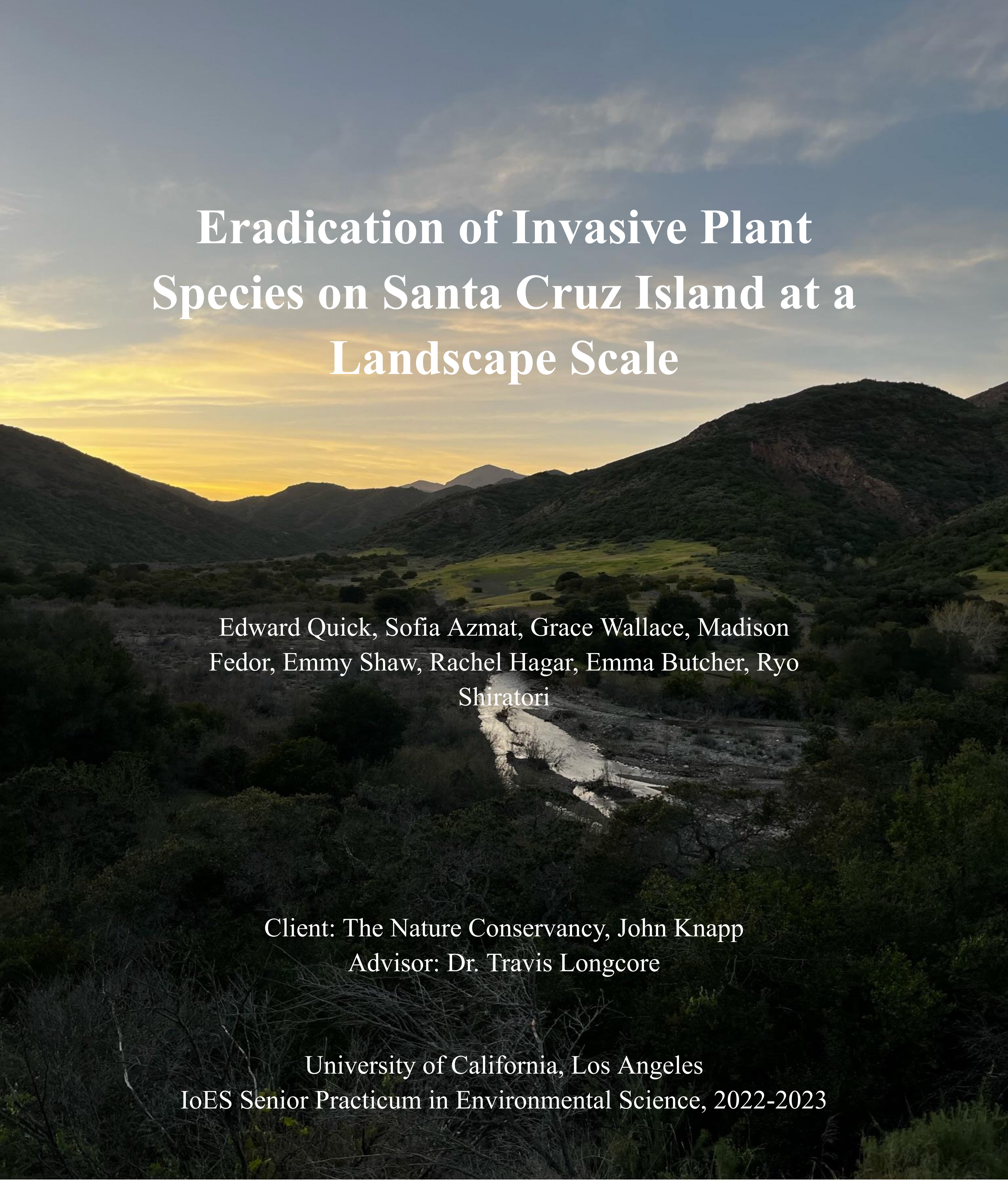

Eradication of Invasive Plant Species on Santa Cruz Island at a Landscape Scale

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Disclaimer

The information presented in this report is strictly the opinion of the authors and does not reflect the University of California as a whole nor The Nature Conservancy as a whole.

About the Authors

As part of the Environmental Science major senior practicum project, all authors are Environmental Science majors working toward their Bachelor of Science from UCLA. Edward Quick is a fourth-year student with a concentration in Conservation Biology, who wants to work in wildland fire science. Sofia Azmat is a fourth-year student with a concentration in Atmospheric & Oceanic Sciences. She is planning to pursue a career in the field for a few years before returning to school to pursue a higher degree related to Environmental Science. Grace Wallace is a fourth year student with a concentration in Environmental Systems & Society. Madison Fedor is a fourth-year student with a concentration in Conservation Biology and a second minor in Geospatial Information Systems & Technology. She ultimately plans to pursue a PhD in Marine Biology, working at the intersection of ecosystem ecology and biogeography in aquatic communities. Emmy Shaw is a fourth-year student with a concentration in Conservation Biology and a minor in French. She plans to pursue a career in sustainability consulting. Rachel Hagar is a fourth-year student with a concentration in Conservation Biology. After graduating she plans to work in the field and eventually conduct research on endangered tropical birds. Emma Butcher is a fourth-year student with a concentration in Conservation Biology. She is pursuing a M.A. in Biology through the Advanced Inquiry Program in association with the University of Miami, Ohio and the San Diego Zoo Wildlife Alliance. She plans to pursue a career in wildlife conservation and research. Ryo Shiratori is a fifth-year student with a concentration in Environmental Systems and Society who plans on pursuing a career in sustainability and conservation.

For More Information

For more information about invasive weeds and The Nature Conservancy, please visit https://www.nature.org.

To view our story map which includes additional maps, figures, and access to the data, please visit link

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Executive Summary

In collaboration with The Nature Conservancy (TNC), our team will be researching the efficacy of eradication efforts for highly invasive plant species on Santa Cruz Island (SCI). Situated off the coast of Southern California, Santa Cruz Island is the largest and most diverse of the five Channel Islands, and is home to over one thousand species of plants and animals. Unfortunately, invasive species are overwhelming the geographically isolated, Mediterranean-climate island's ecosystem and are threatening a high number of endemic species.

Over the last 15 years, The Nature Conservancy has utilized novel, cost-effective, and quick eradication methods to address the invasive plant problem. This project focuses on using georeferenced survey and treatment data collected by The Nature Conservancy from 2007, 2011, and 2014 to 2022 to create time series maps and projection maps depicting what invasive plant distributions look like today and what distributions may look like if TNC were to halt its eradication efforts. Our report discusses how the importance of invasive plant management has changed over time and discusses attributes of several of the invasive plant species TNC is currently working towards eradicating. The results we collect will advance understanding of invasive plant species eradication methods on the landscape scale, for both the Channel Islands and The Nature Conservancy's preserves worldwide.

Project Introduction

CHAPTER 1

Santa Cruz Island and The Nature Conservancy

Situated off the coast of Southern California, the Channel Islands are five extraordinary islands that are home to an abundance of natural and cultural resources. The largest and most diverse of these islands, Santa Cruz Island, is home to over one thousand species of plants and animals. The island also houses remarkable features such as sea caves, kelp forests, tide pools and scenic hiking trails. Though only accessible by boat, many people visit Santa Cruz Island every year. Visitors to Prisoner Harbor doubled from 2019 to 2021 (Boross, 2021), seeking to spend time surrounded by the island's stunning views and variety of flora and fauna.


Figure 1.1. Santa Cruz Island Satellite Image (NASA's Visible Earth).
Figure 1.2. Santa Cruz Island (National Park Service).

However, the island both today and in the past has been under intense threat from invasive species. Being geographically isolated, islands like Santa Cruz tend to have lower species richness than mainland habitats, as well as lower trophic complexity, and functional diversity (Pearson, 2009). There is little overlap in ecological niches; many individual species serve a role that lacks a functional equivalent. As a result, disruption to a single native island species by an invasion can dramatically alter their fragile ecosystems. In addition to its vulnerability as an island, Santa Cruz is also a mediterranean-type ecosystem (MTE). Plant invasions in these types of ecosystems have the ability to alter fuel properties that in turn control fire behavior, a very important ecological characteristic in MTEs (Brooks et al. 2004). Protection against this vulnerability is done by fighting the threats of invasive species on Santa Cruz Island.

In an effort to protect this vulnerable island, The Nature Conservancy (TNC) has conducted a massive invasive plant eradication effort on Santa Cruz Island over the last fifteen years. Originally focusing on 15 species, the organization's initial success has led them to increase their number of target species to 32. Four years following the initiation of their eradication effort in 2008, 73% of the treated populations were deemed inactive (Cory & Knapp, 2014). Using aerial survey techniques, TNC has completed island-wide censuses to detect infestations and treat these species annually.

Our Role

TNC has excelled in removing invasive plant species from SCI, however, an in-depth analysis of their weed distribution and treatment data has yet to be conducted. Drawing from the survey and treatment data collected by TNC, along with our own research compiled from relevant literature, we will undertake an assessment of the efficacy of TNC's invasive plant eradication program. This report will present our findings across the following chapters.

Chapter 2 discusses the greater importance of invasive plant management over time, leveraging literature to make a case for the relevance and priority of invasive plant management amidst competing interests in land management from scientists and the public. Chapter 3 conducts a statistical analysis using presence/absence data, providing key insights on plants that have increased or been reduced throughout the initiative. Chapter 4 centers around a temporal analysis of herbicide application on invasive flora by developing time series maps of the spatial distribution of 21 invasive plant species. Chapter 5 evaluates the invasive potential of plants on SCI through the development of "fright maps" that visually demonstrate how invasive plant species may have proliferated on SCI had TNC not taken action or ceased treatment today. These maps serve as a valuable tool for TNC to secure funding for their initiative by showcasing the potential disturbance these plants could pose to the natural ecosystem of Santa Cruz Island.

Our ultimate goal is for the outcomes of this project to be shared with TNC's land managers, to aid in the advancement of invasive plant eradication strategies and protect Santa Cruz's native biodiversity. Moreover, our research can inform future decisions by TNC on conservation strategies applicable not only to the Channel Islands, but their hundreds of other preserves and future projects.

Understanding Invasive Plant Management

Santa Cruz Island is subject to challenges in maintaining biodiversity, largely due to the fact that the land mass is geographically isolated. Such conditions can easily lead to the extinction of native plant species because invasive species can have a disproportionate impact on island ecosystems. Therefore, it is critical for TNC to understand how invasive plants arrive on the island, how they propagate, and how and when to eradicate them. The following reads as excerpts describing some of the largest predicaments regarding invasive species in an island habitat as pulled from current literature.

Island Biogeography and Invasion

The three pillars that outline island biogeography are immigration, extinction, and evolution. These variables can take effect independently of one another, or through species interactions on the islands. Other factors of insular biogeography include: degree of isolation, time in isolation, area of the island, species richness (endemic vs. invasive), species composition (trophic levels), and human interaction (Humphries et. al, 2017). For millions of years seeds and spores have traveled via the wind, currents, and birds, but the largest introduction of invasive species can be attributed to humans.

Another concern on islands is the competition among species who share a niche. Each species must have a unique shelter, food source, hunting style or camouflage that only that species occupies, but when these traits are shared, one species can outcompete the other while the other faces extinction (Guo, 2015). Isolation plays a key role in speciation and extinction, because isolated habitats can create local extinctions and entire island takeovers if a new species can exploit an unclaimed niche (Humphries et. al, 2017). On islands, due to the delicate nature of their biogeography, extinctions for reasons like competition with other endemic species, lack of resources, or fighting hypercompetitive invasive biota are likely to cause more harm than on larger land masses. On Santa Cruz Island, TNC is trying to eradicate 55 invasive species. Invasive species are the greatest threat to the Channel Islands endemic biodiversity (Knapp et. al, 2009).

Forecasting Plant Extinctions

Plant extinctions are critically understudied in current literature with a larger focus on animal extinctions, underrepresentation of the IUCN Red List, and the multitude of studies that only examine taxa deemed useful for humans (Lughadha et. al, 2020), but recently there has been an uptick in studies assessing plant species following the Convention of Biological Diversity (CBD) which called for the Global Strategy for Plant Convention (GSPC) in 2011 (CBD, 2012). A few methods that have been utilized in the prediction of plant extinctions are as follows.

There were two methods Lughadha et al. (2019) evaluated which performed consistently well across their three criteria: accuracy, sensitivity, and specificity (Fig. 2). The first method was the “Random Forests” statistical analysis approach which predicts extinction for data-deficient species using climatic variables and threats based upon their range (Bland et al., 2014). The second method was “rCAT”, a package for the open source statistical software R developed as a conservation assessment tool to determine a species’ status according to the IUCN Red List (Moat, 2017). Both methods performed at about 90% accuracy in correctly predicting threat status, about 85% sensitivity to correctly predicting if a species is threatened, and about 91% specificity in correctly predicting species that are not threatened (Lughadha et al., 2019).

Lag Phase

Determining whether a newly introduced plant species will die out, become naturalized, or become invasive can be challenging due to the unpredictability surrounding Lag Phase, the time between an invasive species' introduction and the massive population growth that follows. Some species will follow a general logarithmic growth curve, while others remain stable for generations, before exploding in growth (Mack, 2000).

There are several categories of lag phases and potential causes. Types of lag phases include an influx of new immigrants, increase in population growth rates, and range expansion (Crooks, 2005). Potential causes for lag phases are often linked to changes in the environment or in the ecosystem. This can include shifting weather patterns, increased human activity, genetic changes in the invasive or native species, or removal of predators (Carlton, 1996). These changes in the environment give the invader access to more resources, which in turn increases their overall population size. Growth in invasive population size due to lag phases can increase the negative impact invasive species have on their new habitat. Invasive species undergoing lag phases can make it difficult to determine whether an immigrant species will become an issue in the future. Lag phases can hinder efforts to create an island invasive plant management plan; unexpected population growth is difficult to account for with limited resources.

The Invasion Curve

The invasion curve is an 'S' curve used to guide management strategies of invasive species, based upon time since and extent of establishment.

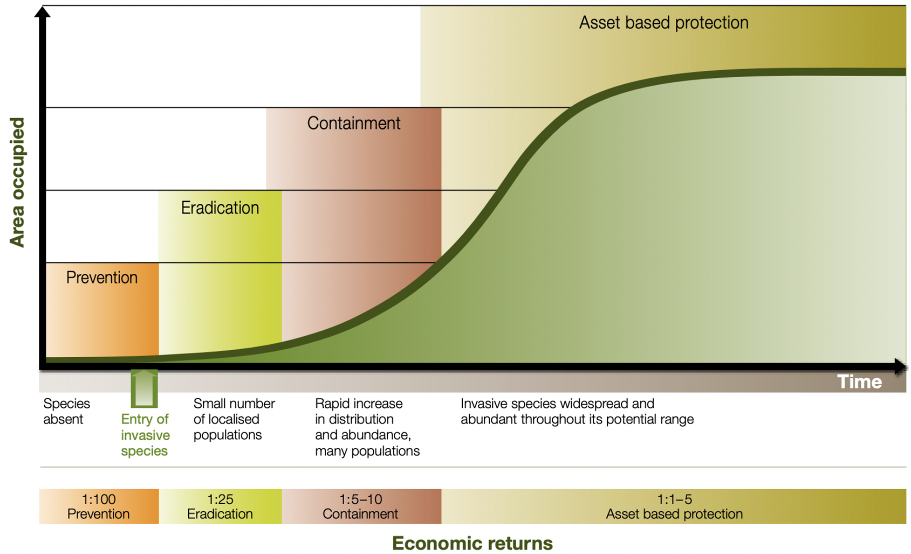

Figure 1.3. An example of an invasion curve (Invasive Plants and Animals Policy Framework, by The State of Victoria & Department of Primary Industries, 2010).

According to the invasion curve, once a species has established, the most appropriate tactic shifts from prevention to eradication - the entire removal of the species from the designated area (The State of Victoria & Department of Primary Industries, 2010; USFWS & Cal-IPC, 2018). Eradication involves short-term funding for the long-term benefit of bypassing the more substantial environmental and monetary issues that arise as an invasive species becomes more widespread. As species becomes more widespread, the most cost-effective solutions become decreasingly feasible, leaving land managers with no choice but to pursue more costly methods over the long term, such as “containment” and “asset based protection” (The State of Victoria & Department of Primary Industries, 2010, p.14).

TNC employs a range of these methods on Santa Cruz Island, chosen based upon surveying and assessment of each invasive plant species’ attributes (Knapp et al., 2009). For example, *Foeniculum vulgare*, fennel, is noted to be very widespread, and is therefore outside of TNC’s current capabilities to eradicate so it is managed under the “containment” and “asset based protection” category (Knapp et al., 2009; The State of Victoria & Department of Primary Industries, 2010, p.14). Recently, TNC’s focus has shifted towards creating an invasive plant management plan incorporating eradication and containment, before select invasive species become too widespread and abundant (Knapp et al., 2009).

Ranking of Plant Management

Rates, age, and timing of reproduction are of particular interest so that any seeds that have germinated after the eradication effort can be monitored and removed prior to reproducing (Cory & Knapp, 2014). On Santa Cruz Island, TNC seeks to prioritize the control of invasive plant species that are currently in low abundance (Knapp et al., 2009).

Prioritization and implementation of strategies such as the invasion curve often depend upon the ability of a land manager, at any level, to assess the threat of an invasive plant species (The State of Victoria & Department of Primary Industries; McGeoch et al., 2016). If a land manager does not have sufficient data or resources, it is unlikely that the management of invasive plant species will be prioritized (McGeoch et al., 2016). As invasive species have been flagged as the greatest risk to Santa Cruz Island, TNC seeks to, as much as their capabilities allow, implement strategies to mitigate the damage caused by invasive species and protect the unique ecosystem (Donlan et al., 2003; Knapp et al., 2009).

Seed Banks

Seed banks are a plant survival strategy entailing the storage of seeds in the soil for use in the future. Often, total elimination of the invasive entails destruction of the seed bank, which is difficult since many are long-lived and hard to find. One must be careful not to disturb seed banks with heavy equipment and agricultural practices as this can “trigger” the bank and accelerate invasive spread (Vosse et al., 2008). One must understand dormancy periods of the particular invasive seeds and also ensure continued monitoring after plant removal to prevent a re-invasion. Additionally, it is important to monitor native seed banks because an invasion can significantly reduce their seed diversity (Maclean et al., 2017).

Effects of Infestation Size on Eradication Efforts

Eradication success depends on the infestation size. If an invader population grows to an extensive size, eradication may be nigh impossible and the best that can be accomplished will be managing the population (Simberloff, 2003). At smaller infestation sizes, targeted eradication methods can lead to complete extinction of invasive species. For example, Asian wild rice once covered an area of roughly 0.1 hectare (ha) in the Florida Everglades, and is believed to be eradicated (Simberloff, 2001). At such scales, mechanical methods such as uprooting weeds by hand, or targeted chemical treatment can be effective options.

Enacting eradication programs are easier when undertaken at early stages of detection. Quick removal lowers the possibility for a lag phase to surface. Leaving invasive species to their own devices increases the chance that environmental, genetic, or biological factors keeping the population in check are altered or removed, leading to explosive population growth (Simberloff, 2001). In the case where a population boom occurs, large-scale eradication efforts will be more costly – both in terms of money and environmental impact.

Criteria for Invasive Plant Eradication

When evidence shows that a species has not been detected for some time, there are two management solutions: end surveillance with a risk that the target species is still present and could reestablish itself, or continue surveillance with the risk that the target species is in fact eradicated making the continued use of resources unnecessary (Rout et al. 2009). There are limitations in our ability to see whether or not a target species is still present in the environment as well as some level of uncertainty in our ability to assess the chances the target species may reemerge. In addition, there are limitations for the amount of resources and time that can be directed towards the eradication of invasive species. At the same time, the larger the uncertainty surrounding the probability of persistence and detection lead to a greater shift in the optimal solution time and therefore uncertainties in these areas have a multiplicative effect rather than an additive one (Regan et al., 2006). In order to navigate these issues, researchers explore different methodologies to help make informed decisions on when to end active control and begin surveillance.

Sighting data could also be useful for eradicating invasive plant species when the species is newly invading the target area or if there is not enough information to calculate probabilities of persistence and detection, or if the population size is relatively small and has not invaded the target area before (Rout et al., 2009).

Long Term Management

In the most ideal and cost-effective eradication plan, the prevention strategy is employed (The State of Victoria & Department of Primary Industries, 2010). Prevention involves blocking the arrival and establishment of the invasive species (The State of Victoria & Department of Primary Industries, 2010). In order to lead a successful prevention plan, there has to be considerable knowledge on how a species is most likely to arrive in an area (U.S. Fish and Wildlife Service [USFWS] & California Invasive Plant Council [Cal-IPC], 2018). Due to the numerous potential vectors of invasive species, prevention requires significant coordination of all potential stakeholders, and in this way often necessitates great assessment and legislation efforts (Lockwood et al., 2013;The State of Victoria & Department of Primary Industries). This method is no longer practical once the species has settled into the new environment, so managers must turn to eradication.

A global analysis completed by Glen et al. (2013) investigates over 1200 eradications of invasive flora and fauna across 800 islands. It was seen that successful plant eradications occurred more frequently on inhabited islands by humans than their uninhabited counterparts. It is likely that invasive plant eradications are more successful on inhabited islands due to the necessity of long-term monitoring of the targeted populations to prevent resurgence; continued management and engagement from humans is essential in preventing residual germinations from the seed bank or a different invasive species from naturalizing over a native one (Glen et al., 2013).

Importance of Spatiality in Invasive Plant Management

Traditionally, there has been limited consideration of propagule dispersal scale in invasive plant management (Fletcher & Westcott, 2013). This means that although management seeks to maximize the quantity of weeds removed, it often omits the necessary element of spatiality (Fletcher & Westcott, 2013). Nonetheless, knowledge of the distance or 'scale' of dispersal is a critical component to invasive plant management (Fletcher & Westcott, 2013). Fletcher & Westcott suggest that effective management is contingent upon not only the extent of management resources used but also how spatial elements of integral dispersal processes are integrated into the management (2013). They propose that there is a minimum level of spatial scale consideration in successful management (Fletcher & Westcott, 2013). This extent or 'level' may be calculated on a species-by-species basis using dispersal data and adjusting life history and population parameters accordingly (Fletcher & Westcott, 2013).

Evaluating the Relevance of Invasive Plant Management in Literature Over Time

Introduction

The goal of this research is to evaluate and highlight the greater importance of invasive plant management in related and general literature over time. We wanted to make a case for the relevancy and priority of invasive plant management compared to competing interests of land management from scientists and the public.

Methods: Invasive Plant Research Across Scales

To understand the scope of invasive plant management in scientific literature over the past 60 years, we examined 3 different geographic scales of symposiums. Symposiums represent the year's more prominent research and share the abstract of each article that is published for that year. Looking to find the importance of invasive plant management at multiple scales, we found symposiums on the California Islands, the Mediterranean ecosystems and UN Biodiversity Conference. Since 1960, the California Islands Symposia, provided a historic overview of important topics in island management. The emergence of MEDECOS Symposium in the 1980's shows an increase in efforts in preservation, conservation and restoration. The UN Biodiversity Conference has made influential global goals starting in 1993. We analyzed how invasive plant management fits into the scientific conversation.

We found online versions of the California Islands Symposia proceedings and searched key terms "exotic", "invasive" and "non-native" in each of the conference papers to find literature that was relevant. We looked at the recurrence of our key terms and what other terms became prevalent research through the years on all three levels. We categorized some terms found to be directly competing for funding and interest, and other terms showing scale of yearly research and intertwined topics of focus. These key search terms allow us to better describe the context and scale of research of "invasive plant management" for the past 60 years.

Methods: Trends in Published Literature on Google Scholar

Breadth of our Search

We chose to start our search from the year 1960. We decided upon this year as Charles Elton first published "The Ecology of Invasions by Animals and Plants" in 1958, marking a start in interest towards invasion biology within the scientific community. The first California Island Symposium was held soon after in 1967. In this way, the year 1960 seemed to be a logical starting point for our search. We ended our search at 2022, the last complete year, to have findings that are relevant and timely. Google Scholar was selected as a non-discriminant web search engine. Unlike alternative options such as databases JSTOR and Web of Science, Google Scholar includes some grey literature that may not be published in journals. We wanted these results to be represented in our numbers to present a more realistic value for the 'popularity' of a search term. Furthermore, Google Scholar simplified our search process as it is non-discriminant to uppercase and lowercase letters.

Search Terms

Most key search terms were selected after an initial search through literature, with particular emphasis upon the California Islands Symposia proceedings so that our research focused upon terms that represented topics that are most directly relevant to the interests of Santa Cruz Island stakeholders.The goal was to have a good spread of terms that could highlight not only the relative relevance of "invasive plant management" and its associated terms and areas of work, but areas that may be of competing interest to investors and decision-makers. Furthermore, we wanted to ensure that we included the synonyms of terms that may have developed and changed over time. For example, after an initial reading, we found that the term "exotic plant" preceded the later term, "invasive plant". The exact selected search terms/google scholar inputs include, in no particular order:

1. ("Invasive plants" | "Invasive plant" | "Invasive plant species" | "Exotic plants" | "Exotic plant" | "Non-native plant" | "Non-native plants" | "Nonnative plant" | "Nonnative plants")
2. ("Invasive plant management" | "Exotic plant management" | "Non-native plant management" | "Nonnative plant management")
3. "Fire management"
4. "Ecosystem restoration"
5. "Ecosystem resilience"
6. ("Exotic animal" | "Exotic animals")
7. ("Endemic" | "Endemics")
8. "Carbon sequestration"

Throughout this paper including the graphs, we reference shortened versions of these exact search inputs, which are as follows:

1. Invasive plants
2. Invasive plant management
3. Fire management

4. Ecosystem restoration
5. Ecosystem resilience
6. Exotic animals
7. Endemics
8. Carbon sequestration

The “fire management”, “exotic animal”, and “carbon sequestration” terms were searched as areas of competing interest, whilst the terms “ecosystem restoration”, “ecosystem resilience” and “endemic” were searched as areas of associated work. We carried out both the “invasive plant” and “invasive plant management” searches in order to see the relevance of both the topic of invasive plants, and the management of them specifically.

The only term searched that was not found in the California Islands Symposia proceedings is “carbon sequestration”, the capture and store of carbon dioxide in an effort to reduce the magnitude of climate change. This term was selected to represent a topic that is currently trending in not only the land management realm, but across fields of work, including to those outside of environmental scence research. In this way we thought it would be interesting to compare against our “invasive plant management” term.

Synonyms for key search terms “invasive plant management” and “invasive plants” were selected after the initial search through literature to ensure that results were fair across time, to encompass differences and changes in language. For example, after reading the first California Islands Symposium proceedings, it became clear that the term “exotic plant” was used in place of the more recent term “invasive plant”. Plurals of each search term were also included for consistency.

Data Presentation and Interpretation

In order to make our findings visually comprehensive, we made graphs to compare trends over time. We used Google scholar to see how many times each term was found in literature each year from 1960 to 2022. Using our numerical yearly data from Google Scholar for each key search term, we calculated how best to compare the terms to each other. For the following categories: all key terms, competing terms, similar terms and “ Invasive Plant Management” alone- we made a graph of the total number of search results per term each year. Totals per year allow us to see what the most and least researched terms are. We also made a graph calibrated to show the growth rates of search results per competing term per year. Growth rate per year allows us to see what terms have exponentially grown per year versus some terms who have had steady growth no matter the total per year. For each term we graphed the totals to show rates by using an equation that calibrated the totals per year on a scale of 0 to 1 to make terms comparable.

Equation of Rate Calibration:

For X year = (X year value - lowest overall value) / range of all values

Table 3.1. Values and equations used to calibrate each search term.

	Invasive plants	Invasive plant manage-ment	Fire manage-ment	Ecosystem restoration	Ecosystem resilience	Exotic animals	Endemics	Carbon sequestration
Lowest value (0)	38	0	1	0	0	12	86	0
Highest value (1)	14300	372	5210	6210	3,520	3360	4430	30400
Range	14262	372	5209	6210	3520	3,348	4360	30400
Equation DP=Data Point	(DP-38)/14262	(DP-0)/372	(DP-1)/5209	(DP-0)/6210	(DP-0)/3520	(DP-12)/3348	(DP-86)/4360	(DP-0)/30400

Note. The values refer to the lowest number of search results from any year, 1960 to 2022, (inclusive of a value of 0) and the greatest number of search results from any year. Equation for calibration = (value - lowest value) / range.

Results: Invasive Plant Research Across Scales

California Islands Symposia

The California Islands Symposia proceedings document the key papers and findings presented at each symposium, and are representative of the vast array of research involving the islands. Upon only a brief glance at the proceedings, it becomes clear that there are a diverse range of interests involving the islands, from paleontology, to archeology, to island biodiversity, to geology, to management of the islands, all across a variety of time periods and timescales. Since the initial symposium of 1967, the interests have continued to expand and diversify. One of the topics that has since entered the conversation is invasive plant management as land managers and researchers began to recognize and acknowledge the major threats invasive plants pose to the islands' unique biodiversity.

The first symposium, held in 1967, largely focused upon the theory now known as 'island biogeography', which was first termed the same year by Robert McArthur and Edward Wilson in their book *The Theory of Island Biogeography*. Resultantly, much of the rhetoric of this symposium's proceedings explores island native plants and endemism. Although there are no papers focusing on invasive plants at this time, there are already a couple of subtle references to the threat that the non-natives may and do pose. For example, in "The Floristics of the California Islands" paper, Raven states,

"[t]he distinctive floras of Guadalupe and San Clemente islands have, not surprisingly been most susceptible to the activities of European man, his weeds, and grazing animals, and thus provide models for the destruction of island biota which is occurring all too rapidly over the entire surface of the globe" (1967).

Additionally, in "Introduction to Insular Zoology", Garth mentions "the contemporaneous presence of man" and how "his responsibility for introduction of new forms and destruction of old, needs evaluating if we are to arrive at a proper understanding of the complex relationships existing in the insular milieu" (1967).

In this way, although invasive plants and their management are yet to gain a spotlight in Channel Islands research, the threat of invasion to the islands and the subsequent importance of their study is already readily apparent to scientists such as Raven and Garth.

In the second symposium proceedings, there are two brief mentions of exotic plant species, with one article that states how the grasslands of Santa Cruz and Santa Catalina Islands are largely composed of "exotic European annuals" and the summary that explains how "purposely-introduced exotic species…have had a severe impact on the landscape of the islands" (Minnich, 1980; Power, 1980). The third symposium proceedings likewise only feature a couple of references to invasive plants. Notably, these references are in relation to invasive plant's impacts and responses to fire, as well the vulnerability of the islands to "deliberate or accidental introductions on non-indigenous species" (Carroll et al., 1993; Wolfbrandt, 1993; Schuyler, 1993).

It was not until the fourth symposium of 1994 that a focus and real conversation around invasive plant species came into fruition. These proceedings feature an article specifically exploring the invasion of fennel: "Modeling the expansion and control of fennel (*Foeniculum vulgare*) on the Channel Islands" (Brenton & Klinger, 1994). In this article, Brenton & Klinger address the threat that not only fennel, but all invasive plant species pose to ecosystems, and they recognize the importance to "control[] or eliminat[e] non-native plants" (1994). In other words, Brenton & Klinger recognize the need for invasive plant management on the islands (1994). Thus, this article represents a pivotal moment for invasive plant management, and for the management of the Channel Islands. Building off of the case of fennel, Brenton & Klinger outline the components necessary to successful invasive plant management, and in this way, form the skeleton of a management plan for those of the forthcoming years to build off of (1994). Several other articles throughout the proceedings delve into invasive plants, with topics including their extensive growth post-disturbances such as grazing and fire, negative impacts on native skunks and foxes, the invasion of non-native grasslands, and the relationship between non-natives and honey bees (Crooks & Van Vuren, 1994; Junak & Philbrick, 1994a; Junak & Philbrick, 1994b; Klinger et al., 1994; Thorp et al., 1994). Previous California islands symposia proceedings established and highlighted the unique and irreplaceable qualities of the Channel Islands. The fourth symposium brought attention to a new threat, and thus invasive plant management was pushed to the forefront of land manager's minds.

The subsequent symposia continued to develop the invasive plant conservation alongside other priorities of land management, such as exotic animals, restoration and fire management. In the preface of the sixth symposium, exotic species are acknowledged as "one of the greatest if the anthropogenic influences' ' (Garcelon, 2005). Likewise in the preface of the seventh symposium, invasive plants, alongside grazers and nonnative animals, are stated as a primary reason for native flora and fauna extinctions (Damiani & Garcelon, 2009). The eight symposium features a paper specifically dedicated to island biosecurity, on how to create protocols to protect the island prevent invasion, as well as the Nature Conservancy's detailed plan to eradicate invasive plant species on Santa Cruz Island (Boser et al., 2014a; Cory & Knapp, 2014).

MEDECOS Symposia

The MEDECOS symposium is held in Mediterranean ecosystems every few years dating back to 1971. The MEDECOS conferences bring together scientists, researchers, practitioners, and policymakers from various fields to exchange knowledge, share research findings, and discuss the challenges and solutions related to Mediterranean ecosystems. The sharing of knowledge throughout the different regions of mediterranean ecosystems has proved to be beneficial in preserving the biome. Research on invasive species has been a significant topic of discussion and inclusion in MEDECOS conferences. Many MEDECOS conferences have featured sessions, presentations, and discussions specifically dedicated to invasive species and their management.

In the IV MEDECOS symposium in 1986, there were eleven articles cited and none directly dealt with invasive plant species. However, all discuss ecosystem resilience. Three chapters explore the plant interactions including invasive species. "Long term exposure of mediterranean systems to disturbance brought by drought and natural fire has not prepared them for human disturbance (agriculture, road-building, quarrying, etc)." (Dell and Lamont, 1986). The paper continues to describe ecosystem changes and loss of species due to human disturbances. It only briefly mentions that migration brings new seeds but thoroughly analyzes the resilience of ecosystems against human, climatic and biodiversity changes.

In 2017, in the XIV MEDECOS invasive plant species got their own section out of 22 sections that heavily dealt with ecology of mediterranean type ecosystems. There were 17 articles written in this section. It ranged from mitigation to eradication research. Some focused on specific species like fabaceae trees in South America while others targeted larger efforts like microwave soil heating in (Arroyo & Vila, 2017). The research topics showed breadth through very specific issues and solutions people are researching around the globe. This shows that in the past 40 years, invasive plant management has become not only more well known, but something people will spend their lives dedicated to researching.

United Nations Conference on Biodiversity

The United Nations Conference on Biodiversity (UNCBD) is held in metropolitan areas around the world every few years dating back to 1994. There have been a total of 15 symposia in the past 30 years. The goal of these symposia is to bring global goals and incite communication and teamwork to create worldwide change that benefit humans and ecosystems alike. The conference outlines a framework of goals and their implementation of current global expectations in dealing with intersectional issues like climate change, poverty, gender inequality and biodiversity. These decisions are written and adopted by the Conference of the Parties (a UN climate change decision making body) to be understood and implemented by States worldwide. The conference makes decisions not only on protecting and restoring biodiversity but also how to communicate and share ideas with multiple nations and protect cultures. Their decisions seem to address all the complexities of how humanity and biodiversity are intertwined, mutually beneficial or not. These decisions address the formidable ecological and social economic impact of invasive species.

Though mentioned in multiple sub categories in decisions on conservation and biodiversity related topics within the first four symposia, “Invasive Alien Species” gets its own full decision section in the fifth symposia in 2000. The decisions in 2000 about invasive species are about introducing and organizing the issue. The decision guidelines how to organize urgency in different regions and plants. It calls for backgrounds on different regions and monitoring methods and a well constructed cost benefit analysis. Decisions are based around researching the history of ecosystems and the introduction of invasive species within and between states (United Nations, 2000).

Over the years, the severity of invasive species become clear through more urgent decisions combatting larger consequences. In 2000, the first year invasive species had its own category or decisions, there were 15 guided principles outlining goals for states of invasive plants. Not only were there many additional categories added each year that addressed interdisciplinary issues of ecology and society but they became more in depth with nore breadth. By 2010, the invasive species decision section doubled in length and had subcategories of the creation of task forces to further establish and enforce prevention and mitigation techniques throughout States (United Nations, 2010).

There were 31 different topics discussed at the 15th UNCBD, in 2022, 10 had to do directly with ecology and biodiversity. Others were housekeeping items like finance, future meetings and science communication. Out of the 10, one entire section was dedicated to “invasive alien species” that has been rewritten since the 10th conference. There were mentions of “invasive alien species” in “Biodiversity in Health”, “Biodiversity and Agriculture” and “Biodiversity and Climate Change”. The decisions focused on invasive species were complex and interdisciplinary but most importantly they were stringent. Recognizing the detrimental impacts of these species on ecosystems, biodiversity, and human well-being, the decisions emphasized the urgency for coordinated global action. The decisions called for the development and implementation of comprehensive strategies to prevent the introduction and spread of invasive alien species that could lead to accelerated climate change or natural disasters. They highlighted the importance of risk assessments, early detection systems, and rapid response mechanisms to mitigate the threats posed by these species. The decisions highlighted the significance of international cooperation, capacity-building, and knowledge sharing to effectively address the challenges associated with invasive alien species.

Results: Trends in Published Literature on Google Scholar

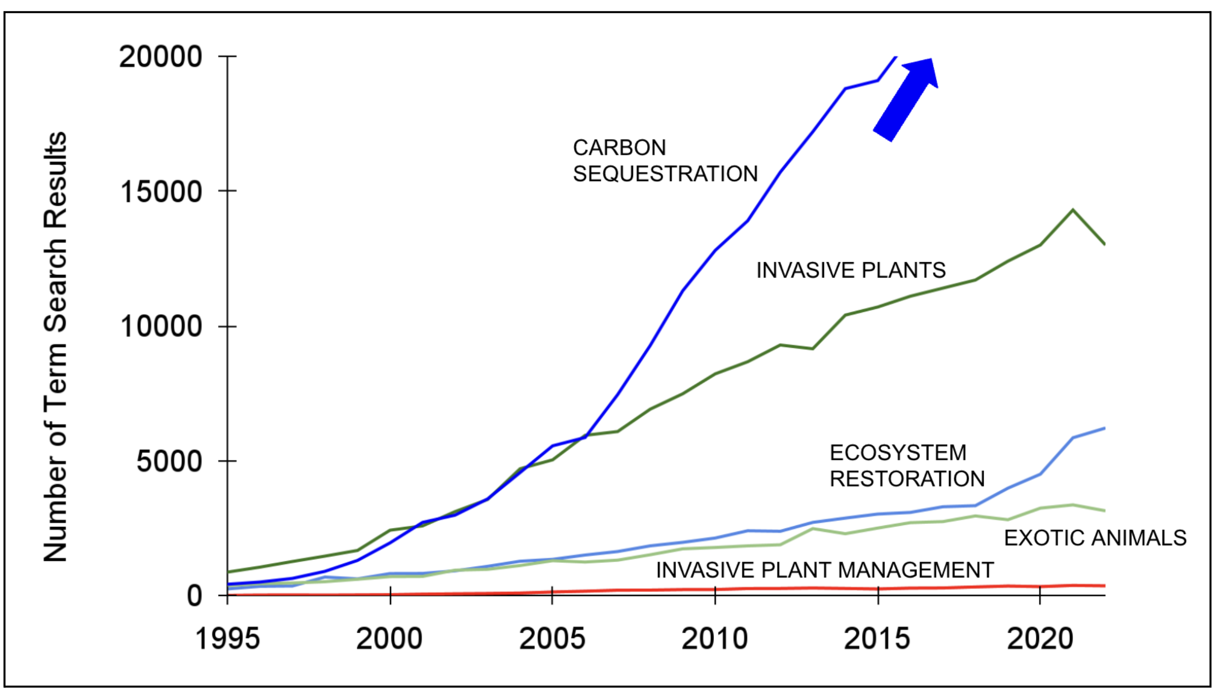

Figure 3.1. Overview graph of the number of search results for select terms over time. *Note:* This graph takes a closer look at the terms, zooming in on 1995 and onwards as this was when search terms began to rocket.

Over the past 27 years, all terms have increased in search results. However, some terms have increased in the number of search results much greater than others, and in this way have been discussed to varying degrees. The total number of times these terms has been researched can be found as search results each year in Google Scholar. Invasive plant management had few search results in comparison to the other terms, only reaching a total of 357 times in 2022. Interestingly, Exotic Animals and Ecosystem Restoration increase over time rather similarly and reach only about 4,000 search results by 2022. Much higher than all 3 topics is the term invasive plants. This term tarted to rapidly increase in 1995 with similar rates of increase as carbon sequestration until 2005. After, it kept a steady slope to 13,000 search term results in 2022. Carbon sequestration research has increased rapidly and has been the largest topic researched since 2006. It continues out of frame to reach a total of 29,800 times in 2022.

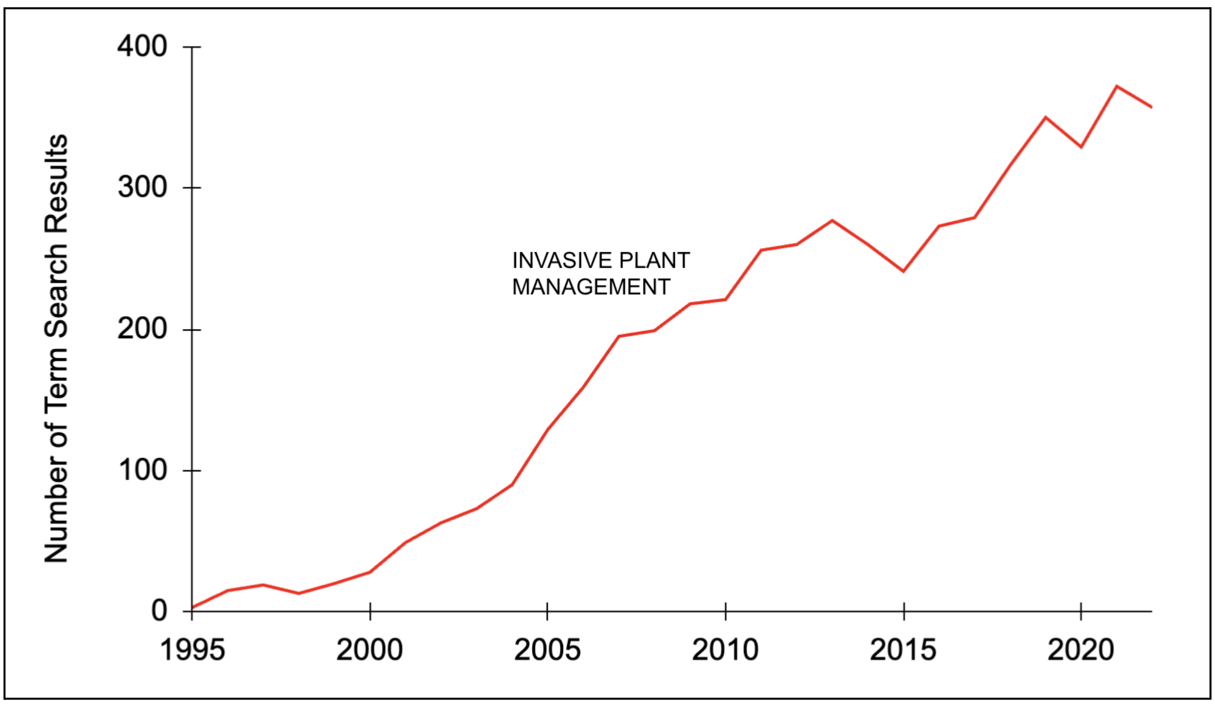

Figure 3.2. Graph of the number of search results for invasive plant management terms over time.

Though largely no search results 1960 through to 1995, invasive plant management increases in search results starting 1995. Its slope increased in 2000. This slope continued until 2013 and followed a dip in 2015. In 2022, it reached a high of 357 search results and a high of 372 in 2021.

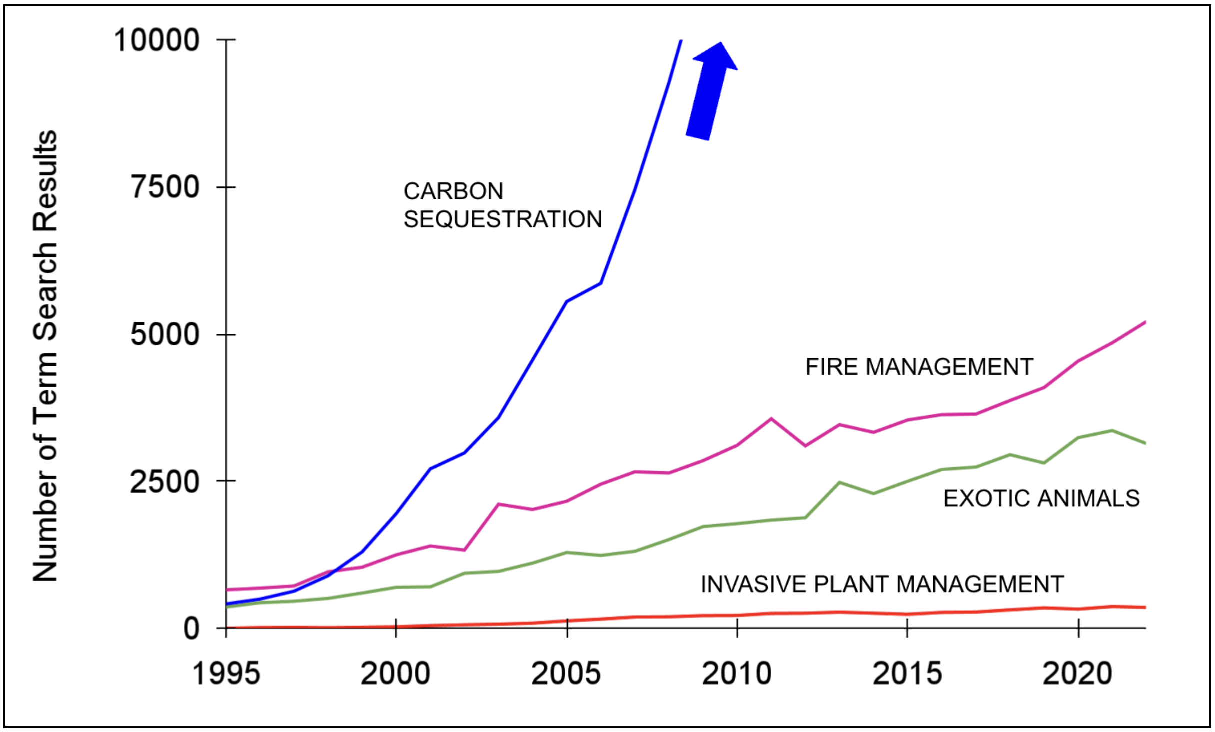

Figure 3.3. Graph of the number of search results for competing terms over time.

In Figure 3.3, there is parallel growth between invasive plant management, exotic animals, and fire management. Exotic animals and fire management have similar trajectories, passing 2,500, while invasive species never break 500 search results. Carbon sequestration has increased exponentially, with more than six times the search results of the second lead, fire management, in 2022.

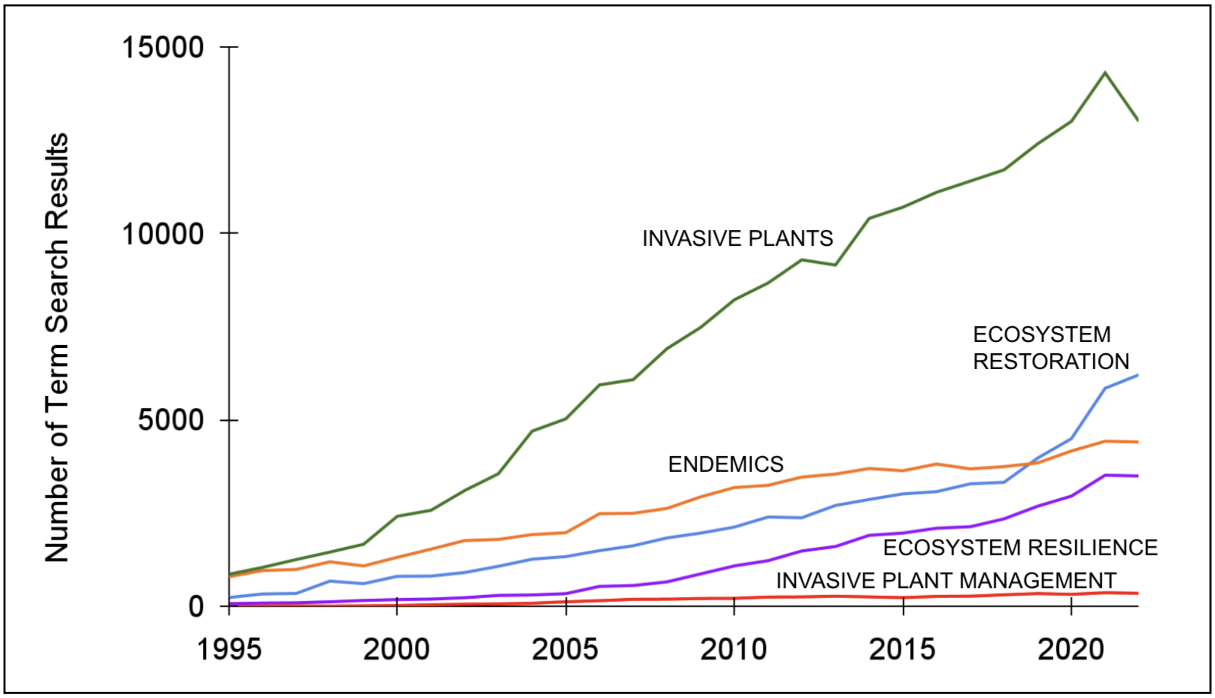

Figure 3.4. Graph of the number of search results for related terms over time.

Since 1995 there has been an increase in interest in invasive plants. This can be seen in an increase of all the following words: ecosystem, endemics, ecosystem resilience, invasive plants and invasive plant management. The most popular term is invasive plants which is about twice as researched as the rest of the terms. All topics have increased over the past 25 years however the term invasive plants has increased in popularity by almost three times as much as ecosystem restoration, the next leading term. There is more of an emphasis on invasive plants in the literature of 2022 than back in 1995. The more articles discussing invasive plants, the more they are inherently adding to the research of invasive plant management.

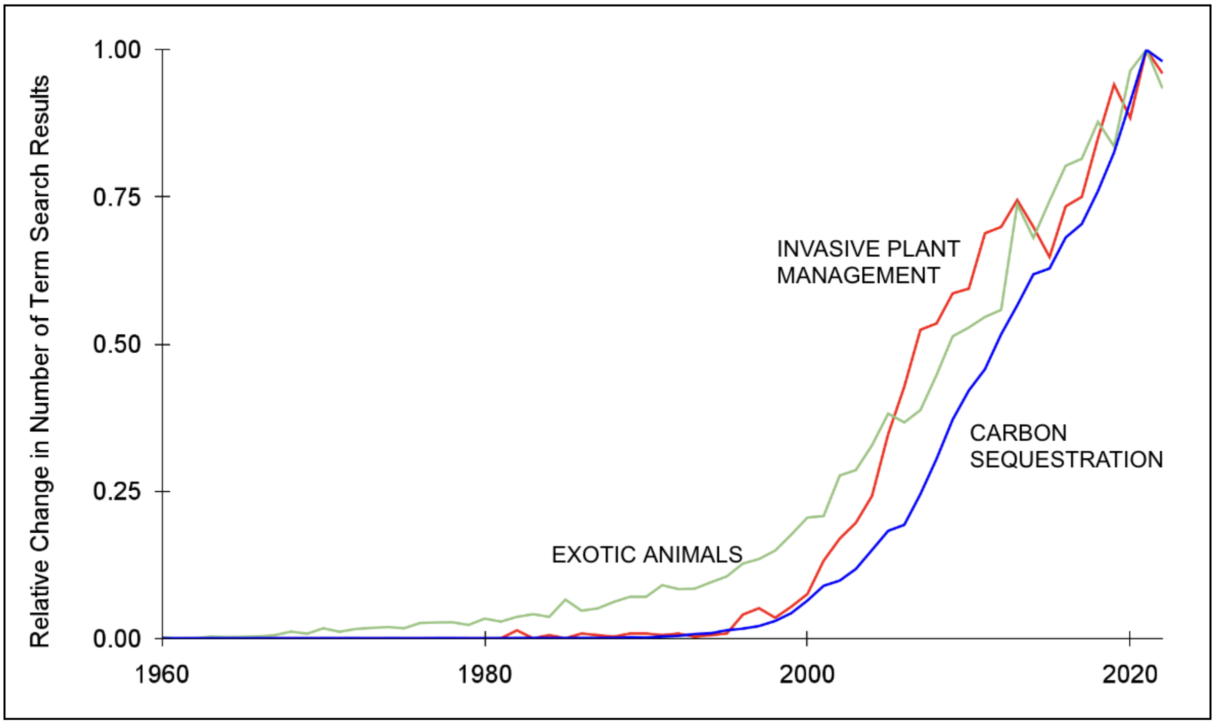

Figure 3.5. Graph of the relative change in the number of search results for select terms over time. *Note.* 0 and 1 values for each term are different, depending on the minimum value and the maximum value for the number of search results over the 62 years.

This graph shows a calibration of each term to show growth rates through time. Exotic animals started with the largest growth rate, becoming apparent in 1980 to 2000. Exotic animals have historically been researched for a longer amount of time than invasive plant management and carbon sequestration. However, in 2000, invasive plant management and carbon sequestration started to increase in frequency at similar rates from seemingly no research being done prior. In 2005, invasive plant management passed exotic animals and then dropped in 2016 and increased again. Since 2000, invasive plant management and exotic animals have increased at higher rates than carbon sequestration.

Discussion

It is clear from the various symposia that invasive plant management is important and relevant across scales: locally (Channel Islands), regionally (Mediterranean Ecosystems), and globally. In recent years, the topic of invasive plant management has come to the forefront of discussion in these circles, not only because of scientific interest, but because of the significant threat that invasive plants pose to ecosystems at all levels.

However, this importance and relevance of invasive plant management is not readily reflected in our key term search. As discussed in our results section, invasive plant management appears to be irrelevant when compared against other key terms of the environmental field. In figure 3, showing competing terms, it seems that they increase in term search results in accordance to the potential impacts on humans, with the smallest amount of research on invasive plant management. Another temporal impact on the data is COVID-19. Most research and journal releases paused from 2020-early 2022 which caused for most maximum term search results to be reached in 2020 and then start declining after.

Although all the terms' number of search results has grown over time not all terms have grown at the same rate. The more discussions there are about restoration and endemics, the more people must focus on the management of invasive plants and their role in maintaining healthy ecosystems. Therefore, an increase in search results in any of these terms shows an increase in efforts in invasive plant management even though the term stays below 500 results for the past 25 years. This disparity in search term results is particularly stark when in comparison to carbon sequestration, which received far more results than any other term searched in recent years.

This great gap in the number of search results is representative of the shift that has occurred in the intellectual environment since the early 2000s. There was a large increase in all search results, seemingly in correlation to social trends of digitalization of journals, and more rapid online communication which could increase research speed and totals. This also correlates with an increase in public concern for the environment and climate change. After Al Gore's infamous "An Inconvenient Truth" spotlighted the great threat of climate change to the planet in 2006, a significant focus has been placed upon climate change and all of its related topics in and outside of academia (Guggenheim, 2006). As a consequence, other research topics, such as the topics of our other search terms, now have a relatively smaller reach.

Carbon sequestration is a form of climate change management that has evidently garnered broad public and stakeholder attention. At the same time, subjects such as invasive plant management require significant funding for management to come into fruition, but acquiring this funding has become increasingly difficult with a focus upon climate change. Even though invasive plants are ranked as one of the greatest threats to the channel islands, it has become increasingly challenging to justify the funding of invasive plant management projects when climate change is on the horizon. It is without a doubt that climate change is a great threat to ecosystems and that solutions should be the concern of all stakeholders, but it does not mean that other topics, such as those concerning ecosystem function, should not be of importance.

Links between term topics

The goal of the latter half of this research was to contrast and compare the number of search results of related and competing terms of invasive plant management, but, with a closer look, all topics searched are ultimately related to one another.

Invasive plant management & carbon sequestration

In California, the invasion non-native, annual plant species into native, perennial grasslands has resulted in a loss of carbon storage. Annual, invasive grasses have shallow roots and lower rates of net primary production, meaning that their roots do not shed as much as natives and don't bring down as much carbon into the soil (Koteen et al., 2011). Reversely, through invasive plant management and ecosystem restoration, the carbon sink or 'sequestration' ability of native grasslands can be enhanced again. In this way, invasive plant management can used as a carbon sequestration tool, and could therefore be considered under carbon sequestration.

Invasive plant management & fire management

Invasive plant species, like annual grasses, disturb natural fire regimes (Lambert et al., 2010). At the same time, the disturbed fire regimes make landscapes more vulnerable to invasive plants (Lambert et al., 2010; Brooks et al., 2004). This is because invasive plants change the fuel structure of the fire, for example through adding dry fuel during the wildfire season. In turn, invasives alter fire regime aspects such as the intensity, frequency, and extent (Ustin et al., 2009; Brooks et al., 2004). These disturbed fire regimes then perpetuate the further spread of invasive plant species (Ustin et al., 2009). This cycling may be known as the "invasive plant-fire regime cycle" (Brooks et al., 2004). This link is evident throughout the California Islands Symposia proceedings, too. For example, in "A Study on the Natural History of *Cytisus* on Santa Catalina Island with an Emphasis on Biological Control", Mastro states in reference to invasives Dyers' broom (*Cytisus linifolius*) and French broom (*C. monspessulanus*) that the "re-establishment of these invasive weeds is rapid following fire and disturbance" (Mastro, 1993). In this way, the relationship between invasive plants and fire is well established on the islands. This intrinsic link means that land managers should and do factor invasive plant management into fire management, and vice versa (Brooks et al., 2004). This can for example be seen in Figure 6, where the invasive plant and fire management method with the highest "probability of successful prevention" and with the lowest "cost of successful prevention" is invasive plant species exclusion. In this way, this invasive plant management method is simultaneously a fire management method.

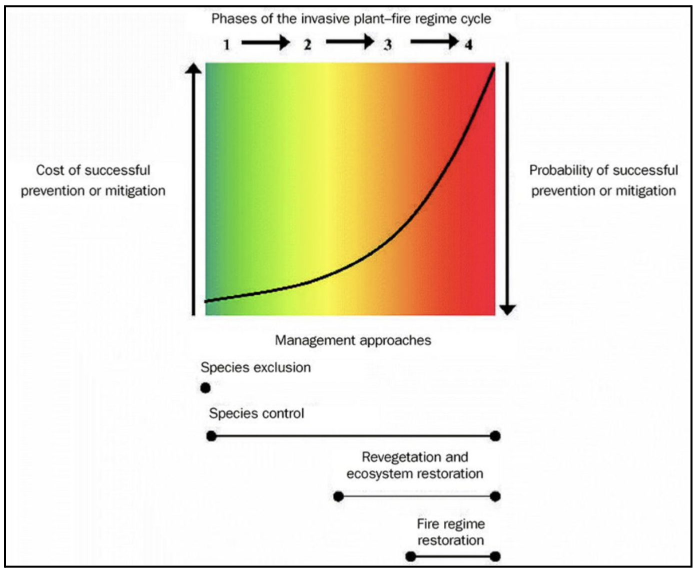

Figure 3.6. Cost-benefit of "Invasive plant-fire regime cycle" management. *Note.* This figure highlights the interplay of invasive plant and fire management. From "Effects of Invasive Alien Plants on Fire Regimes" by M. L. Brooks et al., 2004, *BioScience*, *54*(7), p.677-688 (https://doi.org/10.1641/0006-3568(2004)054[0677:EOIAPO]2.0.CO;2).

Final Conclusions & Limitations

Our research highlights that invasive plant management is relevant and related at a range of geographic scales and to a variety of modern-day topics. Invasive plant management, albeit niche, ties into the greater problems we care about and has larger implications in efforts such as fighting climate change, conserving insular biodiversity, and controlling natural disasters.

Although our research presents the current relevance of invasive plant management research, it does have its limitations. For one, to determine the trends in published literature, we used google scholar. Although google scholar does provide a vast array of articles, including gray literature, it is ultimately limited by what is uploaded online and validated by google. In this way, the number of search results that appear in google scholar is only a proxy for the level of conversation surrounding a topic. We referred to the number of search results as a numeric for the ‘relevance’ of a topic, but search results is just one potential measure. Future research could explore alternative modes to calculate relevance.

Additionally, the number of search results for each term are not exact and are limited to google scholar’s estimate of search results. In this way, the accuracy of the number of search results is limited to google scholar’s accuracy. Nonetheless, as we seeked to provide an overview of trends, this accuracy is sufficient.

Another limitation of our research is that we decided our search terms on the basis of what we deemed to be significant from initial readings of the symposia, and therefore there is inherent bias in the topics that we chose to discuss. To minimize some of this bias, future research could apply our methods to more terms to gain a more holistic understanding of the relevance of invasive plant management in literature.

Further research could include the examination of the implementation of research, to compare how certain topics are being funded and have actual programs in land management. The priority of invasive plant management in maintaining ecosystem health can be researched in a wider lens, looking at more topics and search engines to get a better scope of its relevance.

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Ecological Trends in the Effectiveness of Invasive Plant Control

CHAPTER 3

Introduction

The invasive plant attribute summaries consolidate relevant invasive plant species information on 27 of the 32 invasive plants managed by TNC. Information has been collected on the time the plant takes to germinate and mature, seed mass and seed bank longevity, methods of dispersal and dispersal range, bloom period, response to fire, and geographical origin. Information collected for this report provides insight on what plants may be most difficult to eradicate and what their common attributes are.

Methods

Geodatabase Management

The data received from TNC was stored in geodatabases, requiring data preparation within a GIS software in order to facilitate statistical analysis in R. Each plant was categorized into new shapefiles by year, with plants labeled “Dead” or “No Target Detected” filtered out from the dataset. To gain clear insight on the effects of consistent plant treatment over time, observations from Channel Islands National Park were excluded from the analysis, as TNC and National Park Service (NPS) had inconsistent collaboration throughout the course of the initiative.

In 2019, TNC changed their data recording methodology and adopted a grid system with 25 by 25 meter plots; these grid data layers did not cover the entire island and instead encompassed regions where the plant had been previously found. Each plot contained information about plant detection, phenology, and herbicide usage for treated plants. Given the different methodology used in field observations, further geoprocessing for the years following 2019 was necessary to make the data comparable across the entire initiative.

Before 2019, infestations were recorded as points that represented populations of a specific plant, with details about the extent of the infestation linked to the spatial data. Therefore, data recorded in the new grid system required a workflow to consolidate 25-meter plots into a single population when appropriate. We transformed each polygon into a point, utilized density-based clustering to to provide calculated recommendations on points that could be grouped as a single infestation, and cross referenced these values with literature on the species’ life history in order to establish a reasonable standardized distance for plants to be considered part of the same population (Appendix A.1).

Once the distances were determined, the geospatial observations were buffered accordingly, overlapping buffers were dissolved, and the resulting polygons were converted into single records based on their centroids. This process was applied to each plant across all years of observation, generating output points that could then be used to determine their intersection with the standard base grid to create presence/absence tables.

The base grid for the presence/absence tables is a polygon layer that encompasses the entire island and consists of 50 by 50 meter polygons. Each plot within the base grid had a unique "PageNumber" identifier, which was retained during the intersection tabulation in order to facilitate the joining of the output table with the base grid. Once all years of plant intersection data were joined with the base grid, new fields were calculated to indicate the presence or absence of plants within each plot for a given year. These new, binary fields constituted the table that was used for statistical analysis in R.

Statistical Analysis

A binomial logistic regression was run on the presence/absence data collected from the 2500 m^2 grid for each of the years in which data was available, in R studio. The year was used as a predictor variable for whether or not a presence or absence (1 or 0) was recorded in each grid. Each logistic regression with a p-value < 0.2 was determined to be statistically significant. Positive value coefficients determined that the plant was trending towards having more presence values than absence values. Negative value coefficients determined that the plant trended towards having more absence values than presence values.

Results

Three plants trended towards having more presence values than absence values: *Tamarix ramosissima*, *Cortaderia selloana*, and *Pinus pinea* ($p = 0.18$, $p = 0.0109$, $p = 0.025$). Six plants trended towards having more absence values than presence values: *Eriogonum giganteum var. Giganteum*, *Rubus discolor*, *Acacia melanoxylon*, *Ficus carica*, *Olea europaea*, and *Paraserianthes lophantha* ($p = 0.000281$, $p = 0.000272$, $p = 0.00043$, $p = 0.0109$, $p = 0.121$, $p = 0.108$). The other plants did not trend, statistically.

Significant Plant Summaries

***Tamarix ramosissima*, 'Tamarisk spp.'**

Family: Tamaricaceae

The tamarix genus is a shrub/tree native to dry areas of Africa and the Middle East (USDA, n.d.). The genus includes 54 species (The Editors of Encyclopaedia Britannica, 1999). It tends to populate sites inhospitable to native plants, causing debate about its negative impacts as an invasive (United States Geological Survey, 2021). They propagate heavily by seeds that are dispersed by wind and water (National Park Service, 2015). Seeds weigh 0.1462 mg (SER, n.d.).

Vegetative reproduction occurs as well: even the smallest of broken plant pieces can take root and mature (National Park Service, 2015). It is not dispersed by animals (Pasiecznik, 2022). The species take about one year to mature, and hydroscopic hairs allow germination within 24 hours; seeds do not survive the winter (Pasiecznik, 2022). Tamarix spp. sprout from April to August (Gaskin, 2012). Dense strands reduce biodiversity and increase fire fuel load. The plant is very hard to burn when dry, and often resprouts from the root crown if it is damaged; however, severe fires may destroy the crown completely (USDA, n.d.).

***Cortaderia selloana* ‘Pampas grass’**
Family: Poaceae

Pampas grass is native to Brazil, Argentina, and Uruguay (DiTomaso, n.d.). The plant matures in approximately 2 to 3 years. The seeds are dispersed by wind and can be spread for several kilometers (CDFW, n.d.). Additionally, in 1945 the Soil Conservation Service planted the grass on Santa Cruz Island to provide “supplementary dryland forage and prevent erosion” (DiTomaso, n.d.). The grass blooms around August to September (DiTomaso, n.d.) and is highly tolerable to drought, frost, and sunlight. (CDFW, n.d.).

***Pinus pinea* ‘Italian stone pine’**
Family: Pinaceae

Italian Stone Pine was originally found along the North Mediterranean coast beginning at Lebanon and extending to Portugal (Bracewell, 2005). Italian stone pine flowers in the spring (USDA, 1994), and its seeds are dispersed primarily by gravity where the seeds will fall nearby the original plant (Bracewell, 2005). The seeds are very heavy, and average around 717.92 mg (SER n.d.). The thick bark of the Italian stone pine plant helps to protect it against surface fires, however the plant remains vulnerable to crown fires (Madrigal et al., 2019).

***Eriogonum giganteum var. Giganteum*, ‘St. Catherine’s Lace’**
Family: Polygonaceae

St. Catherine’s lace is a wild buckwheat endemic to the Channel Islands. Its 0.52 mg seeds take 7-30 days to germinate and the plant grows rapidly (SER, n.d.; PlantFlowerSeeds, n.d.). It emerges from May to December (Las Piltas Nursery, n.d.). It propagates by seed. Fire fuels and ignition rates are naturally low for this species. Additionally, it threatens the genetic purity of *E. arborescens* through hybridization (Reveal, n.d.).

***Rubus discolor*, ‘Himalayan blackberry’**
Family: Rosaceae

Himalayan blackberry originates from Western Europe and Northern Africa (Klein, 2011). It blooms in the summer, and produces 5.26 mg seeds (Washington State University, n.d.; SER, n.d.). Seeds are dispersed over long distances via animals and water, and shorter distances via gravity (Klein, 2011; Warner, 2004). Seed bank longevity is over 3 years (Warner, 2004). The seeds are slow to germinate, and the plant takes over 2 years to reach maturity (Klein, 2011; Warner, 2004). Himalayan blackberry is a prolific invasive species, displacing both native plants and wildlife, resulting in great economic costs (Fryer, 2021). Fire can kill the top of the plant, but most seeds in the soil survive, allowing for regeneration and aggressive invasion of post-fire sites (Tirmenstein, 1989).

***Acacia melanoxylon*, 'Blackwood acacia'**
Family: Fabaceae

Acacia melanoxylon is a fast-growing tree from Southeastern Australia that can grow to heights of up to 15 meters. Blackwood seeds average around 13.58 mg and are primarily adapted for dispersal by birds, in addition to air and water (Society for Ecological Restoration (SER), n.d. & O'Dowd and Gill, 1968). Blackwood has a long-lived seedbank, with seeds remaining dormant for over 50 years (Holmes, 1989). Seeds readily resprout after fires, and Arán et al., 2017 found that fire can stimulate germination up to 90%.

***Ficus carica*, 'Fig tree'**
Family: Moraceae

Fig tree originates from the Mediterranean and Western Asia, and blooms in the spring (Moore & Nazeri, 2022; NC State Extension, n.d.). The fruit weighs roughly 36g, with each fruit containing around 1530 very small seeds (Victoria State Government, n.d.). Seeds are dispersed largely by animals, in particular birds, but can also spread vegetatively (Victoria State Government, n.d.; Randall, 2004). Fig tree has a large dispersal range, often greater than 5 km (Victoria State Government, n.d.). Seedbank longevity is unknown (Randall, 2004). Fig trees can reach maturity in 1 to 3 years (Victoria State Government, n.d.). Fig tree establishment can benefit from flooding disturbance, and they can re-grow after fire (Randall, 2004; DiTomaso et al., 2013).

***Olea europaea* 'Olive tree'**
Family: Oleaceae

Olive trees were originally found in the Mediterranean and eventually spread to other parts of the world including Australia, South America, and Hawaii (Brusati, 2004). The seeds can take about 4 to 5 weeks to germinate (Voyiatzis, 2015). The total mass for 1000 seeds has been determined to be approximately 250 g (Tree Seed Online LTD, n.d.). They can remain dormant for up to 20 months. The fruit can appear on this tree in cycles of 2 to 3 years (Brusati, 2004). Olive trees are primarily dispersed by humans as the plant is widely sold as an ornamental or crop plant, and can also be dispersed through avian dispersal as well (Brusati, 2004). These trees can also regrow from burnt tree stumps so its reaction to fire proves to be favorable (Agriculture Victoria, 2020).

***Paraserianthes lophantha*, 'Plume acacia'**
Family: Fabaceae

Plume acacia is a perennial shrub/tree originating from Western Australia and Indonesia. (USDA et al., 2016). The shrub produces 94.28 mg seeds (SER, n.d.) that are covered in a dense shell coating, making germination difficult without external forces such as fire (Grant, 2021). At a genus level, the various species tend to take 36-48 months to fully mature and regularly produce large quantities of seeds (Windrock International, n.d.). The seeds are likely viable for up to 20 years (New Zealand Plant Conservation Network, n.d.). It flowers from May to July. (USDA et al., 2016). Plume acacia has a large dispersal range of over 100 meters, with seeds dispersing through birds, ants, wind, and water; occasional dispersal occurs through dumped garden waste as well (USDA et al., 2016; Weeds of Australia, n.d.). The shrub responds positively to fire (Gordon et al., 2017).

The plant summaries for plants found insignificant as well as the references for the plant summaries can be found in Appendix A.

Discussion

Of the 27 invasive plant species assessed as part of the plant attribute report, 9 plants showed statistically significant trends, with three trending towards having an increased presence on the island over the years and six plants trending towards increased absence. By examining the attributes of these plants, we have determined characteristics that may explain why certain plants have proven to be more or less difficult to eradicate.

Two of the three invasive plants with an increased presence on the island, *Tamarix ramosissima* and *Cortaderia selloana*, have small, light seeds and can disperse by wind (Pasiecznik, 2022, Cal-IPC). The other plant with increased presence, *Pinus pinea*, has large, heavy cones and cannot disperse by wind. However, *Pinus pinea* is extremely well adapted to the island climate and can spread with ease (*Stone Pine*, n.d.). In addition, we discovered that all three of these plants produce a large number of seeds, further increasing dispersal viability (Pasiecznik, 2022, Cal-IPC, *Stone Pine*, n.d.).

For the invasive plants with a decreased presence, *Rubus discolor*, *Acacia melanoxylon*, *Ficus carica*, *Olea europaea*, and *Paraserianthes lopantha*, we found that they all have large seeds or have seeds contained within heavy fruit, and will not disperse by wind (SER, Tree Seed Online, Victoria State Government). While additional research is required, it is likely that several, if not all, of the plants with decreased presence on the island were brought and cultivated by humans due to their desirable fruits and byproducts. We hypothesize that these plants were then easier to eradicate as they did not inhabit the island through natural means. Another potential reason for such poor dispersal of some of the plants on the island may be because several rely on animals for dispersal in their natural habitat, but the animal or its island analogue is not present on the island. More research will be required to draw any further conclusions.

We faced multiple limitations in this plant attribute and presence-absence study. To begin, the transition from a point system to a polygon system halfway through the data collection may lead to inaccuracies in data collection uniformity. Further, human error in data collection must be considered as well. There was also a halt in herbicide use during the COVID-19 pandemic, which may mean that plants that appear to be increasing may only appear that way as a result of regrowth after herbicide application ceased momentarily. Finally, there was limited data available on plant attributes for some of the plants studied meaning that the shared attributes listed in our discussion may not fully encompass those in the island habitat.

While we consolidated populations using our buffer workflow for all years in order to maintain consistency, a future analysis that only buffers the years following the data recording transition may indicate more plants to have a statistically significant reduction. Plant dispersal methods and longevity should be studied on the island habitat of the plants that resist eradication to determine if there are shared attributes beyond what was discussed here. Finally, herbicide use should be examined in relation to plant populations' presence absence data to determine its impact on plants eradication or resistance to eradication.

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Temporal Analysis of Herbicide Application on Invasive Flora

CHAPTER 4

Introduction

The Nature Conservancy has conducted island-wide surveys over a fifteen year time period, recording names, locations, phenology, and treatment types for each of the invasive plants. Because not all plants experienced a statistically significant change throughout the initiative, we created a series of maps for each plant across each year of recorded data in order to investigate the data visually. These maps enable TNC to look at the movement of plants from year to year, identify persistent populations, and highlight regions of interest moving forward. The temporal analysis encompassed 20 of the plants, considering that some plants either lacked a sufficient number of recorded years or were exclusively found within Channel Islands National Park.

Methods

Data Preparation

For the temporal analysis, we worked with shapefiles representing individual years for each plant. Recognizing the variations in data collection techniques and observation standards throughout the initiative, we introduced a new attribute field within the attribute table of each file. This field was intended to capture the amount of herbicide applied to a plant, measured in ounces.

The process of populating this field differed based on the specific year. In the case of 2011, there were multiple fields associated with a single plant that documented the herbicide quantity applied in ounces. To consolidate this information, we calculated the new attribute field as the sum of these existing fields. For the years 2014 to 2018, the herbicide amount was originally recorded in gallons. To ensure consistency, we converted these quantities to ounces before populating the new herbicide field. In the years 2019 to 2022, a field named “FinishedOu” already contained the desired herbicide quantities. Consequently, we leveraged this pre-existing field to populate the new attribute field accurately.

Cartography

The implementation of a grid-based presence/absence system in 2019 resulted in a notable increase in the number of plants recorded for the years 2019 and 2022 compared to the previous years, where entire populations were represented by a single point. To address this disparity in our statistical analysis, we employed buffers based on the plants’ dispersal range and defined the population at the centroid. However, extending this methodology to the entire time series would have meant sacrificing all associated attribute data. As an alternative approach, we employed graduated classification symbology for each point, utilizing the quantity of herbicide applied. By employing this symbology, viewers can infer that while more points may appear in these later years, the application of less herbicide signifies the continued success of the program.

The basemap for these time series was constructed using mosaicked Digital Elevation Models (DEM) sourced from the United States Geological Survey (USGS). This raster layer was then clipped based on a polygon feature layer digitized with reference to ESRI's Satellite Imagery basemap. The DEM was laid over a hillshade layer and symbolized with standard topographic colors in order to create a visually appealing basemap for the time series. Subsequently, the polygon representing the island outline was divided according to the NPS/TNC boundary, with the Channel Islands National Park region faded to visually indicate that no analyses were conducted in that particular area.

Results

Links to full-page PDFs and animations of all 20 plants for which the temporal analysis was conducted can be found in Appendix B.

Genista monspessulana, French broom, was recorded for eight years and remained confined to a single watershed through the entire initiative (Figure 4.1). The plant was not detected in 2022. *Carduus pycnocephalus*, Italian thistle, demonstrated an intriguing pattern of spatial distribution. It persisted throughout all recorded years, yet remarkably remained within the same tenth of a mile as observed during the initial two infestations (Figure 4.2). *Pelargonium x hortorum*, geranium, was present for five years of surveys but was not detected in the final two years of recorded data, 2019 and 2022 (Figure 4.3). *Yucca gigantea*, Spineless yucca, was only recorded for a total of four years. It was not detected in 2019, but was detected and treated again in 2022 (Figure 4.4). *Olea europaea*, Olive tree, also was not detected in 2019, after four years of treatment, and resurged in 2022 (Figure 4.5).

Across the 20 plants investigated for the temporal analysis, there was a wide range of the maximum amount of herbicide that was applied to each species (Table 4.1). Further, the year associated with the highest herbicide quantity varied within the sample. By considering the year of maximum herbicide application, we can use it as an indicator for determining when a plant reached its peak population, with a decrease in herbicide usage in subsequent years suggesting a decline in the species' infestation intensity. This table also highlights the plants that have recently encountered their greatest herbicide exposure, indicating these species demand additional attention in the following years. Specifically, *Olea europaea* and *Paraserianthes lophantha* had their highest herbicide quantities applied in 2022.

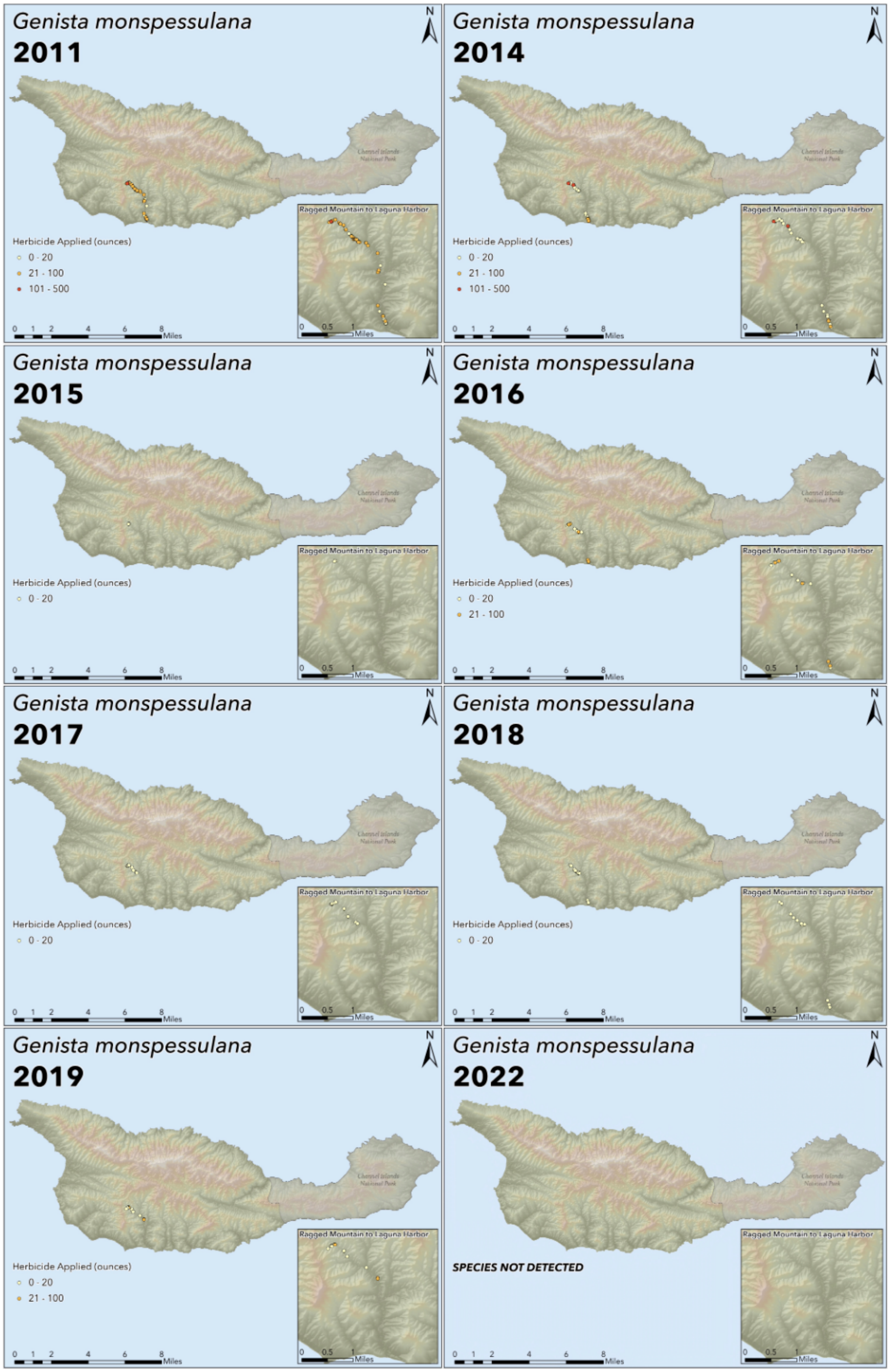


Figure 4.1. *Genista monspessulana* 2011, 2014-2019, 2022.

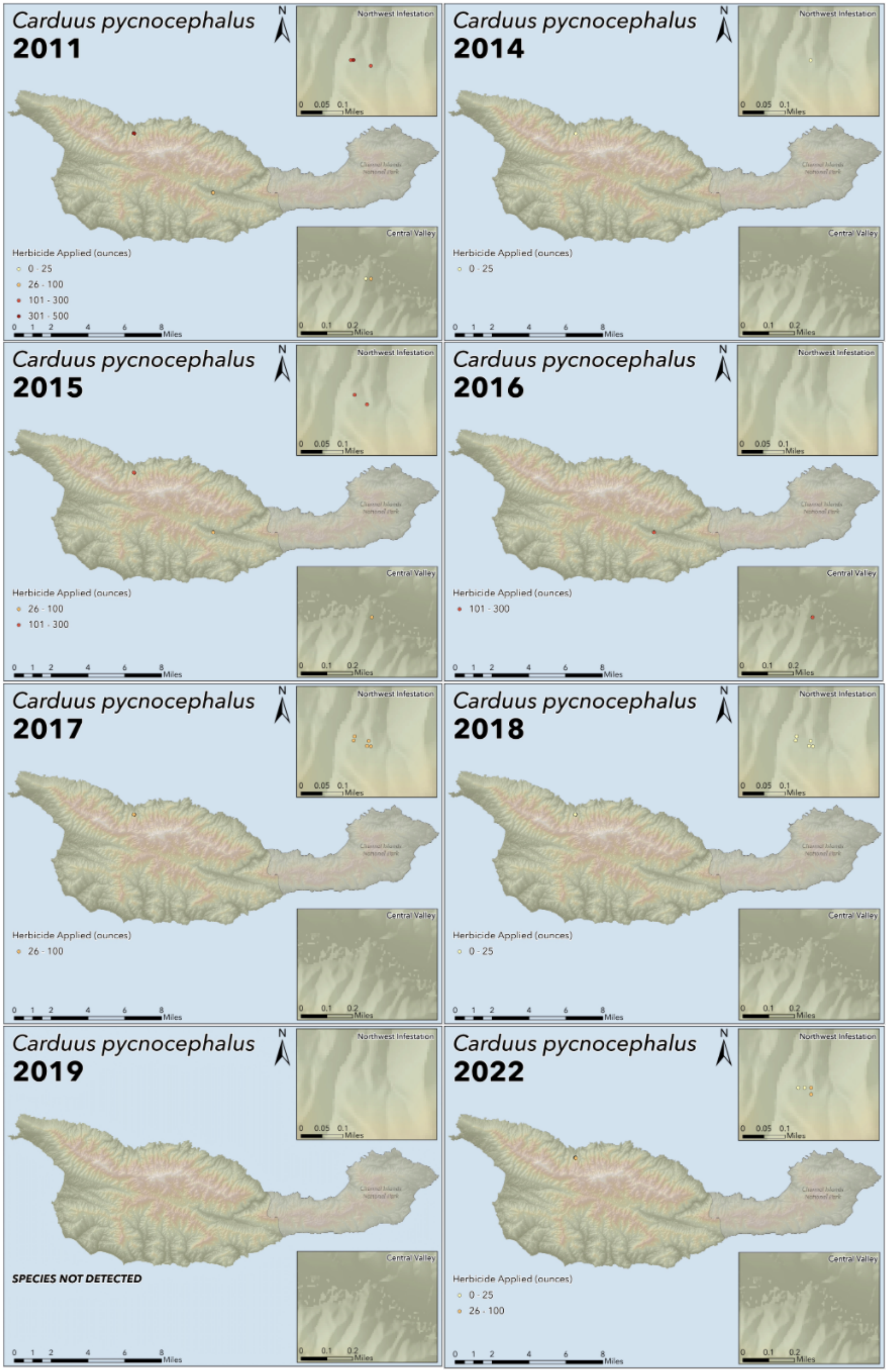


Figure 4.2. *Carduus pycnocephalus* 2011, 2014-2019, 2022.

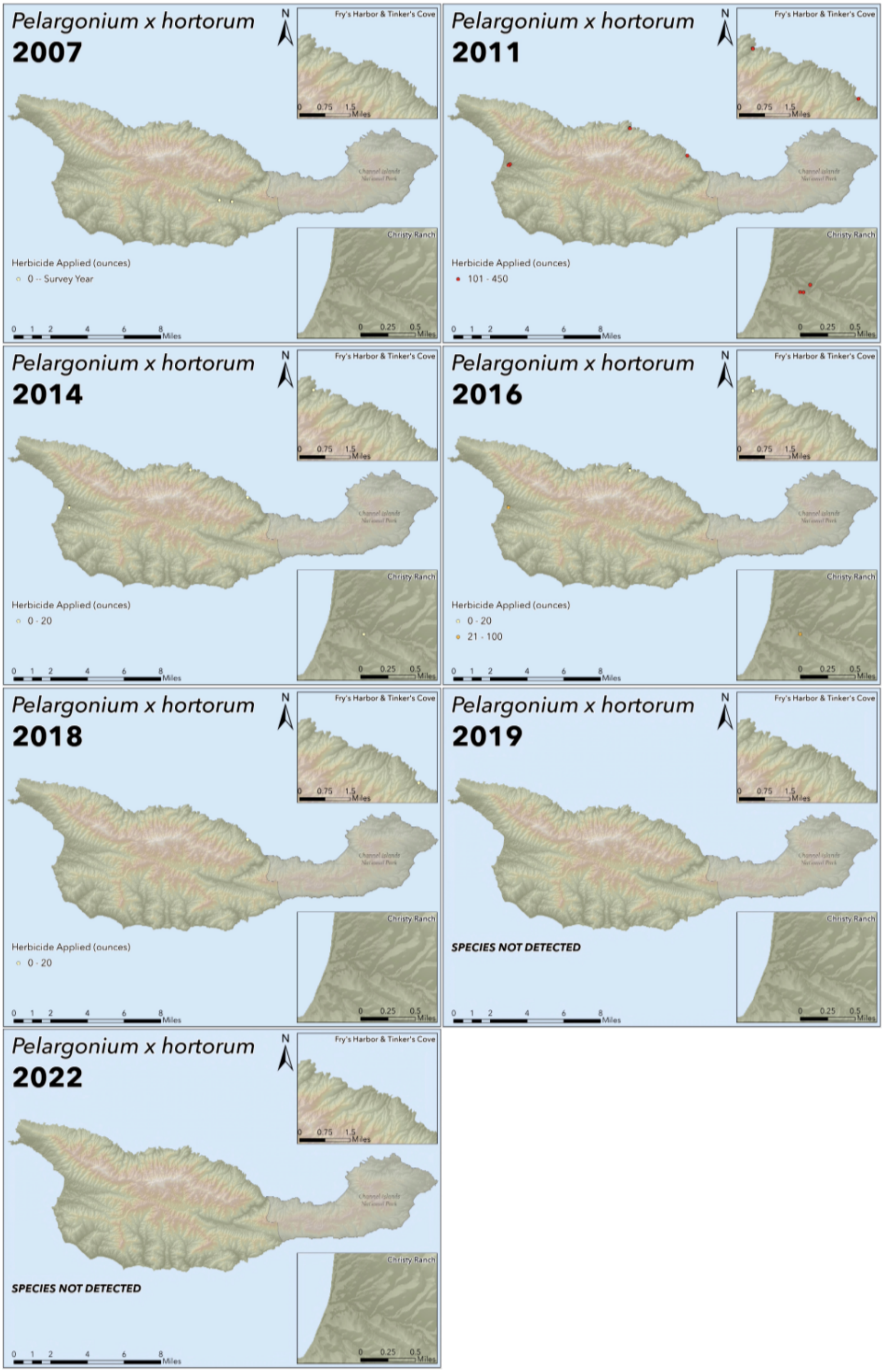


Figure 4.3. *Pelargonium x hortorum* 2007, 2011, 2014, 2016, 2018, 2019, 2022.

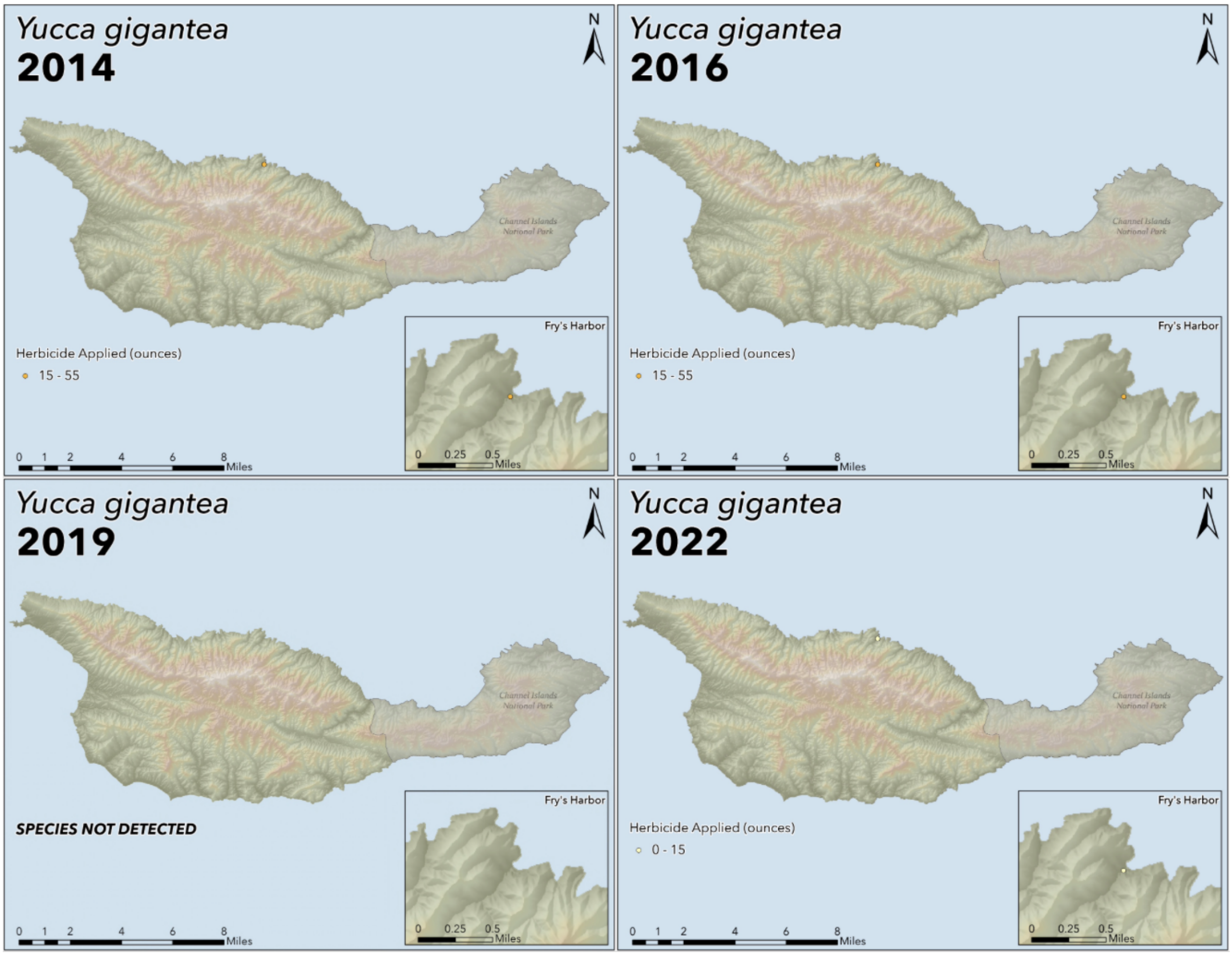


Figure 4.4. *Yucca gigantea* 2014, 2016, 2019, 2022.

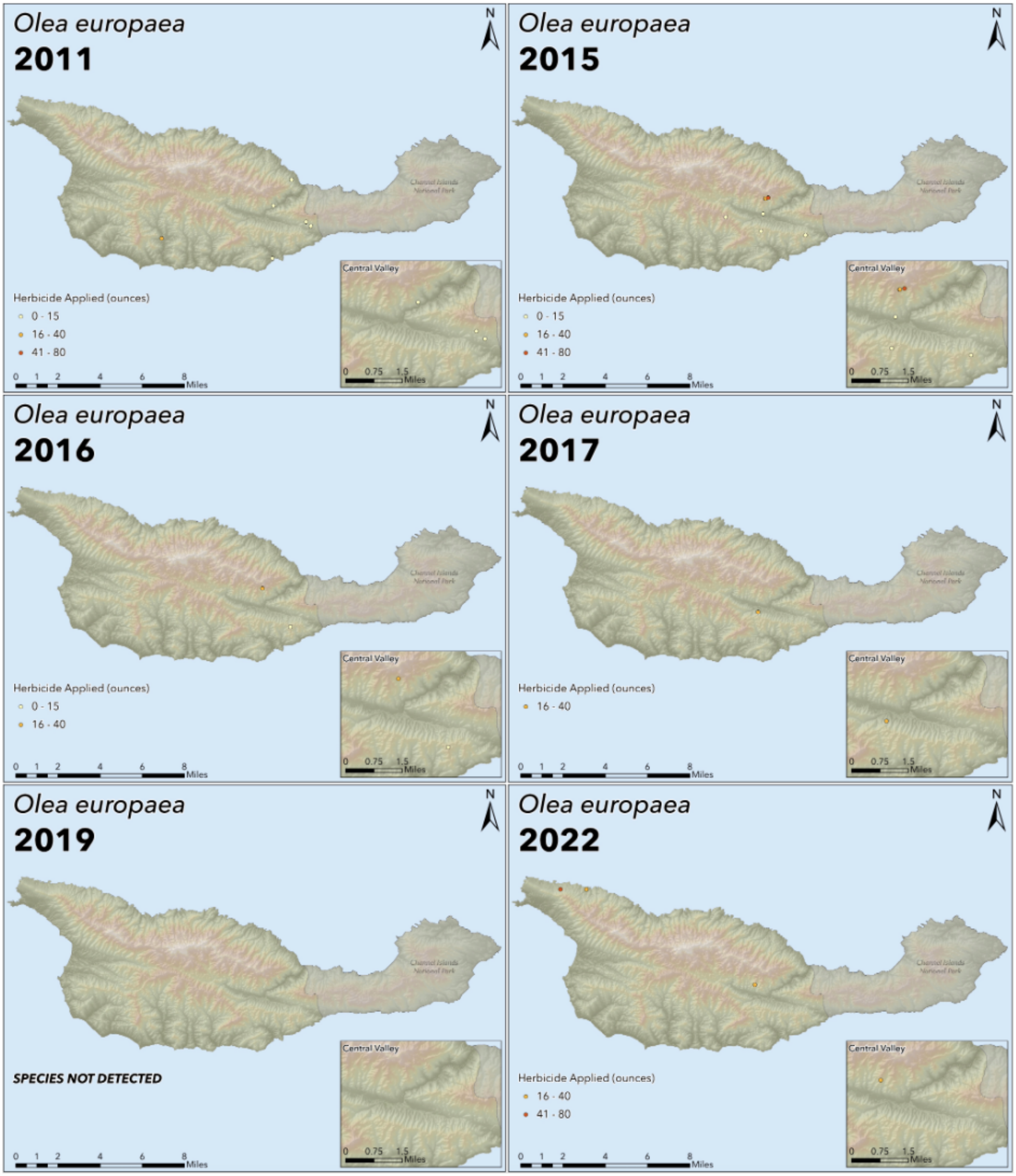


Figure 4.5. *Olea europaea* 2011, 2015-2017, 2019, 2022.

Table 4.1. Maximum Herbicide Applied

Species	Maximum Herbicide Applied (ounces)	Year of Maximum Herbicide Applied
Pelargonium x hortorum	432	2011
Ficus carica	432	2011
Pinus pinea	432	2011
Carduus pycnocephalus	354	2011
Genista monspessulana	302	2011
Eriogonum giganteum var giganteum	45	2011
Opuntia ficus-indica	30	2011
Phalaris aquatica	2560	2014
Hedera spp	448	2014
Tamarix ramosissima	192	2014
Oenothera xenoguara	1920	2015
Cortaderia selloana	1280	2015
Centranthus ruber	256	2015
Schinus molle	256	2015
Yucca gigantea	51.2	2016
Solanum elaeagnifolium	1702.4	2017
Rubus discolor	204.8	2017
Vinca major	640	2019
Acacia melanoxylon	192	2019
Paraserianthes lophantha	51.2	2022
Olea europaea	76.8	2015, 2022

Discussion

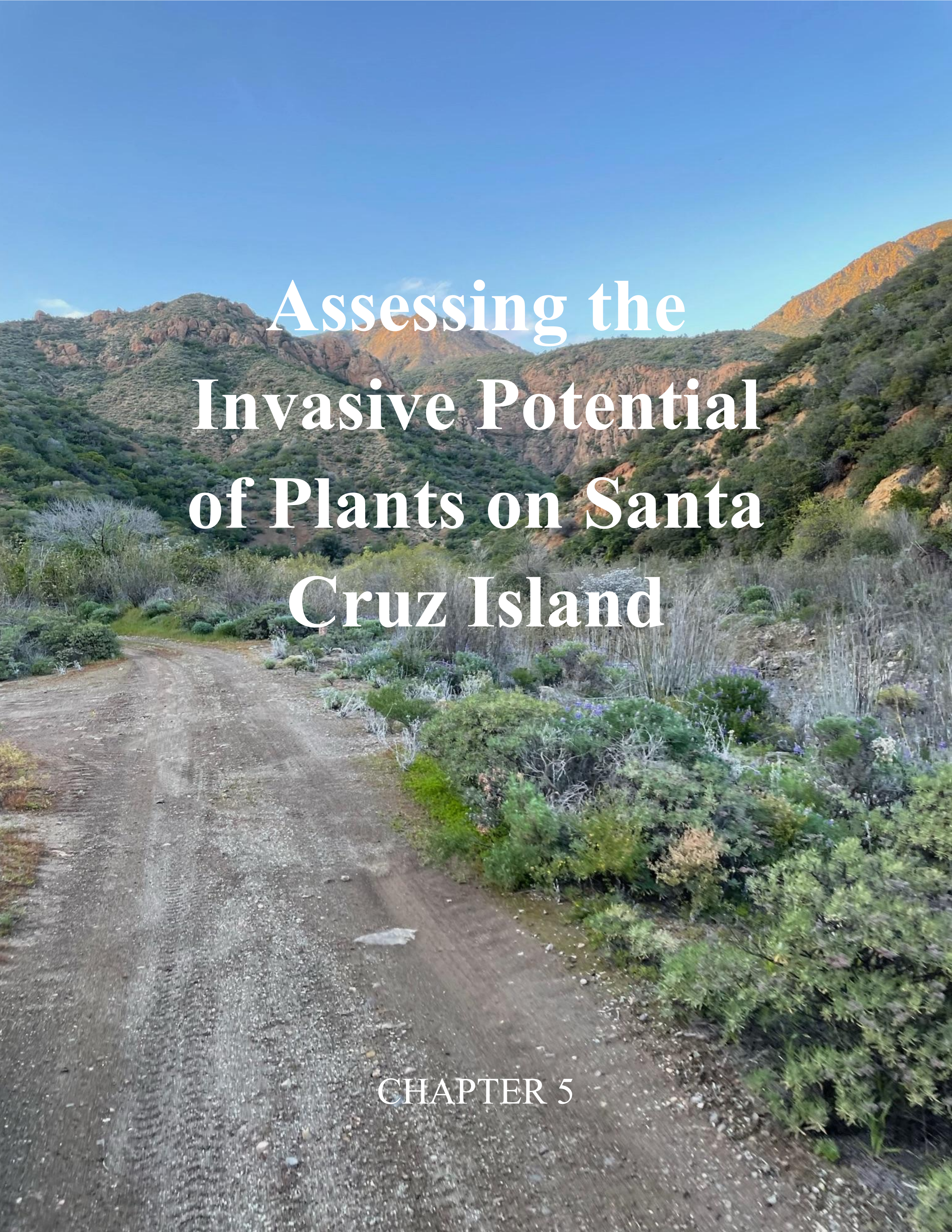
The temporal analysis provides valuable insights into the data, revealing regions of interest and distinct patterns for each species. Across the majority of species investigated, there was a noticeable rise in plant observations and/or herbicide application between 2019 and 2022. It is essential to recognize the distinction between these two years, as the management initiative was temporarily paused in 2020 and 2021 due to the global COVID-19 pandemic. Notably, certain plants such as *C. pycnocephalus*, *Y. gigantea*, and *O. europaea* were absent in 2019 but experienced a resurgence in 2022. These observations underscore the significance of diligent management efforts for successful eradication of invasive species.

Furthermore, the results of this analysis highlight the success of plants that did not exhibit statistical significance in the binary regression on presence/absence data. One such example is *Pelargonium x hortorum*, which was not detected in both the final years of recorded data, 2019 and 2022. Despite not showing a statistically significant reduction, the disappearance of this species highlights TNC's achievements. This outcome is likely attributed to the fact that only a maximum of five plants were present at any given time. Similarly, *Genista monspessulana*, did not have any living plants detected in 2022 but did not prove to have a statistically significant reduction; *G. monspessulana* is a species that had large observation numbers across seven recorded years, which likely prevented it from reaching statistical significance in reduction.

Surprisingly, *Brassica tournefortii*, listed as an invasive species, had no recorded observations within the provided data from TNC. Although this mustard species was sighted near Christy Ranch, it was not documented during the yearly surveys. Considering this plant's sister species, *Brassica nigra*, is a notorious invasive with severe infestations across the Channel Islands, it is crucial to note the location of *B. tournefortii* and continue surveying efforts, even in the absence of data that would support this effort.

Although a comprehensive analysis of the complete statistical trends regarding herbicide application over time was not conducted in this study, we did document the maximum amount of herbicide applied to each species throughout the initiative. By referring to Table 4.1, viewers can infer the current severity of a plant's infestation on the island based upon the year in which the maximum herbicide quantity was applied.

The temporal analysis offers a more holistic approach compared to the statistical analysis, yielding a broader range of insights beyond what can be gleaned from simple binary data. Instances of plants not being detected in later years, even if they experienced a resurgence after the management hiatus during the pandemic, highlight the success of TNC's invasive plant management endeavor. With ongoing treatment, it is probable that several of these plants may be effectively eradicated in the coming years.



Assessing the Invasive Potential of Plants on Santa Cruz Island

CHAPTER 5

Introduction

In order to better quantify the success and importance of The Nature Conservancy's (TNC) invasive plant eradication work on Santa Cruz Island, we sought to develop “fright maps” that visually demonstrate how invasive plant species could have spread on the island had TNC never taken action, or they stopped treatment today. We used maximum entropy modeling software, MaxEnt (Phillips et al., 2004) because it can be trained on presence-only data. Past studies have used MaxEnt to model potential distributions of invasive species. Wang et al., 2007 modeled the potential invasion of a burrowing nematode in China as part of a risk analysis to inform mitigation efforts. Here, we aim to do something similar, and use MaxEnt to develop species-specific habitat suitability models to identify areas of Santa Cruz Island vulnerable to invasion to inform future decision making.

Methods

Species distribution models were created for 13 of the 32 invasive plants managed by TNC on Santa Cruz Island.

Data

Environmental layers for Santa Cruz Island were obtained from Nina Noujdina and Travis Longcore (2022).

Elevation data for Santa Cruz Island was obtained using the NOAA Coastal Access Data viewer engine. The data layers were spatially referenced to NAD 1983 NSRS2007 UTM Zone 11N. This spatial reference and resolution was used as the basis for the rest of the layers.

Slope is the degree of steepness at each pixel measured in radians.

Aspect is the direction of a compass on the slope at each pixel classified into 13 categories. 12 are associated with compass direction, and 1 is for flat.

North-east-ness describes the orientation in conjunction with the slope (Amatulli et al., 2020). This layer serves as a generalized proxy for “wetness”.

Terrain Wetness Index (TWI) is a proxy for long-term soil moisture availability. It is calculated as the logarithm of the cumulative upstream catchment area divided by the tangent of the local slope angle.

Ruggedness Index is a quantitative measure of terrain heterogeneity (Riley et al., 1999). It is measured as the difference between the elevation of a cell to that of the eight cells surrounding it. The values are squared to generate positive integers then summed. The square root is taken to express the total difference in elevation.

Topographic Position Index (TPI) is the difference between the elevation of a focus cell and the mean elevation of cells within a 20 meter radius.

SSURGO Soils was obtained from USDA Natural Resources Conservation Service (https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

Spring NDVI was computed from the time-series of Sentinel-2 Multispectral data (March 2017 – present) using Google Earth Engine API (https://developers.google.com/earth-engine/datasets/catalog/sentinel-2). Converted to 1 meter spatial resolution using a cubic convolution algorithm.

Occurrence Data Points

All occurrence data points for the 13 invasive plants: *Acacia melanoxylon, Centranthus ruber, Cortaderia sellona, Eriogonum giganteum var. giganteum, Genista monspessulana, Hedera spp., Olea europaea, Paraserianthes lopantha, Phalaris aquatica, Pinus pinea, Shinus molle, Tamarix ramosissima and Vinca major,* were obtained from John Knapp at The Nature Conservancy. The data for a single plant was consolidated into a single layer for all the years it was recorded, as MaxEnt does not incorporate a temporal aspect. The occurrences for each plant were stored as point data within a feature class layer, and geographic coordinates were calculated for each point in the same projection as the environmental layers. Only plants with more than 30 occurrence points over all 11 years were modeled in MaxEnt.

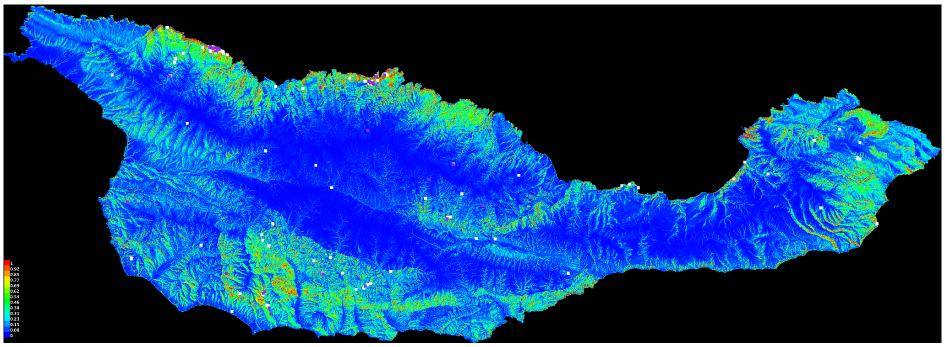
Modeling Approach

Maximum entropy modeling is a machine learning algorithm that requires only occurrence data and explanatory variables to predict probability of presence across an area without consideration of locations of documented absence of the species (Lissovsky & Dudov, 2021). This unique feature of MaxEnt can make it more advantageous than alternate species distribution models. We utilized MaxEnt to predict the potential distribution of these 13 invasive plants on Santa Cruz Island. The program is available for free at the Center of Biodiversity Informatics of the American Museum of Natural History.

Invasive Plant Models

We iteratively ran MaxEnt models for each plant, starting with all layers and then removing those reported as least important by the program. For each plant, the combination of environmental layers reported to be least important varied given ecological differences. After the first initial trials, it was understood that the SSURGO Soils layer was repeatedly causing the models to become overfit, and thus it was not included in any of the final models for any plant.

a)



b)

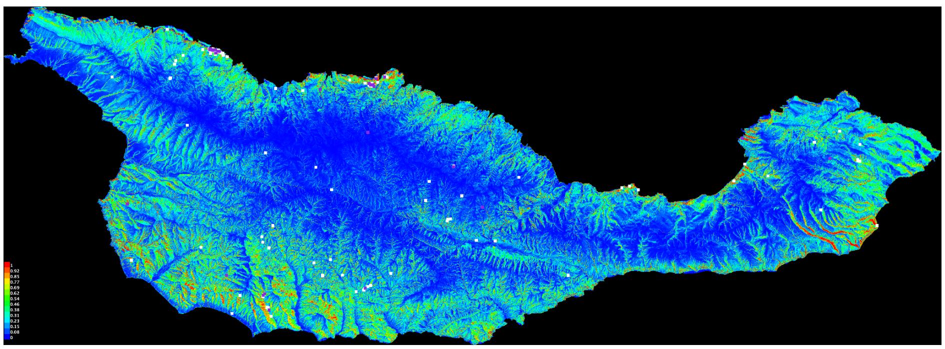


Figure 5.1. Comparison of raw MaxEnt models for *Cortaderia selloana* a) with soils layer and b) without soils layer.

MaxEnt exports completed models as an ASCII file. These models were then classified and finalized in ArcPro to produce the final product.

Results

Models were produced for *Acacia melanoxylon, Centranthus ruber, Cortaderia sellona, Eriogonum giganteum var. giganteum, Genista monspessulana, Hedera spp., Olea europaea, Paraserianthes lopantha, Phalaris aquatica, Pinus pinea, Shinus molle, Tamarix ramosissima and Vinca major.* Each map will contain a description, what environmental layers were utilized to create the model, and the test data Area Under Curve (AUC) coefficient for the model. AUC is an evaluation of how accurately the model classifies data. A model with an AUC of 0.7 to 0.8 has acceptable exploratory power, 0.8 to 0.9 is excellent, and above 0.9 is outstanding.

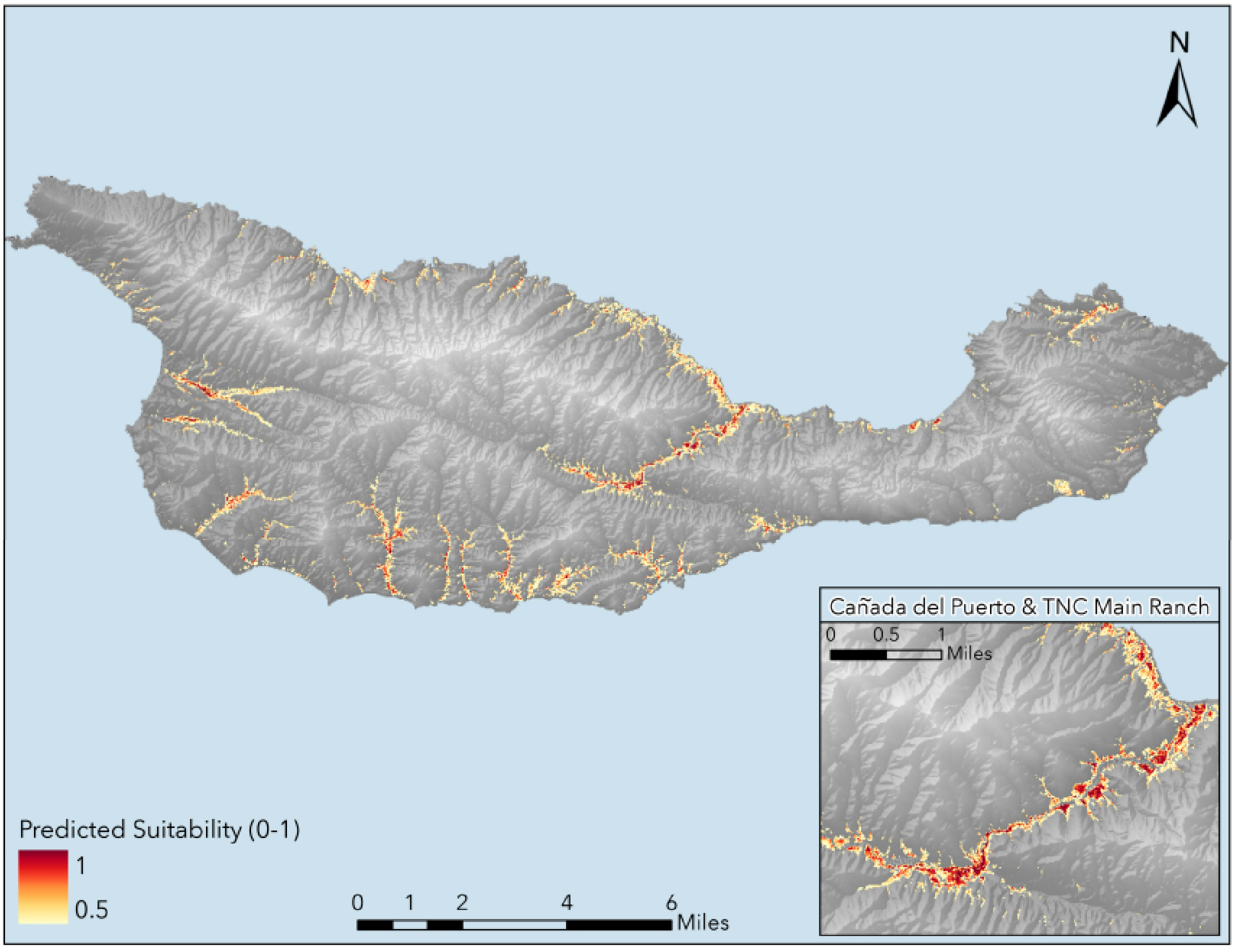


Figure 5.2. *Acacia melanoxylon* (Blackwood acacia).

The model for blackwood was constructed using the NDVI, Slope, Elevation and North-east-ness environmental layers. This model's AUC coefficient was 0.940. Blackwood spreads with moisture, and thus suitable habitat is found in deep canyons where there is sufficient fog.

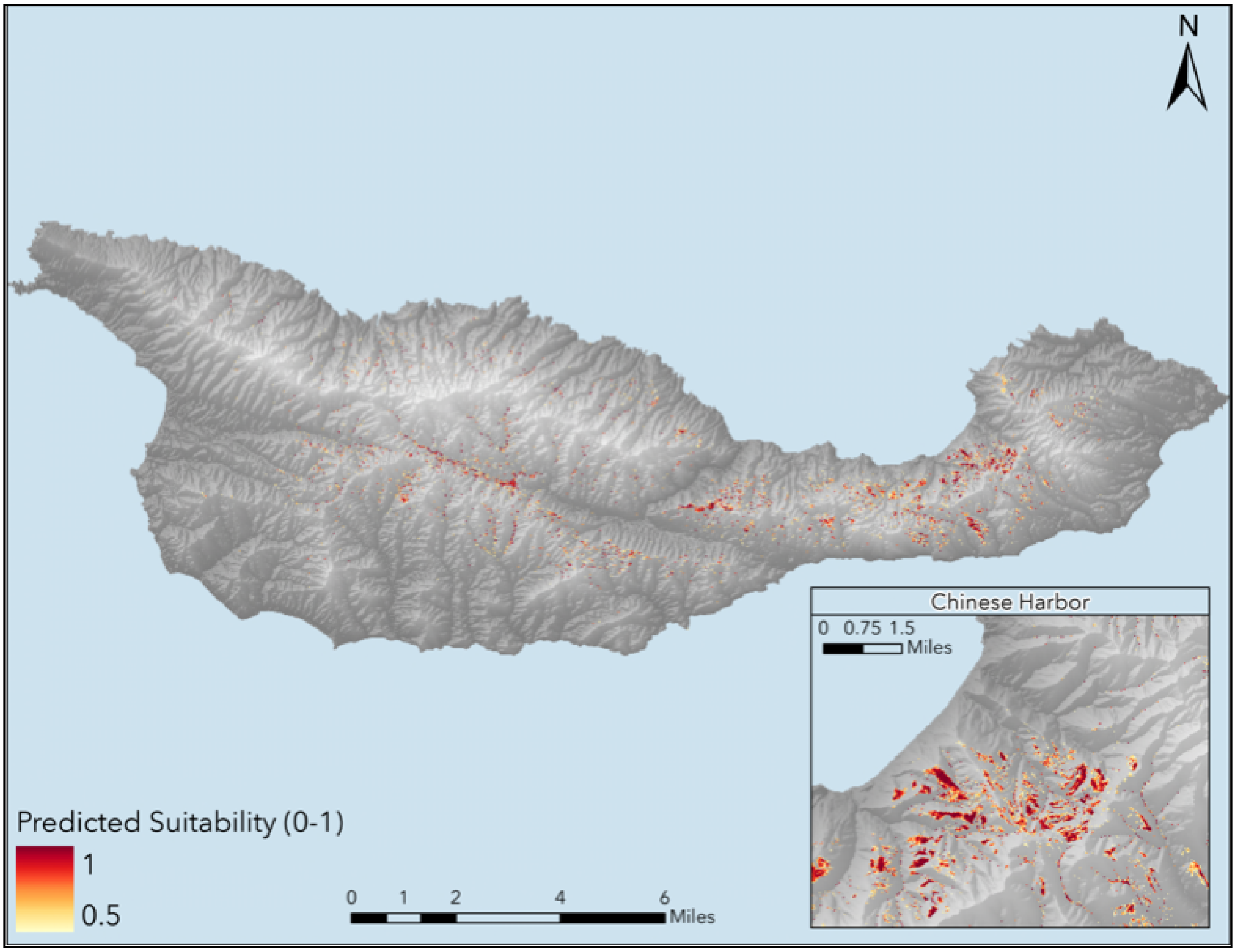


Figure 5.3. *Centranthus ruber* (Red valerian).

The model for red valerian was constructed using the NDVI, Slope, Elevation and TPI environmental layers. This model's AUC coefficient was 0.957. Based on populations on Santa Catalina Island, red valerian grows well in coastal sage scrub habitats.

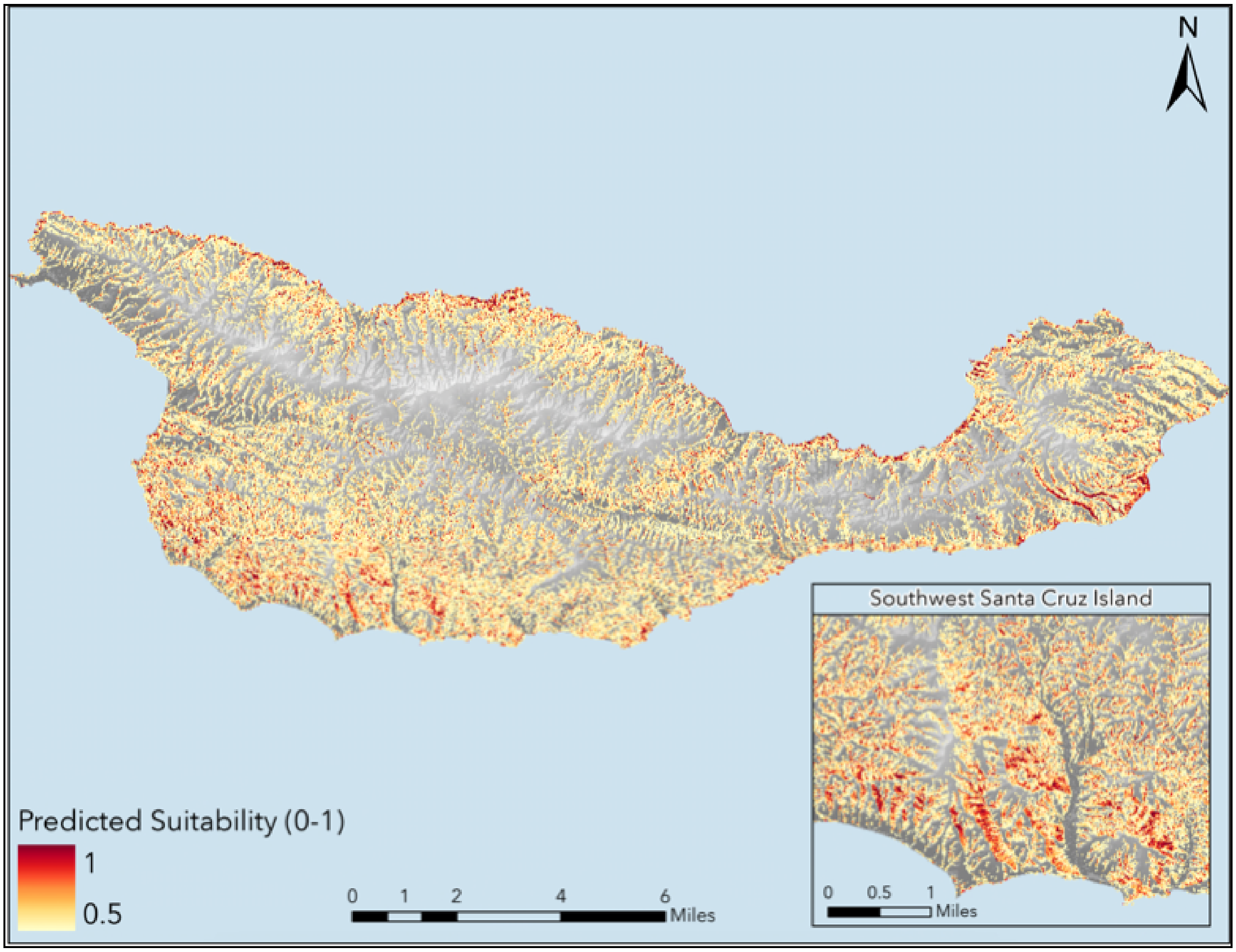


Figure 5.4. *Cortaderia sellona* (Pampas grass).

The model for Pampas grass was constructed using the Elevation, Ruggedness, NDVI, TPI, North-east-ness and Aspect environmental layers. This model's AUC coefficient was 0.848. Pampas grass heavily invades coastal sites, in addition to inland riparian areas.

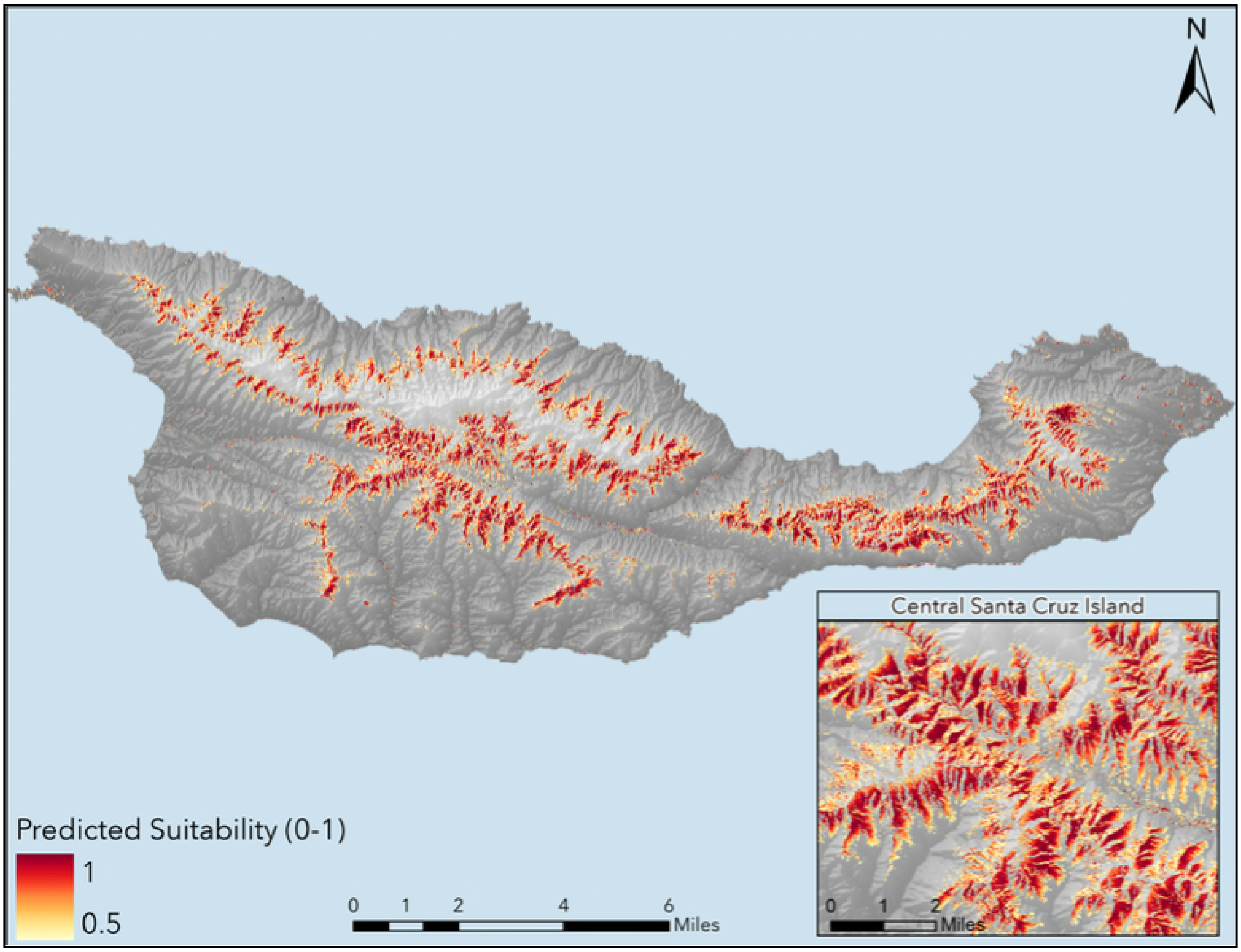


Figure 5.5. *Eriogonum giganteum var. giganteum* (St. Catherine's lace).

The model for St. Catherine's lace was constructed using the Elevation**,** North-east-ness, Ruggedness and Aspect environmental layers. This model's AUC coefficient was 0.797. St. Catherine's lace is endemic to Santa Catalina Island and prefers higher elevations.

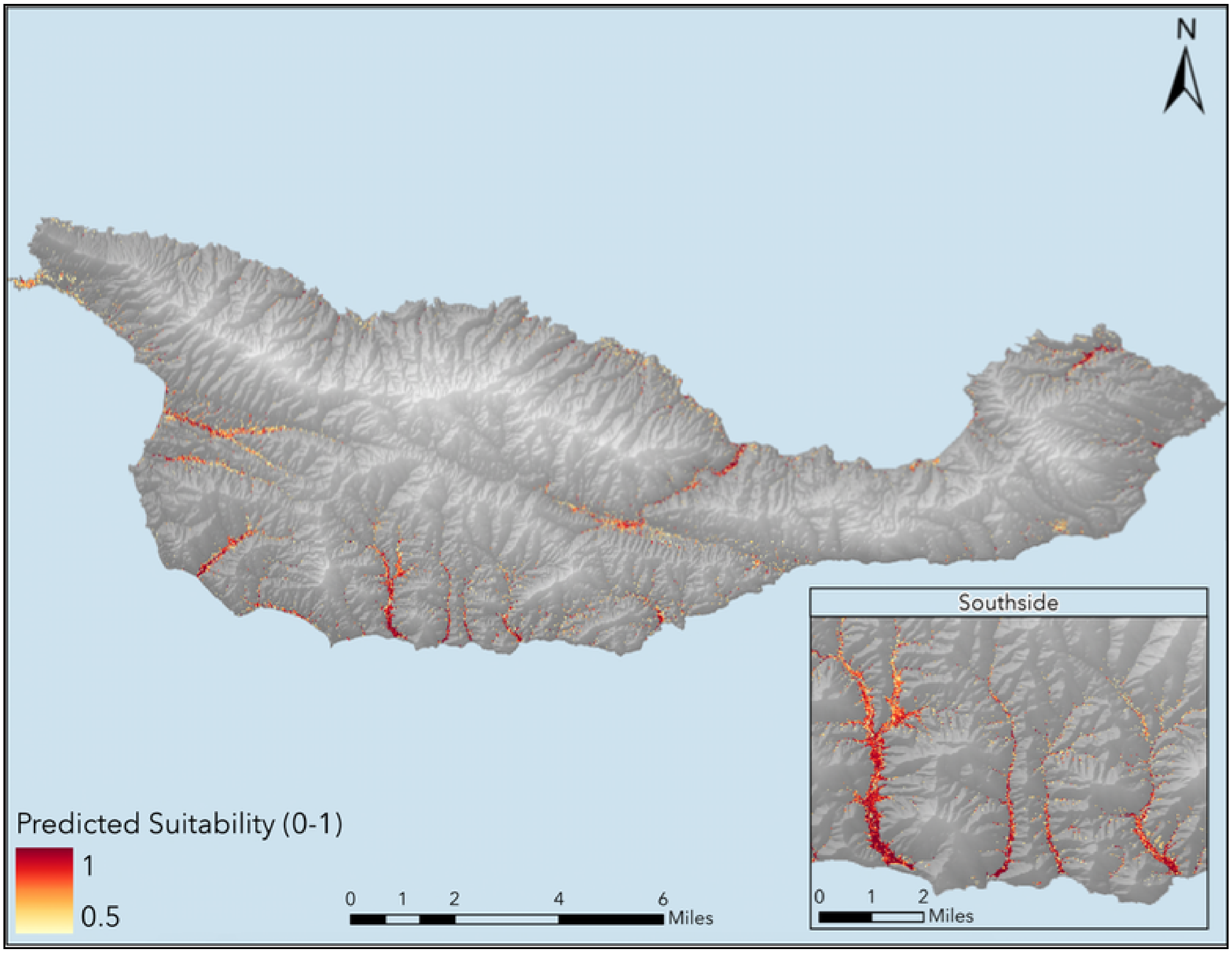


Figure 5.6. *Genista monspessulana* (French broom).

The model for French broom was constructed using the Elevation, Slope, NDVI and TPI environmental layers. This model's AUC coefficient was 0.962. French broom has the ability to invade a wide range of habitats on Santa Cruz Island, including in full shade and open rocky south facing slopes.

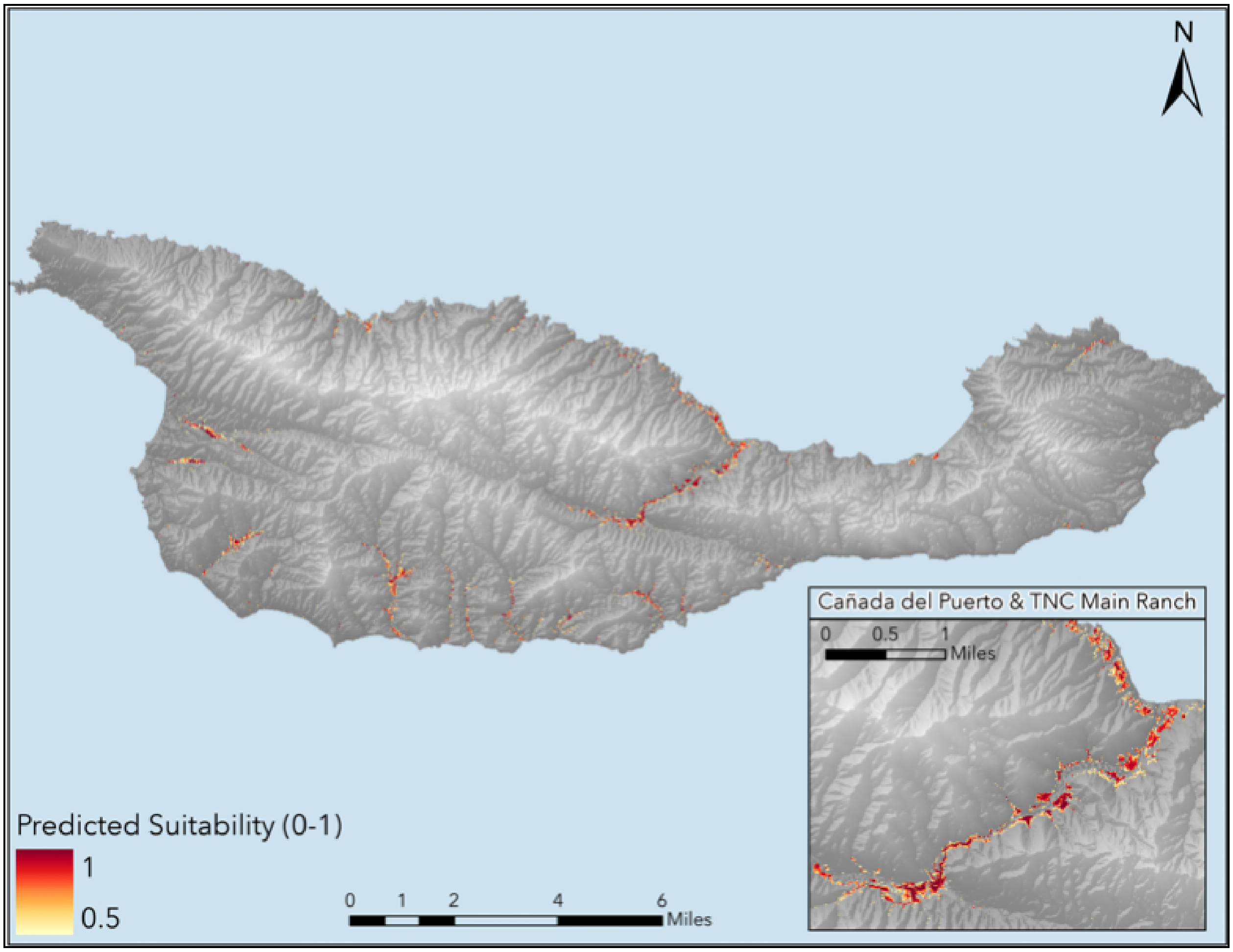


Figure 5.7. *Hedera spp.* (Ivies).

The model for ivies was constructed using the NDVI, Elevation, Ruggedness and TPI environmental layers. This model's AUC coefficient was 0.930. Ivies prefer riparian sites with sufficient moisture.

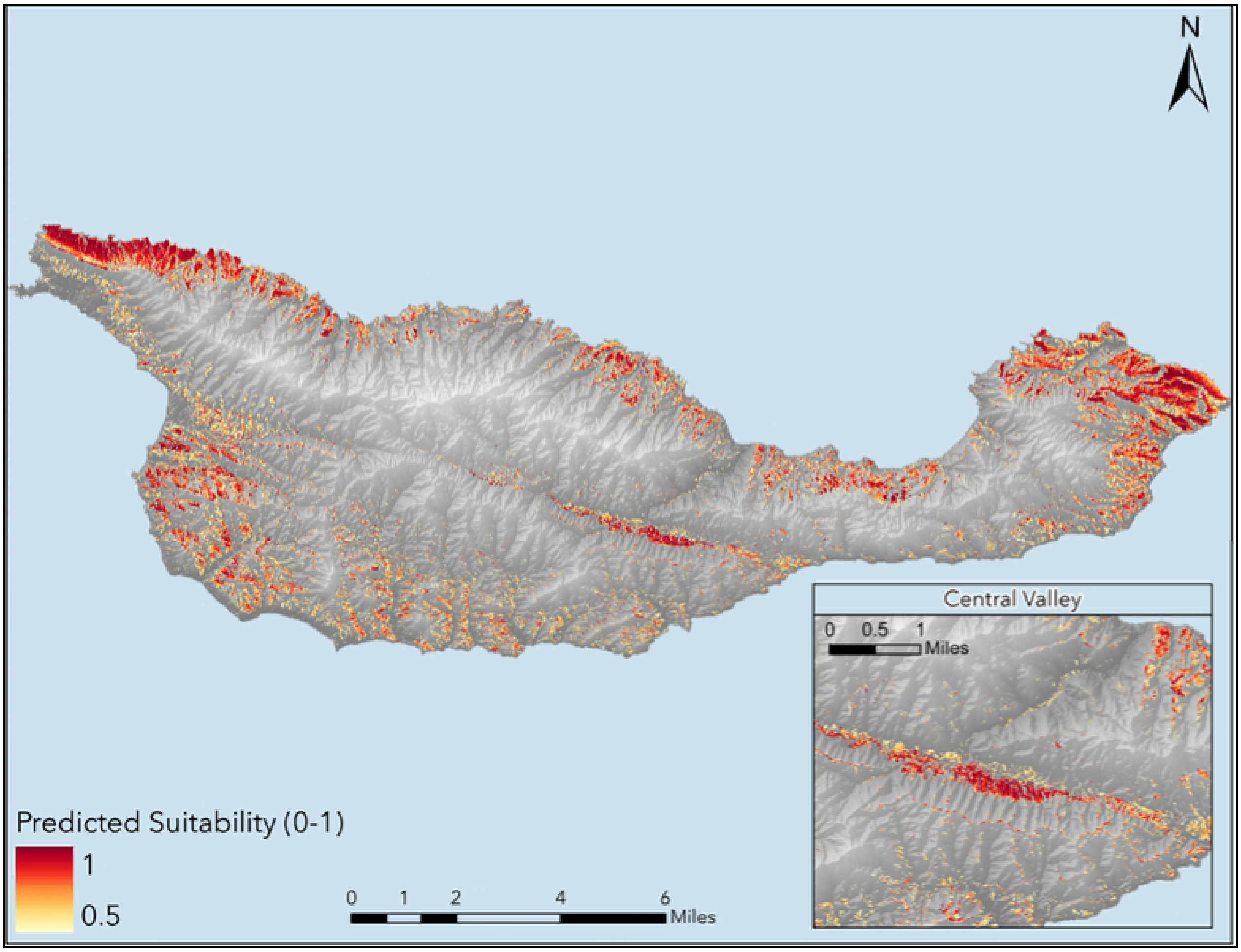


Figure 5.8. *Olea europaea* (Olive tree).

The model for olive tree was constructed using the Elevation, Ruggedness, North-east-ness, Aspect and NDVI environmental layers. This model's AUC coefficient was 0.851. Olive trees heavily prefer grassland, as well as chaparral and coastal sage scrub.

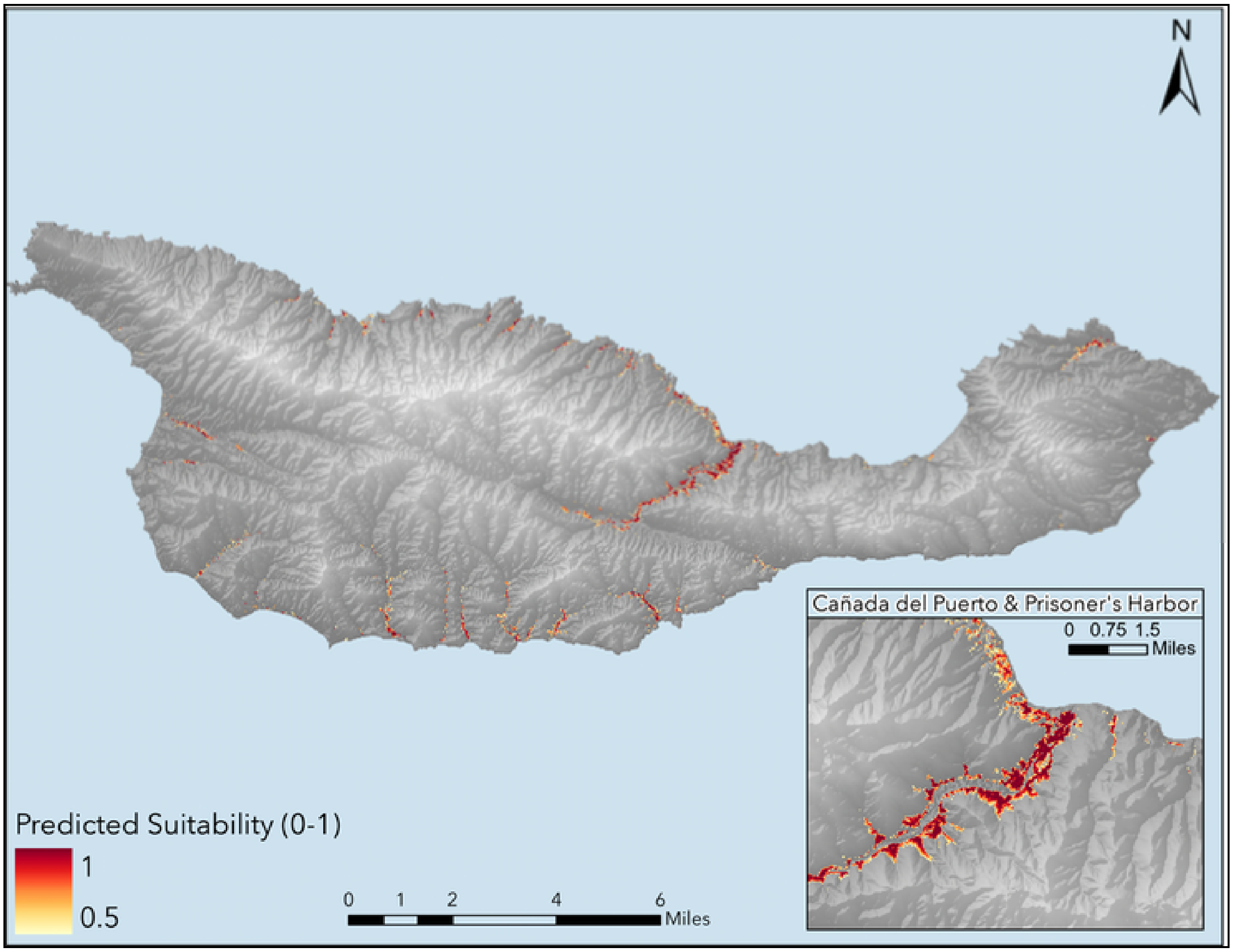


Figure 5.9. *Paraserianthes lopantha* (Plume acacia).

The model for plume acacia was constructed using the Elevation, NDVI and Ruggedness environmental layers. This model's AUC coefficient was 0.987. Plume acacia is highly associated with riparian areas.

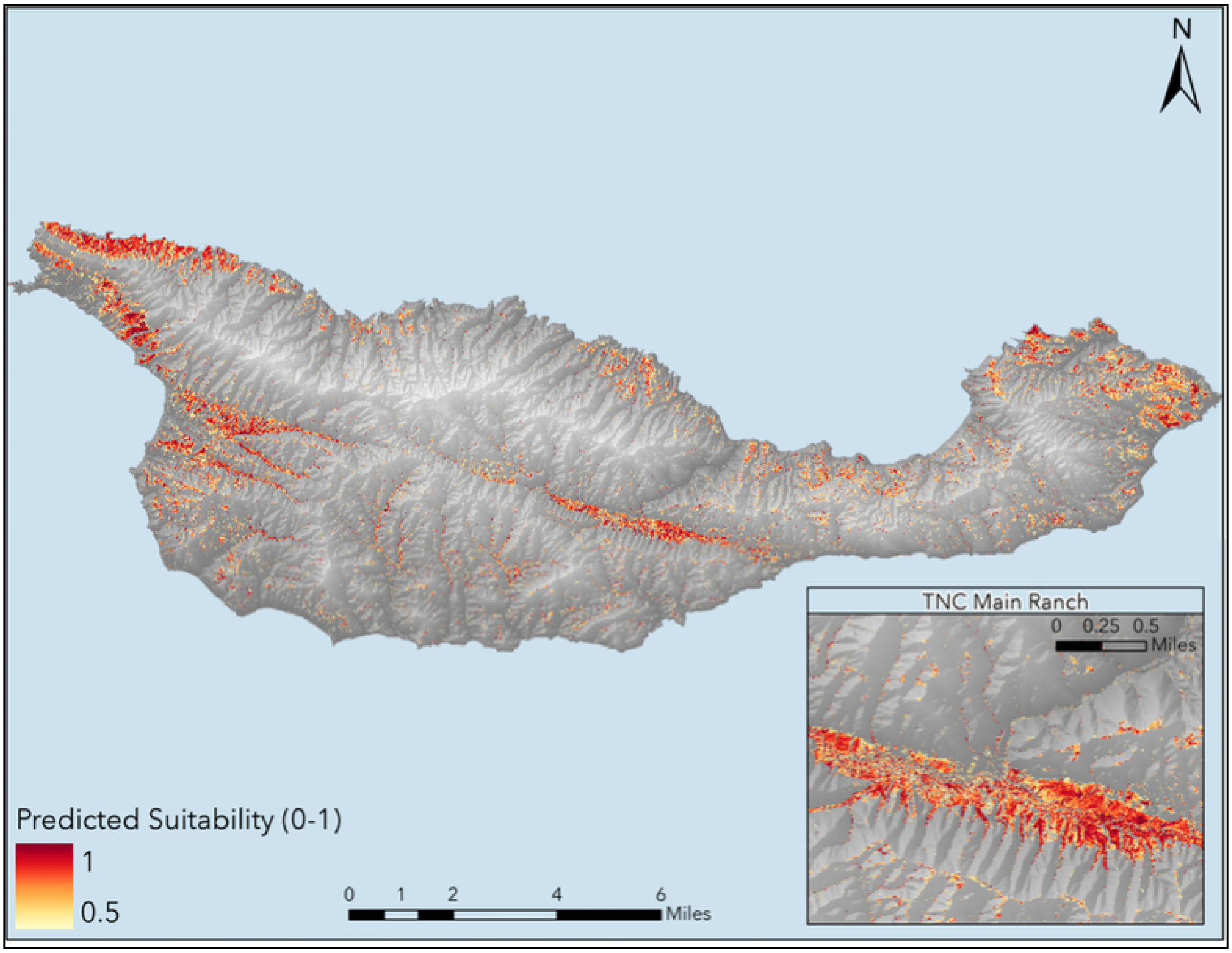


Figure 5.10. *Phalaris aquatica* (Harding grass).

The model for harding grass was constructed using the Ruggedness, Elevation, Aspect**,** Slope, North-east-ness and TPI environmental layers. This model's AUC coefficient was 0.890. Harding grass heavily favors grassland and riparian areas on the island.

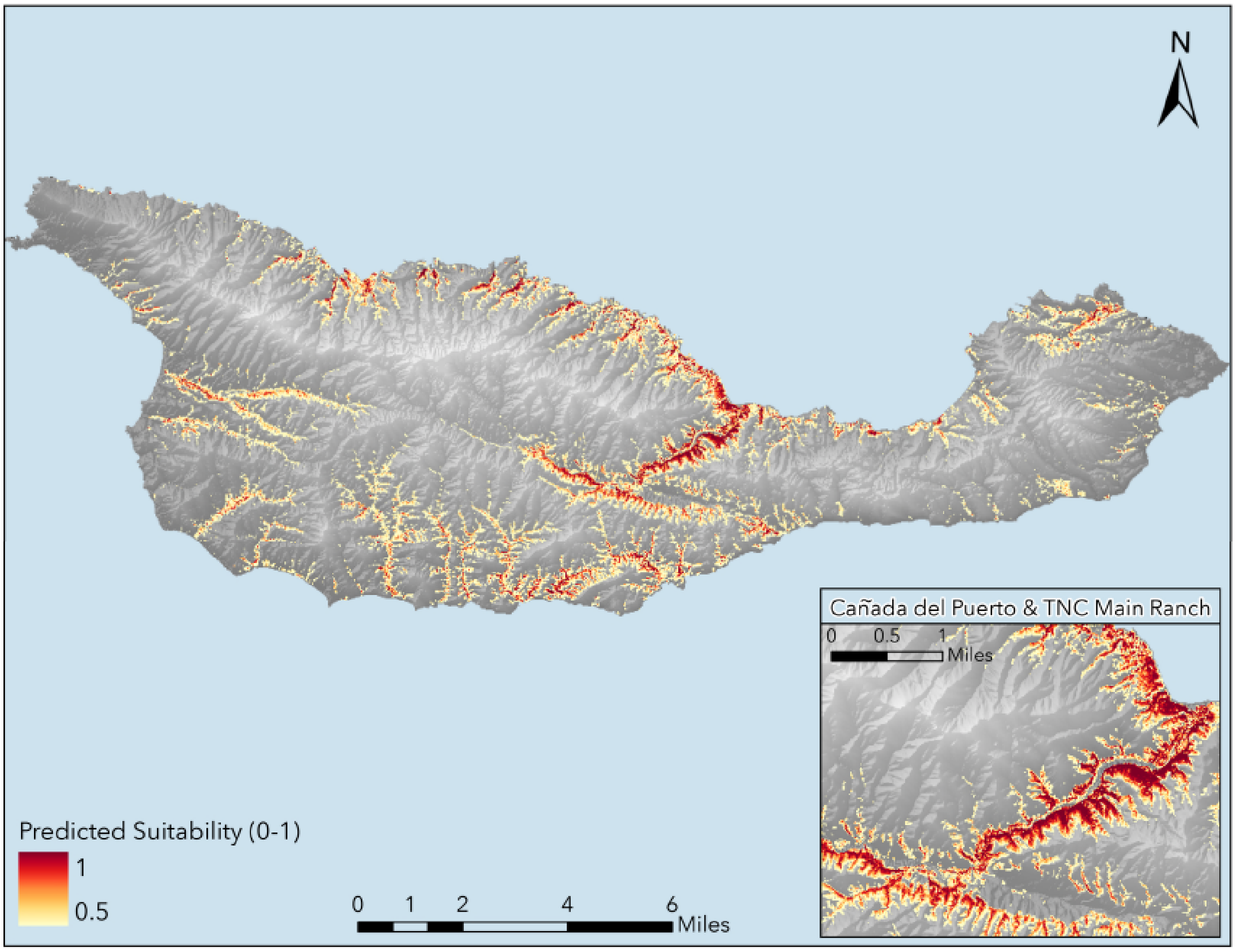


Figure 5.11. *Pinus pinea* (Italian stone pine).

The model for Italian stone pine was constructed using the NDVI, Elevation, North-east-ness, Slope and Aspect environmental layers. This model's AUC coefficient was 0.869. Stone pine grows well in riparian areas and chaparral habitat.

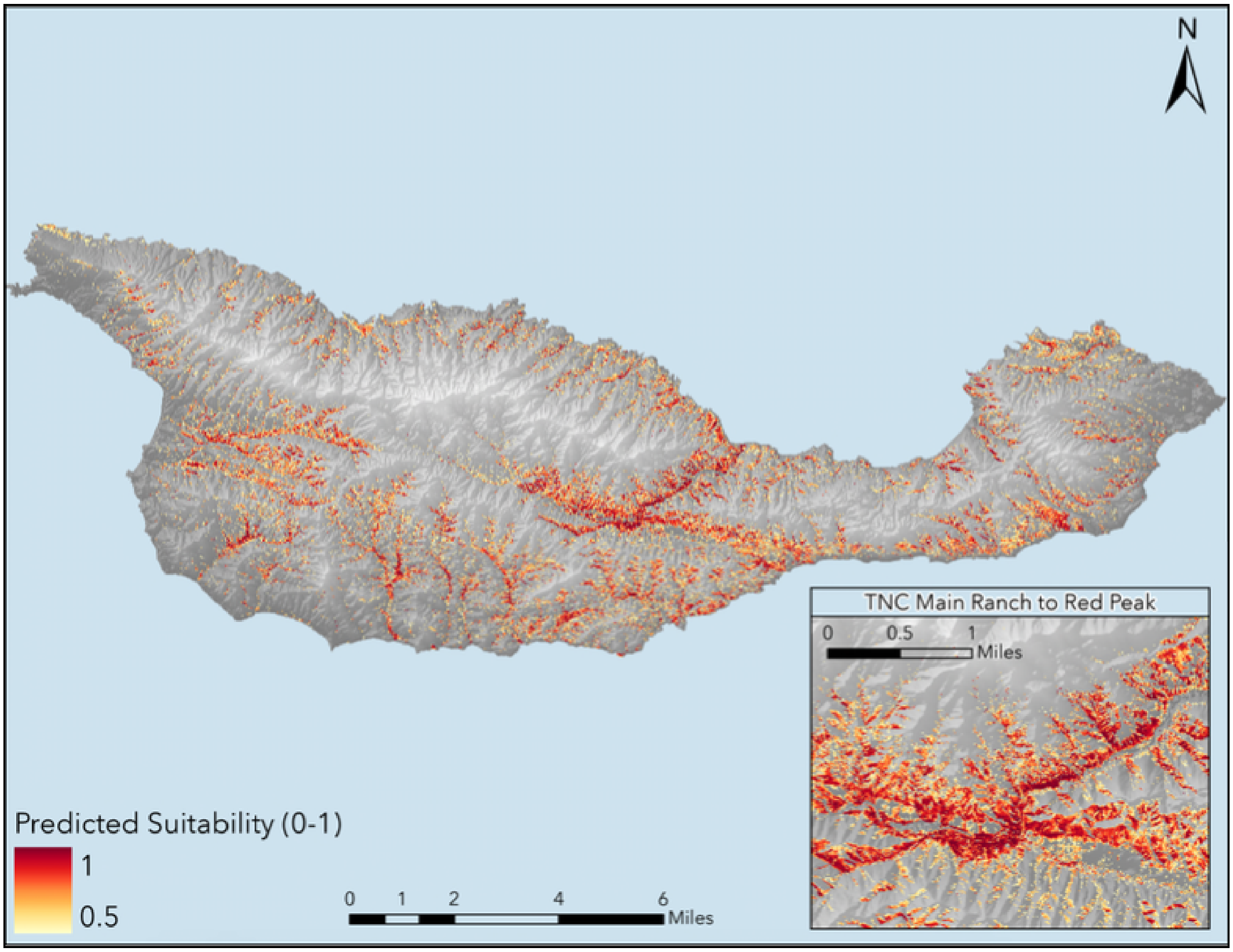


Figure 5.12. *Shinus molle* (Peruvian pepper).

The model for Peruvian pepper was constructed using the Elevation, NDVI, Aspect**,** North-east-ness, Slope and TPI environmental layers. This model's AUC coefficient was 0.859. Peruvian pepper has suitable habitat all over the island, with major areas consisting of coastal sage scrub, followed by riparian areas, grassland and chaparral.

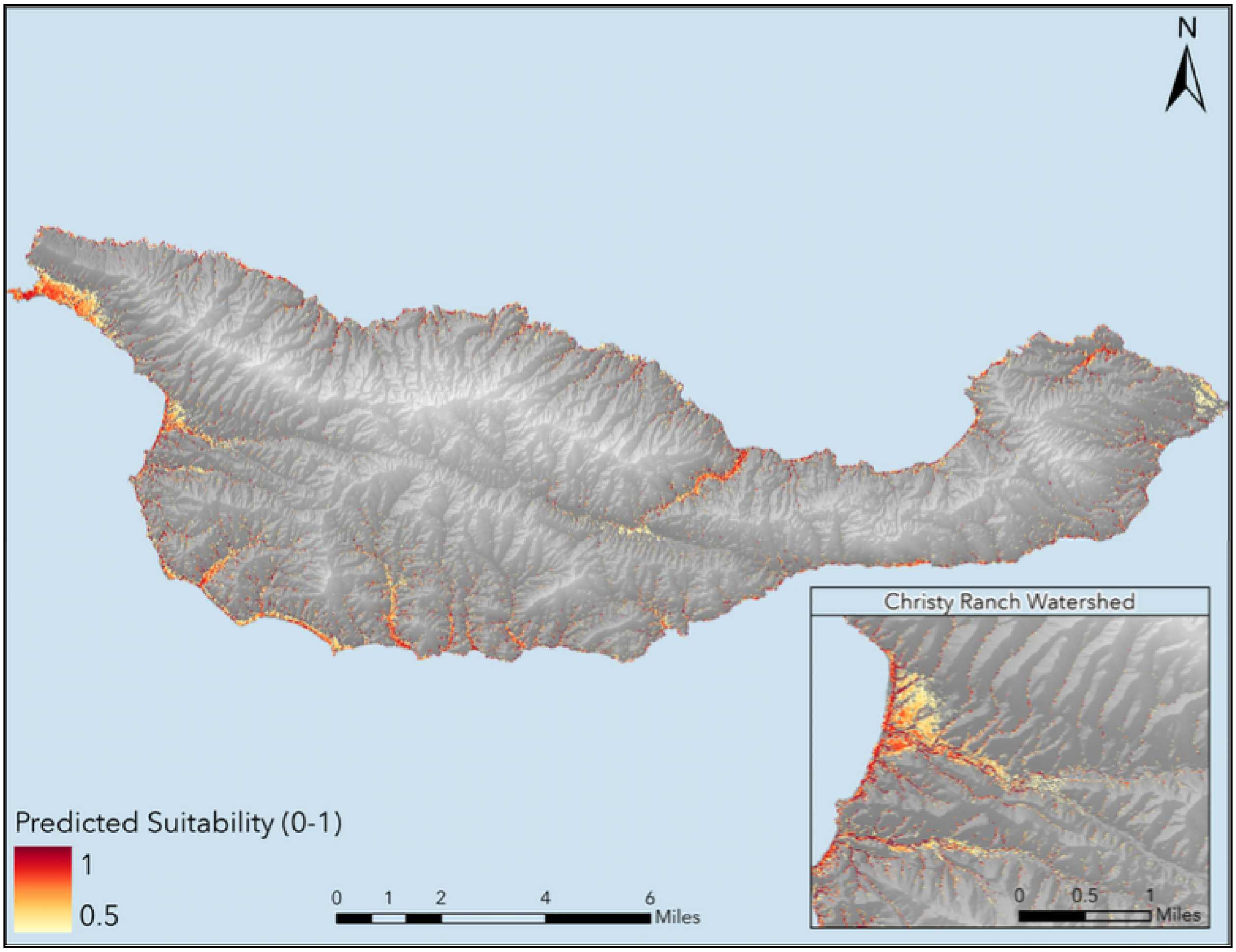


Figure 5.13. *Tamarix ramosissima* (Tamarisk spp.).

The model for tamarisk was constructed using the Elevation, TPI and Slope environmental layers. This model's AUC coefficient was 0.872. Tamarisk grows well in areas with moisture, specifically coastal areas with saltwater spray and interior riparian areas.

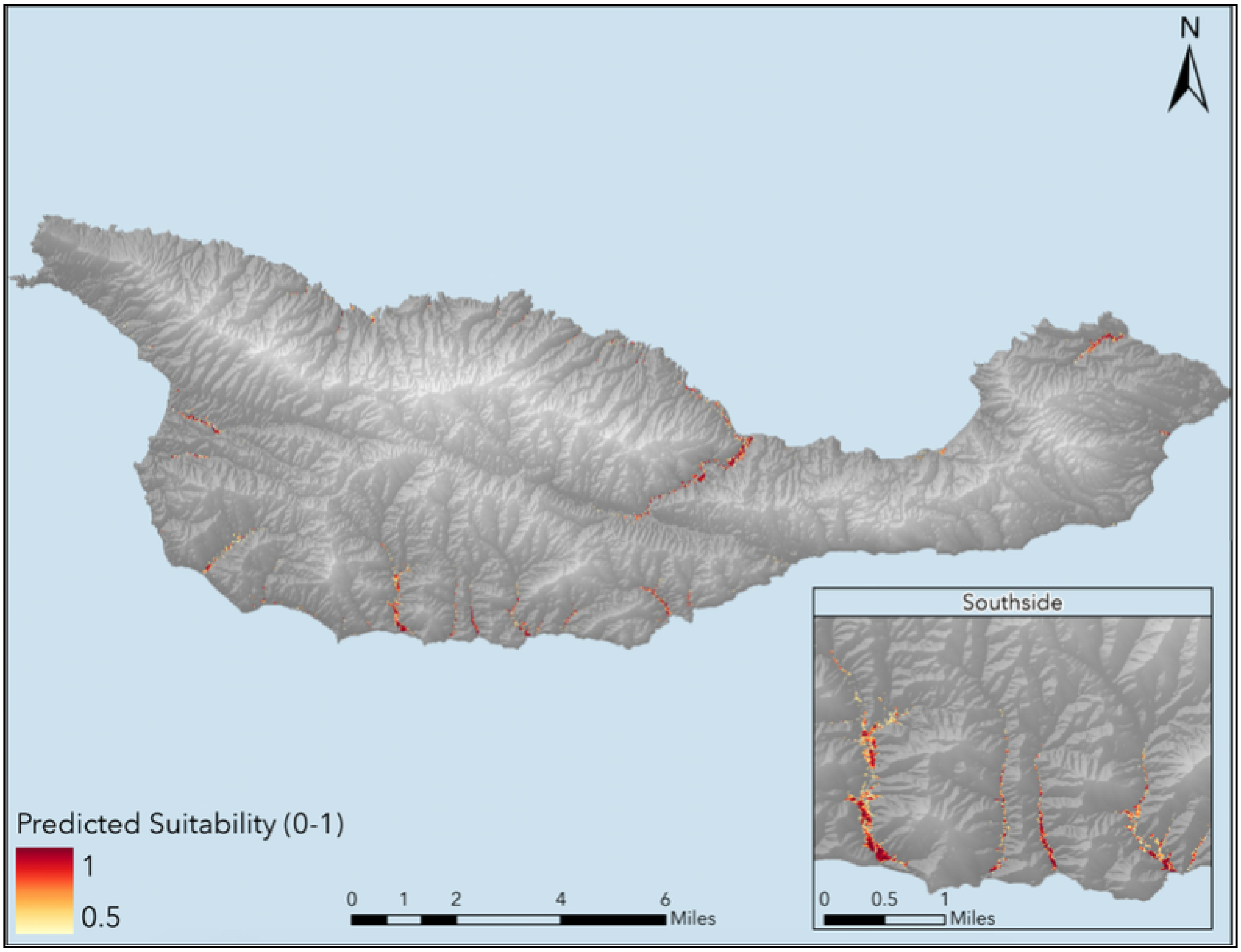


Figure 5.14. *Vinca major* (Greater periwinkle).

The model for greater periwinkle was constructed using the Elevation, NDVI and Slope environmental layers. This model's AUC coefficient was 0.995. Greater periwinkle is highly associated with riparian areas.

Discussion

Here we aim to analyze the results and implications of these habitat suitability models. These maps tell a story about vulnerability on Santa Cruz Island and represent a possible course of invasion if TNC halted all current efforts, or never began them in the first place. These models must be interpreted within the context of the modeling approach discussed in this chapter.

Vulnerability of Santa Cruz

These models have identified potential suitable habitat for invasives on nearly every corner of the island. Riparian areas are particularly vulnerable, as MaxEnt identified these areas as suitable habitat for a majority of the plants. Other habitats on the island such as grasslands, coastal sage scrub, and chaparral were also highly suitable areas for different combinations of invasives. Riparian sites have the potential to become infested with blackwood and plume acacia, ivies, tamarisk, pampas grass, French broom, periwinkle and Italian stone pine. Tamarix and Pampas grass would crowd the coastal areas of the island. High ridges would be overrun with St. Catherine's lace. Grasslands would fill with olive trees, pepper trees, harding grass and Pampas grass. Coastal sage scrub, a rare and endangered California habitat, is at risk of invasion by red valerian, Peruvian pepper trees, harding grass and Pampas grass. These habitats are home to many of the Channel Islands' unique animal species, and disturbance by invasives has the potential to enact cascading changes in the ecosystem.

Modeling Extent

A majority of the plants modeled in Maxent have suitable habitat that is contained to areas with moisture, such as in riparian and creek areas. However, *Cortaderia selloana*, *Olea europaea, Schinus molle* and *Eriogonum giganteum var. giganteum* have suitable habitat that spans large portions of the island. *E. giganteum var. giganteum* is endemic to Santa Catalina Island, and thus the similar conditions of the islands favor invasion from one to the other. The three other plants originate from areas outside of the Channel Islands, but they have established large populations on Santa Cruz Island. *C. selloana, O. europaea* and *S. molle* were the plants with the most occurrence data points out of all plants modeled. Their widespread island populations in conjunction with their extensive habitat suitability models suggests that these plants are far closer to their full invasive potential on Santa Cruz Island. MaxEnt can only predict additional suitable habitats using known occurrence points. Thus, there is no possibility that the model can anticipate additional areas on the island that might be suitable that have not been reached yet by an invasive plant. Therefore, MaxEnt models for plants further along in their invasion, such as *C. selloana, O. europaea* and *S. molle* will more accurately represent their true potential habitat suitability. This is in contrast to plants like *Centranthus ruber* and *Genista monspessulana,* where the models underestimate invasion potential and the true extent of suitable habitat on Santa Cruz Island (J. Knapp, personal communication, June 1, 2023). *C. ruber* is also invasive on Santa Catalina Island and is known to invade north facing coastal bluff scrub. However this habitat is not highlighted in our model for this species. The model for *G. monspessulana.* severely underestimates potential island habitat. Based on populations on Santa Catalina Island and coastal Central California, *G.monspessulana.* has the potential to invade all types of habitat on Santa Cruz Island except for beach and dune, which is not reflected in our MaxEnt model.

Therefore, our models for each plant represent a best case scenario for their unchecked invasive dispersal on Santa Cruz Island.

Implementation

Modeling the potential habitat of invasive species can serve as an important tool for conservation managers and policymakers to guide decision making (Saranya et al., 2021). The maps produced in this chapter can guide surveying efforts and assist in the development of more effective mitigation measures to reduce the spread of invasive species on Santa Cruz Island.

Limitations

In order to get the most accurate species distribution models, starting environmental variables should be selected for each plant based on its ecology. However, due to the relatively limited time span over which this project was completed, we utilized the same layers for each plant when running initial Maxent models. Additional research could focus on fine tuning environmental layers to the ecology of these 13 plants to then be modeled in MaxEnt.

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Conclusion

CHAPTER 6

Conclusion

Our research on the history of invasive plant management has shown that while its popularity has decreased in comparison with other topics over time — namely carbon sequestration — is it not an isolated topic by any means, nor should it be allowed to fall by the wayside. In fact, invasive plant management has significant implications for combating climate change, conserving biodiversity, and mitigating fire disturbances. While climate change is a major threat, this does not mean that topics relating to ecosystem function, like invasive plant eradication, are of any less importance.

The plant attribute report was created in order to consolidate all reliable information found on the ecological attributes of 27 invasive plant species TNC is currently working towards eradicating. This data was then used to conduct an analysis of ecological trends in hopes of finding some connection between invasive plant species to explain why some continually persist while others are more easily eradicated. From our analysis, we found some trends in the data, however, due to our limited sample size and the lack of reliable information for some of the attributes, more research is needed for more rigorous conclusions. Additional ecological attributes should be assessed, including how the invasive plant species arrived on the island. Additional research would provide a more conclusive analysis on any ecological trends that may exist.

The invasive plant habitat suitability models show just how vulnerable Santa Cruz Island would be if management efforts were stopped. The models highlight the susceptibility of riparian areas and other habitats to invasion, posing a major threat to the island's unique ecosystem. These models provide valuable insights to conservation managers and policymakers, which can help guide decision-making and serve as a funding justification for future mitigation efforts. Due to time constraints, these models used a standardized selection for environmental variables; thus, fine tuning the variables to match each plant's individual ecology would improve future models.

Overall, our research emphasizes the importance of invasive plant management and its long term implications. For Santa Cruz Island in particular, their control is crucial for preserving the largest of the Channel Islands and its role as a testbed for management. Invasive plant management must compete for funding, and our work justifies future eradication efforts by showing how big a danger invasive plants present. Lessons we've learned include the fact that long-term data collected in the field can lack standardized organization, so a consistent method of recording data like what we've done in our cleaning procedure can help researchers analyze and draw conclusions. Preserving native plant distribution preserves the integrity of ecosystems, so conservationists must fight invasive plants in order to build a sustainable future.

Appendices

CHAPTER 7

Appendix A. – Supplementary Information

Appendix A.1. Buffer distances used to consolidate plant observations into populations. Determined by cross-referencing literature review on species' life history (Appendix A.2) and density-based clustering in ArcGIS Pro.

Species	**Buffer Distance**
Acacia melanoxylon	100m
Cynara cardunculus	20m
Arundo donax	50m
Araujia sericifera	500m
Oenothera xenogaura	50m
Ehrharta erecta	50m
Washingtonia robusta	200m
Ficus carica	1500m
Genista monspessulana	250m
Pelargonium X hortorum	100m
Acacia dealbata	100m
Phalaris aquatica	300m
Rubus discolor	50m
Pinus pinea	75m
Carduus pycnocephalus	100m
Hedera spp.	75m
Opuntia ficus-indica	50m
Olea europaea	1000m
Cortaderia selloana	750m
Vinca major	300m
Schinus molle	500m
Paraserianthes lophantha	150m
Centranthus ruber	50m
Solanum elaeagnifolium	50m
Yucca gigantea	50m

Eriogonum giganteum var. giganteum	75m
Tamarix ramosissima	300m

Appendix A.2. Plant Summaries and References

***Cynara cardunculus*, 'Artichoke thistle'**
Family: Asteraceae
Biome of Origin: Chaparral Mediterranean

Artichoke thistle is a rapidly growing plant originating from the Mediterranean region of Europe(Gominho et al., 2018; Mandim et al., 2022). It germinates in around 15 days and matures and flowers within its first or second year (Invasive Species Specialist Group [ISSG], 2011; Steinmaus, 2004). It has a seedbank longevity of 5 years, and a mean seed mass of 33.21 mg per seed (California Invasive Plant Council [Cal-IPC], n.d.; Society for Ecological Restoration [SER], n.d.). Artichoke thistle blooms in the early summer from April through July, dispersing its seeds largely through wind, but also through anthropogenic means such as agricultural equipment (Cal-IPC, n.d.; Victoria State Government, 2020). The dispersal range is generally around 20m, as the pappus of the larger seeds tends to fall off prior to dispersal (Victoria State Government, 2020; ISSG, 2011). Like many invasives, artichoke thistle are opportunistic in that disturbances such as fire allow for their establishment. In this way, they tend to do well in fire-prone ecosystems such as sage scrub (Steinmaus, 2004).

***Arundo donax*, 'Arundo' 'Giant reed'**
Family: Poaceae

Arundo donax is a perennial grass originating from East Asia that flowers in late summer and can grow up to heights of 9 meters. (Bell, 1997). Giant reed grows very quickly and can reach maturity in around 12 months (UC Riverside, n.d.) *Arundo* reproduces almost exclusively vegetatively, and rarely produces any viable seeds (Bell, 1997). Thus, when *Arundo* is burned in a fire, its extensive rhizomes are very likely to survive and resprout. Vegetative reproduction also allows giant reed to be easily dispersed by water and mud, where it can be transported long distances. (Cal-IPC) Rapid spread occurs during flood events when rhizomes and stems are fragmented and further transported by high waters.

***Araujia sericifera*, 'Bladder vine'**
Family: Apocynaceae

Bladder vine is rapidly growing, germinating in 3 to 6 weeks, and reaching final height in 2-5 years (Bay of Plenty Regional Council Toi Moana, n.d.; NC State Extension, n.d.; The Royal

Horticultural Society [RHS], n.d.). Its mean seed mass is roughly 11mg, with each fruit having as many as 400 seeds (Rarepalmseeds, n.d.; NSW Department of Industry, 2020). These seeds can be dispersed up to 30 km primarily via wind. (Weed Action, n.d.; NC State Extension, n.d.) Bladder vine's seed bank longevity is greater than 5 years (United States Department of Agriculture [USDA], 2012). Bladder vine originates from South America, and blooms during the late summer and fall (NC State Extension, n.d.). This hardy plant has a high tolerance to "water stress and moderate salinities" and poses a threat to native shrubs and trees by smothering them (Bellache et al., 2022; Brunel et al., 2010). Although there is no direct information on bladder vine's response to fire, a species under the same genus, *Araujia ordorata*, has been observed to appear after hot fire (Becker, 2014).

***Oenothera xenogaura*, 'Drummond's beeblossom'**
Family: Onagraceae

Oenothera xenogaura is a perennial plant originating from Texas and Central Mexico. It is aggressively rhizomatous (Wagner et al., 2007). Little information is available for this species, but Hoggard et al., 2004 hypothesized that *Oenothera xenoguara* arose as a result of interspecific hybridization followed by genome doubling in the family Onagraceae.

***Ehrharta erecta*, 'Erect veldtgrass'**
Family: Poaceae

Ehrharta erecta is a perennial grass originating from South Africa. Erect veldtgrass seeds are very light, averaging .85 mg., and are dispersed by wind or occasionally carried on animal fur (SER n.d. & Sigg 1996). Thus, long distance dispersal is rare. Seeds are estimated to remain dormant in the soil for several years. Veldtgrass induces litter accumulation that can lead to increased fire potential (DiTomaso et al., 2013) When veldtgrass is burned, the fire usually does not damage the knotty stem bases which can lead to increased population density when less fire-tolerant species are damaged or killed.

***Washingtonia robusta*, 'Fan palm'**
Family: Arecaceae

Fan palm originates from Mexico and California, and blooms during the summer (Hodel et al., 2015; Brickell & Zuk, 1997). Seeds are large, with an average weight of 70.2mg (SER, n.d.). As they are largely dispersed by animals and secondarily by gravity and water, the seeds can frequently have a long distance dispersal range (DiTomaso et al., 2013; Martin, 2009; Brusati, n.d.). The seed bank can be as long as 6 years (Daehler, 2005). Germination can take 14 to 60 days, and maturity can take over 4 years (Chimera, 2017). Fan palms are able to grow in a variety of soil environments, and are drought tolerant (Martin, 2009). Fire facilitates fan palm growth through creating gaps in the overstory (Minnich et al., 2011). Fire generally does not kill fan palm and in fact, the charring can increase the trunk's resistance to future fire (Minnich et al., 2011).

***Genista monspessulana*, 'French broom'**
Family: Fabaceae

French broom comes from the Mediterranean and Azores (DiTomaso et al., 2013). It blooms from spring into early summer, spreading its seeds 4m via explosive release and further via animals and water (Zouhar, 2005; D'Antonio, n.d.; DiTomaso et al., 2013). Seeds weigh 7.35 mg on average and last at least 5 years, up to as long as 30 years (SER, n.d.; Knapp, 2004; DiTomaso et al., 2013). French broom can take from 18 months to 3 years to reach maturity (DiTomaso et al., 2013). Fire can have varied effects, although french broom can facilitate wildfire spread (Leblanc, 2001; King County, 2018).

***Pelargonium X hortorum,* 'Geranium'**
Family: Geraniaceae

Geranium is a genetic cross of parents *Pelargonium zonale* and *Pelargonium inquinans*, originating from South Africa (Ohio State University, n.d.). Geranium blooms during the summer, and disperses its seeds principally by wind, but also via water and the soil (Ohio State University, n.d.; Datiles & Acevedo-Rodríguez, 2015). One parent, *Pelargonium zonale*, produces seeds weighing 4.72 mg on average and has a seedbank longevity of 2 to 3 years in "commercial storage conditions" (SER, n.d.; Priestley, 1986). Dispersal has the potential to be long distance (Schram, 2019). Seeds germinate in 7 to 21 days, and the plant reaches maturity in 3.5 months (Gilman & Howe, 1999; Jauron, n.d.). The genus, *Pelargonium* doesn't appear to pose a fire hazard but could benefit from the disturbance (Daehler, 2005; Datiles & Acevedo-Rodríguez, 2015).

***Acacia dealbata*, 'Silver wattle'**
Family: Fabaceae

Acacia dealbata is an evergreen tree native to Australia. Silver wattle seeds average around 12.38 mg and are dispersed via gravity, remaining very close to the mother tree (SAR & Fu et al., 2006) Seeds have the potential to move further distances when carried by water (Cal-IPC, n.d.). Seeds can remain viable in the lower seed bank (10cm - 80cm) for 50 years or longer (Richardson and Kluge, 2008). Fire has been found to stimulate germination of silver wattle seeds, as is common in many *acacia* species. (Adair, 2008) This species can also be spread by rhizomes (Cal-IPC, n.d.)

***Phalaris aquatica*, 'Harding grass'**
Family: Poaceae

Phalaris aquatica is a perennial grass originating from Europe. Harding grass seeds average 1.17mg and are dispersed short distances by animals and longer distances by water (SER, n.d. & DiTomaso and Healy, 2003) This plant can also spread through rhizomes (Cal-IPC, n.d). Many *phalaris* seeds fail to survive in the soil for over 2 years (DiTomaso and Kyser, 2013). Watson et al. 2003 state that Harding grass is a persistent species that recovers excellently from bushfires.

***Carduus pycnocephalus* 'Italian thistle'**
Family: Asteraceae

Italian thistle is originally found in the Mediterranean, Southern Europe, and from North Africa to the regions near Pakistan (Bossard, n.d.). The plant blooms from mid-September to December, takes approximately 4-14 days to germinate (Evans, 1979), and 3 ½ months to mature (Bossard, n.d.). The seed bank for this plant can last up to 10 years (CNPS SLO, n.d.). The seeds are dispersed by wind, vehicles, animals, and ants with a dispersal range of about 23 to 108 meters (Bossard, n.d.).

***Hedera spp*. 'Ivy spp.'**
Family: Araliaceae

Various species of ivy are originally found throughout the Eurasian continent (Waggy, 2010). Ivy takes approximately 5 to 20 days to germinate (Waggy, 2010) and blooms in the fall (Reichard, n.d.). This particular plant does not have a persistent seed bank (Waggy, 2010); in fact it is short-lived and the plant can take several years to mature (King County, 2020). Seeds are primarily dispersed through birds, who regurgitate the seeds, in addition to dispersal by gravity up to 3 meters (Waggy, 2010). The response of Hedera spp. to fire is not fully known because there is limited data available to determine this; however, some research does suggest that Ivy has the potential to respond favorably to fires (Waggy, 2010). The plant is recommended for reducing the risk of fires as it is somewhat resistant; the plant does not readily ignite and when it burns it may burn slowly.

***Opuntia ficus-indica* 'Mission Cactus'**
Family: Cactaceae

Opuntia ficus-indica is a plant species originally found in Central Mexico. These plants bloom in the Spring and Summer (The University of Arizona, n.d.). It takes 40-60 days to germinate (Altare et al., 2006) and 3-4 years to mature (UCANR, n.d.). The following plant is a succulent with a high water content that can be used as a fire suppression barrier (The University of Arizona, n.d.).

***Vinca major* ‘Periwinkle’**
Family: Apocynaceae

Periwinkle is native to Europe and North Africa (NPS, 2020). The plant blooms between January and May and the seeds for this plant take approximately 7 to 21 days to germinate (UMN Extension, 2021). The plant dispersal is largely due to human activity and can also be dispersed via waterways since the plant is located nearby riparian areas (CDFW, n.d.). The plant population rapidly expands around wet periods (Newhouser, 2005).

***Schinus molle* ‘Peruvian pepper’**
Family: Anacardiaceae

Peruvian pepper is native to Western South America (Schmidt, 2021). The plant takes about 3 years to mature (CSBE, n.d.). The mass for the Peruvian pepper seeds is standardized using 1000 seeds and is determined to be 30.75g (SER, n.d.). The plant begins to flower in the summer (CSBE, n.d.). One of the primary methods of dispersal for the Peruvian pepper is via birds (Brusati, 2005).

***Centranthus ruber*, ‘Red valerian’**
Family: Caprifoliaceae

Red valerian is a subshrub that originates from the Southern Mediterranean region (Europe, North Africa and Asia Minor) (Invasive Plant Atlas of the United States, n.d.). The 1.77 mg seeds take 14-21 days to germinate; the plant matures in less than 24 months (SER; Select Seeds). The seed bank can last more than 3 years (California Invasive Plant Council, n.d.). Its pink-red flowers bloom from May to October (The Wildlife Trusts, n.d.). There is a high potential for human-induced dispersal, because the seeds get sticky when wet and can adhere to tires; this is especially important to note because the plant tends to spread rapidly along roadsides and watersheds (California Invasive Plant Council, n.d.). Hence there is potential for long distance dispersal, but not through natural means. Seedlings have been shown to emerge after fires, but there is not much data on whether fire benefits this plant (California Invasive Plant Council, n.d.).

***Solanum elaeagnifolium*, ‘Silver horse nettle’**
Family: Solanaceae

Silver horse nettle is a perennial herb. The toxic plant originates from Northeast, Central and Southwest South America (Boyd et al., 1984). The 4.11 mg seeds take 2-3 weeks to mature and are viable for up to 10 years in the soil (SER n.d; California Invasive Plant Council., 2016; Datiles & Acevedo-Rodríguez, 2022). This species blooms from May to October (Missouri Department of Conservation, n.d.). It can disperse vegetatively, via cut root sections, and by seed (Datiles & Acevedo-Rodríguez, 2022). Agriculture facilitates seed dispersal, as seed can be carried by livestock, contaminated vehicles and tools. The seeds can also be spread by water and birds, where digestion may enhance germination. Rhizome fragments as small as 0.5 cm can still regenerate (Datiles & Acevedo-Rodríguez, 2022). Closely related species were found to have a low impact on fire regimes, with an overall lack of information regarding the subject (California Invasive Plant Council, 2016).

***Yucca gigantea*, 'Spineless yucca'**
Family: Asparagaceae

Spineless yucca originates from the deserts of Mexico and the Southwestern United States. (SC Garden Guru, n.d.). Its seeds take 1-12 months to germinate and the plant matures in 24-36 months. It blooms in the summer and utilizes seed, spore, and vegetative propagation (Rojas-Sandoval, 2022). It most likely cannot repopulate after fire (Fire Effects Information System, n.d.)**.**

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Appendix B. – External Documents

Appendix B.1. Public Google Drive folder with all full-page time series PDFs.

Appendix B.2. Public Google Slides document with animations for all time series maps