weighted counts are better than individual counts for the model because feral pigs usually travel in groups, called sounders. Treating each group as an observation meets the assumption of the N-mixture model because observations from a binomial distribution are counted as an independent event. Besides, using groups also accounts for the limited scope of view of cameras. However, the overall group size might still be underestimated for the systematic limitation of using camera trap stations. Counts of pig per image were manually done by group members in `Timelapse2`.

We defined one day as one visit for each camera trap site. We assumed one episode contains one pig group, and that each group is unique from one another for any given day to prevent double-counting. We also assumed the maximum pig count per image in each group represents the number of individuals in the group (i.e. group size). This approximation could lead to an underestimation of pig group size if the cohort did not gather together within the scope of the camera. This bias could vary among camera station sites where different surrounding environments and camera positions could influence the number of pigs captured in each photo.

We used the time difference of 5 minutes and 30 seconds to divide successive photos into episodes and counted the number of episodes in each day as the daily group counts. To fit this data into the N-mixture model, the data was organized by group counts per day per camera station id. The data contained 11 months of pig counts and 38 camera station IDs. The data contains 0 and NA values. Zero values indicate that pigs were not captured by the specific camera station ID and day. NA values represent missing data or when cameras were not operating at that time. We divided the data into April and September checks due to the different placement and number of camera trap stations used for the two time periods.

Transform estimated number of groups to number of individuals

The model gave estimated numbers of pig groups at each camera station for the two time periods. We used the probability distribution of group size over all camera stations (**Figure 6**) to find the weight parameter (w_i) for each unique value of group size. Using equation (1), we calculated the weighted average of group size at each camera station. We then multiplied the weighted average of groups size by the estimated number of groups to find the estimated pig abundance at each camera station.

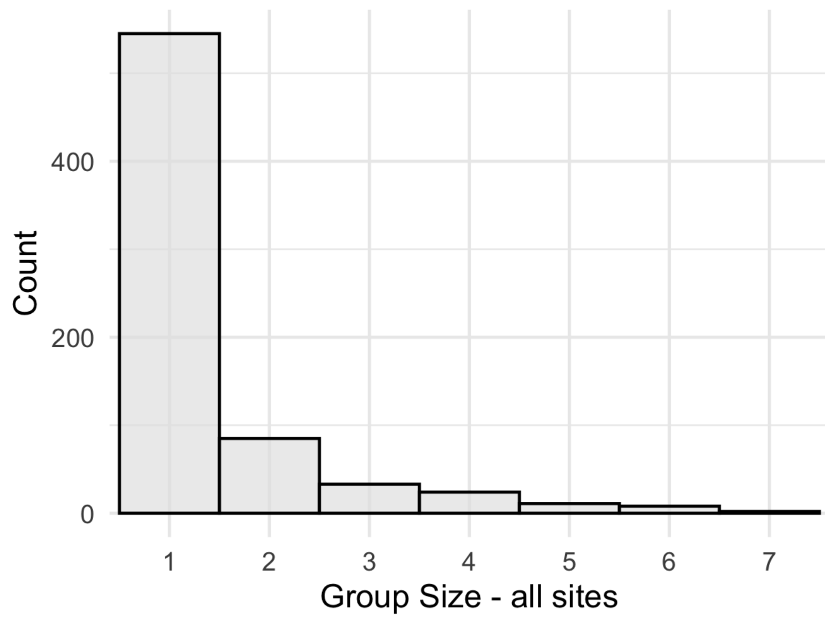

Figure 6. Distribution of group size over all camera stations.

$$W = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

W : weighted average
w_i : weighting parameters for i^{th} group size
X_i : value of the i^{th} group size
n : number of unique group size to be average

3. Assessing spatial abundance of feral pigs on the Dangermond Preserve

Spatial interpolation uses data values at selected points to estimate the values of the variable over the entire region of interest. In other words, it turns discrete point observations into a variable surface. In our project, we used the estimated pig abundance data at camera trap stations and used spatial interpolation to estimate pig density over the entire preserve.

The original data of camera trap stations includes spatial locations of all camera trap stations on the JLDP. Since not all of them were used to record photos during the time of our study, we first filtered out all cameras that were used. We then cleaned the data by removing duplicates and checking for location information recorded during the study time period. Lastly, we merged the estimated abundance data from the previous step with camera trap stations data and exported the spatially referenced data as a shapefile.

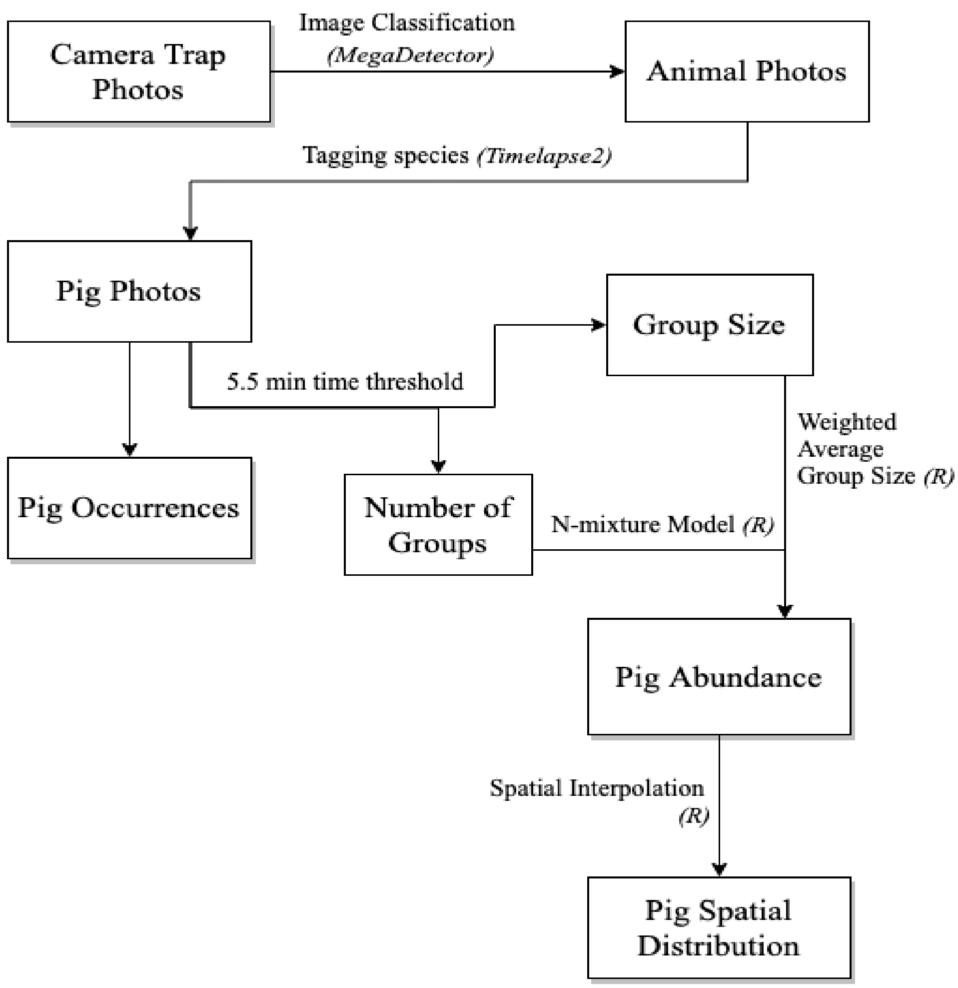

Figure 7: Population estimation workflow. Shaded boxes are major inputs and outputs. Softwares or tools that were used for analysis are italicized in parentheses.

Spatial interpolation assumes that spatially close locations are more correlated than locations far from each other. Methods can be grouped into deterministic approaches (e.g. proximity interpolation, inverse distance weighted techniques) and statistical approaches (e.g. surface trend, kriging). In this project, we used ordinary kriging to interpolate the wild pig abundance at the camera trap stations to the entire preserve. To conduct the spatial interpolation in R, we first detrended the spatial trend to meet the assumption of constant mean and variance through the study area. We determined the global trend to be removed by comparing first order and second order polynomial fit. We then looked at the sample experimental variogram plot and fitted it with the Spherical model. We then sent the fitted variogram to kriging interpolation, which used the localized pattern produced by sample data to compute the weights of neighboring pig counts. Following kriging, we combined the output with the previously removed global trend to produce the final result of the interpolation. In addition to the heatmap of pig density, we assessed the variance of this spatial interpolation process to conclude uncertainty of the estimated values.

iii. Potential Wild Pig Management Strategies

Exclusion Fencing:

Robust non-electrified fencing has had great success in excluding pigs from sensitive areas, even when many miles of fence are required. A study conducted by the Forest Service in 2001 found that pigs were seemingly completely excluded from treatment areas with a fence design as follows: 0.9 meter tall fencing attached to 1.9 meter rebar stakes every 3 meters with 10cm by 10cm mesh openings. This design was chosen to prevent pigs from passing while its short height allows large mammals to cross and the mesh openings are sufficient for small mammals and invertebrates (Sweizer and Van Vuren 2001). Similar designs have been successfully used in various pig control operations throughout the United States. During the process of total pig eradication on Santa Catalina, this design was used with the addition of barbed wire strands above and below the mesh to discourage leaping over and rooting beneath the fence (Garcelon et al. 2005). The pig exclusion fencing currently in use at the Dangermond Preserve is of a comparable design.

Wild pig fencing can be an expensive endeavor upfront for installation with continued maintenance and monitor costs over time. Costs to install fencing can vary greatly based on the type of fence chosen and the ease of access for installation and maintenance. Pig eradication projects on Catalina Island, Santa Cruz Island, and Pinnacles National Park purchased fencing at respective costs of $34,000/km, $42,000/km, and $54,000/km (Garcelon et al. 2005, Parks et al. 2009, Sweizer and McCann 2007). Fencing can be as expensive as $140,000/km if a helicopter is required to bring in materials to remote locations (Massei, 2011). TNC has already constructed 26,340 feet of fencing around 5 areas on the preserve designated for oak restoration. This was done at a cost of $8.95 per foot ($29,356/km).

While fencing off of critical habitat on the Preserve can stress the pig population, it alone does not lead to mortality of pigs. The exclusion of pigs from fenced areas will shift the population to more accessible areas while likely shifting pig damages as well. The rewards typically outweigh the drawbacks of a targeted fencing operation because it allows for land managers to exclude wild pigs from high-priority conservation areas. While it hasn't been shown to reduce wild pig abundance on its own, fencing is almost always a good first step before implementing lethal control methods.

Early on in discussions with The Nature Conservancy, two key habitat areas were identified in need of protection from wild pigs. Coast live oak woodland and coastal sand dune habitats were identified as needing protection from wild pig incursion. Logistically, it was determined that fencing off all oak woodlands on the preserve would be extremely difficult, expensive, and time consuming. To account for limited resources, the team asked The Nature Conservancy for priority areas to protect within the preserve with fencing. For the two key habitats, TNC suggested 3 options for the protection of :

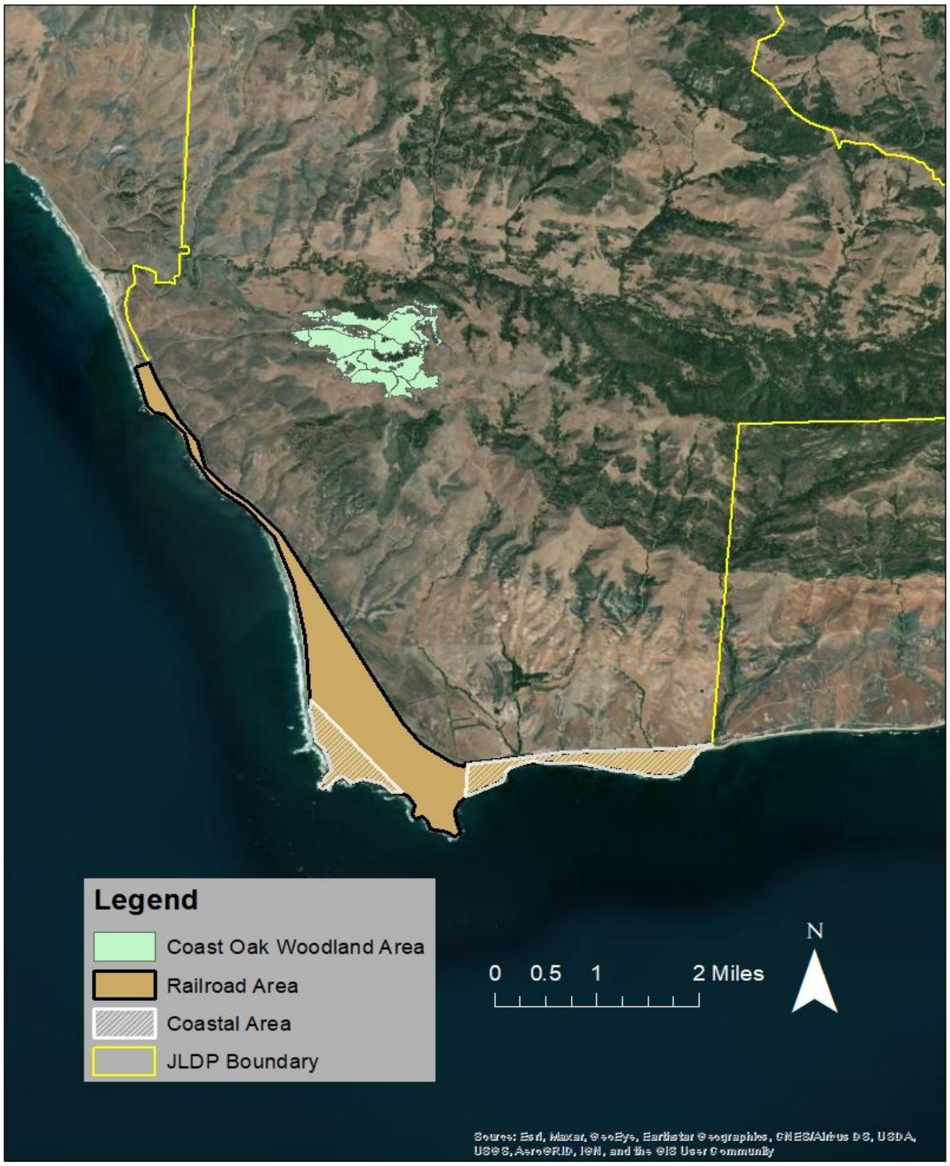

Figure 8. The four different areas designated to selective fencing on the Preserve.

1. Coast Live Oak Woodlands
    - Fencing around the Army Camp Oak Woodland Area
2. Coastal Sand Dunes
    - Fencing Along with Railway Tracks to protect majority of coast OR
    - Fencing Selectively Along the Coastline to protect Coastal Sand Dunes

The protection of coast live oak woodland habitat involves the fencing of Army Camp, which is independent of the installation of the other two areas in this analysis. For the protection of coastal sand dunes, fencing along the railway tracks would protect more area than the selective fencing along the dunes, but would be more costly. Both would not be done as the protection would be redundant. These protected areas are shown in **Figure 8**. The area in green represents the coast oak woodland area near army camp, the brown represents the areas south of the railroad track, and the two white areas near the coast represent the coastal dune areas that would be selectively protected. These areas were prioritized for protection by TNC.

<u>Hunting:</u>

While the concept of a recreational hunting program for the purpose of wild pig reduction can seem attractive due to its potential to be cost-negative, the research does not support this strategy. Recreational hunting has never been proven to provide long-term control of a wild pig population (VerCauteren et al. 2019). While sustained recreational hunting removes on average 23% of a wild pig population annually, the high fecundity of wild pigs dictates that 60-80% need to be removed each year to have a negative effect on abundance (Mayer 2014). Besides its unproven efficacy, recreational hunting of wild pigs creates incentives that are contrary to population reduction efforts. In states with well established populations like California, recreational hunting provides a source of income to landowners which increases tolerance for pigs on the landscape (VerCauteren et al. 2019). Worse than simply increasing acceptance of pigs, it's generally been accepted by the wildlife management community that the illegal transport of pigs for recreational hunting purposes is one of the drivers of the species' rapid population spread (Bevins et al. 2014). All of these factors lead us to conclude that implementing a recreational hunting program for the purpose of wild pig reduction at the Dangermond Preserve is not a sound management strategy.

Although recreational hunting won't meet the needs of TNC and creates misaligned conservation incentives, targeted staff/professional hunting of wild pigs can be a viable part of pig management at Dangermond. There are many different ways to hunt pigs for the purpose of population reduction (hunting dogs, VHF "Judas Pigs", aerial gunning, etc.) and they vary in effectiveness and cost efficiency. Importantly, hunting without other population control measures such as fencing and trapping is unlikely to achieve the 60-80% annual reduction to significantly decrease abundance on the Preserve. That said, a targeted seasonal approach to hunting can be used to slow the growth of pig populations at Dangermond instead. When considering this approach, it's important to understand that wild pigs respond to hunting pressure by changing their behavioral patterns and territory use (Thurfjell at al. 2013). In short, pigs that are under constant or near constant threat from hunting and trapping will become harder to remove as they begin avoiding areas of perceived danger. For this reason, intense and focused hunting efforts should be applied over short time periods to remove as many pigs as possible before they adapt and engage in avoidance behavior. The costs of such a regime depend on how much TNC staff time is occupied with the hunting or what contracted hunters cost to hire. Cost efficiency of removal is highly dependent on density and terrain factors. Lethal control in general has diminishing returns due to behavioral change and density reduction.

<u>Trapping:</u>

When considering the use of traps for wild pig population management at the Preserve, there are a number of important factors to take into account. Before implementing a trapping regime, it's important to recognize the goals and likely outcome of such actions. First, recall that removal efforts need to be intense (~70% population per year) in order to just hold a wild pig population at a constant value. For large properties, this can dictate that a great number of traps is needed to achieve population reduction. Another consideration is what's considered trapping strategy. While simply setting a large number of traps where pigs are believed to frequent can lead to the removal of many animals, a more effective way to use traps for population control may be to pursue whole sounder removal (VerCauteren et. al 2019). This strategy is generally viewed as superior to alternative trapping methodologies because it diminishes the possibility of creating trap-shy individuals (especially females) who may pass that behavior onto offspring. However, whole sounder removal is a lengthy process that involves monitoring of specific sounders and individuals within those sounders. Large traps are then placed and baited for each sounder and left open so pigs become accustomed to it. The actual trapping and removal takes place once the maximum number of pigs are contained in an effort to remove whole sounders at a time. This method has proven to be very effective in areas where wild pigs display high levels of site fidelity. Whole sounder removal may be a viable method for population control at Dangermond if future camera trap study reveals high site fidelity among the wild pigs present.

Wild pig traps come in a variety of designs and capabilities, each with their own benefits and drawbacks in terms of both effectiveness and cost. Decisions need to be made regarding trap type, gate design, bait type, and location. Of the different types of traps, corral traps are usually preferred and would make the most sense at the Preserve. These are circular or teardrop shaped with typically a single gate and can capture more animals at a time than simpler box traps (Williams et. al 2011).

iv. Cost benefit analysis of three levels of Pig Management

1. Reduction of damage (fencing priority areas)

The first conservation strategy proposed is to reduce the damage caused by pigs on the preserve by fencing managed areas. In 2019, TNC began implementing this strategy by hiring a contractor to install pig exclusion fencing around the five oak rehabilitation sites shown in **Figure 9**. The five sites Ramajal Main, Ramajal East, West, Narrow, and Venadito) were fenced with a combined perimeter length of 26,340 feet at a cost of $8.95/foot. Four double gates and eight single gates were also added at respective costs of $1,395 and $795. Finally, old fencing was removed at a cost of $1.50/foot, bringing the total cost of the new fencing at the five oak rehabilitation sites to $254,283.

The monitoring hours for each section were calculated based upon conversations with the Wildlife Biologist at Pinnacles National Park, Paul Johnson. The management and monitoring of the pig exclusion fencing at Pinnacles National Park occurs on a monthly basis and depending upon the habitat, it can take a person 30 minutes to 2 hours to walk one kilometer of fencing. This time is significantly increased if a maintenance action needs to be performed, which can include repairing a hole, clearing downed branches, filling in burrowing activity, or clearing overgrown vegetation. For our analysis, we estimated that it would take 1.25 hours to complete a km of fencing.

Because TNC has begun to implement exclusion fencing on oak wood restoration sites in 2019, it makes sense to continue this strategy to protect other natural resources. TNC has prioritized two types of habitats, coast live oak woodland and coastal sand dunes, to protect from feral pigs on the Preserve. A survey was given to TNC to identify specific areas of these habitats to potentially protect with fencing, as fencing all coast live oak woodland and coastal sand dunes is extremely costly and unrealistic. These specific areas can be seen in **Figure 8**. The estimated fencing perimeter for the protection of coast live oak woodland area is ~6,400 meters or 20997 feet. At a rate of $8.95/foot, the installation costs would be around $57,400. TNC suggested two options for the protection of the coastal sand dunes: (1) fencing along the railway tracks to protect the majority of coastal habitats or (2) fencing selectively along the coastline to target coastal sand dune habitats. The first option is to fence along the railroad tracks and fully exclude the coastal areas from feral pigs. This first option would require an estimated fencing perimeter of ~10,500 meters or 34,449 feet. The fencing installation costs would be around $94,000. The second option is to fence off specific regions of the coast that mainly contain coastal sand dune habitats. These regions are shown in white in **Figure 6**. Fencing these two coastal regions would require an estimated total fencing perimeter of ~5,400 meters or 17,717 feet. The fencing installation costs would be around $48,600.

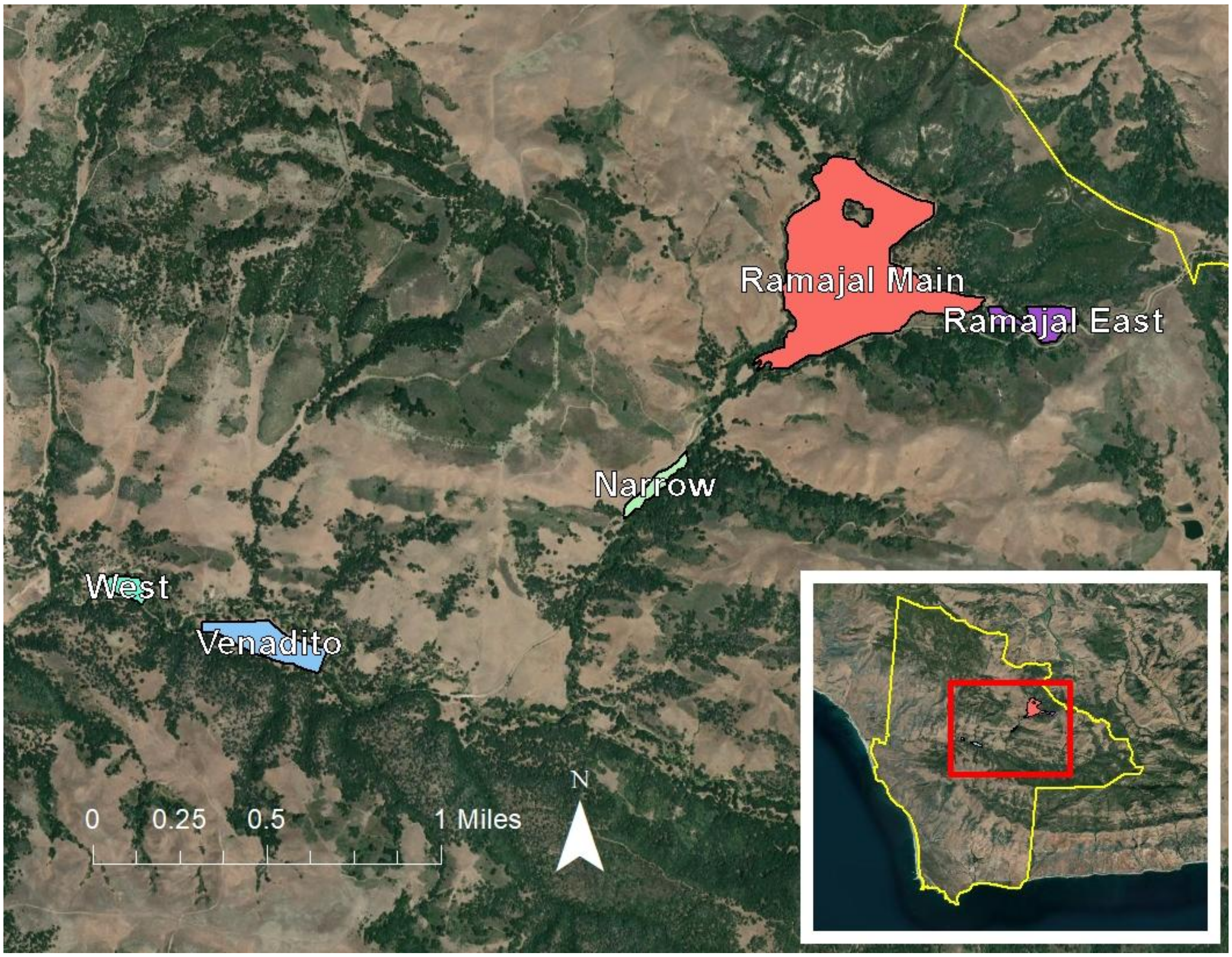

Figure 9. The 5 coast live oak woodland restoration areas that have already been fenced off on the Preserve.

2. Active management of pig population

The second conservation scenario for wild pig management at the Preserve is to take a more active role in monitoring and controlling the pig population. This includes fencing some areas (though not necessarily on the scale of scenario 1), the creation of a Preserve-wide camera network for monitoring, and the use of hunting and trapping with the aim to remove 70% of the population annually to prevent further growth. Scenario 2 is an attractive option because it gives

TNC more control over their own wild pig destiny by setting the tools needed to control pig population growth. The costs and benefits of each aspect of scenario 2 are discussed below.

The level of additional fencing that TNC can include in this scenario is variable. This is because Scenario 2 focuses on population control rather than the protection of specific land areas. It's worthwhile to note that no aspects of Scenarios 1 and 2 are mutually exclusive. TNC can go forward with increased monitoring and population control with either no additional fencing or the entire suite of fencing options offered in Scenario 1. One way to use fencing for population control that was not discussed in Scenario 1 is to exclude pigs from water. In theory, fencing off watering holes and wallows would stress the population and reduce reproductive potentials. While it's known that pig populations suffer during drought periods (VerCauteren et. al 2019), the mechanism for this lowered reproductive potential is usually observed to be the reduced availability of hard mast (Servanty 2009), rather than reduced access to fresh water. Our team has heard anecdotally about the potential to stress wild pig reproduction by fencing water sources but haven't seen success with this method in the research. The difficulty in locating and fencing many watering holes and wallows across 25,000 acres for a tactic with questionable benefits prevents us from recommending water exclusion fencing. That being the case, TNC can pursue water exclusion and any other fencing options for Scenario 2 based on the costs and benefits shown in the previous scenario.

The success of active population control measures for Scenario 2 first requires the implementation of a more robust monitoring effort. Out of the monitoring options available and discussed in previous sections, we have chosen a network of wildlife cameras as the best approach for pig monitoring for this scenario. The primary driver of this decision is the multitude of uses that TNC will have for such a network both within and outside the perspective of wild pig management. Another important factor is that TNC already has plans in development to install a network of 30 cameras across the preserve for the purpose of monitoring all wildlife at Dangermond through time. An example of their deployment locations are shown in **Figure 10**.

The installation of a network such as this would result in camera density of 0.32 cameras/km^2. This density, though lower than proposed by most studies, would be sufficient for the purpose of wild pig monitoring because of the longer timeframe available to collect data. Davis et. al., observed that camera densities lower than 1.3/km^2 would be insufficient to accurately estimate pig abundance over an eleven day period. We are confident that having a virtually infinite time frame to collect occurrence data will negate the comparatively small density of the proposed camera network and provide enough information to support active population control efforts.

Once this network is in place, population control measures can begin for Scenario 2. The goal we've set for removal in this scenario is 70% of the pig population annually. This value was chosen as our removal target because it's widely reported that pig populations will grow year after year unless culled 60-80% each year. By striving to remove 70% of pigs each year, TNC has the ability to limit rates of damage to their current levels by avoiding the rapid population growth that's occurring elsewhere in the state and country. At the current pig density we've calculated for Dangermond, this means about 140 pigs should be removed every year. Based on the evaluation of different removal strategies in previous sections, we've determined that the lethal control aspects of Scenario 2 that make the most sense for the Preserve are trapping and ground hunting. Due to literature findings on cost efficiency of these methods, trapping should be prioritized with hunting used to finish what is left over.

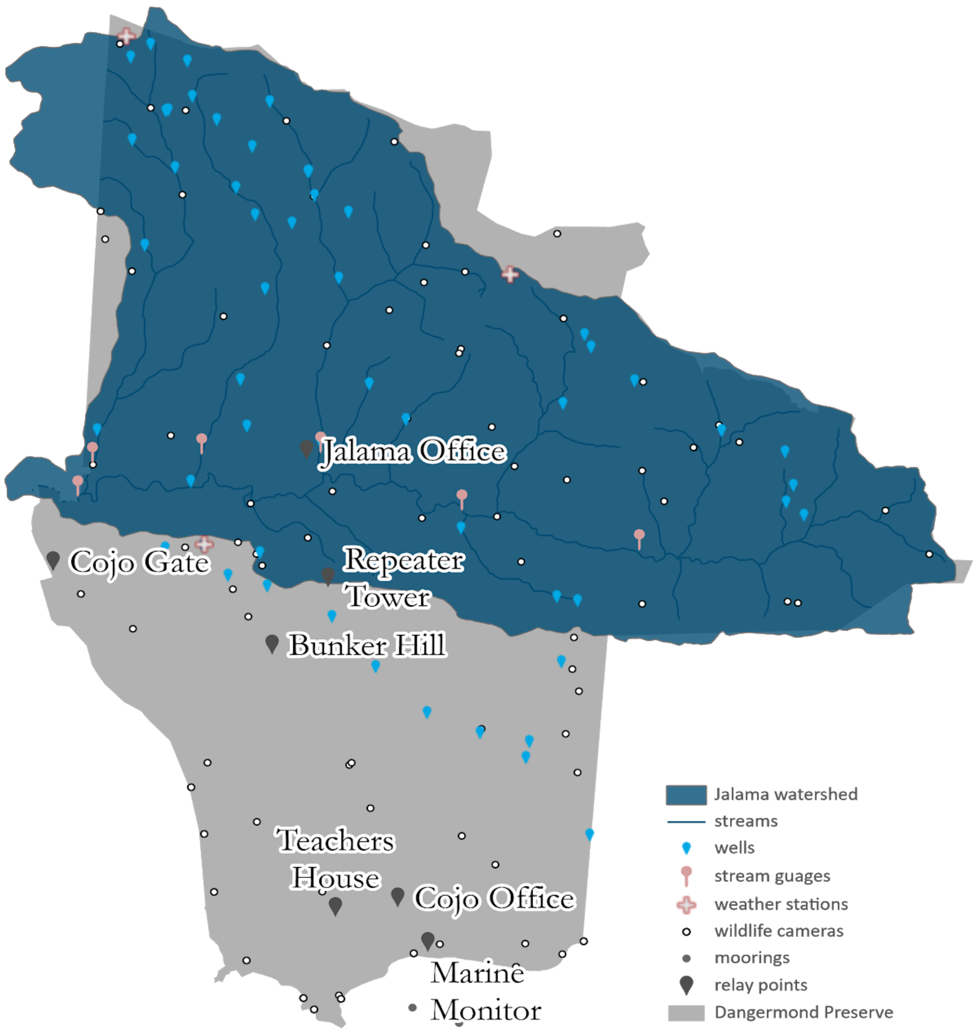

Figure 10. TNC Map of monitoring locations (TNC 2021).

The costs of wild pig trapping depend on the number, type, and location of traps. Whole sounder removal is the most prudent trapping strategy to prevent easy replacement of culled individuals and reduce the risk of creating trap-shy individuals. To be most effective, each sounder and all individuals within the sounder should be identified and their fidelity to specific sites noted. This is why the establishment of the monitoring network prior to pig trapping is essential. Once the sounders are identified and located, a corral trap should be built at the most frequented location for each sounder. A design that has been successfully used for whole sounder removal in the past consists of 5-10, 4.9-m panels attached to 1.6-m t-posts driven into the ground on the outside of the panel. Panels are to be arranged with a 0.5-m overlap between panels and attached to t-posts with baling wire (Lewis 2020). A remote activated gate would then be installed and dropped once the entire sounder is observed inside. An example of a similar design setup is shown in **Figure 11**.

In the event that whole sounder removal is insufficient or not appropriate for Dangermond (if pigs do not exhibit site fidelity), staff hunting would be necessary to achieve the 70% removal target in Scenario 2. The reasons staff hunting was chosen instead of recreational hunting are discussed in previous sections. The degree of hunting necessary depends on the outcome of trapping operations. Hunters may be required to take anywhere from zero (if trapping is 100% successful) to 140 (if trapping is not used or is wildly unsuccessful) wild pigs per year. This aspect of Scenario 2 is where TNC has the opportunity to be creative in mitigating costs. Donors and visitors are occasionally invited to the Preserve to participate in wild pig hunts. This activity should continue and if possible, be expanded to hunt as many pigs as possible throughout the year. This would lessen the staff time needed to close the gap between total trapping removal and 70% removal. If all participating hunters (staff and visitors) are encouraged to target younger sows, a greater negative impact on wild pig reproduction can be expected in comparison to public hunters who typically target larger males. The total costs of hunting operations would depend on the success of trapping and the proportion of paid staff time vs. visitor time that is used to achieve 70% removal.

Figure 11. Corral trap with bait feeder and two remote gates (image from JAGER PRO store)

The primary benefit from seeking to remove 70% of the wild pig population at Dangermond is the knowledge that pig harms to natural systems will be limited to their current levels. Even if the target is not ultimately achieved, the efforts would still have a negative effect on population growth and slow the accumulation of damages. The costs of the necessary monitoring, fencing, trapping, and hunting are significant but the ecological benefits and knowledge gained from this scenario may well be worth it.

3. Total eradication of wild pigs from the Jack and Laura Dangermond Preserve

The total eradication of wild pigs at the Jack and Laura Dangermond Preserve would be a difficult and expensive undertaking though there is precedent for such an action. Previous wild pig eradication was successfully implemented at Santa Catalina Island (Garcelon, Ryan, and Schuyler 2005), Santa Cruz Island (Parkes et al. 2010), Santa Rosa Island (Lombardo and Faulkner 2000), and Pinnacles National Park (McCann and Garcelon 2008), Hawaii Volcanoes National Park (Katahira, Finnegan, and Stone 1993), and Fulton County, Illinois (Fischer et al. 2020). Detailed costs associated with these projects can be seen in the appendices. The initial conditions prior to eradication were also outlined to show the extent of the wild pig problem in each area prior to the eradication.

The costs associated with the complete eradication of wild pigs at the Jack and Laura Dangermond Preserve would be significant. The project would have two main cost components: additional fencing and active pig removal. Permanent pig exclusion fencing would have to be installed around the entire land boundary of the preserve to prevent future immigration after eradication. Additionally, temporary fencing would be needed to divide the preserve into several zones to facilitate the process of removing pigs over time. If TNC purchased pig exclusion fencing at the rate they were given for the fencing of the oak rehabilitation sites ($8.95/foot) the cost to fence the entire boundary (excluding coastline) would be 44,550 meters or 146,161 ft. This would also require monthly monitoring of the fenceline to ensure that no breaches or gaps are present, resulting in increased staff hours for this project. This project will only examine the staff hours required for monitoring and will not extrapolate on the costs.

Once the perimeter and zone fencing has been installed, active pig eradication efforts would begin. These would likely involve some combination of ground hunting, trapping, hunting with dogs, use of judas pigs, and aerial hunting. Costs for these activities were taken from prior case studies that undertook eradication efforts of pigs. The amounts for these activities were adjusted for 2021 values using an inflation calculator. The total cost of each activity was added up which included all management activities for the eradication, and the total cost of activities minus fencing was also tallied. In order to get a rough estimate of the cost of eliminating pigs from the preserve, the average cost of removal for the case studies minus fencing was found. The number was then multiplied by the total number of pigs estimated to be on the preserve to give a rough estimation of the active management cost of eliminating pigs on the Dangermond Preserve.

The total cost of eliminating the wild pigs is then calculated by adding the total fencing costs and the active management costs together. It also then shows the required staff hours for monitoring the fenceline. There may also be other costs associated with this management activity that would need to be considered, but are hard to be quantified. Relationships with neighboring property owners may be strained if they begin to see an increase in pig activity on their properties as a result of the Dangermond Preserve being closed off to migrating populations. It may also draw attention from animal rights groups such as PETA, or local hunting organizations that want sustained pig populations for recreational purposes. There may be monetary investments made to combat these problems as they arise, but they will not be factored into this analysis as quantifying the costs would be far too prohibitive.

III. Results

i. Occurrences of feral pigs over time

Occurrence is defined as the number of individual pigs tagged for each photo. The bar graphs below show the total number of occurrences, or total number of pigs tagged for all photos, by month and hour from October 2013 to September 2014. These results contain all pig counts for each episode and may result in repeats, so it does not accurately represent pig activity. Instead, these show a temporal bimodal distribution of images with feral pigs. From the graphs, there are higher feral pig occurrences in the spring and winter months (**Figure 12**). There are higher feral pig occurrences in the morning and evening times (**Figure 13**).

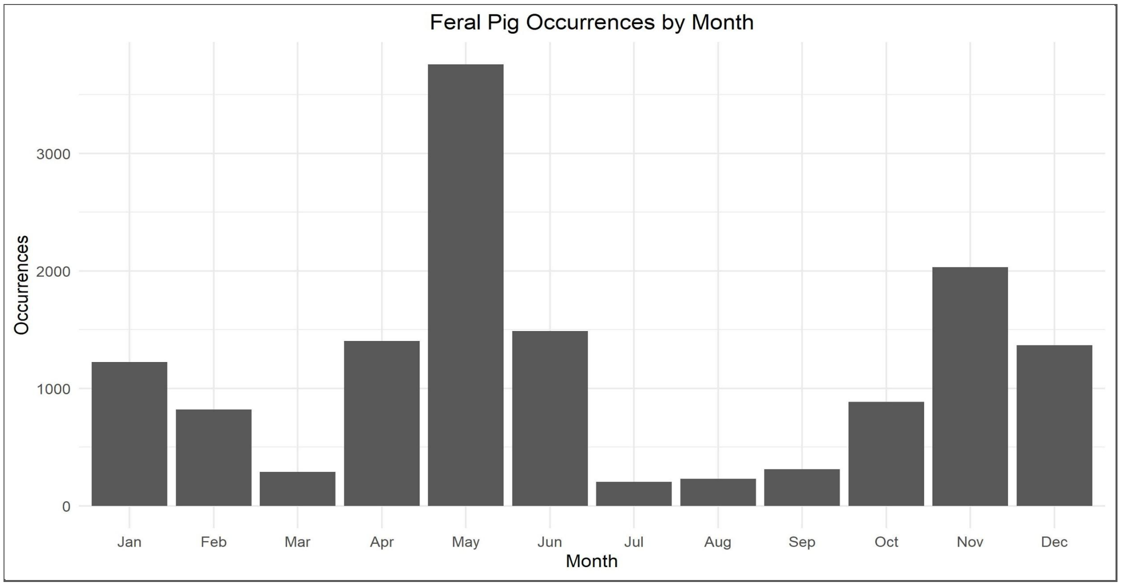

Figure 12. Total feral pig occurrences by month (2013-2014).

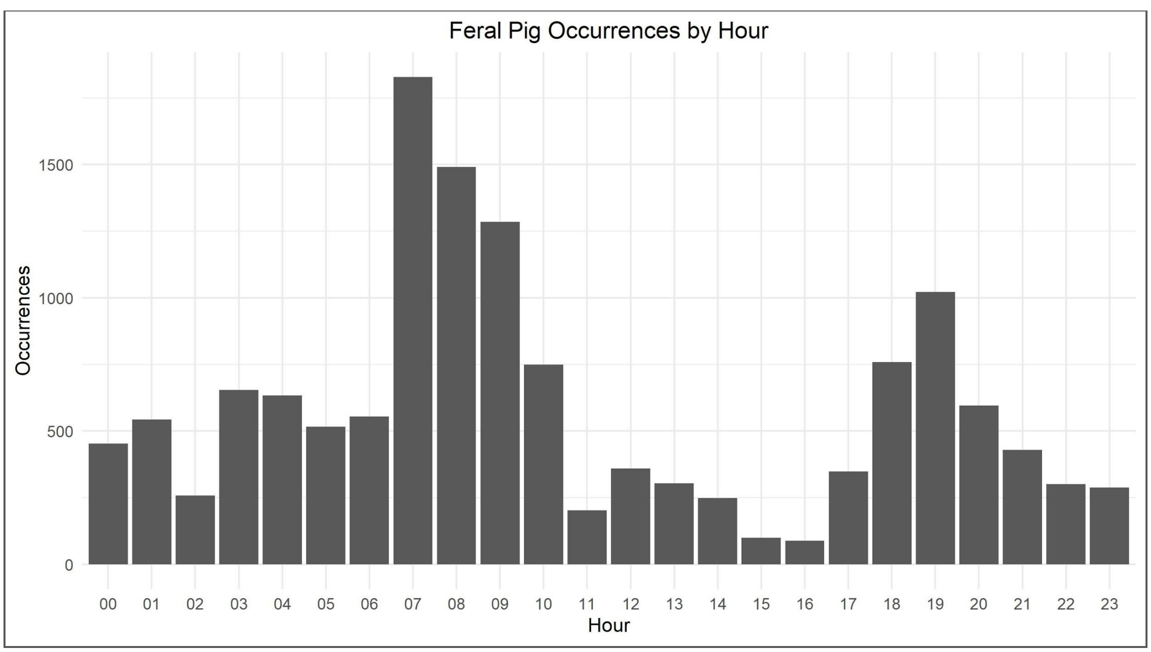

Figure 13. Total feral pig occurrences by hour (2013-2014).

High occurrences in May and November might be caused by more cameras in operation in those months. Similarly, high occurrences at 7 am and 7 pm might be a result of pigs spending longer time resting in the shade or searching for food in front of camera stations. Although these graphs do not accurately inform pig activity at the preserve, it indicates that our data is temporally distributed in a systematic way.

ii. Estimate of abundance from N-mixture modelling

April and September checks had different camera station sites, so we ran the N-mixture model twice to find the abundances for both checks. **Table 2** shows the estimated abundances for each camera site for both checks. From our result, only a few and specific camera sites, such as L3-1 for April check and K4-1 for September check, contained high abundances of feral pigs. Majority of the camera sites contained low pig abundances. For the April check, the aggregate pig abundance was 167 pigs, while September had had 114.

Table 2. Feral pig abundances for each camera station site.

April Chek (2013-10-23 to 2014-04-22)							
Site	**Abundance**	**Site**	**Abundance**	**Site**	**Abundance**	**Site**	**Abundance**
C2-1	6	E5-1	3	G6-1	2	I3-1	3
C2-2	11	F2-1	0	H1-1	2	I5-3	1
C3-1	1	F3-1	7	H4-1	1	J2-1	3
C3-2	1	F4-1	3	H5-1	3	J4-1	5
D5-1	1	F5-1	1	H6-2	1	K3-1	26
E2-1	2	G5-2	3	H7-1	2	K5-1	4
E4-2	2	G5-3	4	I2-1	5	L3-1	64

September Check (2014-04-24 to 2014-09-25)							
Site	**Abundance**	**Site**	**Abundance**	**Site**	**Abundance**	**Site**	**Abundance**
C2-1	3	F2-1	3	G6-1	0	J2-1	4
C3-2	1	F3-1	3	H2-2	2	K3-1	10
D5-1	1	F4-1	3	H2-3	4	K4-1	47
E2-1	0	F5-1	0	H2-4	5	L3-1	2
E4-2	2	G5-2	2	H4-1	0	M4-2	16
E5-1	1	G5-3	2	I3-1	3		

iii. Spatial distribution on the preserve

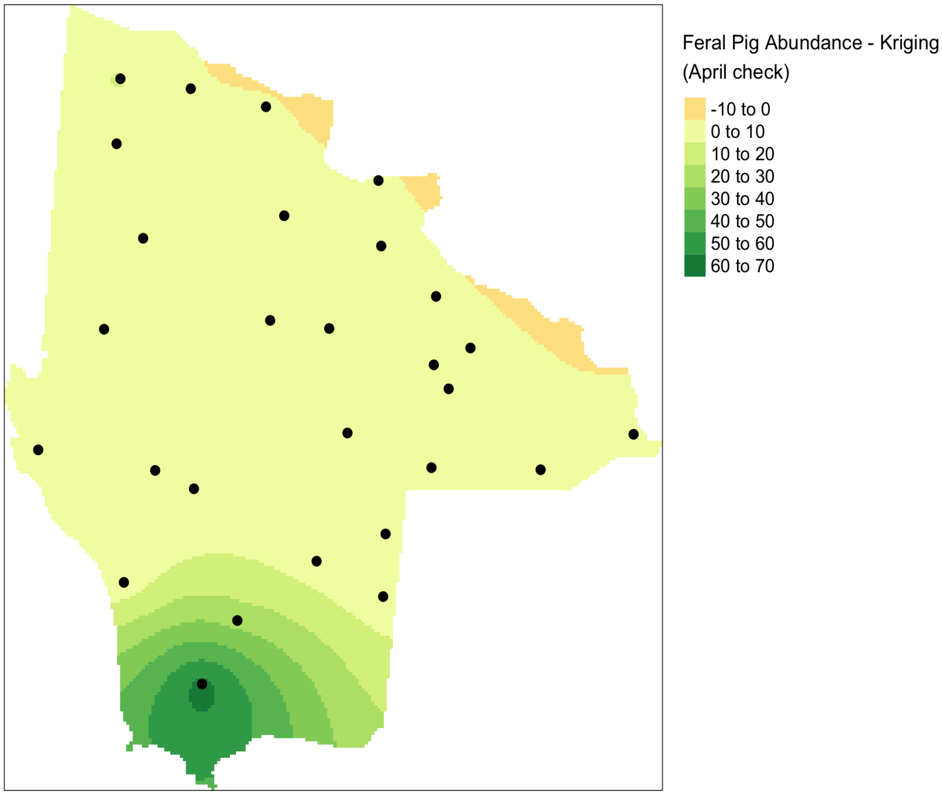

Figure 14. Feral pig spatial distribution for April check.

Spatial interpolation takes the abundances from each camera site and estimates the abundance of pigs over a surface. For both April **(Figure 14)** and September **(Figure 15)** checks, feral pigs are spatially distributed at the southernmost part of the preserve. From April to September checks the pigs appeared to move slightly more inland and away from coastal areas, while still remaining on the southern tip of the preserve. The maximum density of pigs (60-70) from the April check also decreases to a maximum of (40-50) pigs in the September check. This may be because the pigs are moving off of the preserve or are migrating to areas where cameras were not present. In either scenario, it is likely that the pigs are primarily located in the south due to the nearby wetland habitats. Wetlands provide freshwater to pigs and are high in biological productivity which provide year round sources of food. The southern part of JLDP is a good area for pigs to stay hydrated and feed on smaller animals found in the wetlands. The more inland areas of the preserve tend to have more oak woodland habitats. As the pigs migrate towards acorn masting events that occur in the fall, it is likely that there would be a migration of pigs inland. This idea is briefly backed up by figures as there is a shift in the heat map of pig densities, but not to the extent that would suggest a wide spread seasonal migration.

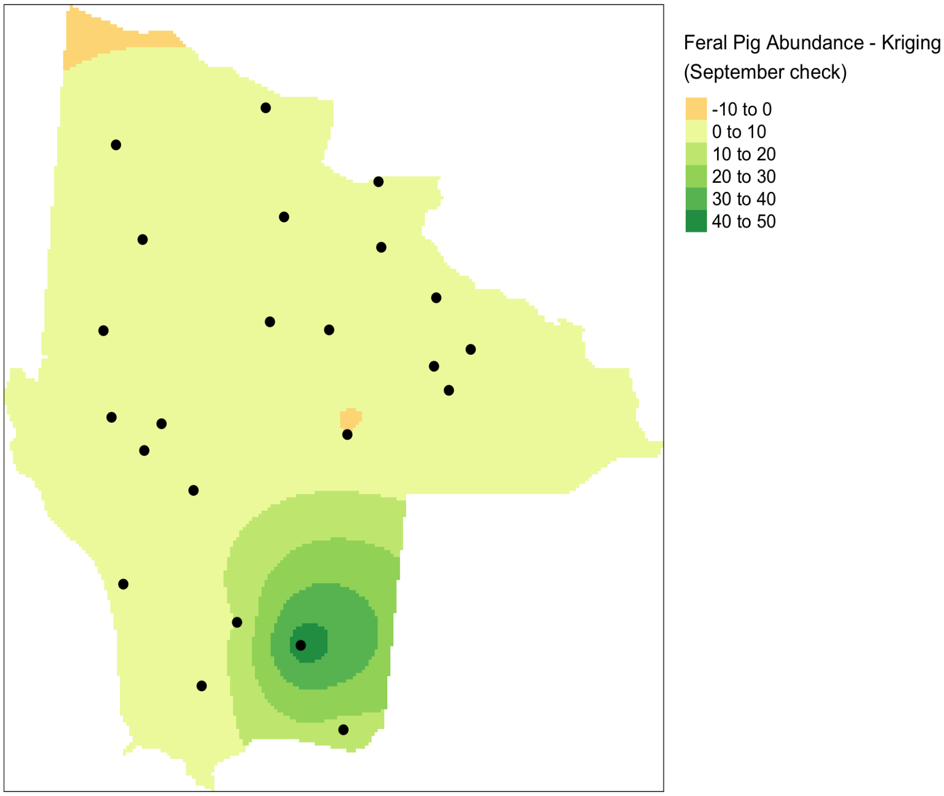

Figure 15. Feral pig spatial distribution for September check.

iv. Results of cost benefit analysis for three conservation scenarios.

1) Reduction of damage (Fencing Priority Areas)

One of the more significant results for the difference in monitoring of fencing is the number of staff hours that would be required for monitoring the fence installations. As seen in **Figure 16**, the railroad would require the greatest amount of monthly and yearly hours for monitoring purposes. The Army Camp Coastal Oak Woodlands area would be on par with the areas already completed, and the coastal dunes areas would be requiring the least amount of monitoring staff hours. **Figure 16** does not include maintenance costs. As we discuss in section IV, maintenance costs can vary greatly depending on the specifics of fenced areas in ways that make general estimations impractical.

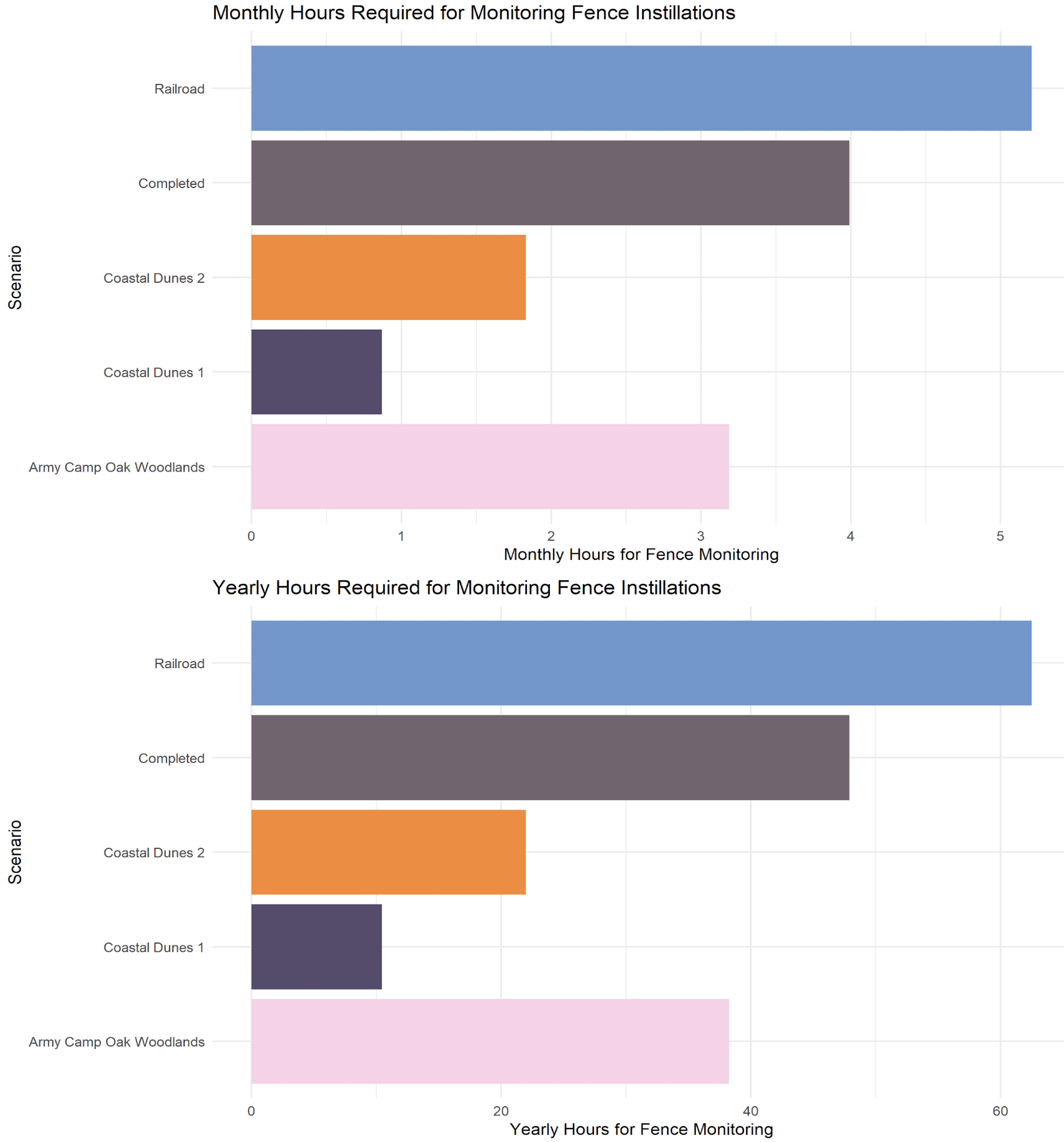

Figure 16. Estimated numbers of staff hours for the monitoring of different fencing installations on the Dangermond Preserve.

The staff hours above indicate only a portion of the resources that TNC would need to dedicate to the fencing installation on the Dangermond Preserve. As seen in **Figure 17** there are different costs associated with each installation as well as different amounts of areas protected. The total costs only represent the cost of installing fencing for those areas and does not include cost for monitoring or maintenance. Thus for a scenario like the Railroad installation would be anticipated that the total cost and average cost per area protected would increase. For the area that has already been completed, an explanation as to why the average cost of the area protected is higher than any other section is that the current protected areas on the preserve are not one continuous section of fencing but are rather broken up into five different areas (**Figure 9**). Larger patches that are protected by one area of fence, such as the railroad scenario, have a lower cost. This is also why the Army Camp scenario, despite having roughly the same amount of fencing costs, has a larger area that is protected as well as a much lower average cost for the area protected. With these results it can be concluded that protecting a larger area with a continuous fence is better than protecting a smaller patchwork of fencing areas.

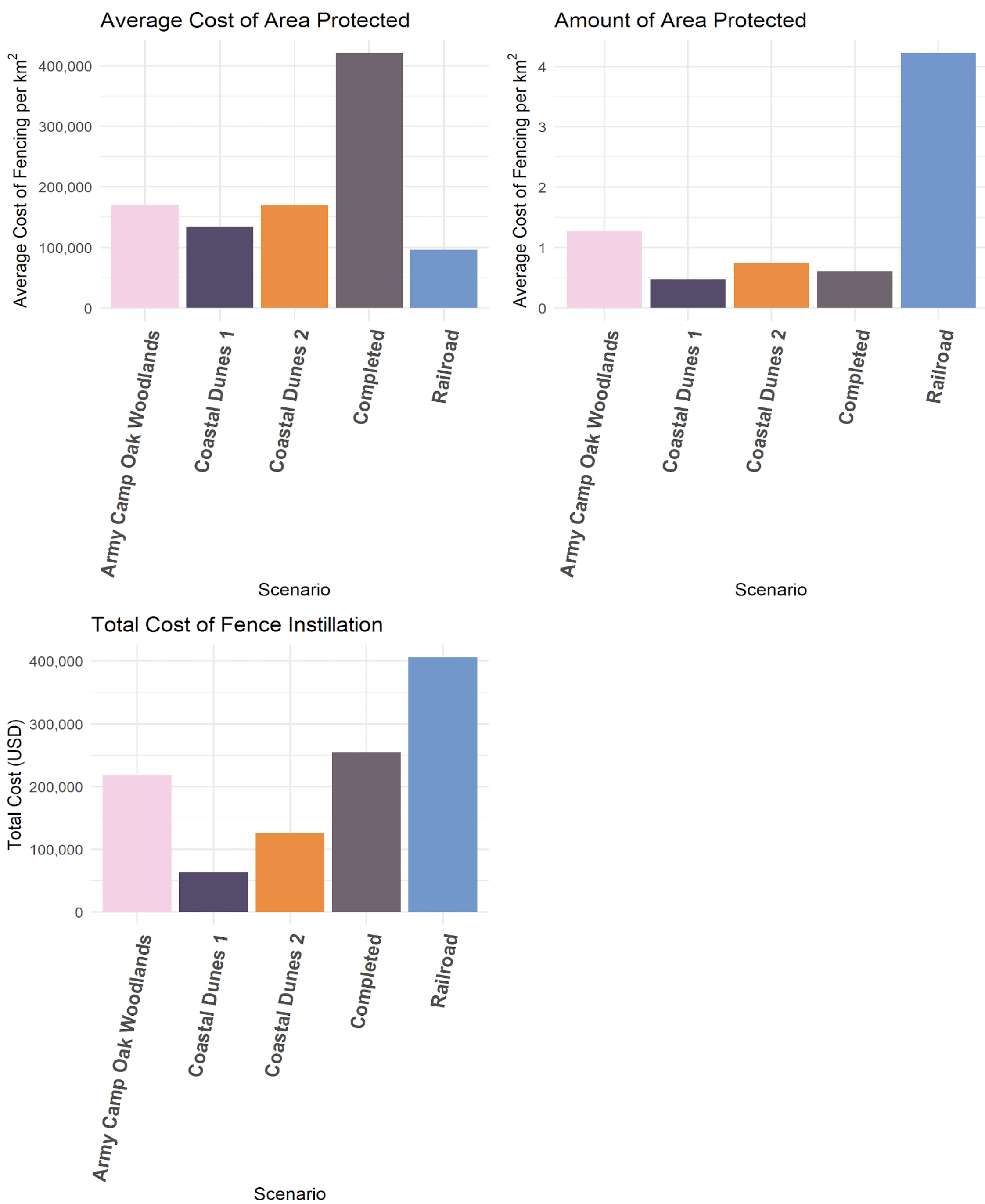

Figure 17. The average cost of protecting each area (top left), the total area protected (top

right), and the total cost of fencing installation (bottom left) for 4 different scenarios and one completed scenario.

2) Monitoring Results

The costs of implementing a 30 camera network depend on the capabilities of the cameras TNC chooses to use. There are two cameras that our client has expressed specific interest in for this project. The first type is already installed at three locations on the southern boundary of the Preserve. These are the Reconyx™ HF2X HyperFire 2™ GEN3 Game Camera which costs $400 apiece. Using this option for the entire network would cost about $10,900 to just purchase the cameras. The Reconyx is a good option used by many monitoring networks but requires periodic changing of the SD cards to download photos. Another option is a camera system with wireless connectivity and the ability to transmit photo data. Researchers on Santa Cruz Island have successfully deployed the Buckeye X80 Series Wireless Camera for this purpose. The Buckeye costs about $900 apiece and has the ability to transmit images for more frequent analysis and less labor costs to change sd cards. Using solely Buckeye cameras, the proposed monitoring network would cost about $25,000 to purchase. We suspect TNC will go forward with a mix of these two camera types to benefit from some of the additional functionality of the Buckeye and some of the cost savings of the Reconyx. A network composed of any mix of these two cameras would likely be sufficient to inform the population control methods of Scenario 2.

Figure 18. Reconyx Hyperfire (left) and Buckeye X80 (right) wildlife cameras

While the cost of materials for the traps themselves would cost $200-$400, remote activated gates (with necessary cameras) run anywhere from $2000-$5000. Assuming a mean sounder size of 10 (Sweitzer et. al 2000), 20 traps would need to be installed across the Preserve. That puts costs for the corral trap materials at $4000-$8000. Purchasing 20 remote gates would be prohibitively expensive, however the adjustment and pre-baiting period necessary in the course of whole sounder removal means that a smaller number of gates can be purchased and moved as necessary once the corrals are built. Assuming that two remote gates are sufficient, the average total cost for the 20 traps falls at around $76,000. Additional costs for bait as well as staff labor for the installation and execution of trapping and removal would be necessary. All told, this is a relatively expensive undertaking but if done properly and assuming Dangermond pigs exhibit high site fidelity, it is highly likely that a whole sounder trapping strategy would achieve 70% removal, perhaps more.

Figure 19. Jager PRO remote activated gate

Furthermore, equipment costs are one-time and materials can be reused so costs of subsequent trapping operations would be limited to staff labor in moving and operating traps.

In summation, Scenario 2 provides TNC an exciting opportunity to participate in active population management and safeguard the ecological resources at the Preserve from the current and future wild pig threat.

3) <u>Total Eradication Results</u>

The initial densities for each pig eradication study can be seen in **Figure 20**. Santa Cruz (20 pigs per km^2) and Santa Catalina (61 pigs per km^2) were the studies with the highest densities of pigs. The Dangermond Preserve is estimated to have a density of around 2 pigs per km^2 which would be the lowest of the above case studies for pig removal.

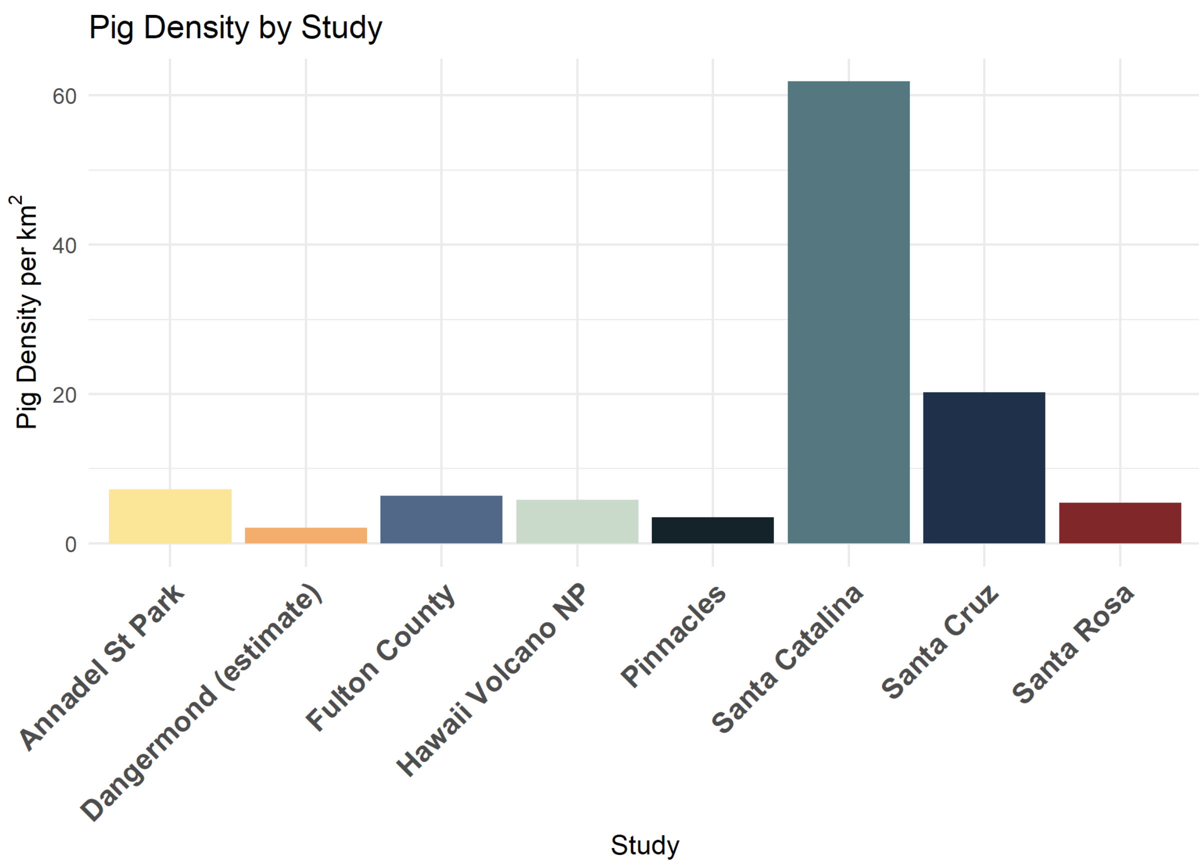

Figure 20. The figure above shows the pig density from each of the studies that are used in this analysis. It was derived by taking the total number of pigs eradicated by the total square kilometers of the preserve.

Santa Catalina, Santa Cruz, Pinnacles, Hawaii Volcano National Park, and Annadel State Park all made use of exclusion fencing for wild pig removal. Those results, as well as the estimates for the Dangermond Preserve can be found in **Figure 21**. Pinnacles was the most expensive installation as the whole area was fenced in, crossing a non-homogenous landscape that included rocky hills, streams, and dense brush which all required additional costs for the fencing. The Pinnacles team also opted for a more expensive fencing option (Steel versus wood for posts) as the maintenance costs over time were diminished and would have a longer lifetime (30 years versus 5-10 for wood). For the Dangermond Preserve, the staff hours required for monitoring would be ~22 hours per month of fenceline monitoring and ~250 hours per year, the associated costs were not factored into the analysis but are important to note.

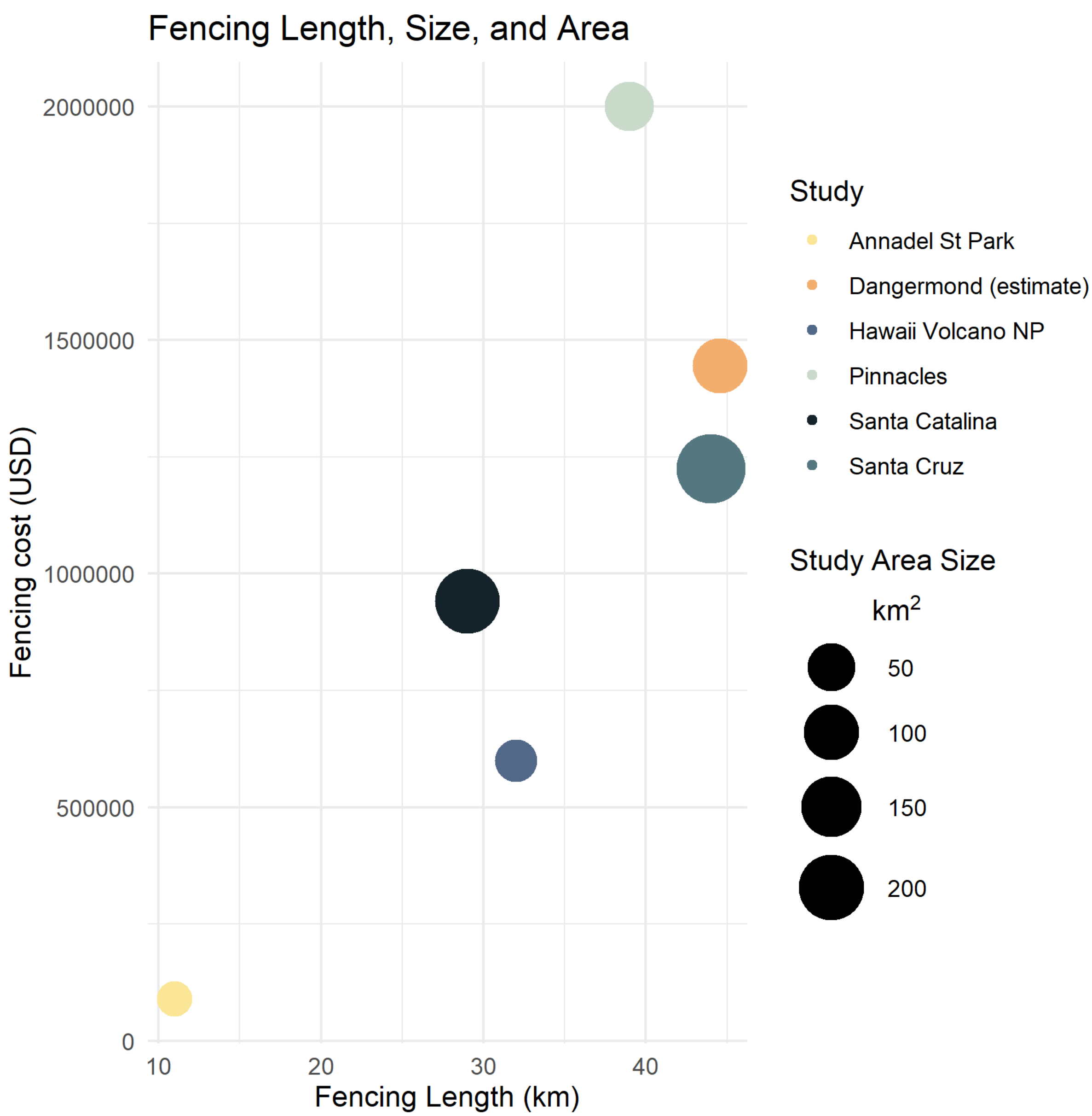

Figure 21. The figure above shows different fencing costs, length of fencing, and area protected for different case studies.

The total cost of eradication for the Dangermond Preserve is conservatively estimated to be around **$1.7M USD**, with the largest expenditure of that coming from the cost of fencing installation (~$1.4M USD). This cost was compared to other cases for the total documented amount for pig removal as well as the average cost per pig. As seen in **Figure 22** the total costs that are associated with pig removal were the highest for Santa Cruz and Santa Catalina islands, yet their average cost per pig was lower than the estimated removal for the Dangermond Preserve and for the Hawaii and Pinnacles studies. Santa Catalina had the lowest average cost of any removal outside of the Fulton county removal. This can be attributed to the high pig densities as seen in **Figure 20**.

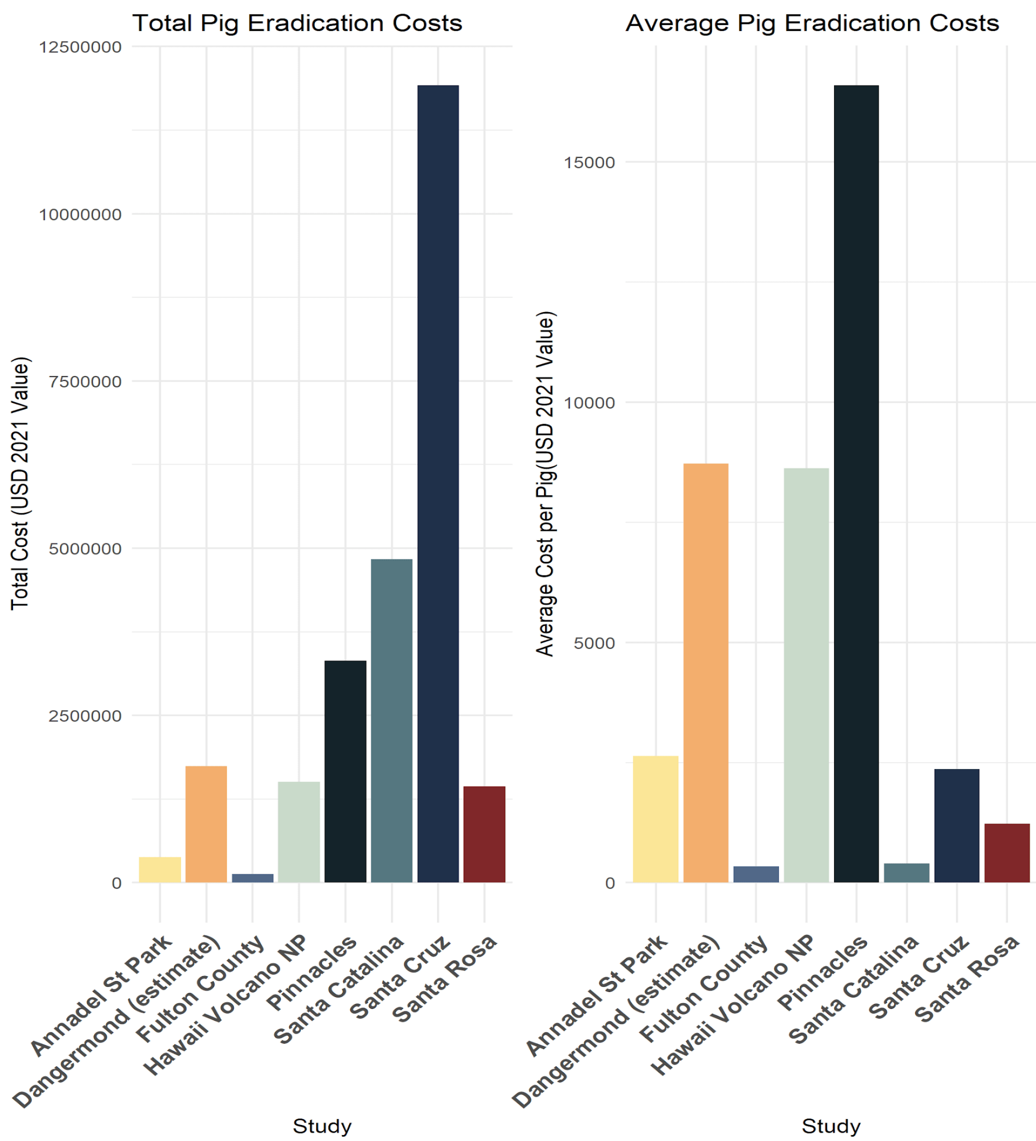

Figure 22. The two graphs show costs associated with pig removal, both documented and estimated. On the left, the total cost is graphed, while the cost per pig (total cost divided by number of pigs removed) is shown on the right.

To see if density was a predictor of average cost a linear regression model was used and the results were documented in **Figure 23**. The figure shows a non-significant value (p=0.2861) but does show a general trend line associated with increasing densities being associated with lower costs for removal. Fulton County and Santa Rosa did not install fences for removal which kept the cost per pig lower, as fencing tends to be the most expensive part of an eradication. Santa Rosa as an island had little chance of reintroduction while Fulton County was surrounded by counties that did not have documented wild pig populations.

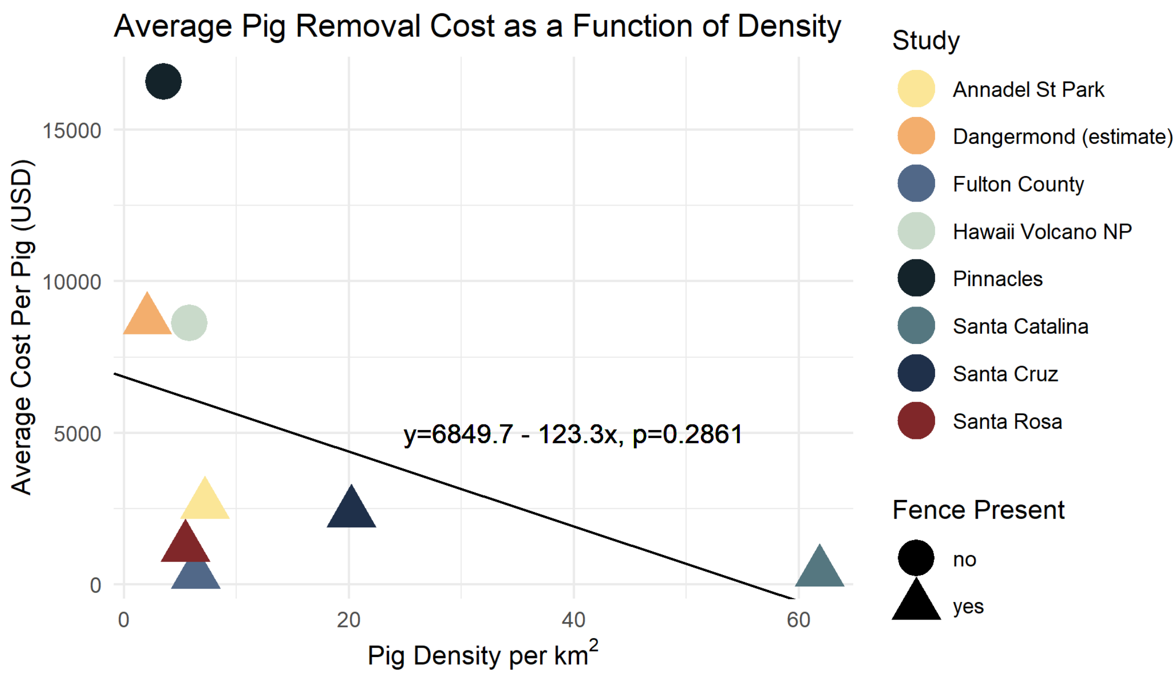

Figure 23. The figure above shows the density of pigs for different studies and the average cost associated with removing a pig. The trend line shows a negative correlation of density and cost that is not statistically significant.

IV. Discussion

i. N-Mixture Model

The results of our N-mixture analysis indicated the density of wild pigs at the preserve is roughly 2 pigs/km^2, which would come out to roughly 200 total pigs on the preserve. Expert estimates as well as literature estimates predicted that there would be approximately 200 pigs on the preserve (Sweitzer et al. 2000). This number may represent a low mark for pig abundance for several reasons. One error that was not able to be resolved through processing the data was tracking pigs. The N-mixture model assumed that this was a closed system and not an open system, which may have also likely lowered the abundance of pigs. The boundaries of the Dangermond Preserve were open from October 2013 to September 2014. Immigration and emigration likely occurred and were not considered in the population abundance analysis. In this way, it's likely that the estimated abundance (**Table 1**) was lower than the actual number of pigs that visited the Preserve during the period of study. On the other hand, N-mixture models with modification on robustness can be used for open populations (Ketz et al. 2018). Future studies can improve the population estimation by incorporating robustness on the probability of capture.

The model also assumes the abundance of pigs at the preserve was constant throughout the survey period while it might not be true given the immigration was unlikely to accurately cancel out emigration. In addition, the Preserve, in addition to other parts of the central coast, experienced drought throughout the study period which likely caused a decline in the pig population. Also, the analysis ignored the seasonality of pig activities which might influence the number of pigs present at the Preserve during study time.

When transforming image data to pig count, we assumed the number of pigs in each group can be represented by the maximum number of pig counts per image in each group, which could result in an underestimate of group size. In general, it's more likely to underestimate a large group of pigs rather than a small group. The degree of underestimation would vary across camera stations based on the pig activities, movement, and the camera's scope of view. For camera trap stations with a wide scope of view where pigs tend to stay for a longer period of time in front of the camera, like rooting for food or wallowing in mud, the maximum number of pigs per image was likely to accurately reflect the group size. Contrarily, if camera trap stations were installed near fences where animals simply went by the camera, the maximum number of pigs per image was likely to underestimate the group size because a group of pigs usually travels in a line instead of gathering together. When the last pig entered the view of the camera, the first ones could have already left the view. Following that, the movement direction of pigs might also influence the accuracy of this assumption. If pigs traveled in the same direction as camera trap stations faced, the maximum number of pigs per image was likely to accurately reflect the group size because the cameras were likely to capture all pigs in one image. However, if pigs traveled in a direction that is perpendicular to where the cameras faced, underestimation was very likely to happen. Therefore, future camera trap installation might measure or consider the cameras' camera trap photos from 2013 and 2014.

Our final assumption regarding the estimation of wild pig abundance is that the data reflects the current state at Dangermond. As stated previously, our analysis of wild pig abundance was done using data collected approximately seven years ago. Despite the age of our data, we still feel confident that our population estimate can be useful for TNC. Conversations with Dangermond's management staff as well as land managers at the neighboring properties of

Vandenberg AFB and the Hollister Ranch have led us to believe that approximately 2 pigs per square kilometer is a good estimate of wild pig abundance in the area currently. That said, a renewed monitoring effort with ongoing data collection would give TNC a greater level of certainty regarding the current population as opposed to relying on aging photo data.

ii. Cost Analysis

The cost analysis required a number of assumptions that also likely produced a lower than realistic expectation for the projected costs, especially in the total eradication scenario. In each case study, the marginal cost for removing one pig increased as the population decreased, meaning that the cost of removing the very last pig on the preserve is greater than removing the first pig. This follows the logic found in **Figure 23** that as density increases cost decreases, while the results of the simple linear regression run in our model was not significant, this is a well documented situation.

Additionally for the fencing cost, what was not modeled or factored in was the geography that is associated with installation of fencing. An average cost of $8.95 per foot was used to calculate the cost of fencing the whole preserve as well as for the installation of smaller areas as seen in the selective fencing analysis (**Figure 16, 17**). This is a low estimate for several reasons, notably the terrain and accessibility that the fencing would need to be installed on. If the whole preserve were fenced off there would be higher costs associated with installation on more remote sections of the preserve boundary that would likely exceed the $8.95 per foot cost. This assumption also does not factor in the type of fencing that would be installed. Pinnacles used steel t-posts as they would last longer and require less maintenance, the current installation of posts at the Dangermond Preserve were made of wood (P. G. Johnson, personal communication, February, 3, 2021). Salt water can degrade posts fairly easily so whether TNC wants to install steel posts for a slightly longer lifespan versus wood posts in specific areas would be a decision that needs to be made by them. Areas more inland and farther away from the ocean would be better served with steel as the maintenance and replacement costs over the lifetime of the fence would likely be lower.

Our analysis treated the landscape as a homogenous area for the purpose of a simple analysis which is not an accurate representation of the Dangermond Preserve. Stream and river crossings require a specialized type of fence that needs to be designed after consultation with hydrologists to ensure that maximum stream flow and flood conditions do not blow out the fencing. Rockier and hillier areas are often prone to failure of the fence as it is difficult to secure the posts. These areas require additional maintenance and monitoring time and are not as easy to monitor as a grassland boundary. Areas that are dense in brush also take extra time to monitor and install as shrubs like Poison Oak *(Toxicodendron diversilobum)* can make maintenance activities hazardous and extra laborious if it is overgrown on the fence, which is likely to be an issue in riparian corridors.

Modeling the number of staff hours and costs resulting from these assumptions would have been too difficult to complete in the scope of this project. Conversations with TNC also showed that this type of analysis is ultimately not at the scale they are looking for with this project as the costs are likely to change and TNC would contract out much of this work to a third party vendor for the installation of fencing. The cost estimate of ~ $1.4M for the fencing of the whole preserve is still likely a severe underestimate, but the costs associated with fencing off the smaller tracks with selective fencing is likely more accurate. Monitoring also would be handled in house by TNC, which is why costs were not projected, but only staff hours for the different projects. If TNC decides to hire a new staff member for monitoring the fenceline, then it is obviously not the place of this analysis to determine the salary and pay rate of that employee. If TNC decides to allocate current staff hours to monitoring then it takes time away from other projects and activities which are also not going to be projected with this analysis.

The staff hours for monitoring the fenceline also can be viewed as a cost to TNC for the activities that would need to be done for trapping, hunting, processing camera trap data, and other active management activities. While this analysis discussed the costs of active management with respect to buying equipment and generally estimating the costs of hunting, this is by no means what TNC would pay. Again, whether TNC wants to control all of this cradle to grave in house, or hire a third party to manage these operations to a certain extent will influence the costs. It is impossible to pinpoint the exact cost of what these activities would take and what possible rates TNC may be able to negotiate down to. The numbers represented throughout the costs section generally are going to be representing a lower bound of the range as the complexities that have been outlined above and requirements for staff hours to perform the related activities are not factored into the cost that is presented.

The costs explored for the implementation of a 30 camera monitoring network took into account only the purchase price of the cameras and is therefore a low estimate. Additional staff time will be required for the installation of the cameras and ongoing photo processing/analysis. It is our belief that the costs associated with purchasing and operating the camera network are a worthwhile investment for TNC because of the many different wildlife management applications they can be used for. This network would directly support two of the overarching goals for the Dangermond Preserve: Protection, restoration, and management of natural resources and promotion and support of new research and technology.

The cost of trapping efforts at the Preserve have also been presented thus far only as equipment costs. Purchase price of materials was researched and reported while the actual cost of implementing trapping will reflect significant staff (or contractor) time for installation as well as checking the traps and disposing of pigs. While the additional staff time associated with the monitoring network is multi-use, the efforts needed for trapping operations will solely be for the purpose of wild pig management. Considering it's lack of applications to other conservation projects on the Preserve (compared to a camera network), trapping may seem like a very expensive endeavor for a narrow goal. However, if it comes to be the case that pig removal is needed at Dangermond, trapping efforts are likely to be the most cost effective option for TNC (Williams et. al 2011).

Hunting is also a component of this study that was not deemed to be a worthwhile investment for mitigating the pig population. As previously stated, to maintain a stable pig population there needs to be roughly a 70% take annually of pigs (Hiroyasu, 2020). Previous studies that were examined used aerial hunting, ground hunting with dogs, and hiring professional hunters. These case studies all had higher pig densities than Dangermond (**Figure 23**) which lowers the cost per pig removal as hunting operations can be fairly expensive. Even if TNC were to employ an extensive hunting program on the preserve, without a barrier to block pigs from migrating back on to the Preserve from nearby source populations, large culling would need to be a relatively frequent undertaking to maintain the population.

There are also concerns about allowing hunters on a wildlife preserve that also has an active cattle operation. Without guidance, hunters may inadvertently damage cultural resources, disturb endangered/threatened species, or interfere with cattle operations. As mentioned with other management activities, this takes staff hours to ensure compliance or training of personnel to oversee the operation. A better solution may be using hunting as a control in years of high pig abundance with limited guided tours. This would allow for more control over the operation, lower the intensity of possible unintended damages while lowering costs as well. Allowing for hunting by donors, local Chumash bands, or other small groups may improve goodwill in the community and help mitigate pig damages in years of high pig abundance.

iii. Spatial Analysis

Early on in the analysis it became apparent that there was a need for data about pig movement on the preserve. While the camera stations were moved through the preserve during the 2013-2014 monitoring, the coverage still may not have been adequate for getting a proper estimation of pig density, population, and movement across the preserve. Massei et al., 2018 recommends installing up to 9 cameras per km^2, which would be ~900 cameras for all of Dangermond but would be cost prohibitive. Other studies (Kays et al., 2020) recommend that >35 cameras are needed per site to properly estimate pig abundance, a number that was not achieved in the initial data collection period. So the results of the data could be strengthened in a new study with the installation of new camera traps. While the number of pigs on the preserve may be more accurately projected with the installation of additional camera traps, it may not be necessary. The results of this study fall in line with other projections of population abundance throughout the Central Coast of California, and the next steps of data collection should be focused more on where pigs are on the preserve, as opposed to how many.

Another option that would give TNC a better understanding of how wild pigs are spatially distributed throughout the Preserve is the use of VHF radio tracking. Radio-equipped collars on wild pigs have been used in the past in the California central coast region in order to ascertain home ranges and site fidelity (Sweitzer et al. 2000). Such a study undertaken at the Preserve would provide useful information to guide future management decisions. VHF radio tracking does require a significant investment in both equipment and staff hours. There is also the added drawback of releasing a captured pig back into the breeding pool when the goal of management is population reduction. It is possible to eliminate the captured pigs' reproductive potential by catstrating the animal before releasing it (VerCauteren et al. 2019) but this would require additional investment and consideration of ethics. In any case, a VHF radio tracking project of some type in addition to a robust camera monitoring network would give TNC valuable data on pig fidelity and movement across Dangermond.

V. Conclusions and Recommendations

Given a density estimate of ~200 pigs and a high preference for choosing oak woodland habitats for foraging, we recommend that TNC install exclusion fencing to protect vulnerable oak woodland habitats as well as the coastal dune areas. In order to inform and guide future wild pig management actions, we also recommend that TNC install a monitoring network of at least thirty cameras across the Preserve. This network will prove useful for a host of wildlife monitoring applications including tracking wild pigs. The specifications of the cameras can be determined based on available funding and management priorities but image data should begin being collected as soon as possible. Those images can then be processed using the workflow we developed to estimate abundance. The goals of the monitoring network should be to refine population estimation and track changes through time. By doing this, TNC can determine how many distinct sounders are at the Preserve and what degree of site fidelity they exhibit. To that end, we also recommend the commission of a VHF radio tracking project. This would support the goal of ascertaining site fidelity while also providing insight into the home ranges and seasonal movement patterns of pigs at Dangermond.

The successful implementation of the monitoring network and VHF tracking study would put TNC in the position to effectively begin population control, if desired. We do not recommend trapping operations at this time because the damages from wild pigs at their current density do not warrant the expense of sustained removal efforts. However, if in the future the monitoring efforts reveal a rapidly growing population and/or potential damages that threaten the goals for the Preserve, trapping should begin as outlined in Scenario 2.

Hunting operations at this time should be limited to donors/visitors accompanied by staff. We believe fee-based recreational hunting should be avoided due to the lack of efficacy and ethical considerations discussed in previous sections. Paid staff hunting for population reduction would only be necessary if trapping operations were implemented and needed augmentation to achieve a 70% population reduction. Hunters should be encouraged to target younger females if possible to have a greater negative effect on reproductive potential.

A final recommendation that the team has for TNC on the JLDP is to work on mitigation of pigs by working collaboratively with nearby communities and properties like Hollister Ranch and Vandenberg Air Force Base. Fencing the areas between properties would be cost prohibitive, and the pigs are a nuisance on these adjacent properties as well. In one instance, pigs rooted up the front lawn of the commanding officer of Vandenberg. Conversations with the ranch hands on Hollister indicated that they do not have a pig management plan but are interested in whatever plan TNC implements. A regional approach that examines movement of pigs and identifies areas that act as a population source through the region, then selectively curtailing that source through intensive hunting, fencing, or other control methods might yield better long term mitigation of pig damages for the region than any one party acting alone.

Wild pigs are highly destructive species to ecological and cultural resources among the landscape, especially without proper and effective conservation management actions. Pig Patrol has initiated efforts to characterize the population of wild pigs at the Jack and Laura Dangermond Preserve and developed conservation management recommendations for The Nature Conservancy. Given the estimated low pig density on the Preserve, exclusion fencing of high priority and vulnerable natural resource areas is ideal. Future implementation of intensive monitoring networks would allow TNC to more accurately estimate pig abundance and predict seasonal movement for better management actions more accurately. The management of wild pigs at Dangermond gives TNC an opportunity to work with neighboring organizations and stakeholders to solve a world-wide conservation issue.

Acknowledgments

The creation of this report was made possible due to the support of a wide range of educators, conservation professionals, environmental organizations, and donors. We'd like to thank the James S. Bower foundation for donating our project budget. Among the Bren School faculty and staff we'd like to thank Dr. Bruce Kendall and Dr. Chris Costello for their technical guidance and Sean Kerr and Satie Airame for logistical support. We also appreciate the many environmental professionals who granted us interviews in the early stages of scoping our project and understanding the problem. They include: Mike Gialketsis, Craig Huff, Colby Boggs, Elizabeth Hiroyasu, Michael Glow, Wayne Moses, and Rhys Evans. Our client TNC was represented by three incredibly talented and inspiring individuals, Mark Reynolds, Kelly Easterday, and Moses Katkwoski. Finally, thank you to our faculty advisor Dr. Kelly Caylor, whose unending support made this possible.

References

1. Baber DW, Coblentz BE (1986) Density, home range, habitat use, and reproduction in feral pigs on Santa Catalina Island. J Mamm 67:512–525
2. Barrett, R. 1982. Habitat Preferences of Feral Hogs, Deer, and Cattle on a Sierra Foothill Range. Journal of Range Management 35.
3. Bengsen, A. J., Gentle, M. N., Mitchell, J. L., Pearson, H. E., & Saunders, G. R. (2014). Impacts and management of wild pigs Sus scrofa in Australia. *Mammal Review*, *44*(2), 135-147.
4. Bevins, S. N., Pedersen, K., Lutman, M. W., Gidlewski, T., & Deliberto, T. J. (2014). Consequences associated with the recent range expansion of nonnative feral swine. *BioScience*, *64*(4), 291-299.
5. Boyce, C. M., Vercauteren, K. C., & Beasley, J. C. (2020). Timing and extent of crop damage by wild pigs (Sus scrofa Linnaeus) to corn and peanut fields. *Crop Protection*, *133*, 105131.
6. Butterfield, H.S., M. Reynolds, M.G. Gleason, M. Merrifield, B.S. Cohen, W.N. Heady, D. Cameron, T. Rick, E. Inlander, M. Katkowski, L. Riege, J. Knapp, S. Gennet, G. Gorga, K. Lin, K. Easterday, B. Leahy and M. Bell. 2019. Jack and Laura Dangermond Preserve Integrated Resources Management Plan. The Nature Conservancy. 112 pages.
7. CDFW. 2020. Wild Pig Management Program. https://wildlife.ca.gov/Conservation/Mammals/Wild-Pig.
8. Challies, C. 2010. Feral pigs (Sus scrofa) on Auckland Island: Status, and effects on vegetation and nesting sea birds. New Zealand Journal of Zoology 2:479–490.
9. Dartt-Newton, Deana and Erlandson, Jon (Summer/Fall 2006), "Little Choice for the Chumash: Colonialism, Cattle, and Coercion in Mission Period California," *The American Indian Quarterly*, Vol. 30, No. 3 & 4, 416
10. Davis, A. J., Keiter, D. A., Kierepka, E. M., Slootmaker, C., Piaggio, A. J., Beasley, J. C., & Pepin, K. M. (2020). A comparison of cost and quality of three methods for estimating density for wild pig (Sus scrofa). *Scientific reports*, *10*(1), 1-14.
11. Engeman, R. M., Massei, G., Sage, M., & Gentle, M. N. (2013). Monitoring wild pig populations: a review of methods. *Environmental Science and Pollution Research*, *20*(11), 8077-8091.
12. Frederick J Mark. Overview of wild pig damage in California. *vertebrate_pest_conference*. 1998;18. doi:10.5070/V418110169
13. Fry T, Dunbar M (2007) A review of biomarkers used for wildlife damage and disease management. In: Nolte DL, Arjo WM, Stalman DH (eds) Proceedings of the 12th wildlife damage management conference, pp 216–222
14. Garcelon, D. K., Ryan, K. P., & Schuyler, P. T. (2005). Application of techniques for feral pig eradication on Santa Catalina Island, California. In *Proceedings of the Sixth California Islands Symposium. National Park Service Technical Publication, CHIS-05-01. Institute for Wildlife Studies, Arcata, California* (pp. 331-340).
15. Haley, B. D., & Wilcoxon, L. R. (1999). Point Conception and the Chumash Land of the Dead: Revisions from Harrington's Notes. *Journal of California and Great Basin Anthropology*, *21*(2), 213–235.

16. Hamrick, B., T. Campbell, B. Higginbotham, and S. Lapidge. 2011. Managing an Invasion: Effective Measures To Control Wild Pigs. USDA National Wildlife Research Center - Staff Publications.
17. Herold, A. and Harder, D. 2007. 'The legendary Bixby Ranch in Santa Barbara County has a new owner. What's to become of ... the last perfect place?' Los Angeles Times, 19 May 2020 [onine]. Available at: https://www.latimes.com/archives/la-xpm-2007-may-13-tm-bixby19-story.html
18. Hoehne, V. M. 1994. Wild pigs in Santa Cruz County. Fremontia, 22(2):18-19.
19. Holtfreter, R. W., B. L. Williams, S. S. Ditchkoff, and J. B. Grand. 2008. Feral Pig Detectability with Game Cameras:5.
20. Hudson, T., & Blackburn, T. C. (1982). The Material Culture of the Chumash Interaction Sphere. 5 vols. *Menlo Park, CA: Ballena P and Santa Barbara Museum of Natural History Cooperative Publication*.
21. Ilse, L. M., and E. C. Hellgren. 1995. Resource Partitioning in Sympatric Populations of Collared Peccaries and Feral Hogs in Southern Texas. Journal of Mammalogy 76:784–799.
22. Lewis, A. (2020). *Pigs by the Sounder: Wild Pigs, Whole Sounder Removal, and their Effects on Deer and Turkey* (Doctoral dissertation, Auburn University).
23. Jackson, R. M., J. D. Roe, R. Wangchuk, and D. O. Hunter. 2006. Estimating Snow Leopard Population Abundance Using Photography and Capture-Recapture Techniques. Wildlife Society Bulletin 34:772–781.
24. Jolley, D. B., S. S. Ditchkoff, B. D. Sparklin, L. B. Hanson, M. S. Mitchell, and J. B. Grand. 2010. Estimate of herpetofauna depredation by a population of wild pigs. Journal of Mammalogy 91:519–524.
25. Joseph, L. N., C. Elkin, T. G. Martin, and H. P. Possingham. 2009. Modeling abundance using N-mixture models: the importance of considering ecological mechanisms. Ecological Applications 19:631–642.
26. J.B, C., and C. F. 1996. Conservation of the dark-rumped petrel Pterodroma phaeopygia of the Galápagos Islands, 1982-1991. Bird Conservation International 6:23–32.
27. Karanth, K. U. 1995. Estimating tiger Panthera tigris populations from camera-trap data using capture—recapture models. Biological Conservation 71:333–338.
28. Ketz, A. C., T. L. Johnson, R. J. Monello, J. A. Mack, J. L. George, B. R. Kraft, M. A. Wild, M. B. Hooten, and N. T. Hobbs. 2018. Estimating abundance of an open population with an N-mixture model using auxiliary data on animal movements. Ecological Applications 28:816–825.
29. Kotanen, P. M. 1995. Responses of vegetation to a changing regime of disturbance: effects of feral pigs in a Californian coastal prairie. Ecography 18:190–199.
30. King, Chester D. 1991. *Evolution of Chumash Society: A Comparative Study of Artifacts Used for Social System Maintenance in the Santa Barbara Channel Region before A.D. 1804*. New York and London, Garland Press
31. Kreger, A., M. Ludington, J. Christie, E. DeMarco, and E. Hiroyasu. 2014. Bren School Group Project 2014:117.
32. Lewis, J. S., J. L. Corn, J. J. Mayer, T. R. Jordan, M. L. Farnsworth, C. L. Burdett, K. C. VerCauteren, S. J. Sweeney, and R. S. Miller. 2019. Historical, current, and potential

population size estimates of invasive wild pigs (Sus scrofa) in the United States. Biological Invasions 21:2373–2384.

33. Lewis, T. E., D. Atencio, R. Butgereit, S. M. Shea, and K. Watson. 1996. Sea turtle nesting and management in northwest Florida. Pages 162-166 in J. A. Keinath, D. E. Barnard, J. A. Musick, and A. Bell, editors. Proceedings of the fifteenth annual workshop on sea turtle biology and conservation. NOAA Tech. Memor. NMFS-SEFSC-387.
34. Loggins, R. E., J. Wilcox, D. H. Vuren, and R. A. Sweitzer. 2002. Seasonal diets of wild pigs in oak woodlands of the central coast region of California. California Fish and Game 88:28–34.
35. Lombardo, C. A., & Faulkner, K. R. (2000). Eradication of feral pigs (Sus scrofa) from Santa Rosa Island, Channel Islands National Park, California. In *Proceedings of the fifth California islands symposium (DH Browne, H. Chaney, and K. Mitchell, editors). Santa Barbara Museum of Natural History, Santa Barbara, California* (pp. 300-306).
36. Massei, G., J. Coats, M. S. Lambert, S. Pietravalle, R. Gill, and D. Cowan. 2018. Camera traps and activity signs to estimate wild boar density and derive abundance indices. Pest Management Science 74:853–860.
37. Mayer, J. (2014). *Estimation of the number of wild pigs found in the United States* (No. SRNL-STI-2014-00292). Savannah River Site (SRS), Aiken, SC (United States).
38. McCann, B. E., & Garcelon, D. K. (2008). Eradication of feral pigs from Pinnacles National Monument. *The Journal of Wildlife Management*, *72*(6), 1287-1295.
39. McLendon, S., & Johnson, J. R. (1999). Cultural Affiliation and Lineal Descent of Chumash Peoples in the Channel Islands and Santa Monica Mountains, 2 vols. *Report submitted to the Archaeology and Ethnography Program, National Park Service. Santa Barbara Museum of Natural History, Santa Barbara*.
40. Parkes, J. P., Ramsey, D. S., Macdonald, N., Walker, K., McKnight, S., Cohen, B. S., & Morrison, S. A. (2010). Rapid eradication of feral pigs (Sus scrofa) from Santa Cruz Island, California. *Biological Conservation*, *143*(3), 634-641.
41. Frederick, J., Mark. 1998. Overview of wild pig damage in California. Proceedings of the Vertebrate Pest Conference 18.
42. Parkes, J.P. et al. 2009. Rapid Eradication of feral pigs (sus scrofa) from Santa Cruz Island, California. *Biological Conservation* 143:634-641.
43. Pimentel D, Zuniga R, Morrison D. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Economics*. 2005;52(3):273-288. doi:10.1016/j.ecolecon.2004.10.002
44. Rattan, J. M., Higginbotham, B. J., Long, D. B., & Campbell, T. A. (2010). Exclusion fencing for feral hogs at white-tailed deer feeders.
45. Reidy, Matthew & Campbell, Tyler & Hewitt, David. (2011). A Mark—Recapture Technique for Monitoring Feral Swine Populations. Rangeland Ecology & Management. 64. 316-318.
46. Rowcliffe, J. M., J. Field, S. T. Turvey, and C. Carbone. 2008. Estimating animal density using camera traps without the need for individual recognition. Journal of Applied Ecology 45:1228–1236.
47. Royle, J. A. 2004. N-Mixture Models for Estimating Population Size from Spatially Replicated Counts. Biometrics 60:108–115.

48. Savarie PJ, Johns BE, Gaddis SE (1992) A review of chemical and particle marking agents used for studying vertebrate pests. Proceedings of the Fifteenth Vertebrate Pest Conference. University of Nebraska, Lincoln, pp 252–257
49. Schlichting, P. E., J. C. Beasley, R. K. Boughton, A. J. Davis, K. M. Pepin, M. P. Glow, N. P. Snow, R. S. Miller, K. C. VerCauteren, and J. S. Lewis. 2020. A Rapid Population Assessment Method for Wild Pigs Using Baited Cameras at 3 Study Sites. Wildlife Society Bulletin 44:372–382.
50. Servanty, S. Jean‐Michel, G., Carole, T., Serge, B., & Eric, B. (2009). Pulsed resources and climate‐induced variation in the reproductive traits of wild boar under high hunting pressure. *Journal of Animal Ecology*, *78*(6), 1278-1290.
51. Strickland, M. 2015. Predators and anti-predator behavior of Wilson's Plover (Charadrius Wilsonia) on Cumberland Island, Georgia. MS thesis. Georgia Southern University, Statesboro, Georgia.
52. Sweitzer, R. A., Van Vuren, D., Gardner, I. A., Boyce, W. M., & Waithman, J. D. (2000). Estimating sizes of wild pig populations in the north and central coast regions of California. *The Journal of Wildlife Management*, 531-543.
53. Sweitzer, R. A., and D. H. V. Vuren. 2002. Rooting and foraging effects of wild pigs on tree regeneration and acorn survival in California's oak woodland ecosystems. In: Standiford, Richard B., et al, tech. editor. Proceedings of the Fifth Symposium on Oak Woodlands: Oaks in California's Challenging Landscape. Gen. Tech. Rep. PSW-GTR-184, Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture: 219-231 184.
54. Timmons, J., J. C. Cathey, N. Dictson, and M. McFarland. (n.d.). Feral Hogs and Water Quality in Plum Creek:2.
55. Thurfjell, H., Spong, G., & Ericsson, G. (2013). Effects of hunting on wild boar Sus scrofa behaviour. *Wildlife Biology*, *19*(1), 87-93.
56. USDA APHIS | History of Feral Swine in the Americas. 2020, June 2. . https://www.aphis.usda.gov/aphis/ourfocus/wildlifedamage/operational-activities/feral-swine/sa-fs-history.
57. VerCauteren, K. C., Beasley, J. C., Ditchkoff, S. S., Mayer, J. J., Roloff, G. J., & Strickland, B. K. (Eds.). (2019). *Invasive Wild Pigs in North America: Ecology, Impacts, and Management*. CRC Press.
58. Waithman, J. D., R. A. Sweitzer, D. Van Vuren, J. D. Drew, A. J. Brinkhaus, I. A. Gardner, and W. M. Boyce. 1999. Range Expansion, Population Sizes, and Management of Wild Pigs in California. The Journal of Wildlife Management 63:298–308.
59. Wilcox, J. T., and D. H. van Vuren. 2009. Wild Pigs as Predators in Oak Woodlands of California. Journal of Mammalogy 90:114–118.
60. Williams, B. L., Holtfreter, R. W., Ditchkoff, S. S., & Grand, J. B. (2011). Trap style influences wild pig behavior and trapping success. *The Journal of Wildlife Management*, *75*(2), 432-436.

Appendix

Detailed analysis can be found at https://github.com/Shuhanstack/PigPatrol.