ESIP Pollinator Project Summary

Insect Pollinator Network Composition in Post-Fire Recovery of Coastal Sage Scrub

Project Background

San Diego County, situated within a global biodiversity hotspot, faces escalating fire-related challenges that impact its rich ecological diversity. Insect pollinators play a pivotal role in the recovery of native plant communities following fire, yet our understanding of the species composition and changes in post-fire succession remains limited (Force, 1981; van Mantgem et al., 2015). The recolonization of insects, which constitute a substantial portion of the pollinator community, in post-fire sites is further complicated by increasing fragmentation in the region. The availability and significance of reservoir sites for these vital pollinators demand a comprehensive investigation. To address these knowledge gaps, the San Diego Pollinator Monitoring Program (SDPMP), initiated by Principal Investigator Christina Simokat, offers a robust framework of methodologies for in-depth exploration and understanding of these critical ecological dynamics.

Monitoring insect populations in the diverse ecosystems of San Diego County, including coastal sage scrub (CSS) habitats, requires a multifaceted approach. CSS habitats are characterized by their unique plant communities and ecological significance, serving as critical refuges for numerous wildlife species, including insects (Sawyer et al., 2009). To comprehensively monitor insect populations in such habitats, visual surveys are an effective non-lethal approach to identifying the occurrence of pollinators (Lowenstein et al., 2014). Visual surveys involve direct observation and identification of insects and interactions with specific plants, offering insights into the presence of specific species and their behavior within coastal sage scrub habitats. The insect monitoring approach of the SDPMP includes a combination of video data collection and focal observations that document the assemblage of flower-visiting insects associated with CSS plants.

Coastal sage scrub habitats are of particular ecological importance in Southern California, harboring numerous endemic and specialized species. They face various ecological challenges, including habitat fragmentation and invasive species encroachment (Wilcox & Fiedler, 2015). CSS habitats are strongly influenced by fire, which plays a crucial role in shaping both the plant communities and insect pollinators within these ecosystems (Keeley & Fotheringham, 2001). Fire is a natural part of the coastal sage scrub ecosystem, and many plant species have evolved to be fire-adapted (Keeley, 2006). The plant community provides insects with various requirements, most importantly nutrition, shelter and nesting sites. After an area burns, these resources are removed, but may be substituted by reservoir areas, defined as adjacent undisturbed habitat that may be accessed by surviving insects (Zozaya, 2011). The quantity and quality of these reservoir areas along with their distance from the burn site may influence the use by the surviving insect assemblage.

Fire can trigger the germination of certain plant species' seeds, promote new growth, and maintain habitat structure, ultimately benefiting insect pollinators in some habitats (Rohde et al., 2019).

However, the frequency and intensity of fires can have varying effects on insect populations. While some insects may benefit from increased floral resources in early post-fire succession, others may be negatively impacted due to habitat destruction and changes in vegetation composition (Dahms, 1984). Currently, there is little known of the influence of fire in relation to pollinator composition within the CSS regions of Southern California. The complex interactions between fire, plants, and insect pollinators in CSS habitats underscore the need for ongoing research to understand and conserve these ecosystems.

Local observations offer insights into one aspect of pollinator colonization, but a holistic understanding of larger ecosystems requires the framework of natural capital and ecosystem services. Natural capital refers to the Earth's natural resources and ecosystems, while ecosystem services encompass the benefits and functions these ecosystems provide to humans, such as clean water, pollination, and climate regulation. (Guerry et al., 2015). The Natural Capital Project (developed by Stanford University, the University of Minnesota, the Nature Conservancy, World Wildlife Fund, and the Chinese Academy of Sciences) is a pioneering initiative committed to achieving a delicate equilibrium between thriving ecosystems and robust economies in the face of escalating global challenges. This initiative stands out by offering decision-makers a distinctive software toolkit rooted in four transformative pillars, which employ scientific analysis and a holistic perspective encompassing economic, ecological, social, and cultural aspects. InVEST is an open-source, spatial analytical software that outputs results in either biophysical or economic terms (Zhong & Wang, 2017). The InVEST software provides a Crop Pollination Model which can be used to predict bee abundance in grid cells within a landscape (Lonsdorf et al., 2009; Sun et al., 2022). The InVEST Pollination model places a specific emphasis on the critical role played by wild bees in crop pollination, recognizing their significance alongside managed honeybee populations. This model assesses the landscape's suitability for supporting insect populations, taking into account the availability of nesting substrates and floral resources. It effectively translates the characteristics of land cover into an index reflecting bee abundance. This model outputs modified to evaluate pollinator habitat for coastal sage scrub can provide context to research into the effects of fire and large-scale habitat suitability. Through careful monitoring and research, conservationists and scientists can better understand the changes occurring in coastal sage scrub habitats and implement effective management strategies to protect and preserve these unique ecosystems.

The **Insect Pollinator Network Composition in Post-Fire Recovery of Coastal Sage Scrub** project evaluates the influence of several factors on the pollinating insect assemblage in post-fire CSS habitat in three sites in San Diego County. In this study, we are examining how burn interval or frequency, or abundance or distance of reservoir habitat may impact the diversity of flower-visiting insects. We approach this project through a combination of focal observation monitoring, application of the InVEST pollination model to evaluate honeybees versus all other insect pollinators, and ancillary video data collection to augment observations.

Methods

Site Selection

Sampling took place over ten weeks between June 12 and August 20, 2023, on three preserves owned by the Fallbrook Land Conservancy in the cities of Fallbrook and Bonsall, in northeastern San Diego County in southern California. Coastal Sage Scrub (CSS) is a plant community found along the coast of California from San Francisco into Baja Mexico. Sometimes called "soft chaparral", this community is found at lower elevations than chaparral, generally from sea level to 1000 meters. Plants in this community include low, woody, soft-leaved, drought-deciduous subshrubs, with grasses and forbs found in open areas. The community is named after its dominant species, California sagebrush (*Artemisia californica*). Southern sage scrub has three main subtypes primarily influenced by availability of moisture at different latitudes, with variations in plant species accordingly (*County of San Diego*, n.d.). Succession following disturbance by fire in CSS plant community results in high numbers of herbaceous annuals in the first growing season, with shrubs reaching more than 50 percent of plant cover by year 7, and many annuals, legumes and vines associated with the CSS community are no longer present 20 years after a burn (Westman, 1981).

While fire disturbance has been an important factor in maintaining biodiversity in CSS communities, historical and current human impacts, including grazing, climate change, and increasing development, have increased fire frequency, which can lead to type-conversion of CSS to invasive annuals (Fleming et al., 2009). We chose sites of varying burn interval and burn frequency to examine the impact of those factors on the associated insect assemblages. The three sites were P81 Rock Mountain, P82 Fairview and P83 Pala Mesa, all comprised predominantly of CSS habitat (**Figure 1**). To establish the burn history of the study sites, we reviewed historical CalFire data displayed in two different formats, covering the years 1898 to 2020 (Conservation Biology Institute, 2021) and 1878 to 2020 (Anderson, et al., 2021). The most recent burn site was P81, experiencing a burn less than one year prior in September 2022. P82 had a burn event in 2017 (6 years prior), and P83 had a burn event in 2007 (16 years prior) (**Table 1**). A historical perspective revealed that since 1900, P81 had witnessed 10 burn events, P82 had experienced three, and P83 had seen two burns. Burn data between 2020 and 2023 was provided by the preserve manager at Fallbrook Land Conservancy.

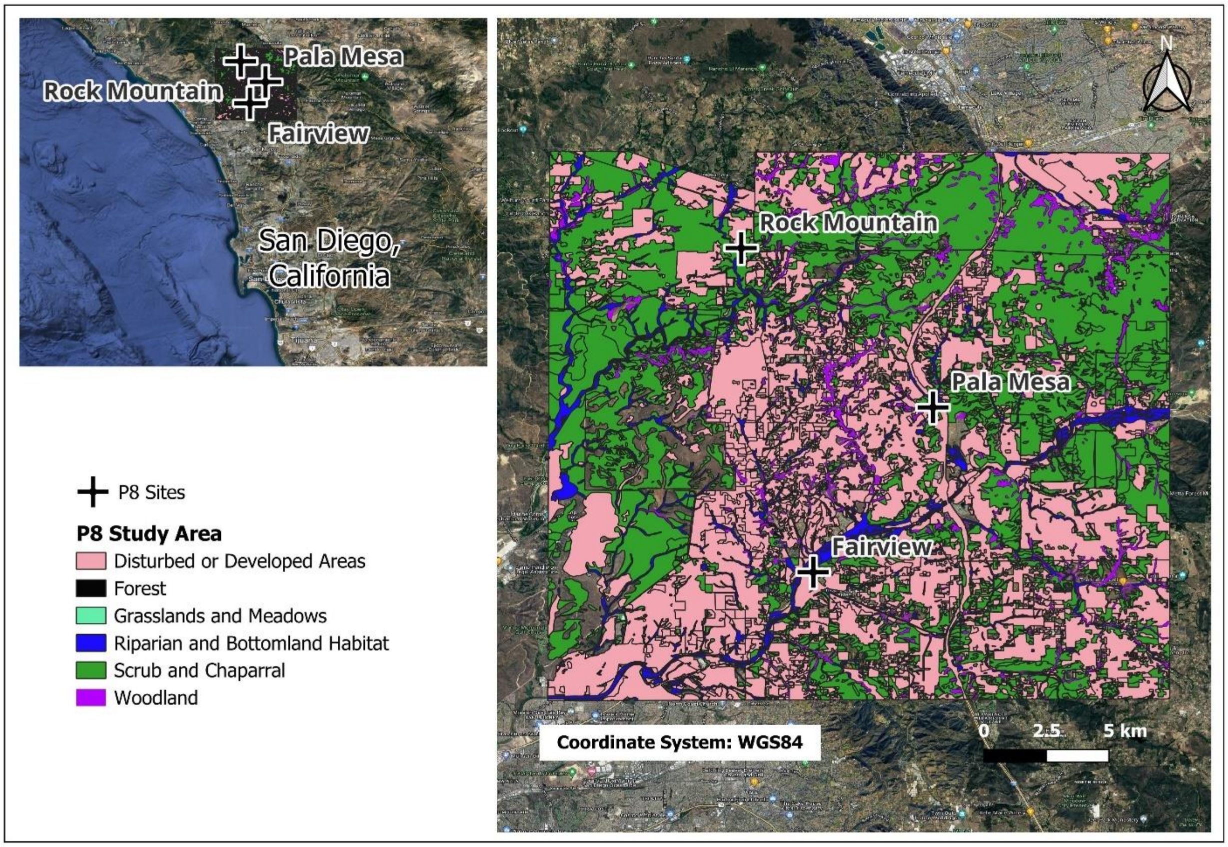

Figure 1: Project study area located in northern San Diego County. Sites are representative of varying degrees of burn int4erval and frequency and include P81 Rock Mountain (last burn in 2022), P82 Fairview (last burn in 2017), and P83 Pala Mesa (last burn in 2007). Land cover designations are overlayed to provide context for land use in the study area region.

Table 1: Details of burn interval and frequency for the P81 Rock Mountain, P82 Fairview and P83 Pala Mesa sites.

Site	Most Recent Burn year	Burn Interval (years)
P81 Rock Mountain	1911	pre-1900
	1945	34
	1953	8
	1955	2
	1968	13
	1969	1
	2002	33
	2007	5
	2018	11
	2022	4
P82 Fairview	2007	pre-1900
	2017	10
P83 Pala Mesa	1975	pre-1900
	2007	32

Insect Groupings

Of the approximately 30 orders of insects, the San Diego Pollinator Monitoring Program (SDPMP) focuses on 18 orders that include flower-visiting insects and the order Araneae, spiders, with the goal of producing a broad insect assemblage of pollinators of our target plant community, CSS (**Table 2**). Two large orders were further separated into families: *Apidae*, *Bombidae*, *Vespidae* and *Sphecidae* from order *Hymenoptera*, and *Syrphidae*, *Bombyliidae* and *Asilidae* from order *Diptera*. Non-native European honeybees (*Apis mellifera*) were coded separately from all other bees. *A. mellifera* is native to Africa or Asia and is now found on every continent except Antarctica. Brought to the United States for agriculture, it is known to produce negative effects on native bee populations, and on native plants (Iwasaki & Hogendoorn, 2022; Nabors et al., 2018; Travis & Kohn, 2023).

Table 2: Insect groupings used by the San Diego Pollinator Monitoring Program for collecting identification information. Group codes are assigned based on taxonomic category and examples of specific species included in the grouping code is indicated.

Grouping Code	Insect Grouping	Grouping Label	Examples
ARAN	Araneae	Spiders	
ARMA	Isopoda: Armadillidiidae	Pillbugs	
COLE	Coleoptera	Beetles	Flower longhorn beetle (S. emarginata), Tumbling Flower Beetle (Mordellistena spp.), Stink Beetle (Eleodes spp.), Darkling Beetle (A. pubescens), Black Rain Beetle (P. puncticollis), Asian lady beetle (Harmonia axyridis), Convergent Lady Beetle (Hippodamia convergens)
DASI	Diptera: Asilidae		Robber flies
DBBY	Diptera: Bombyliidae		Bee flies
DIPT	Diptera	Flies	Flies not otherwise categorized
DSYR	Diptera: Syrphidae		Hover flies, flower flies
FONA	Formicidae: native	Ants	Native ants -- California Harvester Ant (Pogonomyrmex californicus), Small Honey Ant/ winter ant (P. imparis), Field Ant (F. moki), Odorous House Ant (T. sessile),
FONO	Formicidae: non-native		Non-native ants - Argentine ant (Linepithema humile), Red Fire Ant / RIFA (S. invicta)
HANT	Hymenoptera: Clade Anthophila	Bees	Bees not otherwise categorized: Carpenter, Digger, mining bees (family Andrenidae), leafcutter bees (family Megachilidae), families Colletidae, Andrenidae, Halictidae, Melittidae
HAPI	Hymenoptera: Apis mellifera		Honey bees
HBOM	Hymenoptera: Bombus spp		Bumble bees
HEMI	Hemiptera	Bugs	True bugs -- aphids, leafhoppers, cicadas, Small Milkweed Bug (Lygaeus kalmii), Say's Stink Bug (C. sayi), Leafhopper (G. angulata)
HSPH	Hymenoptera: Sphecidae, Crabronidae		Thread-waisted wasps, mud dauber wasps
HVES	Hymenoptera: Vespidae		Yellow jackets (Vespula pensylvanica, V. vulgaris), paper wasps (Polistinae spp.), hornets, paper, mason (all social wasps found in this family)
LEPI	Lepidoptera	Moths	Moths, butterflies
MANT	Mantodea	Mantids	
NEUR	Neuroptera	Lacewings	
ODON	Odonata	Dragonflies, damselflies	
ORTH	Orthoptera	Grasshoppers	Grasshoppers, katydids, crickets
PHAS	Phasmatodea	Stick-insects	Stick-insects, walking sticks

The ant family *Formicidae* was separated from *Hymenoptera* and noted as native or non-native ant species, so that we could discuss the presence and activity of native ants within the context of the California super colony of Argentine ants (*Linepithema humile*). This distinction is important because the vast majority of ant species encountered are invasive Argentine ants, and they are more prevalent in areas with greater human activity (Van Wilgenburg, et al. 2010).

Finally, we noted spiders (order *Araneae*) which are not insects and have varied interactions and impacts on plant-pollinator networks, being incidental pollinators, but also predators of pollinating insects, and of plant-eating insects (Knauer, et al. 2018).

Discriminating between species can be challenging during field operations, so we obtained photographs of observed insects whenever possible to confirm identifications through use of our SDPMP photo database, iNaturalist. The three student researchers performing data collection at this site are part of the SDPMP and had approximately one year of experience monitoring insect pollinators at other CSS research sites. Each observer had two to three hours of field training with more senior student researchers, and they were given photographic and written references describing the insects and plants they may encounter.

In-Situ Focal Observations

We used two primary sampling methods: focal observations and camera traps. Focal monitoring occurred one to two times weekly on an approximately 50-meter transect at each site, using informal access trails as baselines. Monitoring was performed on successive 10-meter trail segments each visit and consisted of a five-minute observation of three abundant plants in bloom in the segment from the SDPMP master CSS plant list (**Table 3**). Monitors recorded each pollinator interaction during the five-minute period, which we define as an individual insect touching a flower in any way that it could gather pollen or deliver pollen.

Table 3: Codes and associated identifications for plants observed within the study area.

Code	Plant Common Name	Scientific Name
ACGL	Deerweed	*Acmispon glaber*
ACMI	Yarrow	*Achillea millefolium*
CAMA	Coastal morning glory	*Calystegia macrostegia*
CAWE	Weed's Mariposa lily	*Calochortus weedii*
CHGL	Pincushion	*Chaenactis glabriuscula*
ERCO	Golden Yarrow	*Eriophyllum confertiflorum*
ERFA	Buckwheat	*Erigonum fasciculatum*
MIAU	Bush monkeyflower	*Mimulus aurantiacus*
RHIN	Lemonade Berry	*Rhus integrifolia*
SAAP	White Sage	*Salvia apiana*
ZEVE	California centaury	*Zeltnera venusta*

All field data were digitally collected using Kobo Toolbox which allows for collection of monitoring data and images (Harvard Humanitarian Initiative, 2021). Focal observations were performed between 10am and 4pm. During a given observation period, researchers stood adjacent to the plant, and collected information on the frequency of flower-insect interactions. Insects were classified according to standard groupings used by all sites in the SDPMP (**Table 2**).

Video Observations

To augment the information obtained on pollinators within each site, we collected video from wildlife camera traps. Annotation of pollinators in videos can be used for collecting information on the temporal distribution of insects at a given site. Benefits also include the ability to collect data on night pollinators. We deployed a VOOPEAK Solar Powered Trail camera WiFi 4K 30 FPS 60MP Dual Lens game camera at each of the three selected sites. Cameras were refreshed with batteries and data were downloaded each time the team conducted a focal observation. Data were annotated by analysts using an AWS hosted version of DIVE, a server-based software tool that enables annotation within images or video (Costa et al., 2022; Dawkins et al., 2022). This involves the fine-scale tracking of all insects that are visible within videos, and grouping identification was only conducted if the analyst was confident in the categorical assignment, as identification is challenging with this method. Annotations of insect pollinators can be used for the development of deep neural networks using the associated software VIAME, though network training and development were not achieved during this project.

InVEST Crop Pollination Model

InVEST uses spatially explicit data for various ecosystem services models, including data on land use, land cover, climate, and habitat suitability, among others, to provide a comprehensive assessment of ecosystem services in a given landscape. These data are used to model and quantify the supply and distribution of services, helping decision-makers understand the value and trade-offs associated with land use and management decisions. The crop pollination model, adapted from Lonsdorf et al. (2009), was originally developed to provide relative information on the abundance and availability of wild bees and honeybees in the form of an index. Developers intended to evaluate the pollination service benefit to crops within a region and thus also includes a predicted yield function for agricultural areas. The index incorporates the following elements: landcover characteristics of a region, the suitability of various landcover categories for nesting, the availability of floral resources, and foraging distances for selected pollinator groupings. Users can distinguish these characteristics by season and by pollinator group. The model outputs suitability of habitat in the form of raster files of pollinator abundance factor, a "supply" index which is a per-pixel value that incorporates abundance factor, available floral resources, and flight distance, and farm-specific crop yield and pollinator abundance if selected. The model is flexible to user needs and can accommodate various combinations of pollinator metrics as long as required inputs are provided.

For this project, we focused explicitly on the pollinator supply index, and separated pollinators into two groups: honeybees (labeled as "bees" in figures) and all other insect pollinators. For the model land cover/land use map, we used the Ecology Geoglogy Flood shapefile available from SANDAG and extracted our study area from the shapefile. Land cover categories include Disturbed or Developed Areas, Forest, Grasslands and Meadows, Riparian and Bottomland Habitat, Scrub and Chapparal, and Woodland. The composition of land cover within a six-kilometer radius of each site was similar in terms of the percent of natural versus developed regions (**Figure 2**). Relatively similar land cover was noted across all sites, with the exception that

Rock Mountain and Pala Mesa contained a greater percent scrub and chaparral and Fairview contained more riparian habitat.

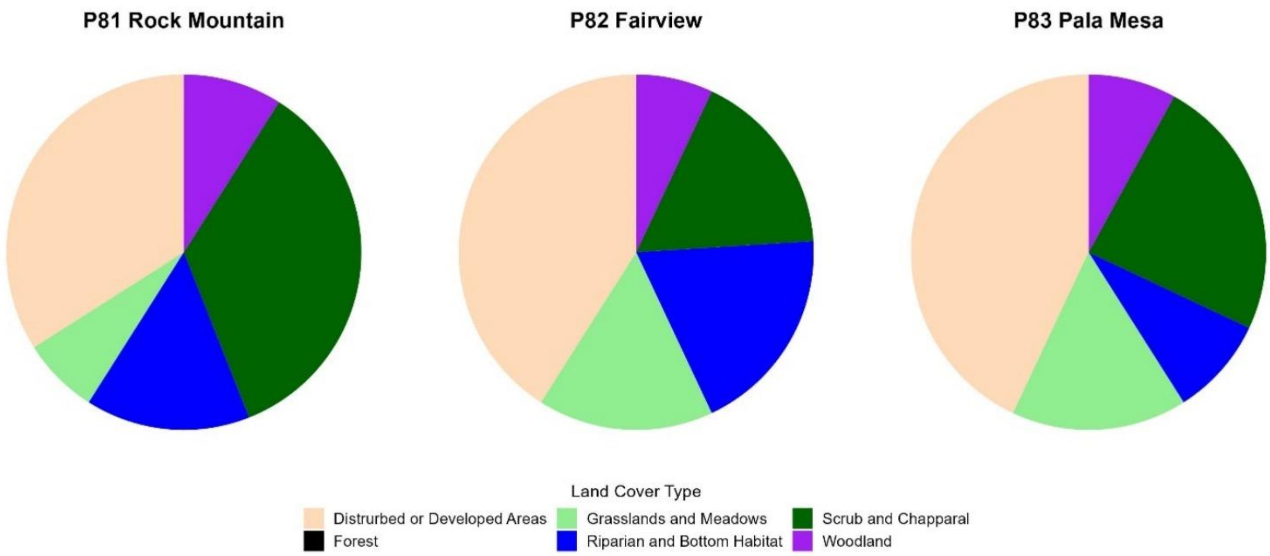

Figure 2: Land cover composition within a six-kilometer radius of each site.

For each of the land cover areas within the study area, estimates of nesting suitability and preferences, relative abundance, mean flight distance and available floral resources were provided. We used a value of 1 (on a scale of 0 to 1) for floral resource availability for all natural habitats, and 0.33 for developed area. Nesting availability index values varied for insects that use hives versus insects that use other nesting methods. For instance, within the "Grassland and Meadows" land cover regions, we assumed that nesting for bees would be minimal, given the low density of trees in these areas that hives attach to. We indicated a higher nesting suitability index for all other pollinators in these habitats due to the greater diversity in nesting strategies for all other pollinators. Foraging flight differences were significantly different for bees versus all other pollinators as honeybee flights can extend to several kilometers (Beekman & Ratnieks, 2000; Gathmann & Tscharntke, 2002). Given the population dynamics of pollinators is not known for all species and habitats within the study area, we made assumptions based on the general knowledge of pollinator habitat preference and the possibility of nesting in each land cover type.

Data management tasks associated with using InVEST occurred for model inputs and outputs. Land cover is required in a raster format for InVEST requiring transformation of the SANDAG polygon shapefile. Additionally, the output of the model supply index raster file did not accommodate the GIS dashboard requirements we were limited by, requiring the transformation of the ouptut raster files into fine-scale grided polygon shapefiles. A further data management step included extracting the land cover and supply index values for a six-kilometer radius surrounding each site (the foraging distance used for "bees"). This information was used to further characterize the sites. Details of the input files used for the Crop Pollination Model can be found in the "InVEST_Data" folder on the GitHub Repository.

Data Summarization and Analysis

Data were summarized for each site including details of the burn history, total pollinator activity, number of insect groupings and most common native insect groups observed. Plant and insect diversity was assessed using various metrics. Species richness, a simple metric, is determined by counting the number of unique species present in a sample. This metric provides a basic measure of biodiversity. We utilized two index metrics for assessing biodiversity at each site. The Shannon-Wiener Diversity Index takes into account both species richness and the relative abundances of species within a community. It is calculated using the formula $H' = -\Sigma (P_i * \ln(P_i))$, where Pi represents the proportion of individuals belonging to the i-th species. Higher values of H' indicate greater diversity, reflecting both species richness and evenness in abundance. The Simpson Reciprocal Index (1/D) is used to quantify diversity within a community, with higher values indicating greater diversity. The formula used for this calculation is 1-D, where D is the Simpson Diversity Index (or Gini-Simpson Index) calculated as 1 minus the sum of the squared proportions of each species in the community [(∑(pi^2)), where pi represents the proportion of individuals belonging to the i-th species]. Values close to 0 indicate low diversity, meaning few species dominate the community, and values close to 1 suggest high diversity and indicate that species are more evenly distributed.

Additionally, we incorporated an index value for assessing species evenness at each site. The Shannon Equitability Index, a component of the Shannon-Wiener Diversity Index, focuses specifically on evenness. It is calculated as $E = H' / H'max$, where H'max is the maximum possible diversity for the given number of species. The Shannon Equitability Index provides insights into how evenly individuals are distributed among species in a community. Values close to 1 suggest a more even distribution of individuals among species, while values closer to 0 indicate a less even distribution. We calculated these three indices for both insect and plant groups. These metrics collectively provide insights into the richness, evenness, and structure of plant and insect communities, aiding ecologists and conservationists in understanding and preserving biodiversity within ecosystems.

ArcGIS Online Dashboard

ArcGIS Online dashboards offer a powerful tool for relaying and communicating environmental science information. They enable the creation of interactive, visually engaging displays of data, maps, and analyses, facilitating clear and accessible communication of complex environmental findings to diverse audiences, from researchers and policymakers to the general public. Additionally, these dashboards can promote data-driven decision-making, enhance collaboration, and foster a deeper understanding of environmental issues by providing real-time, location-based insights in an accessible format. For this project, we enlist the use of an ArcGIS online dashboard for communicating information on the project in an engaging manner. The dashboard includes several figures regarding the results of focal observations, the iNaturalist Project portfolio of images and identifications, and the InVEST model results for the entire region of our study area.

Results

In-Situ Data Collection

Data collected during this project successfully documented the insect-plant interactions associated with the three CSS sites. We collected focal observation data on 15 site visits and acquired collectively over 60 hours of video footage. In the period from June to August 2023, focal observation efforts were conducted in all three locations, including 15 days for both P81 and P82 and 6 days for P83. Video was collected from P81 and P82, but the wildlife camera from P83 was stolen at the start of the project effort. Additionally, the available video footage required extensive data management due to the recording duty cycle, operational issues that were associated with batteries, and changes in analyst availability for annotating. Research analysts annotated approximately one percent of the data at the time of project completion, therefore those results are not considered in the following details.

The results of the focal observation effort include a summary of insect group activity and an assessment of biodiversity and evenness for all sites (**Tables 4 and 5**, respectively). Insects that did not interact with a focal plant were not incorporated in these results as they did not contribute to pollination. Focal observations resulted in a total of 318 observations of insect groups interacting with plants and a total of 4,844 interactions between those insects and plants across all sites (**Table 4**). **Figure 3** indicates the total counts of insect groups observed at each site, broken out by “bees” and “all other pollinators.” To evaluate pollination activity at these sites, this table reports the amount of interaction that occurred by these insects, as opposed to the counts of insect groupings. Non-native honeybees and Argentine ants accounted for 43.9 percent and 46.3 percent of all insect-plant interactions, respectively. After removing honeybees and Argentine ants from the count, 474 insect pollination interactions were recorded, with P81, P82, and P83 contributing 367 (12.8 percent), 76 (4.3 percent), and 31 (14.5 percent) interactions, respectively. Interestingly, the composition of these interactions varied significantly, with honeybees accounting for 9 percent of interactions in P81, a dominant 96 percent in P82, and 86 percent in P83. Conversely, Argentine ants played a substantial role in P81 (78 percent of interactions) and were absent in P82 and P83. We observed a diverse array of insect groupings interacting with plants, with 12, 11, and 7 distinct groups observed in P81, P82, and P83, respectively. Notably, native ants emerged as the most common native insect group observed in P81 (8 percent), while native bees held a minor role at 1 percent. In P82, beetles made up 5 percent of native insect groups, while in P83, native ants (3 percent) and native bees (2 percent) played key roles in the observed interactions. Finally, **Figure 4** indicates the distribution of interactions by plant species across all insect groupings. Pollinators interact with a greater diversity of plants at P81 as compared to P82 and P83. Buckwheat (*Erigonum fasciculatum*) was pollinated most frequently and across all sites. These results provide valuable insights into the dynamics of pollination interactions across these three distinct locations.

Table 4: Summary of focal observation data for the post-fire pollinator project. This data summarization emphasizes the interactions between insect groups and plants and highlights the role of native and non-native groupings.

Period: June - August 2023	**P81 Rock Mountain**	**P82 Fairview**	**P83 Pala Mesa**	**Total**
# of days monitored	15	15	6	
Most recent burn	Sep-22	2017	2007	
	(< 1 year prior)	(6 years prior)	(16 years prior)	
Burn frequency since 1900	10	3	2	
Total pollination interactions	2870	1760	214	4844
Total native insect pollination interactions observed (honeybees and Argentine ants removed)	367 (12.8%)	76 (4.3%)	31 (14.5%)	474 (9.8%)
% of interactions by Honeybees (A. mellifera)	9%	96%	86%	44%
% of interactions by Argentine ants (L. humile)	78%	0%	0%	46%
# of insect groupings observed interacting with plants	12	11	7	30
Most common native insect group observed	Native ants 8%	Native bees 1%	Beetles 5%	Native ants 3%; Native bees 2%

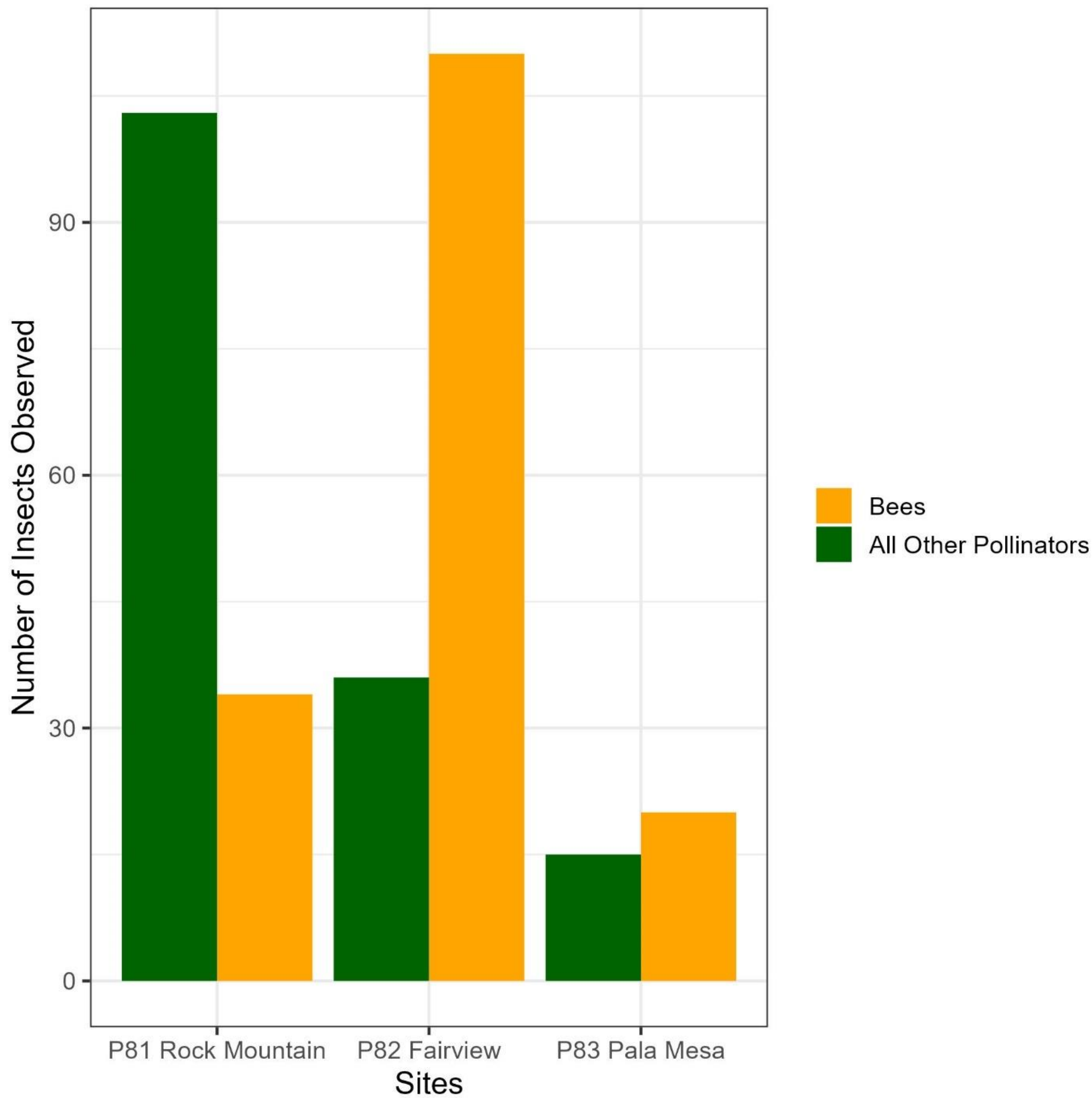

Figure 3: Counts of insect group observations at each site for “Bees” and “All Other Pollinator” insects. These data do not consider the number of interactions of those insect observations, just the occurrence of a specific insect group.

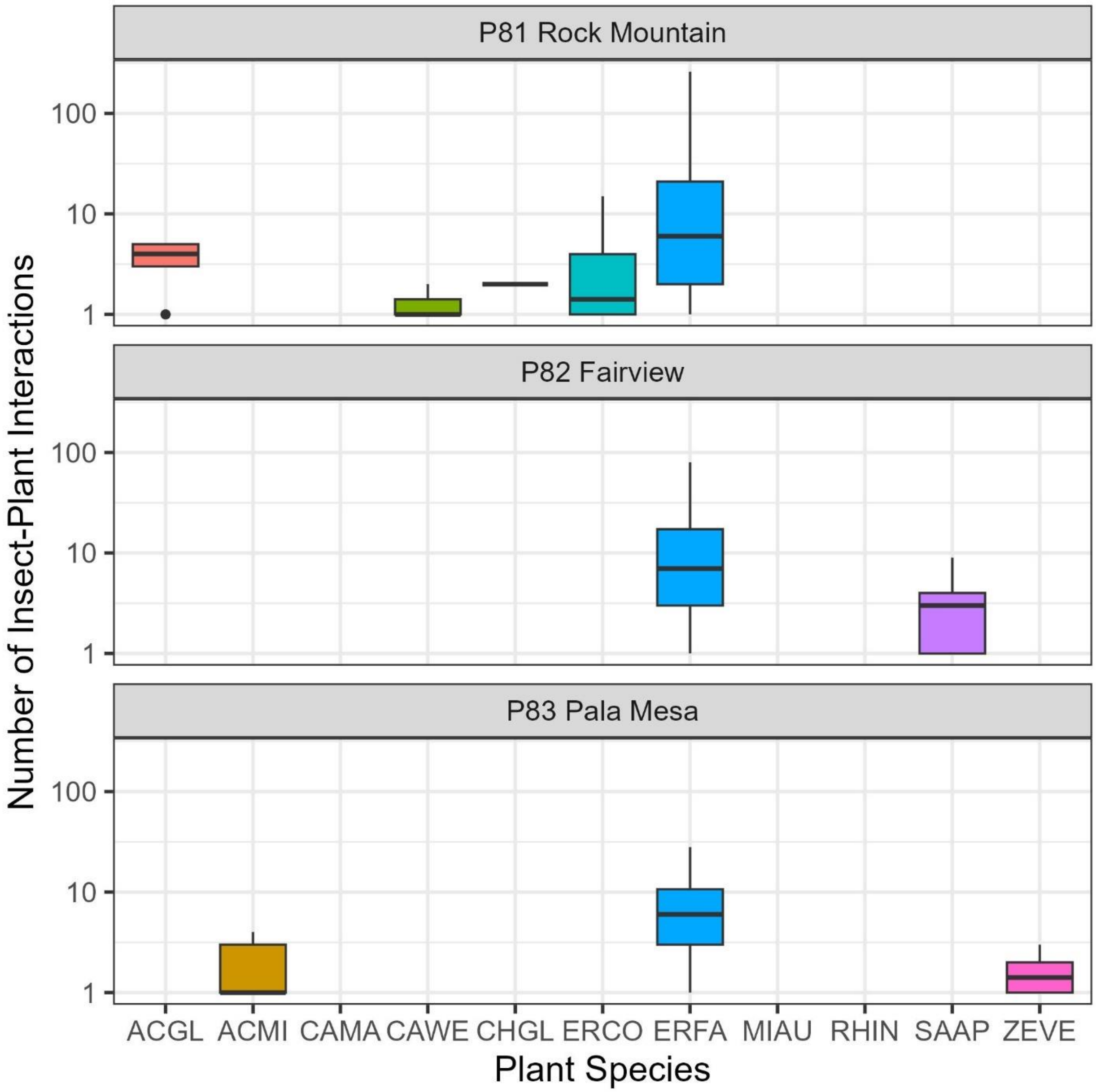

Figure 4: Number of interactions in association with plant species for all sites. Plant species codes are indicated and described in Table 3 of this report. Interaction counts are summarized for all species groups.

In assessing diversity based on insect-plant interactions and insect group counts at sites P81 Rock Mountain, P82 Fairview, and P83 Pala Mesa, some notable similarities and differences emerge (**Table 5**). P81 consistently exhibits greater diversity in both insect assessment approaches compared to the other two sites. The Shannon Diversity Index (H) for insect-plant interactions is highest at P81 (0.83), followed by P83 (0.64), with P82 having the lowest value (0.25). Similarly, when examining insect group counts, P81 maintains higher diversity (H = 2.14), outpacing P83 (H = 1.35) and P82 (H = 1.03). Furthermore, when considering evenness (E_H), P81 displays the highest evenness in both insect-plant interactions (E_H = 0.36) and insect group counts (EH = 0.86), indicating a more balanced distribution of species within the community. However, nuanced observation emerges when considering insect grouping counts as opposed to interactions. In this context, the diversity between P82 and P83 becomes more comparable, with P82 having slightly higher diversity across all three diversity metrics (H, E_H, and 1-D) in the insect group count approach.

Table 5: Calculation of diversity and evenness values for insects and plants at all sites. The insect measurements are assessed in two ways, based on the number of insect-plant interactions and subsequently on the number of insect group counts.

DIVERSITY BASED ON NUMBER OF INSECT-PLANT INTERACTIONS			
	P81 Rock Mountain	P82 Fairview	P83 Pala Mesa
Shannon Diversity Index (H)	0.83	0.25	0.64
Shannon Equitability Index (E_H; evenness)	0.36	0.11	0.32
Simpson's Diversity Index (1-D)	0.38	0.08	0.26
DIVERSITY BASED ON INSECT GROUP COUNT			
	P81 Rock Mountain	P82 Fairview	P83 Pala Mesa
Shannon Diversity Index (H)	2.15	1.03	1.35
Shannon Equitability Index (E_H; evenness)	0.87	0.43	0.69
Simpson's Diversity Index (1-D)	0.87	0.45	0.65
PLANT DIVERSITY			
	P81 Rock Mountain	P82 Fairview	P83 Pala Mesa
Shannon Diversity Index (H)	0.74	0.28	0.84
Shannon Equitability Index (E_H; evenness)	0.38	0.2	0.76
Simpson's Diversity Index (1-D)	0.31	0.12	0.49

In terms of plant diversity, P83 exhibits the highest diversity (H = 0.84) among the three sites, followed by P81 (H = 0.74), while P82 has the lowest plant diversity (H = 0.28). Interestingly, the evenness (E_H) of plant species distribution is somewhat similar across all sites, suggesting a balanced distribution of plant species within each community.

In summary, P81 Rock Mountain consistently demonstrates greater insect diversity in both assessment approaches but stands out for its higher diversity when considering insect group counts and evenness. However, when focusing on insect grouping counts, the diversity gap between P82 and P83 narrows. Additionally, P83 Pala Mesa leads in plant diversity, indicating variations in ecological patterns among these sites.

InVEST Results

Model results from the InVEST analysis revealed interesting trends in the supply of pollinating insects. **Figures 5-7** report the supply index for “Bees” and “All Other Pollinators” for each site. These values were converted from the raster output of the InVEST model to a polygon file to accommodate ArcGIS online requirements with values summarized into approximately 47 meter squared values across the study area. The gridded values each contain a supply value which was summarized and for use in the distribution **Figure 8**. For all sites, the “Bee” supply was predicted to exceed the “All Other Pollinator” supply. The model results for P81 contained slightly less data due to a limit on the land cover shapefile information which was limited to San Diego County (Figure 5). Land cover type influences the supply index for both categories, as there are differences in the inputs regarding forging distances and availability of nesting habitat. The distribution of supply values for each six-kilometer area surrounding a site revealed that supply for “Bees” and “All Other Pollinators” is predicted to be greater at the P81 site as compared to the P82 and P83 sites, which had similar predictions of pollinator supply.

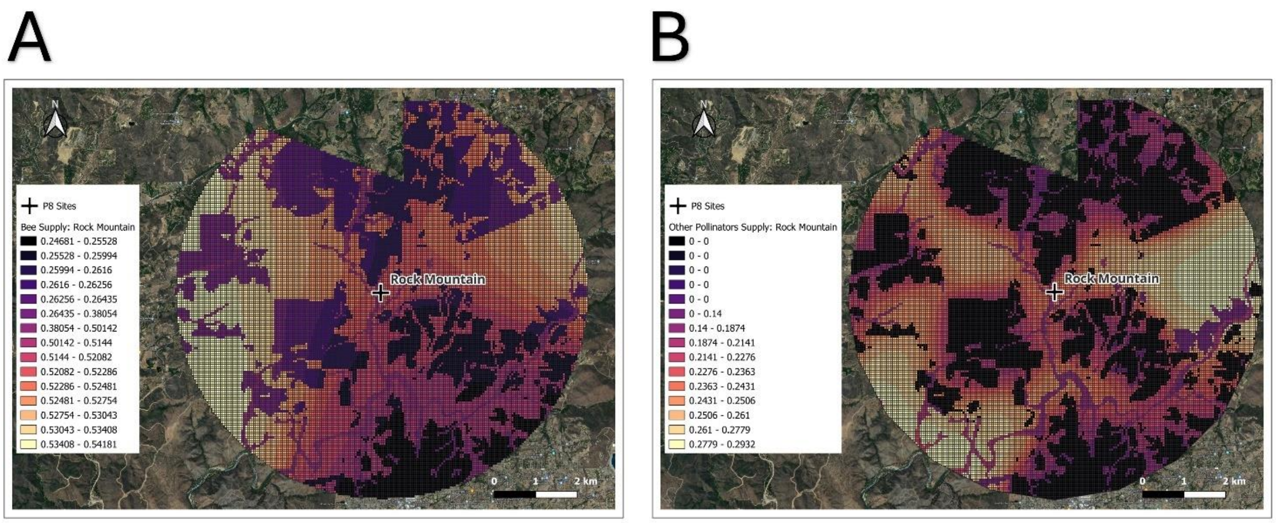

Figure 5: Supply index for “Bees” (A) and “All Other Pollinators (B) at the P81 Rock Mountain site. Values ranging from 0 to 1 indicate a predicted relative abundance of each insect category that incorporates information on land cover, nesting habitat, and floral resources in the estimates. The values extend to a six-kilometer radius surrounding each site.

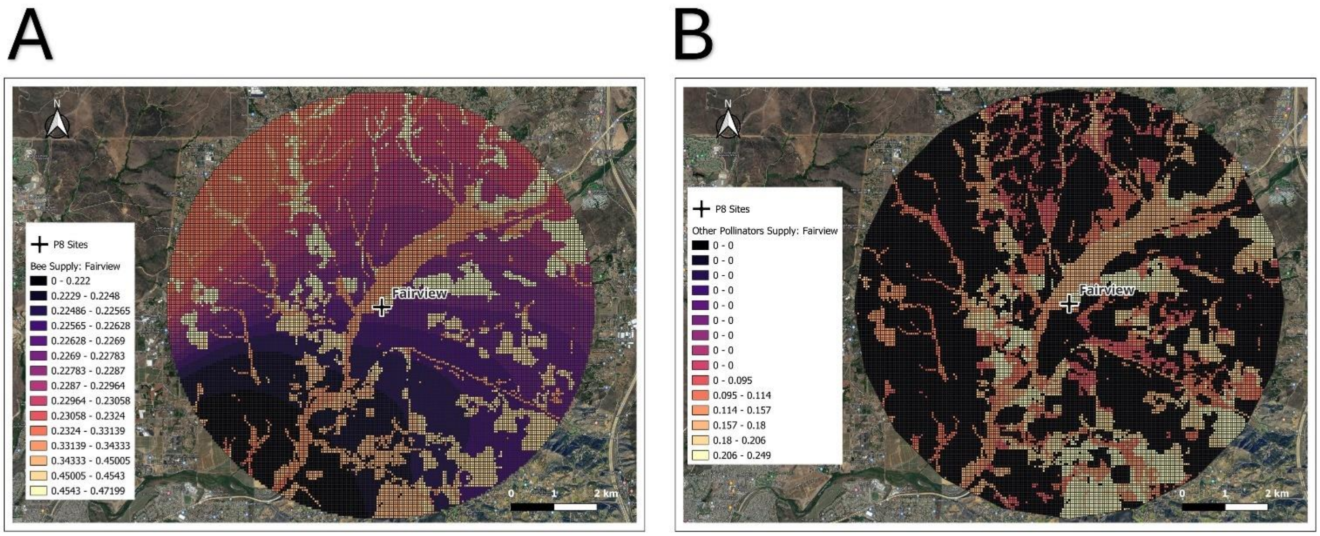

Figure 6: Supply index for "Bees" (A) and "All Other Pollinators (B) at the P82 Fairview. Values ranging from 0 to 1 indicate a predicted relative abundance of each insect category that incorporates information on land cover, nesting habitat, and floral resources in the estimates. The values extend to a six-kilometer radius surrounding each site.

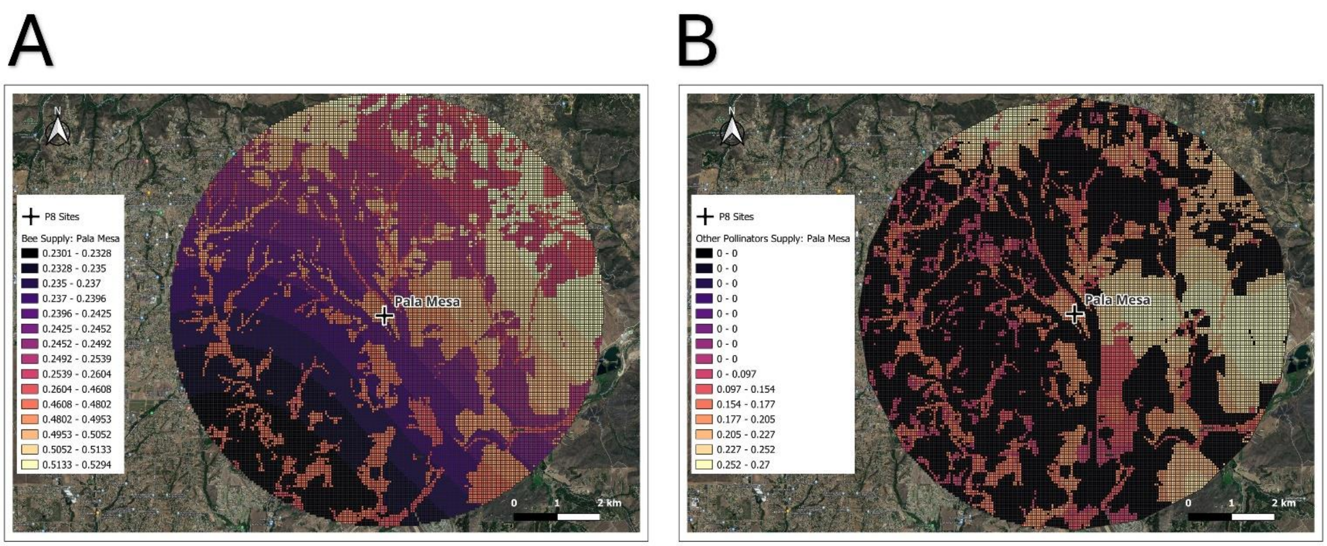

Figure 7: Supply index for "Bees" (A) and "All Other Pollinators (B) at the P83 Pala Mesa. Values ranging from 0 to 1 indicate a predicted relative abundance of each insect category that incorporates information on land cover, nesting habitat, and floral resources in the estimates. The values extend to a six-kilometer radius surrounding each site.

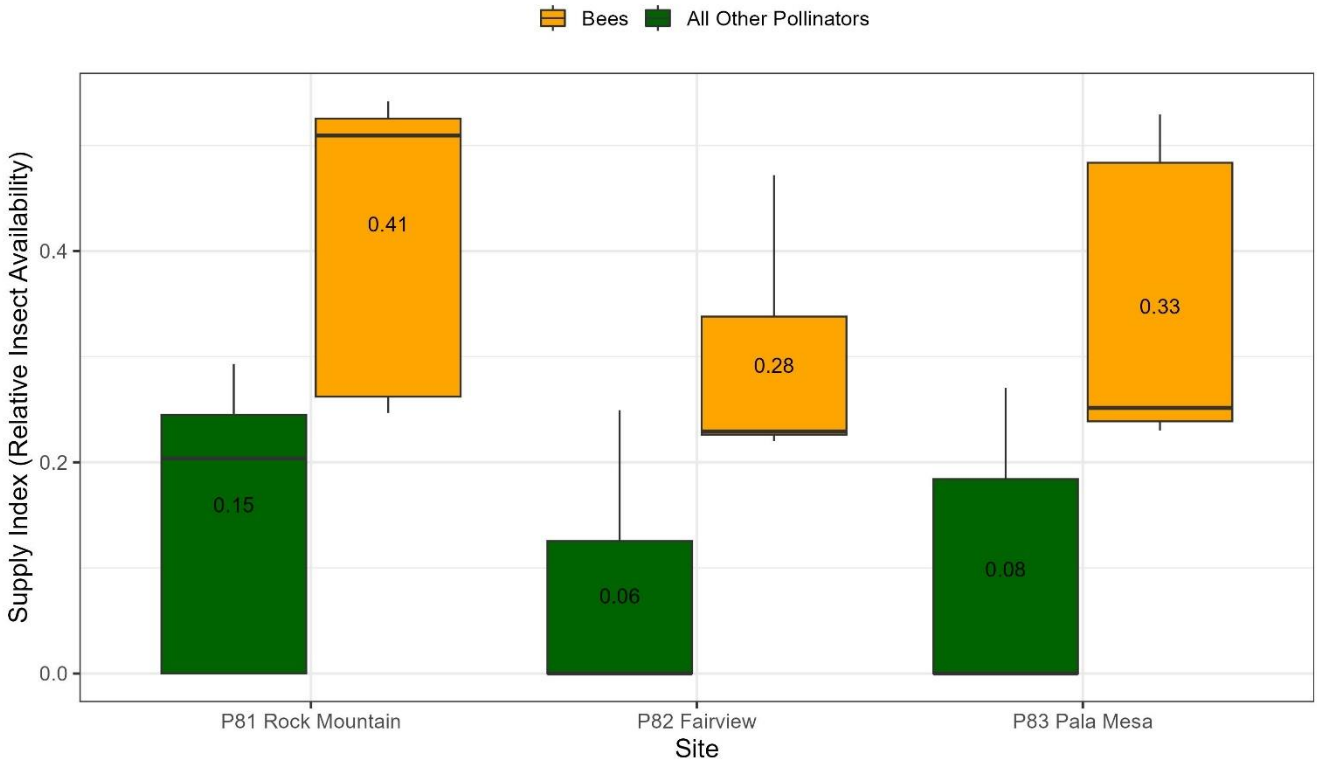

Figure 8: Distribution of supply index values within six-kilometer radius surrounding each site for "Bees" and "All Other Pollinators."

It is important to emphasize that these models do not account for fire occurrence and are representative of a relative abundance of insects within each region based on land cover, nesting habitat, and availability of floral resources. Observation data and model analysis were conducted blindly, so the InVEST inputs were identified without insight from the focal observation data.

ArcGIS Online Dashboard

The "[San Diego County Post-Fire Pollinators]" dashboard provides a summative, interactive online resource for project results. In addition to key figures reported here, the dashboard includes a hyperlink to the iNaturalist project highlighting interesting insect observations and the model results for the entire study area. Using ArcGIS Online's mapping features, users can interact with the model result and land cover layers to further explore the data.

Discussion

Post-Fire Pollination

Effect of Burns on Insect Assemblage

In this study, we set out to investigate how the frequency and timing of burns may influence the diversity of flower-visiting insects within three distinct sites: P81 Rock Mountain, P82 Fairview, and P83 Pala Mesa. Surprisingly, our data did not reveal a straightforward association between burn interval or frequency and insect diversity. According to intermediate disturbance theory, one might expect P82, with fewer and less recent burns than P81, to exhibit the highest biodiversity. However, our findings defied this expectation, as P82 displayed the lowest diversity across all measurement parameters for insects and plants. Despite experiencing only two burns since 1900, which occurred just ten years apart, P82's plant cover was dominated by invasive exotic annuals, underscoring the complex interplay between fire history and invasive species in shaping diversity patterns. This discrepancy hints at the complex dynamics of CSS habitats, where the highly degraded plant community at P82 may not necessitate large or frequent fires for invasive exotic annuals to proliferate.

While observing these sites, we noted varying levels of both plant and insect diversity. P81 Rock Mountain stood out with relatively high plant diversity and the greatest insect diversity, as indicated by both Shannon and Simpson's diversity indices. Notably, buckwheat (*E. fasciulatum*) emerged as the most abundant blooming plant across all sites during most site visits. Even at P81, which experienced the most recent and frequent burns, *E. fasciulatum* remained the dominant blooming CSS plant, highlighting its resilience and importance in early succession within the CSS plant community. Insect diversity, whether based on insect-plant interactions or insect group counts highlights similar trends for the sites. In addition to the notable high diversity and evenness at P81, the results suggest P82 exhibits lower insect diversity and evenness than P83.

Interestingly, the presence of *A. mellifera* (honeybees) strongly influenced the Simpson's index at all locations, including P81, where both *A. mellifera* and *L. humile* (Argentine ants) played a role in shaping insect diversity. Even though the proportion of *A. mellifera* was lower at P81 than at other sites, the actual count of interactions was similar to that observed at P83 Pala Mesa. Upon excluding non-native *A. mellifera* and *L. humile*, we identified the most abundant insect groups as Coleoptera, Diptera, Lepidoptera, and native bees. Moreover, the intriguingly low proportion of *A. mellifera* at P81 warrants further investigation. It may be attributed to direct mortality and hive loss following a recent burn. However, P81 also harbors a substantial population of invasive *L. humile*. Research by Miner and Rankin (2023) suggests that Bombus species may be deterred from foraging by chemical cues emitted by ants. This observation opens the door to potential future research into the response of *A. mellifera* to the presence of *L. humile*, providing further insights into the intricate dynamics of these insect communities.

Effect of Reservoir Habitat on Insect Assemblage

We also explored the potential influence of the abundance and distance of reservoir habitats on biodiversity at our three selected study sites: P81 Rock Mountain, P82 Fairview, and P83 Pala

Mesa. We observed similarities in the types of habitats surrounding all three sites and a similar proportion of developed/disturbed land use. However small differences exist in the extent and fragmentation of different natural habitats at each site. The land cover by site (Figure 2) indicates that P81 contains the greatest abundance of scrub and chapparal of all sites. We also observed a lower percentage of scrub and chaparral but higher riparian habitat at P82 as compared to P83, which suggests greater fragmentation of CSS habitat. However, it's important to acknowledge that a more detailed classification of our data or a wider radius of analysis may reveal a more pronounced effect. One intriguing observation is the presence of several large, managed open space preserves near P81 Rock Mountain, such as Santa Margarita, Santa Rosa Plateau, Cleveland National Forest, and the military site Camp Pendleton, which boasts extensive areas of CSS and chaparral habitat. These larger, contiguous habitat reservoirs could potentially offer better-quality resources for native insect pollinators, which might explain the higher biodiversity observed in this region.

Interestingly, neither the abundance nor the proximity of burn reservoir habitat seemed to explain the significant drop in biodiversity observed at P82 Fairview. Our data did not further categorize the Developed/Disturbed land use category into subcategories based on the type of development. A promising avenue for future research would involve examining whether different types of developments contribute to the dominance of *A. mellifera* at P82. For instance, the city of Fallbrook, which encompasses P82, has historically developed through agriculture, and its community plan emphasizes a rural and agricultural character (San Diego County, 2012). Given that *A. mellifera* is a domesticated, managed insect widely used in North American agriculture, it is plausible that these bees are being utilized on farms surrounding the preserve sites and subsequently foraging within the preserves. California state law mandates the registration of *A. mellifera* hives, making it possible to collect data on the extent of farmland surrounding each site and whether these farms employ managed hives—a potential avenue for further investigation.

Comparison of In-Situ Data to Ecosystem Services

Ecosystem services and the InVEST models are an important resource for understanding the valuation of natural capital accounting, and specifically the value of habitat preservation in this project. We see in the model results that the P81 has the potential to support a greater supply of both “Bees” and “All Other Pollinators” as compared to the P82 and P83 sites when fire is not considered. Though fire frequency has increased over the last few decades, the higher diversity at site P81 Rock Mountain may indicate that natural habitats in southern California can maintain biodiversity if they have adequate reservoir habitats available. Appropriate reservoir habitat would be large, contiguous areas of the dominant plant communities, in this case Coastal Sage Scrub and Chaparral. Conversely, the Crop Pollination model results suggests that increased development and habitat fragmentation has a negative impact on the diversity of insect assemblages. As a healthy abundance of native insect pollinators is directly connected to successful plant reproduction, the impact of development on insect assemblages should be further investigated (Nabors et al., 2018). We furthermore encourage the use of InVEST’s crop pollination model for understanding the contribution of land cover, nesting habitat, and floral resources of insect pollinators.

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