Channel Islands Mammals: A Gap Analysis of Specimen and Observation Data

Final Report

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INTRODUCTION

The mammal fauna of the California Channel Islands is dominated by distinct species and subspecies that have evolved from their mainland counterparts as they adapted to island conditions. The native peoples on the Northern and Southern Islands (Chumash and Tongva respectively) likely aided the transport of several of these animals, such as the Island Fox and Deer Mouse (Collins 1991a, Rick et al. 2009, Walker 1980, Wenner and Johnson 1980). It is a generally depauperate fauna, however, absent of many species that are common on the mainland such as rabbits, squirrels, gophers, moles, woodrats, and coyotes (McEachern et al. 2016).

Through a sequence of European exploration, squatters, and more permanent ranchers and settlers from the 1500s into the 1900s, 21 different non-native mammals were introduced to the Channel Islands (McEachern et al. 2016). Domestic Goats (*Capra hircus*) were one of the first to arrive, followed by European Mouflon Sheep (*Ovis vignei*), and Domestic Cattle (*Bos taurus*), and later joined by American Bison (*Bos bison*), Mule Deer (*Odocoileus hemionus*), Feral Pigs (*Sus scrofa*), and a host of other mammals. The severe and sustained grazing pressure on these maritime but arid islands converted much of the native shrubland to invasive annual grassland and bare, eroded slopes. Meanwhile, introduced predators such as Domestic Cats (*Felis catus*) and Black Rats (*Rattus rattus*) wreaked their own havoc.

More than ten populations of native, non-volant mammals have been extirpated or gone extinct on the California Channel Islands and Pacific Baja California Peninsula Islands in Mexico, resulting from either non-native mammal predators or habitat degradation by non-native herbivores (or both; Knowlton et al. 2007). Recognition of these devastating effects have led to the eradication of 44 populations of non-native mammals from 19 California islands by 2007 (Knowlton et al. 2007). Introduced grazing mammals have been removed or reduced from all of the Channel Islands except for Santa Catalina, which still has American Buffalo and Mule Deer. In addition, House Mice remain on Santa Catalina and San Clemente, and Black Rats remain on San Miguel, Santa Catalina and San Clemente. Feral cats were eradicated from San Nicolas in 2009–2010 (Hanson et al 2010, Ramsey et al. 2011) but are still present on Santa Catalina and San Clemente.

Miscellaneous mammal specimens were collected for museums starting in the late 1800s, but substantial collections weren't made until 1939, when the Los Angeles County Museum launched the Channel Islands Biological Survey. This was an historic interdisciplinary research expedition investigating the biology, geology, archaeology, and paleontology of all eight islands. The expedition proceeded until 1941, before getting cut short by World War II (Comstock 1939, 1946). Jack C. von Bloeker Jr. published accounts describing the Anacapa Island Deermouse (1942a), Santa Rosa Island Deermouse (1940), and Santa Catalina Ornate Shrew (1942b). He also published an overview article describing the land mammal fauna of the Southern California Channel Islands (1967).

Channel Islands National Monument was created in 1938, encompassing Anacapa and Santa Barbara Islands; this was extended to include San Miguel, Santa Rosa, and a portion of Santa Cruz Island with the creation of the Channel Islands National Park in 1980 (National Park Service 2021), which initiated an ecological monitoring program shortly thereafter (Davis 1994). An extensive natural resources study of the Channel Islands National Monument published in 1979 greatly increased our knowledge of island animals and plants, and contributed large numbers of specimens to science (Power 1979). Scientific research was further facilitated with the establishment of the University of California Field Station on Santa Cruz Island in 1965 (Powell 1985).

This study aims to synthesize Channel Islands mammal specimen and observation data, and to identify spatial, temporal, and taxonomic gaps that can inform and help to prioritize future research. The review below of key mammal taxa and scientific studies of them on the Islands will provide some background to the study results that follow.

Endemic and Rare Mammal Taxa

The Deermouse (*Peromyscus maniculatus*) is the most widespread, ubiquitous rodent in North America, and has eight endemic subspecies on the California Channel Islands – one on each of the Islands (von Bloeker 1967, Collins 1979). A large number of Deermouse specimens were collected in the late 1970s as part of a natural resources study of the Channel Islands National Monument led by the Santa Barbara Museum of Natural History (Collins 1979). This study provided comprehensive information regarding the biology of the Deermouse on Anacapa, Santa Barbara, and San Miguel islands, including reproduction, food habits, distribution, and abundance. It revealed that Santa Barbara Island supports a high population density relative to mainland populations, likely due to lack of competition with other rodents. It also showed significantly lower trap success on islands with introduced Black Rats (Anacapa and San Miguel). Pergams and Ashley (2002) used mitochondrial DNA samples collected between 1983 and 1985, as well as fresh tissue samples, to conduct a genetic study of Island Deermice, finding genetic isolation and independent evolution of five island subspecies. They also conducted a morphometric analysis using museum specimens collected over the past century, finding strong morphological differentiation in three island subspecies and extremely rapid change in several character traits over this time period.

Both the Santa Catalina Island Deermouse (*Peromyscus maniculatus catalinae*) and Santa Catalina Island Harvest Mouse (*Reithrodontomys megalotis catalinae*) were studied in six plant communities on Catalina Island in 1986 (Perlmutter 1993). Both were found to be widely distributed on the island and particularly abundant in maritime desert scrub habitat (Perlmutter 1993). Collins (1987) studied the Santa Cruz Island Harvest Mouse (*Reithrodontomys megalotis santacruzae*) at Prisoner's Harbor in the 1980's. Drost et al. (2009) sampled both the Santa Cruz Island Deermouse (*Peromyscus maniculatus santacruzae*) and Santa Cruz Island Harvest Mouse (*R. m. santacruzae*) on Santa Cruz in 2004 and 2006 in order to evaluate their population status following the removal of non-native sheep and pigs. Whereas Harvest Mice were previously known only from Prisoner's Harbor and a few isolated locations in the Central Valley, the later surveys revealed populations throughout the island and in greater abundance. Deermice had also increased in abundance on Santa Cruz Island relative to previous surveys.

Two extinct species of *Peromyscus* are known from the islands via fossils and subfossils: *P. anyapahensis* from Anacapa Island, and *P. nesodytes*, the "giant mouse", from Santa Rosa and San Miguel (Wilson 1936). Both of these species are larger than most fossil *Peromyscus*, which are in turn larger than today's subspecies. *P. nesodytes* may have coexisted with the extant subspecies on San Miguel Island until its extinction (Shirazi 2017). Other fossil mammals include Columbian mammoths (*Mammuthus columbi*) and pygmy mammoths (*Mammuthus exilis*) (Agenbroad 2009; Muhs 2015), an extinct vampire bat in the genus *Desmodus* (Guthrie 1980), and an extinct species of vole on San Miguel Island (Guthrie 1993, 1998).

The Santa Catalina Island ground squirrel is the largest native herbivorous rodent and one of the only burrowing mammals on the Channel Islands. Its burrowing activities provide colonization sites for plants as well as habitat for species such as the burrowing owl, frogs, lizards, snakes, and a variety of insects (Snow 1973; Lidicker 1989; Schiffman 2007; Van Horne 2007). Although this species has been sporadically captured in previous trapping efforts on the island, little is known about its distribution, abundance, and population dynamics.

Island Spotted Skunks (*Spilogale gracilis amphiala*) are currently found on Santa Cruz and Santa Rosa, and occurred in the past on San Miguel (Walker 1980). Study of this taxon increased in the 1990's, as population increases were observed (Crooks and Van Vuren 2002; Jones et al. 2008; Collins and Latta 2009). Van Bloeker (1967) reported that Island Spotted Skunks were once very common on Santa Cruz and Santa Rosa Islands, but by the 1960s they were rarely seen. Skunk populations then increased exponentially between 1992 and 2004 (Crooks and Van Vuren 2002; Jones et al. 2008), linked to a decline in their competitor, Island Foxes (discussed below). Floyd et al. (2011) investigated museum specimens and collected fresh specimens and tissue from 2000 to 2002 for a study of genetic variation in this species using microsatellites. They found strong genetic differentiation both between the two islands with extant populations and between the islands and the mainland.

The Catalina Island Ornate Shrew (*Sorex ornatus willetti*) had been sighted or captured only fourteen times on the island between 1942 and 2005, despite several focused surveys (Collins and Martin 1985; Aarhus 2005). This endemic shrew is one of the most genetically distinct and endangered of the seven subspecies of ornate shrew in southern California and Baja California, Mexico (Maldonado et al. 2001). Following the capture of two individuals in Cottonwood Canyon by the U.S. Geological Survey (Biological Resources Division) in 2002, the Conservancy initiated more intensive sampling for the shrew in maritime cactus scrub, chaparral, and riparian habitats (Aarhus 2005), and genetic research is ongoing. Degradation of the island's mesic habitats by feral ungulates and predation by feral cats are likely important factors limiting the abundance of this species (Aarhus 2005). An Ornate Shrew was once present on San Miguel Island, but is now extinct (Walker 1980).

Seventy eight percent of the mammals on the Channel Islands are bats (Collins 2012; Brown and Rainey 2018). Of the fourteen species known on the Channel Islands, 13 of those are found on Santa Cruz Island, the largest and most ecologically diverse, while Santa Catalina, the second largest island, has 8 (Brown and Rainey 2018). Only four of the islands' bat species breed there; the remaining species have only been captured sporadically while migrating (Brown 1980; Brown and Rainey 2018). Jack von Bloeker collected bats on the islands as part of the Channel Islands Biological Survey around 1940, and reviewed the bat species found on the Channel Islands in 1967. Oliver Pearson of the Museum of Vertebrate Zoology at UC Berkeley collected Lump-nosed Bats (*Plecotus townsendii*) on Santa Cruz Island for a study of their reproduction (Pearson et al. 1952). Patricia Brown (1980) notes that more specimens were collected by scientists at UC Santa Barbara in 1964. Patricia Brown has been conducting island bat work herself since the 1970's, using mist nets and radio-telemetry; she deposited specimens at SBMNH and LACM (Brown 1980, 1994). More recent surveys have incorporated the recording of echolocation calls, which are now considered valid specimen "vouchers" at least for species whose calls are identifiable (Brown and Rainey 2018). Three new bat species for the Channel Islands have been added in this way (Brown and Rainey 2018).

Island Foxes are the largest native mammal predator on the Channel Islands. Six distinct subspecies of fox are found there, one found on each of the six largest islands (Laughrin 1980; Collins 1993; Wayne et al. 1991a, 1991b). It is now thought that foxes colonized the northern islands by either rafting or introduction by Native Americans, then those foxes were translocated by humans from the northern to the southern islands (Collins 1991a, 199b; Rick et al. 2009; Hofman et al. 2016). Island foxes reach greater densities than most any other North American carnivore, with total abundance related to island size; they have relatively little genetic variability, however (Funk et al. 2016; Robinson et al. 2016). The most common animal prey taken by Island Foxes is Deermice, which ties their population dynamics together on these islands (Coonan et al. 2010).

Population declines of Island Foxes were observed on Santa Catalina, Santa Cruz, Santa Rosa, and San Miguel Islands in the late 1990s, for different reasons (Coonan et al. 2010). The Santa Catalina Island subspecies experienced a 95% decline beginning in 1999, due to the introduction of canine distemper virus exacerbated by toxoplasmosis (Timm et al. 2009). The Island Fox decline on the northern Islands was caused by the predation of golden eagles (Roemer et al. 2002) which took up residence in the 1990s. Golden eagles established in the absence of bald eagles, which had declined due to DDT poisoning (Roemer et al. 2002; Collins and Latta 2009). Recovery of these four Island Fox populations across the islands has involved a combination of captive breeding, translocation, vaccination, feral pig and golden eagle capture/relocation, and bald eagle reintroduction (Coonan et al. 2010). In the 2000s, the greatest source of mortality was vehicle trauma, with rates of injury and death higher on islands with paved roads and lowest on islands without roads (Coonan et al. 2010).

METHODS

Two data sources were used for these analyses, which are accessible through the Islands of the Californias Biodiversity Information System (Cal-IBIS) symbiota portal at www.cal-ibis.org. This all-taxa portal was created to consolidate Californian and Mexican Channel Islands biodiversity data for ready use by land managers, scientists, and others, and to facilitate the assessment and management of the islands as a whole archipelago. It is one of only a few all-taxa portals created for defined geographic areas in existence. To maintain this portal, data from other sources are periodically searched and data "snapshots" are imported. Other data sets are unique to this portal. Records from other sources are searched via a series of name and spatial searches. Because data coming from different sources can be redundant, a series of operations are then performed to remove duplicates and clean the data prior to posting on the Cal-IBIS portal. Island records that do not contain either geographic coordinates or key island names may not be recovered through this process, as can records that are problematic for one reason or another.

The two data sources used for the mammal analyses reported on here are: 1) GBIF data, and 2) iNaturalist observation data. Although iNaturalist records are a component of GBIF data, we discovered that not all records were being retrieved (likely an issue with the process to remove duplicates), and ultimately downloaded these separately. We will search for a solution to this problem in the future. Here we examine only "research grade" observations (www.iNaturalist.org). To be research grade, an observation must have a photographic voucher, a community-supported identification, and date and locality data. All iNaturalist observations are from prior to July 14, 2021.

Some iNaturalist observations were "obscured" meaning that available locality data are intentionally offset from the actual observation location. This can occur if the user intentionally changes settings from "open" to "obscured." The iNaturalist platform also automatically obscures all locality data for species of conservation concern. To get access to the unobscured locality data for these observations, researchers would need to contact the individual observers and/or get them to contribute their observations to a project for which the user gives permission to project staff to see unobscured locality data. As a result, getting access to the unobscured locality data is a significant time investment and beyond the scope of the current study.

For all downloaded data (5,222 records), an Island Name field was generated from a combination of place names where given, and coordinates (using scripts in ArcGIS) where not. Year and month fields were standardized, and a Collection Type field was added to standardize the various ways that this was coded in the original data, using data in the collectionCode and basisOfRecord fields. These data were then synonymized using the revised checklist of North American mammals north of Mexico (Bradley et al. 2014).

Once the dataset was finalized, summary graphs and tables were generated using R 4.1.0 (R Core Team, 2021), and the tidyverse (v1.3.1; Wickham et. al 2019). Heat maps showing spatial specimen collecting effort were generated using 1 km grid cells overlaid onto each of the islands. Prior to generating those maps, erroneous points using island centroids were removed. These were identified by combining the latitude and longitude of all vertebrate and invertebrate records into one field, calculating how many records had those coordinates, then checking those with large numbers of records to determine if they were centroids. Records removed are summarized in **Appendix A** to facilitate improvement of the original museum data.

Following all data curation and analyses, we discovered that many Smithsonian Institution (USNM) mammal specimens were not included in our data. These specimens were flagged by GBIF as "collection match fuzzy" and thus removed from the Cal-IBIS portal in the data cleaning stage. These records were flagged because GBIF was unable to link the specimen records to their Registry of Scientific Collections (GRSciColl). This issue is discussed here.

RESULTS and DISCUSSION

Table Mammalia-1 presents the number of data points for each island mammal species by data source, and provides an opportunity to compare specimen records to observations recorded via iNaturalist. A total of 4,118 specimen records have been digitized, whereas a total of 1,104 observations have been recorded. Together, these cover a total of 37 native taxa (35 non-fossil) and 20 non-native taxa. Three unique records evident in this table are the Striped Skunk (*Mephitis mephitis*), European Polecat (*Mustela putorius*), and Botta's Pocket Gopher (*Thomomys bottae*), all of which are in the mammal collection at the Santa Barbara Museum of Natural History. The striped skunk (left lower jaw) is in the osteology collection at the SBMNH, the Botta's Pocket Gopher was a juvenile skeleton recovered from an owl pellet on Santa Cruz Island (above Johnsons Beach) in 2015, and the European Pole Cat was a skull recovered from East Anacapa in 2020. These three specimens have recently been catalogued into the SBMNH collection, and represents a digitization gap, as data added by SBMNH during the past 3–4 years have not yet been added to GBIF or VertNet.

There are two fossil taxa in the digitized specimen records: the San Miguel Island Vole (*Microtus miguelensis*) and the Pygmy Mammoth (*Elephas exilis*). The digitized records are very incomplete for fossils; for instance, SBMNH fossils have not been digitized. Northern Raccoons (*Procyon lotor*) are also missing from these data; this taxon has been introduced multiple times to Santa Catalina Island, then trapped and euthanized. iNaturalist would be a great way to detect new invaders such as these.

Table Mammalia-1. The number of data points for each island mammal species by data source shows the relative proportion of specimens (Cal-IBIS) and observations (Research Grade iNaturalist). Asterisks indicate introduced taxa.

Order	Family	Species	Cal-IBIS	iNaturalist	n
Artiodactyla	Bovidae	*Bos bison**	0	223	223
		*Capra hircus**	13	4	17
		*Ovis vignei**	10	0	10
	Cervidae	*Capreolus pygargus**	1	0	1
		*Cervus elaphus**	3	1	4
		*Odocoileus hemionus**	0	209	209
		*Odocoileus hemionus hemionus**	2	0	2
	Suidae	*Sus scrofa**	33	7	40
Carnivora	Canidae	*Canis familiaris**	13	0	13
		Urocyon littoralis	1	0	1
		Urocyon littoralis catalinae	52	230	282
		Urocyon littoralis clementis	68	126	194
		Urocyon littoralis dickey	166	32	198
		Urocyon littoralis littoralis	76	0	76
		Urocyon littoralis santacruzae	189	46	235
		Urocyon littoralis santaerosae	117	38	155
	Felidae	*Felis catus**	13	19	32
	Mephitidae	*Mephitis mephitis**	1	0	1
		Spilogale gracilis	1	0	1
		Spilogale gracilis amphilus	77	1	78
	Mustelidae	*Mustela putorius**	1	0	2
Chiloptera	Molossidae	*Tadarida brasiliensis mexicana*	3	3	6
	Vespertilionidae	*Antrozous pallidus*	0	2	2
		Antrozous pallidus pacificus	129	0	129

Order	Family	Species	Cal-IBIS	iNaturalist	n
		Corynorhinus townsendii	0	1	1
		Corynorhinus townsendii pallescens	122	0	122
		Corynorhinus townsendii townsendii	23	0	23
		Eptesicus fuscus bernardinus	1	0	1
		Lasionycteris noctivagans	1	0	1
		Lasiurus blossevillii	1	0	1
		Lasiurus cinereus	2	0	2
		Myotis californicus	6	1	7
		Myotis californicus californicus	44	0	44
		Myotis californicus caurinus	12	0	12
		Myotis evotis evotis	3	0	3
		Myotis thysanodes thysanodes	1	0	1
		Myotis yumanensis sociabilis	3	0	3
Lagomorpha	Leporidae	*Oryctolagus cuniculus**	34	0	34
		*Sylvilagus audubonii**	0	1	1
Perissodactyla	Equidae	*Equus asinus**	2	0	2
		*Equus caballus**	0	2	2
Proboscida	Elephantidae	*Elephas exilis* (extinct)	2	0	2
Rodentia	Cricetidae	*Microtus californicus*	30	0	30
		Microtus miguelensis (extinct)	2	0	2
		Onychomys torridus	3	0	3
		Peromyscus maniculatus anacapae	358	4	362
		Peromyscus maniculatus catalinae	56	9	65
		Peromyscus maniculatus clementis	331	14	345
		Peromyscus maniculatus elusus	638	5	643
		Peromyscus maniculatus exterus	168	7	175
		Peromyscus maniculatus sanctaerosae	350	1	351
		Peromyscus maniculatus santacruzae	260	3	263
		Peromyscus maniculatus streatori	268	1	269
		Reithrodontomys megalotis catalinae	161	0	161
		*Reithrodontomys megalotis longicaudus**	35	0	35
		Reithrodontomys megalotis santacruzae	33	0	33
	Geomyidae	*Thomomys bottae**	1	0	1
	Muridae	*Mus musculus**	22	5	27
		*Rattus rattus**	81	14	95
	Sciuridae	*Otospermophilus beecheyi nesioticus*	73	94	167
Soricomorpha	Soricidae	*Sorex ornatus*	1	0	1
		Sorex ornatus willetti	10	0	10
Undetermined Species			12	1	13
All Mammalia			**4117**	**1104**	**5221**
Native taxa					**39**
Non-native taxa					**18**

Figure Mammalia-1 shows both the (a) absolute number and (b) proportional number/island size of mammal data points on each island by data source. It shows a relatively high number of records for Santa Catalina, mainly due to iNaturalist records. This island is the most accessible of the eight to visitors, both in general and across the islands. As Table Mammalia-1 shows, these records are predominated by four relatively large, common, and charismatic taxa: two introduced (American Bison and Mule Deer) and two native endemics (Island Fox and Beechey Ground Squirrel). Santa Cruz Island, the largest and most diverse and also relatively accessible to visitors and scientists, is appropriately well represented on this platform, while Santa Barbara and Anacapa islands, which do not have foxes, are less represented. San Miguel Island, which is difficult to access, is not represented at all. The maps that have been normalized by island size show that the smallest islands (Santa Barbara and Anacapa) are very well covered for their size. This is in large part due to the large number of rat and mice collections on those islands from the Los Angeles County Museum's Channel Islands Biological Surveys in the 1930s-1940s (von Bloeker 1967) and the Santa Barbara Museum of Natural History's surveys in the late 1970s (Collins 1979).

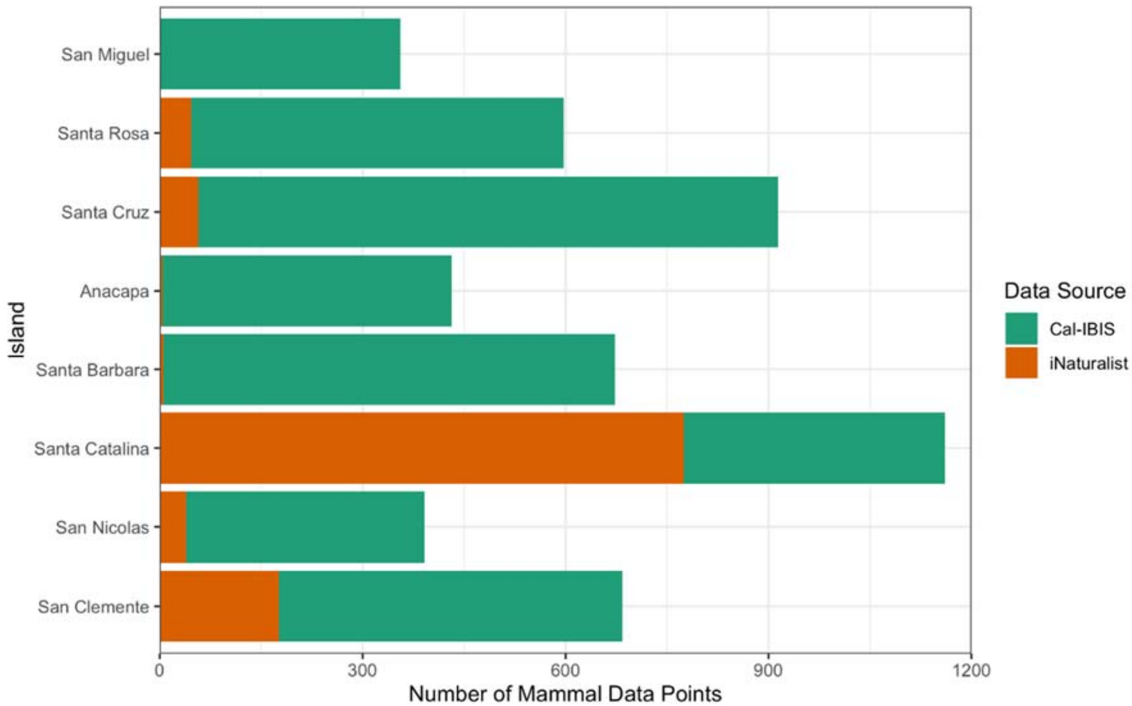
Figure Mammalia-2 shows the number of island mammal data points by year and data source. It reveals pulses of collections that represent a race by museums to obtain specimens of island endemics in the 1920s, the LACM Channel Islands Biological Survey in the late 1930s and early 1940s, and natural resources surveys in the late 1970s. It also shows that over the past decade, iNaturalist observations have contributed a significant amount of data (albeit predominantly of charismatic, day-active taxa). **Figure Mammalia-3** shows the number of mammal data points by month, by island. It shows late summer peaks on San Miguel, Santa Rosa, Santa Cruz, and Anacapa, when access to these islands is relatively easy. It also shows peaks in the spring, when animal activity is high and biologists tend to conduct surveys. San Clemente Island, which has resident staff and contract biologists, has an interesting peak in November. Santa Catalina, which has easy year-around access, has a large amount of data throughout the year.

Figure Mammalia-4 shows the distribution of iNaturalist records. It reveals spotty coverage on the northern islands and relatively good coverage on the southern islands, particularly Santa Catalina and San Clemente, as previously discussed.

Table Mammalia-2 shows the spatial specimen collecting effort, with the number/percentage of empty 1 km^2 grid cells. It shows between 55% and 89% empty cells, with the highest percentage of empty cells (in decreasing order) on San Clemente, Santa Catalina, Santa Cruz, Santa Rosa, San Nicolas, Anacapa, San Miguel, and Santa Barbara Islands. This pattern loosely indicates that the larger and more difficult to access islands are more poorly covered. The low specimen density on San Clemente and Santa Catalina, however, are in contrast to their high iNaturalist observation numbers. **Figure Mammalia-5** shows visually the generally spotty specimen coverage on all of the islands. This is likely more of a digitization gap than a specimen gap, however, as early specimen data is not (or is not accurately) geolocated.

Table Mammalia-3 shows the number of island mammal specimens by collection type within the Cal-IBIS (specimen) data set. It shows that the majority of specimens are either whole specimens or skull/skin/skeletons. Early on, most specimens collected were skins with skulls, which later turned to skins with skeletons. Now, frozen tissue is often collected for genetic studies. There are only 19 digitized collections that include tissue; this is likely because frozen tissues are spread widely in small private collections. This represents a collection gap. Digitized tissue samples are best represented for (in decreasing order) island foxes (collected during the recovery program), deer mice, spotted skunk, harvest mice, and ornate shrews.

(a)



(b)

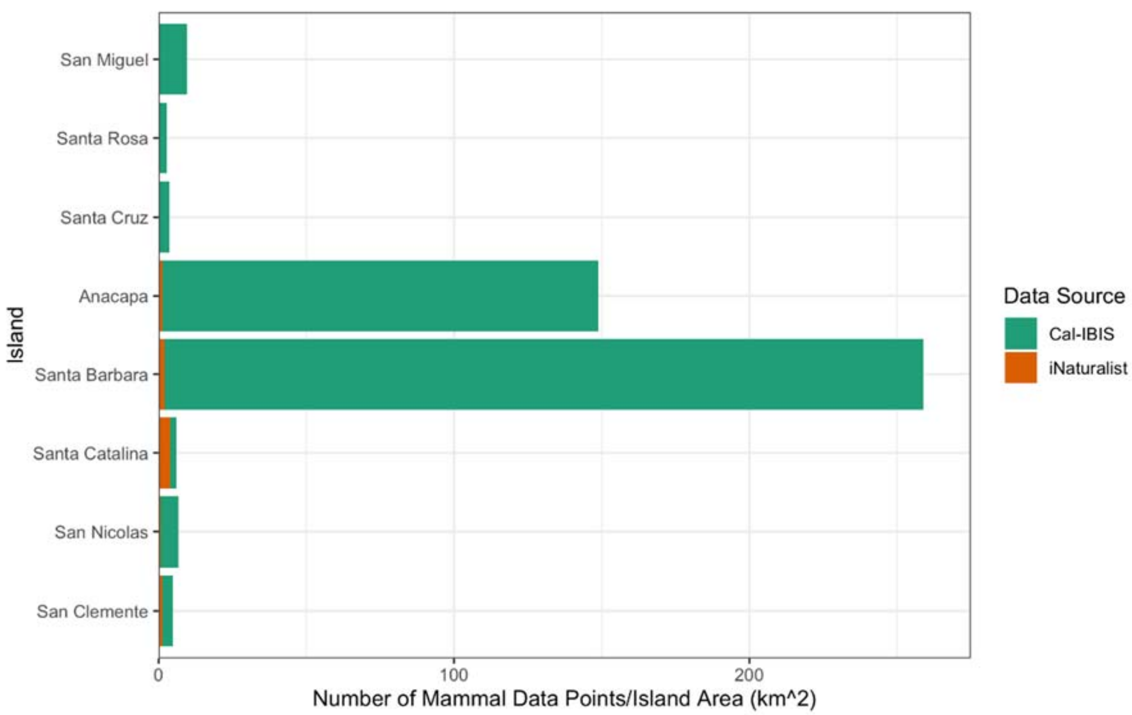


Figure Mammalia-1. The (a) absolute number and (b) proportional number/island size of mammal data points on each island by data source (Cal-IBIS for specimens and Research Grade iNaturalist for observations) reveals spatial gaps in the data.

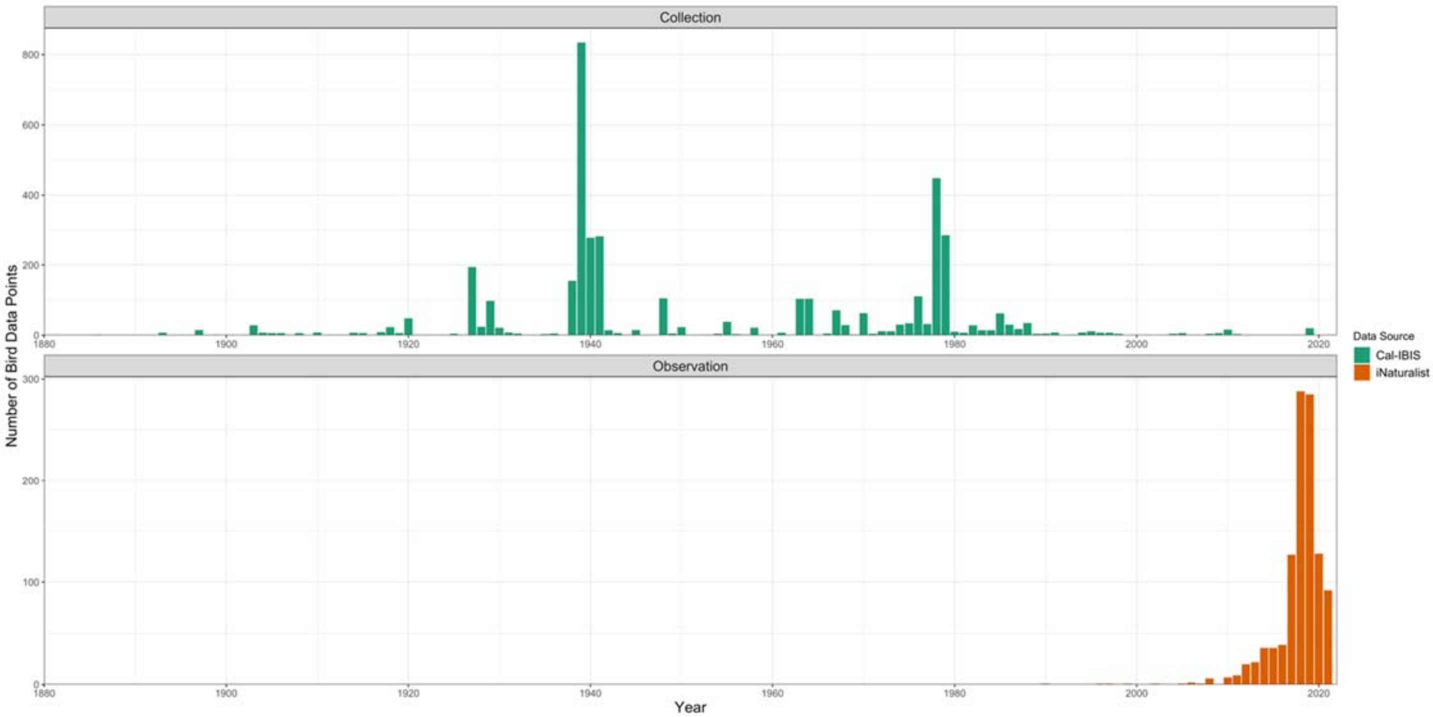


Figure Mammalia-2. The number of island mammal data points by year and data source (Cal-IBIS for specimens and Research Grade iNaturalist for observations) reveals temporal gaps in the data.

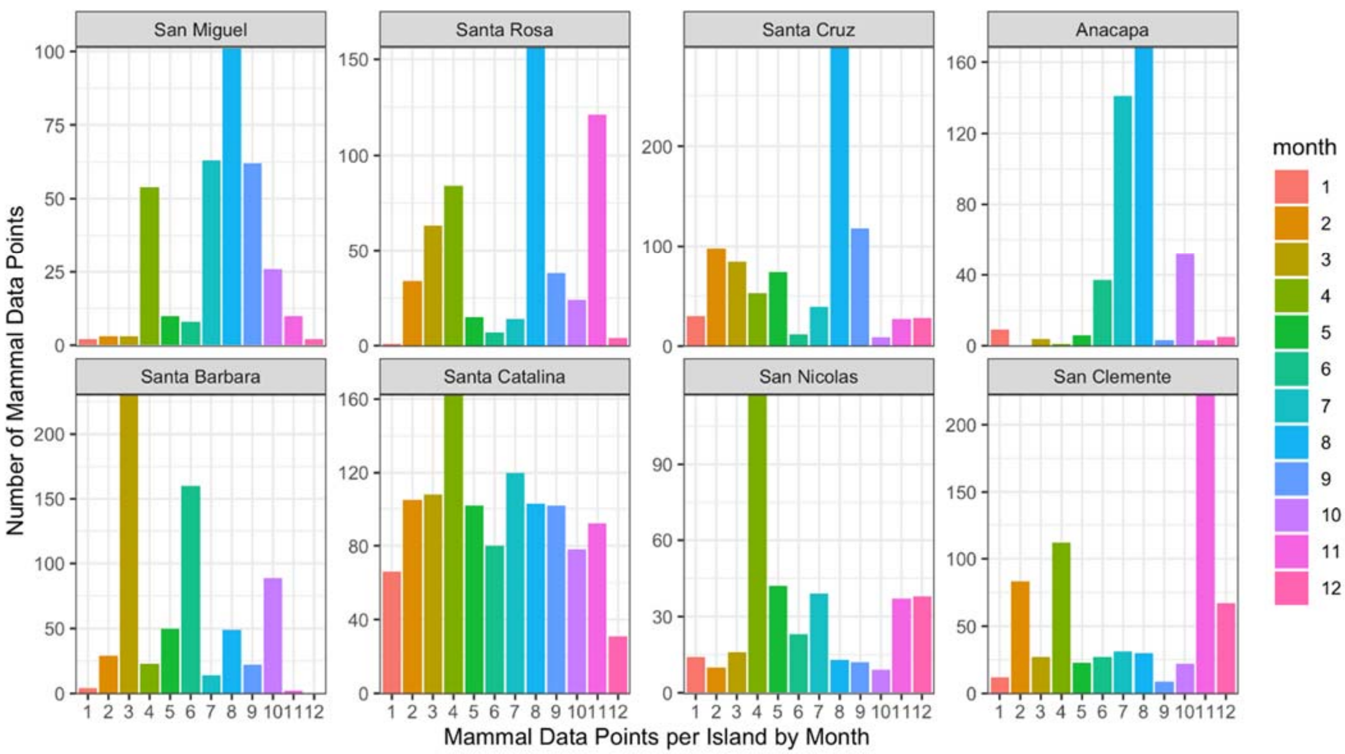


Figure Mammalia-3. The number of mammal data points by month, by island, reveals seasonal gaps in the data. Specimen (Cal-IBIS) and observation (Research Grade iNaturalist) data for all taxa have been combined.

(a) 

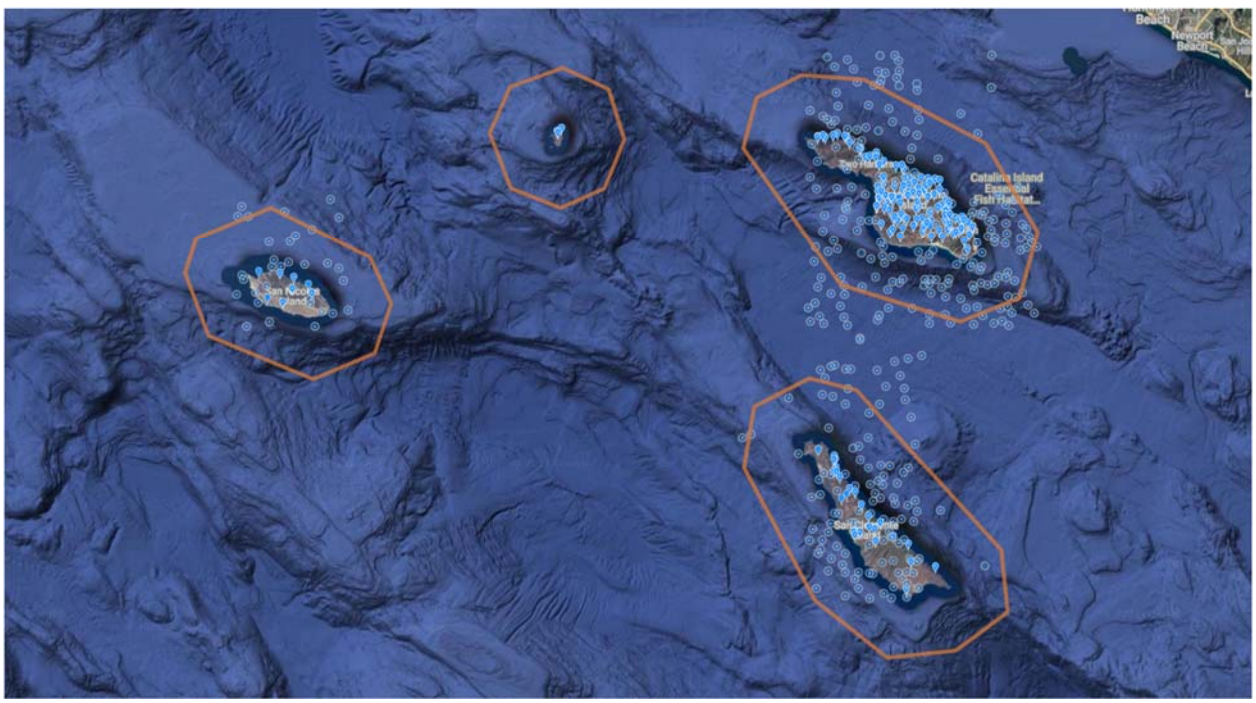
(b) 

Figure Mammalia-4. Distribution of iNaturalist mammal observations on (a) the Northern Islands and (b) the Southern Islands. Note: the bullseye points that scatter into the water are records that were obscured due to taxon rarity.

Table Mammalia-2 & **Figure Mammalia-5**. Spatial specimen collecting effort based on 1 km grid cells overlaid onto each of the eight California Channel Islands. A total of 1,502 records were included (all 4118 records had coordinates, but 2616 were removed because locality information did not match the coordinates or they were obvious centroids).

Island	Island Collections	1 km^2 cells	Empty 1 km^2 cells	% empty cells	Mean records/cell	Mean redundancy
Anacapa	195	14	9	64.3%	39.0	0.08
Santa Cruz	407	313	266	85.0%	8.7	0.99
Santa Rosa	211	263	220	83.7%	4.9	1.69
San Miguel	96	61	36	59.0%	3.8	0.94
Santa Catalina	294	250	220	88.0%	9.8	1.14
San Clemente	111	198	176	88.9%	5.0	2.54
San Nicolas	122	81	59	72.8%	5.5	0.86
Santa Barbara	50	11	6	54.5%	10.0	0.28

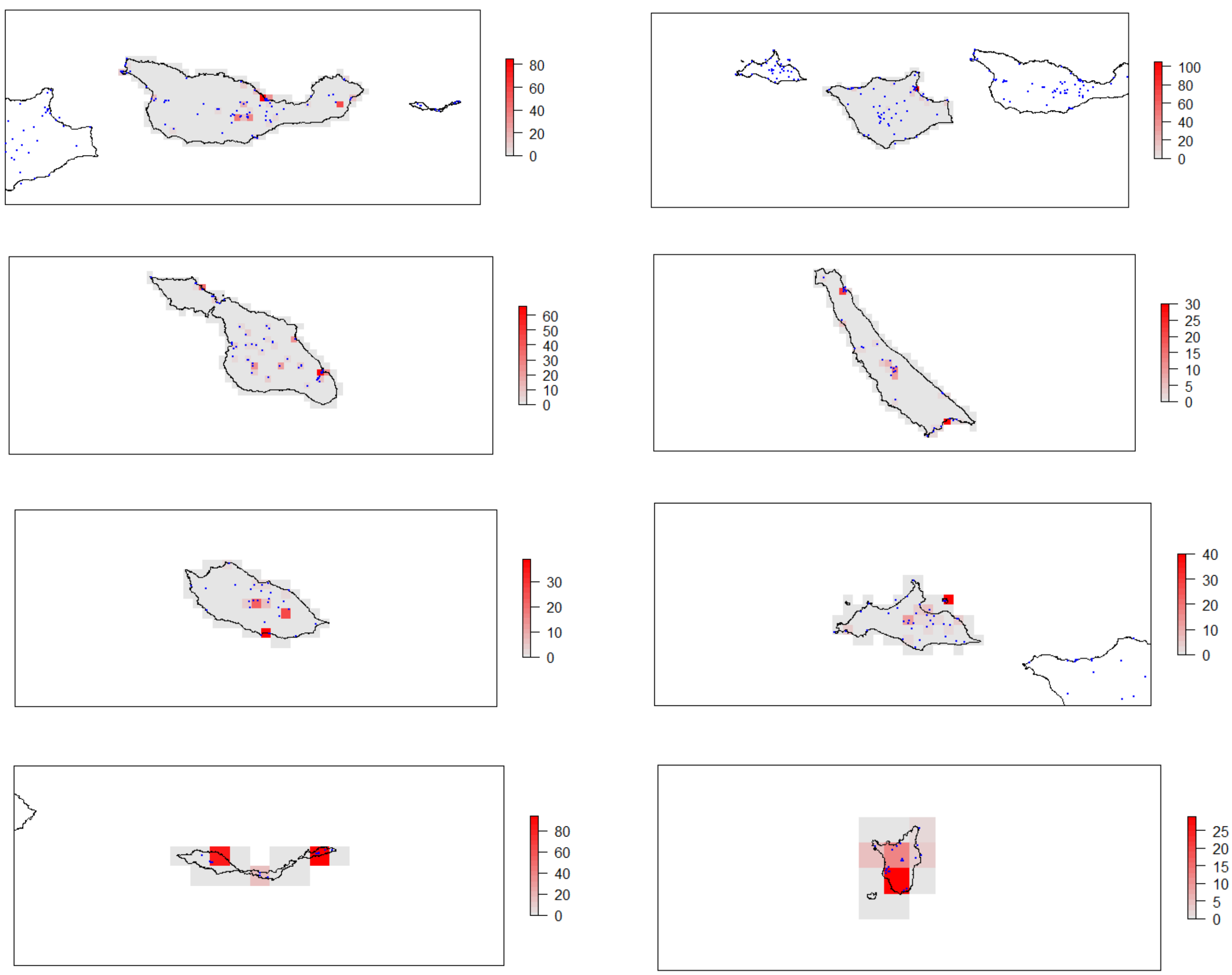


Table Mammalia-3. The number of island mammal specimens by collection type within the Cal-IBIS (specimen) data set.

Mammal Collection Type (Cal-IBIS records only)	n
Fossil	4
Recording	2
Shell Mound materials	1
Skin | Skeleton | Tissue	19
Skull | skeleton | skin | partial	2512
Skull | whole in ethanol	5
Specimen	1337
Whole in ethanol	222

Rare and Endemic Taxa

Figure Mammalia-6 shows the number of Island Fox data points by island. Each island has between 50 and ~175 specimens; Santa Catalina, San Clemente, and San Miguel have the fewest. Santa Catalina has historically supported a lower density of foxes than the other Channel Islands (Laughrin 1980). The number of iNaturalist observations is more variable, with Santa Catalina having the most due to its high accessibility, and San Miguel having none for the opposite reason. **Figure Mammalia-7** shows the number of Island Fox data points by year. Pulses of specimen collection are visible in the late 1920's, around 1940, and in the 1970s and 1980s, with a general drop-off in specimens after the year 2000 (after the drastic population decline on four of the islands). There was a small pulse of collection around 2010, from San Miguel and Santa Rosa. Island fox specimens are in general driven by the availability of carcasses, which were sent to UC Davis for necropsy (cause of death, disease and microorganisms) once the island fox recovery program started. Paul Collins has put substantial effort into getting these specimens once the necropsies have been completed, with little success. As noted previously, Santa Catalina and San Clemente islands both have more than average iNaturalist observations.

Figure Mammalia-8 shows the number of Island Deermouse data points by island. The number of specimens ranges from ~50 on Santa Catalina to over 600 on Santa Barbara Island. The high number of specimens on Santa Barbara, nearly double that of the next most specimen-rich islands, is undoubtedly related to high population densities reported there (Collins 1979) resulting from the absence of predators and competitors on that island. Perhaps the low number on Santa Catalina is related to the high number of predators on that island. There are few iNaturalist data points for these taxa (between one and 14) relative to other mammals, as the Deer Mouse is a nighttime-active animal. More of those records are seen for San Clemente, with many active and resident biologists using this platform, and Santa Catalina, which is more widely accessible to the public and has numerous youth camps and campgrounds. **Figure Mammalia-9** shows the number of Island Deer Mouse data points by year for each island subspecies. Pulses of specimen collection are visible around 1940, and 1980, related to the Channel Islands Biological Survey and Natural Resources Inventory projects. An additional pulse is seen on Santa Cruz Island around 1965, likely related to the opening of the University of California Field Station, which made the island more accessible to researchers.

Table Mammalia-4 presents a list of the endemic and rare mammals of the California Channel Islands, with the listed status of the rare taxa. It shows that there are 18 endemic taxa, 8 of which are listed, and 11 listed taxa.

Table Mammalia-4. Endemic and rare mammals of the California Channel Islands.

Scientific Name	Common Name	Endemic?	Listed Status
Urocyon littoralis catalinae	Santa Catalina Island Fox	X	IUCN 3.1 (Near Threatened)
Urocyon littoralis clementae	San Clemente Island Fox	X	IUCN 3.1 (Near Threatened)
Urocyon littoralis dickeyi	San Nicolas Island Fox	X	IUCN 3.1 (Near Threatened)
Urocyon littoralis littoralis	San Miguel Island Fox	X	IUCN 3.1 (Near Threatened)
Urocyon littoralis santacruzae	Santa Cruz Island Fox	X	IUCN 3.1 (Near Threatened)
Urocyon littoralis santarosae	Santa Rosa Island Fox	X	IUCN 3.1 (Near Threatened)
Spilogale gracilis amphiala (=*amphialus*)	Island Spotted Skunk	X	
Antrozous pallidus pacificus	Pacific Pallid Bat		NatureServe T3 (Vulnerable)
Corynorhinus townsendii pallescens	Pale Lump-Nosed Bat		NatureServe T3 (Vulnerable)
Corynorhinus townsendii townsendii	Townsend's Western Big-Eared Bat		NatureServe T3; CA SSC
Peromyscus maniculatus anacapae	Anacapa Island Deermouse	X	T1 (Critically Imperiled)
Peromyscus maniculatus catalinae	Santa Catalina Island Deermouse	X	
Peromyscus maniculatus santacruzae	Santa Cruz Island Deermouse	X	
Peromyscus maniculatus clementis	San Clemente Island Deermouse	X	T1 (Critically Imperiled)
Peromyscus maniculatus exterus	San Nicolas Island Deermouse	X	
Peromyscus maniculatus elusus	Santa Barbara Island Deermouse	X	
Peromyscus maniculatus sanctaerosae	Santa Rosa Island Deermouse	X	
Peromyscus maniculatus streatori	San Miguel Island Deermouse	X	
Reithrodontomys megalotis catalinae	Santa Catalina Island Harvest Mouse	X	
Reithrodontomys megalotis santacruzae	Santa Cruz Island Harvest Mouse	X	
Otospermophilus beecheyi nesioticus	Beechey Ground Squirrel	X	
Sorex ornatus willetti	Santa Catalina Ornate Shrew	X	

Figure Mammalia-10 shows the number of rare and endemic bat data points by island, while **Figure Mammalia-11** shows the number of data points by year for these taxa. About 100 specimen collections of the Pale Lump-nosed Bat (*Corynorhinus townsendii pallescens*) are recorded for Santa Cruz Island, mostly around 1940 (due to the Channel Islands Biological Survey), but very few are recorded on Santa Catalina, San Nicolas, and San Clemente Islands. While Santa Cruz and Santa Catalina have both been better collected than the other islands (Brown 1980), Santa Cruz likely has even more specimens both because it has the highest bat diversity of any of the islands (Brown 1980; Brown and Rainey 2018), and has been more frequently surveyed and collected (Brown et al. 1994). Patricia Brown, Robert Berry, and Cathi Brown conducted focused surveys for *Corynorhinus townsendii* on Santa Cruz Island in 1991 and 1992 (Brown et al. 1994), but no specimens appear for those years. They reported that in September 1948, Pearson and Pitelka collected specimens of Townsend's Western Big-eared Bat (*Corynorhinus townsendii townsendii*) for the Museum of Vertebrate Zoology at UC Berkeley from a colony of approximately 200 bats at Prisoner's Harbor, and 23 specimens appear in the records. The Pacific Pallid Bat has been collected on both Santa Cruz and Santa Catalina islands as well, but also with a large disparity in the number of specimens (128 for Santa Cruz, and only one on Catalina), likely for the same reasons stated above. The majority of specimens for this taxon were taken in 1938 and 1939, with 16 taken in 1948. There are no iNaturalist observations for these three bat taxa because they are night-active animals.

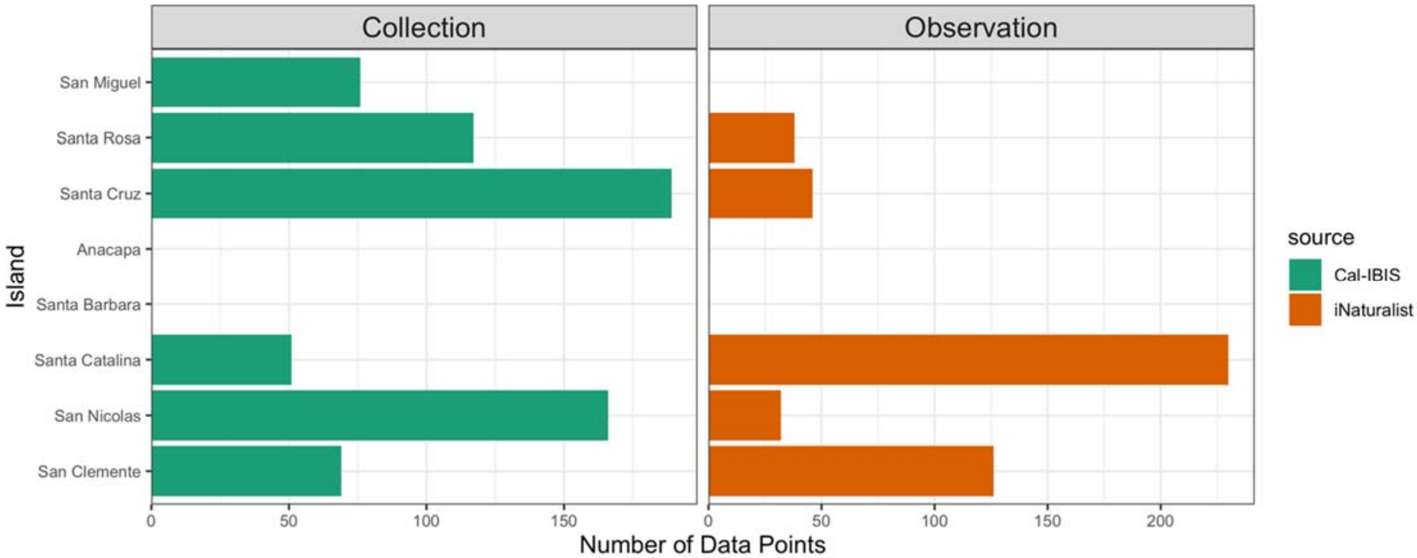


Figure Mammalia-6. The number of endemic Island Fox data points by island reveals island distribution and collection/observation frequency. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

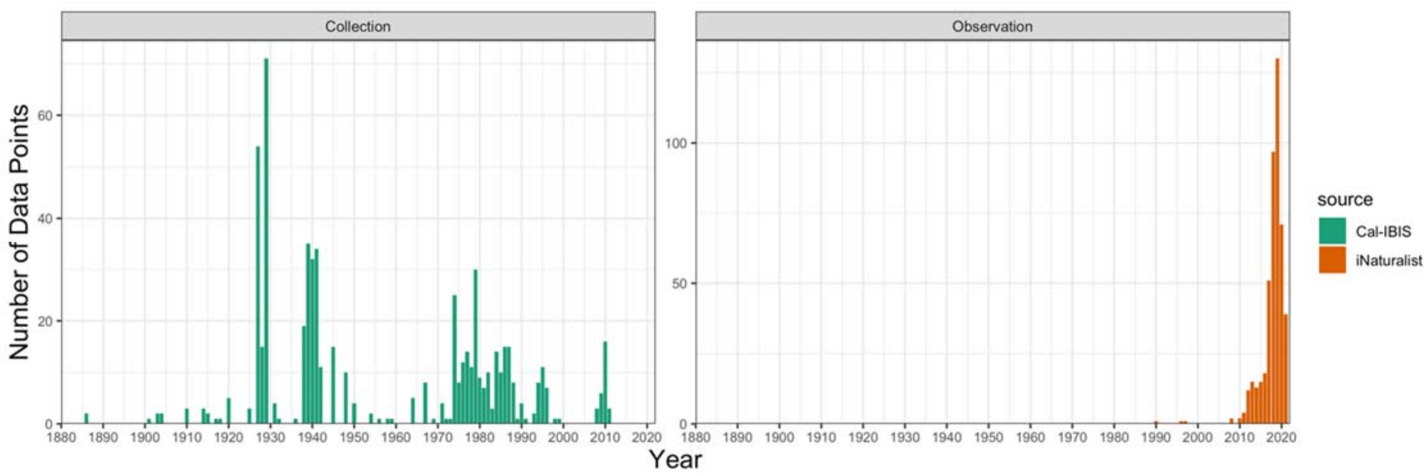


Figure Mammalia-7. The number of endemic Island Fox data points by year reveals temporal trends for those taxa. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

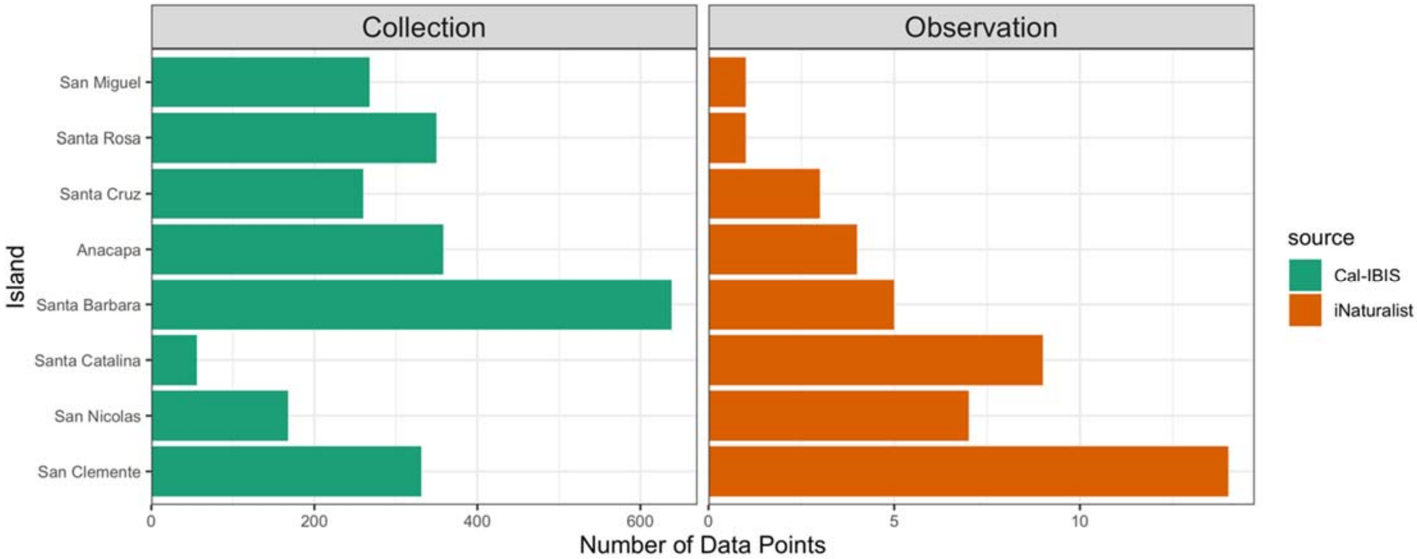


Figure Mammalia-8. The number of endemic Island Deermouse points by island reveals island distribution and collection/observation frequency. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

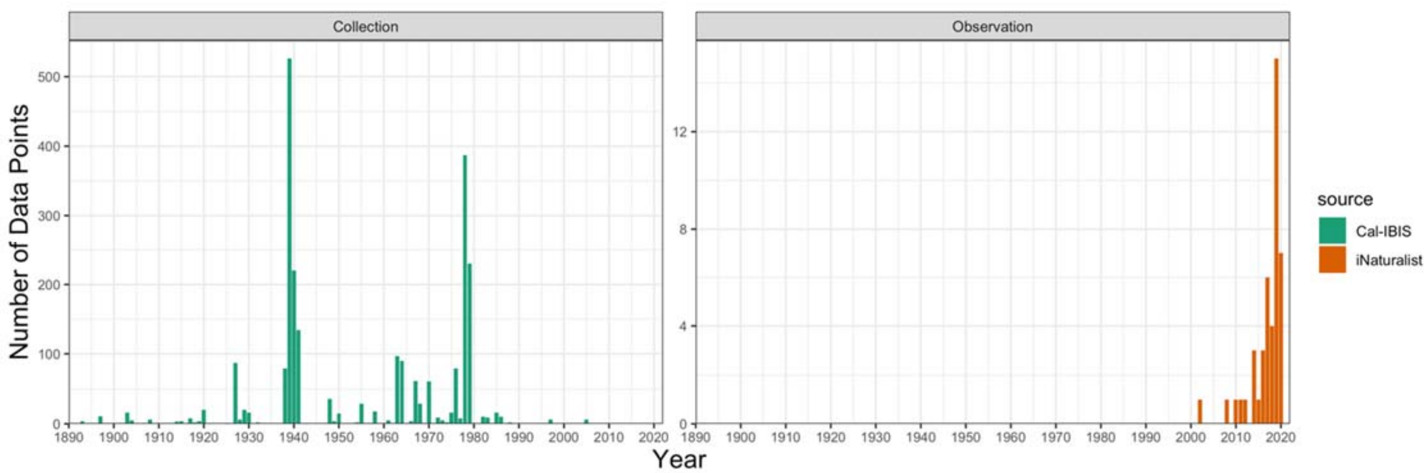


Figure Mammalia-9. The number of endemic Island Deermouse data points by year, for each island subspecies, reveals temporal trends for those taxa. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

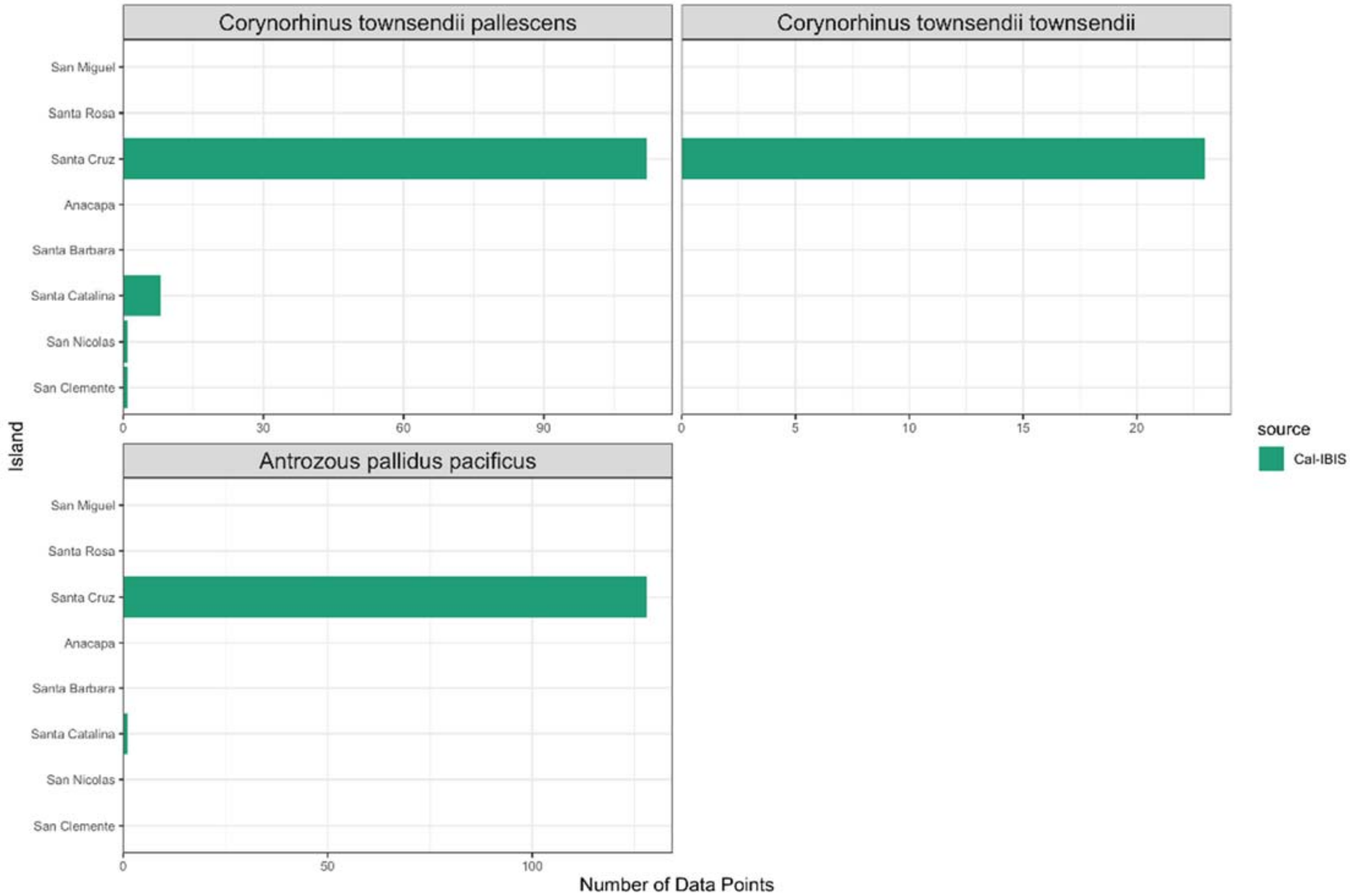


Figure Mammalia-10. The number of rare and endemic bat (Pale Lump-Nosed Bat, Townsend's Western Big-Eared Bat, and Pallid Bat) data points by island reveals island distribution and collection/observation frequency. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

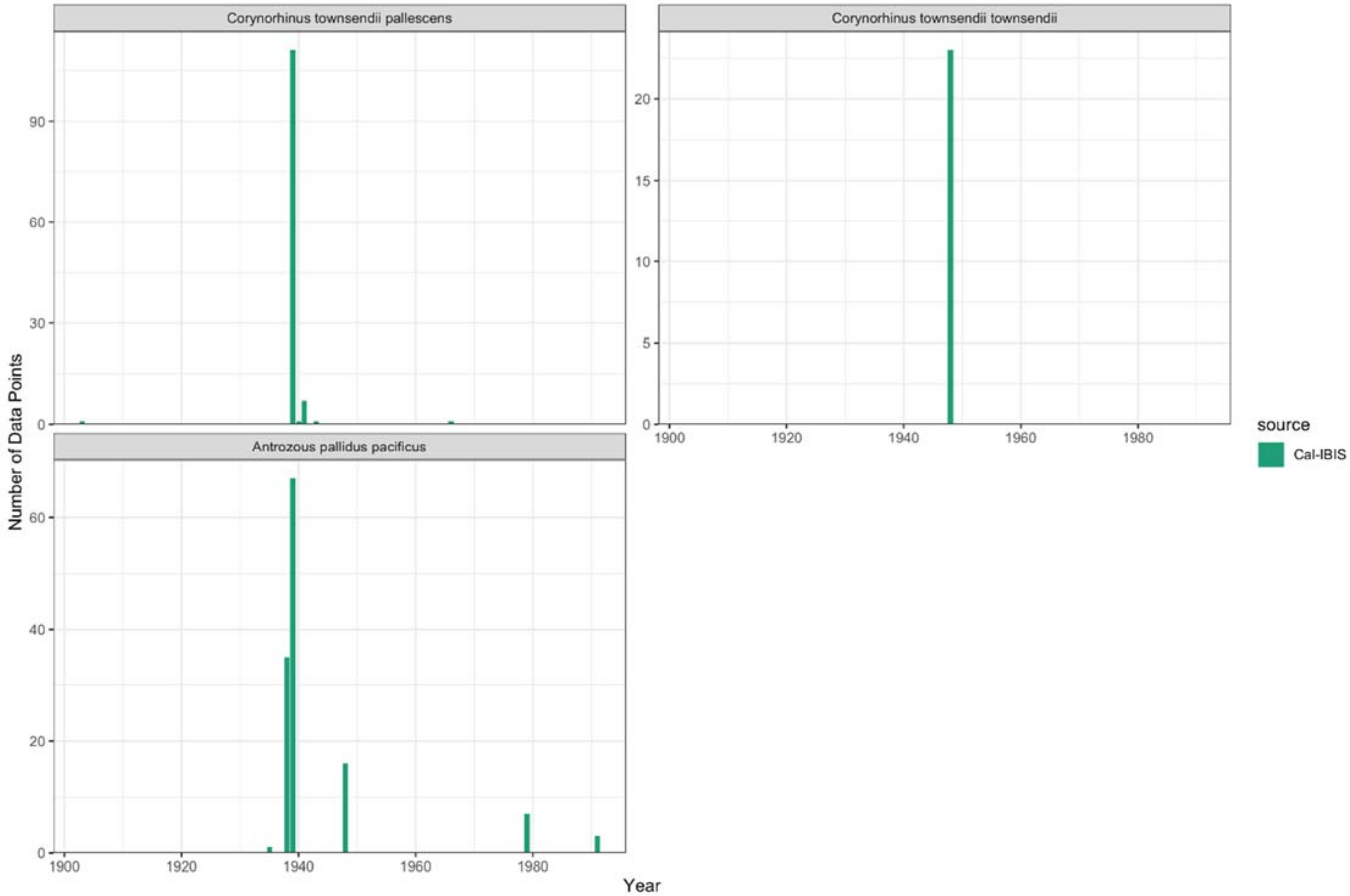


Figure Mammalia-11. The number of rare and endemic bat (Pale Lump-Nosed Bat, Townsend's Western Big-Eared Bat, and Pallid Bat) data points by year reveals temporal trends for those taxa. Cal-IBIS data represent specimens.

Figure Mammalia-12 shows the number of data points by island for the Beechey Ground Squirrel, Santa Catalina Island Harvest Mouse, Santa Cruz Island Harvest Mouse, Santa Catalina Ornate Shrew, and Island Spotted Skunk, while **Figure Mammalia-13** shows the number of data points by year for these taxa. The squirrel is the only one of these animals with a significant number of iNaturalist observations (~95), as a relatively large and conspicuous, daytime-active organism that uses a variety of habitats. The Santa Catalina Island Harvest Mouse has the greatest number of specimens of these taxa (160). It was collected sporadically before a peak around 1941, after which very few specimens were collected (other than a pulse in 1988). In contrast, there have been only 33 specimens of the Santa Cruz Island Harvest Mouse collected, most of them in that same year; these are deposited at the same institutions as the Santa Catalina Island Harvest Mouse. Collections in 1948 and 1950 were deposited at the Museum of Vertebrate Zoology at UC Berkeley. The Ground Squirrel also has a fair number of specimens (75), which were collected sporadically into the 1940s, then not collected again until 1979 (by SBMNH). The Spotted Skunk has the greatest number of specimens for Santa Rosa (62), then Santa Cruz (22), and only one for San Miguel. This taxon has significant collections from 1927,1941, and 1976, but has only had a few specimens collected since that time. The Ornate Shrew has only ten specimens from Santa Catalina, collected in 1941, 1983, 1991, and 2004. The latter is the largest collection, and coincides with Catalina Island Conservancy and USGS surveys at that time (Aarhus 2005).

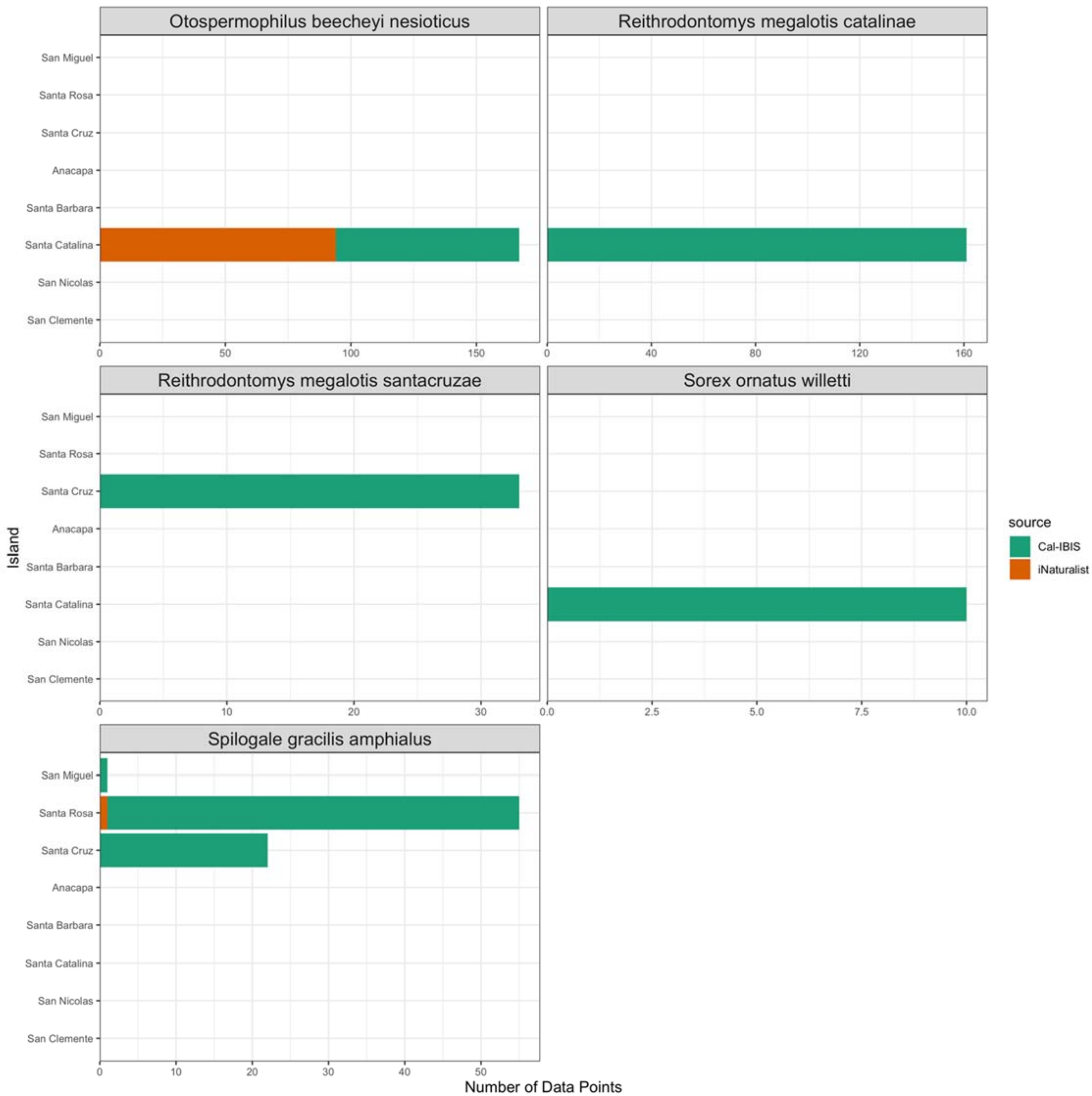


Figure Mammalia-12. The number of endemic Beechey Ground Squirrel, endemic Santa Catalina Island Harvest Mouse, endemic Santa Cruz Island Harvest Mouse, rare Santa Catalina Ornate Shrew, and endemic Island Spotted Skunk data points by island reveals island distribution and collection/observation frequency. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

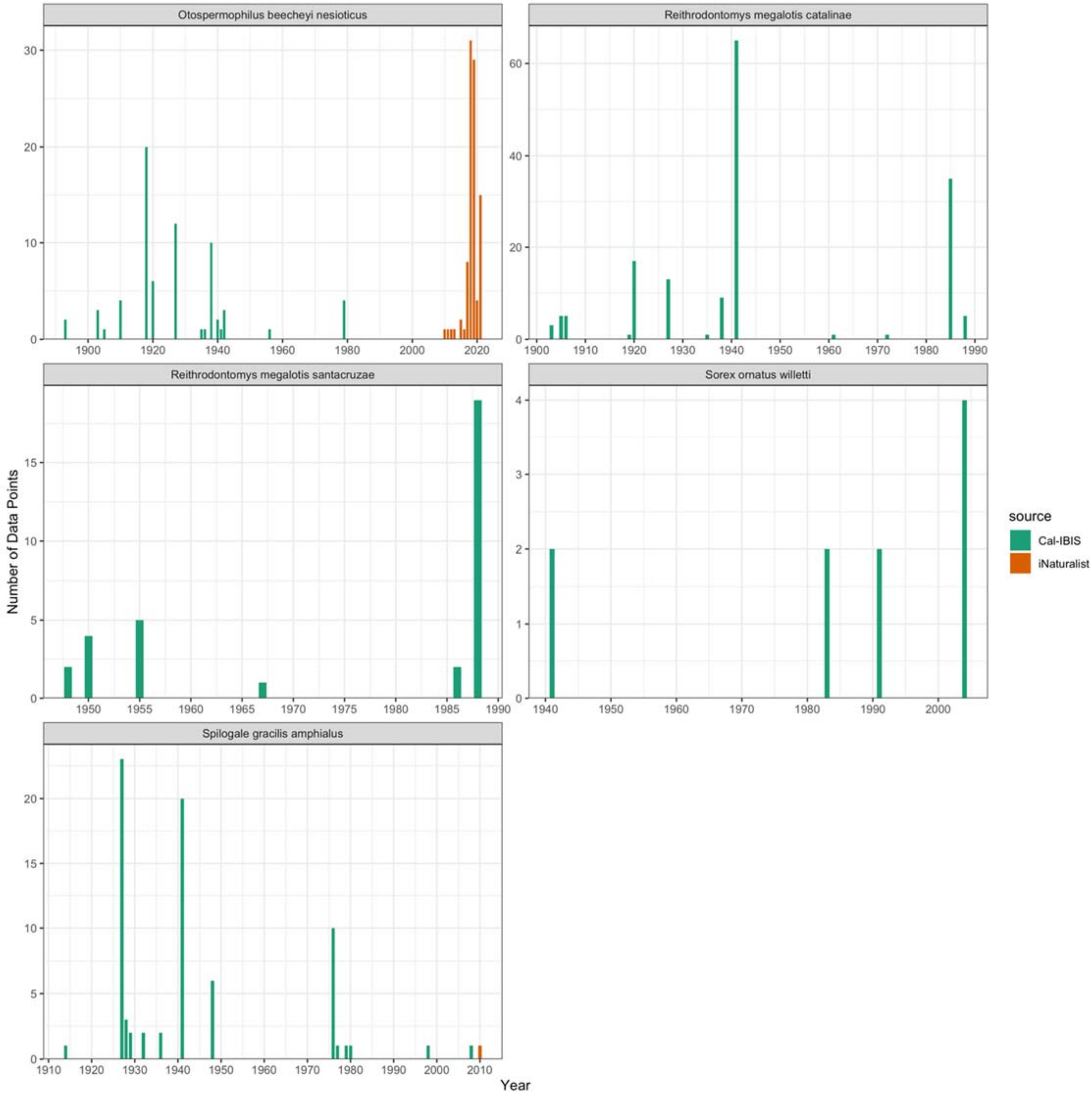


Figure Mammalia-13. The number of endemic Beechey Ground Squirrel, endemic Santa Catalina Island Harvest Mouse, endemic Santa Cruz Island Harvest Mouse, rare Santa Catalina Ornate Shrew, and endemic Island Spotted Skunk data points by year reveals temporal trends for these taxa. Cal-IBIS data represent specimens, and Research Grade iNaturalist data indicate observations.

CONCLUSION AND RECOMMENDATIONS

This project has revealed a number of data, spatial, temporal, and taxonomic gaps. These are summarized below, with recommendations for filling these gaps.

Data gaps

This work has revealed that the digitized records are very incomplete for fossils in particular (SBMNH fossils have not been digitized, for instance). Collecting those data would facilitate analyses such as these, that will inform future surveys and research. Making those data publicly accessible would make those data go farther by inspiring and facilitating future research.

The data gathered here show very few specimens with frozen tissues that can be used for genetic research. However, we know that this does not reflect the amount of tissue that has been collected. The Island Spotted Skunk is an example where we know that tissue samples exist, for example (Floyd et al. 2011). It would be best to have tissues deposited in museum collections (not the labs of individual researchers) where there are staff and resources to ensure long-term availability of these samples. These tissue records should be digitized with their location data so that researchers can easily determine sample availability.

We recommend that tissue samples be procured for priority taxa, after gathering data regarding tissue locality and availability. The Santa Cruz Island Harvest Mouse (*Reithrodontomys megalotis santacruzae*), for instance, should be studied using modern genetic techniques to clarify its relationship to the Santa Catalina Island Harvest Mouse and mainland congeners.

Similarly, while we know that many Island Fox specimens have been collected during the recovery program and sent to institutions like UC Davis for necropsy, those specimens have not been recovered as museum specimens. This would require careful preparation and coordination, but it would help to inform scientific studies. We recommend that island managers and their contractors set up protocols to get fox carcasses to museums for archiving once they have been necropsied. It will also be important for the veterinarians who do the necropsies to agree to save the integrity of the carcasses.

Observations on the iNaturalist platform have contributed a large amount of useful data to analyses such as these. It is, however, skewed to the more accessible islands and more charismatic, day-active taxa. Islands that are very accessible to the public, like Santa Catalina, have many observations distributed throughout the island, making the resulting data most useful. San Clemente Island is not publicly accessible, but has resident staff and contract biologists that are very active on the iNaturalist platform, generating many data points as well. San Miguel is an example of a relatively inaccessible island, however, that has few iNaturalist observations. And while larger, more obvious and charismatic taxa like the American Bison and Island Fox are often “iNatted”, night-active taxa like the Island Spotted Skunk or Pale Lump-nosed Bat are overlooked.

Spatial Gaps

Heat maps of specimen collections reveal generally spotty specimen coverage on all of the islands. This may be a combination of a digitization gap and a spatial gap, however, as early specimens either did not record a specific location, or were digitized very coarsely as the centroid of the island. Early specimen records should be geo-referenced, which would help us to better assess spatial gaps. This would require comprehensive island maps with locality names.

If a spatial gap truly exists, then maps like the ones that we have generated can guide the location of future collections. While we should be judicious in the killing of animals for specimens, and we don’t need collections from every grid cell, covering the islands thoroughly could be important. For example, Langin et al. (2015) showed that Island Scrub-Jays have both morphological and genetic differences across the island, driven by habitat preferences.

Temporal Gaps

The data analyzed here reveal two main pulses of collections (one from the LACM Channel Islands Biological Survey in the early 1940s, and one from natural resources surveys in the 1970s), with smaller numbers of collections prior, in between, and after. While iNaturalist observations have contributed a significant amount of data over the past decade, only certain taxa get attention on this platform (see above). Furthermore, specimens in-hand are necessary for a lot of research purposes. We recommend that a concerted effort be made to collect another pulse of specimens to inform future research including studies of changes over time. Island taxa often undergo rapid evolution (Pergams and Ashley 2001, 2002; Millien 2006; Van Vuren and Bakker 2009), and consistent collections over time will be important for investigation of these changes.

Analyses of the data by month shows that surveys and collections are limited by accessibility and activity, which is generally lower in winter. In addition to stepping up surveys during these times when they would be useful, this temporal gap can be filled through the use of modern technology. Bat data can be collected via acoustic recording devices, for example, which can be left unattended for collection later. While the iNaturalist platform allows sound data to accompany observations, and bat data can be deposited in BatAMP, the Bat Acoustic Monitoring Portal, there is currently no way to serve acoustic data in online biodiversity data portals. To fill this need, one of the developers of Symbiota is currently developing a Cal-IBIS acoustic module, funded by TNC and facilitated by SBBG. Similarly, remote cameras are used to collect images of animals using a site. This is especially useful for catching new species arrivals, and is currently employed to some degree in a multi-island biosecurity program (Boser et al. 2014). These photographs could potentially be posted on iNaturalist, to become part of the species record as analyzed here. The eMammal data management system and archive for camera trap research projects (https://emammal.si.edu/) may also be useful in this regard.

Taxonomic Gaps

Of the 18 non-native taxa, only 14 have specimens and 8 have observations, whereas a total of 21 are known from the Channel Islands (McEachern et al. 2016). Some invaders, like Northern Raccoons (which would be a 22nd species), Domestic Goat, and Blackbuck Antelope (*Antilope cerivcapra*), are missing from the data completely. The Blackbuck Antelope was never common on Santa Catalina Island and was gone by 2011 (McEachern et al. 2016). Other taxa are recorded as either specimens or observations, but not both. The large and charismatic American Bison (*Bos bison*) is popular on iNaturalist, for example, but no specimens have been collected. For other taxa like European Mouflon Sheep, their removal pre-dates the launch of iNaturalist in 2008, and only specimens have been collected.

Final word: The value of museum collections

Besides the well-known applications of biological collections to taxonomy and systematics, preserved specimens make many other contributions to science and society, including public health and safety, homeland security, and monitoring of environmental change (Suarez and Tsutsui 2004, Rocha et al. 2014). Yet financial support for the collection and curation of these specimens has waned, and is insufficient to maintain and improve them (Suarez and Tsutsui 2004). In this era of extraordinary environmental change, an adequate record of current conditions will be critical to future ecologists and conservation managers (Morrison et al. 2017).

While online biodiversity platforms like iNaturalist and eBird are vastly increasing the amount of biological data we can collect, there are many circumstances for which having voucher specimens are preferable. Studies of morphological diversity and its evolution, verification of monitoring data, assessing extinction risk, and utilization of new techniques for studies of ecology, evolution, and conservation are examples (Rocha et al. 2014). In 2014, a total of 122 scientists made the joint statement that "given increasing rates of habitat loss and global change, we believe that responsibly collecting voucher specimens and associated data and openly sharing this knowledge … are more necessary today than ever before" (Rocha et al. 2014).

The data, spatial, temporal, and taxonomic gaps reported on here will help us to prioritize work going forward to build the most consistent and systematic specimen collections possible. This will ensure that current and future scientists have the resources that they need to understand, and ultimately conserve, the irreplaceable biodiversity of the California Channel Islands.

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