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Insect collecting bias in Arizona with a preliminary checklist of the beetles from the Sand Tank Mountains

M. Andrew Johnston[‡], Evan S. Waite[‡], Ethan R Wright[‡], Brian H. Reily[‡], Gilma Juanita De Leon[‡], Angela Iran Esquivel[‡], Jacob Kerwin[‡], Maria Salazar[‡], Emiliano Sarmiento[‡], Tommy Thiatmaja[‡], Sangmi Lee[‡]

‡ Biodiversity Knowledge Integration Center, Arizona State University, Tempe, AZ, United States of America

Corresponding author: M. Andrew Johnston (ajohnston@asu.edu)

Abstract

Background

The state of Arizona in the southwestern United States supports a high diversity of insects. Digitized occurrence records, especially from preserved specimens in natural history collections, are an important and growing resource to understand biodiversity and biogeography. Underlying bias in how insects are collected and what that means for interpreting patterns of insect diversity is largely untested. To explore the effects of insect collecting bias in Arizona, the state was regionalized into specific areas. First, the entire state was divided into broad biogeographic areas by ecoregion. Second, the 81 tallest mountain ranges were mapped onto the state. The distribution of digitized records across these areas were then examined.

A case study of surveying the beetles (Insecta, Coleoptera) of the Sand Tank Mountains is presented. The Sand Tanks are low-elevation range in the Lower Colorado River Basin subregion of the Sonoran Desert from which a single beetle record was published before this study.

New information

The number of occurrence records, collecting events, and taxa are very unevenly distributed throughout Arizona and do not strongly correlate with geographic size of areas. Species richness is estimated for regions in Arizona using rarefaction and extrapolation. Digitized records from the disproportionately highly collected areas in Arizona do not begin to represent the total insect diversity within them. We report a total of 141 species of coleoptera from the Sand Tank Mountains based on 914 digitized voucher specimens.

These specimens add important new records for taxa that were previously unavailable in digitized data and highlight important biogeographic ranges.

Possible underlying mechanisms causing bias are discussed and recommendations are made for future targeted collecting of undersampled regions. Insect species diversity is apparently at best 70% documented for the state of Arizona with many thousands of species not yet recorded. The Chiricahua Mountains are the most densely sampled region of Arizona and likely contain at least 2,000 species not yet vouchered in online data. Preliminary estimates for species richness of Arizona are at least 21,000 and likely much higher. Limitations to analyses are discussed which highlight the strong need for more insect occurrence data.

Keywords

Madrean Sky Islands, beetles, natural history museums, biogeography, Sonoran Desert

Introduction

Insects represent over half of all described species (Mayhew 2007) and perhaps not more than 20% of those that exist have thus far been described (Gaston 1991). The state of Arizona, located in southwestern United States along the Mexico border, has high insect diversity and ranks as the state with the most species actively monitored for conservation (Bossart and Carlton 2002). Entomologists from around the country and around the world descend upon southern Arizona every year during the monsoon season (late summer and early fall) where popular canyons may have five to ten campsites and road pulloffs occupied by blacklights and collectors scrambling around them until early morning. Despite its insect diversity and popularity as a collecting destination, we are unaware of any empirical studies that assessed total insect species richness within the state or its subregions or explored biases in insect collecting therein.

Biodiversity occurrence records represent an enormously important, invaluable, and irreplaceable data source for understanding biodiversity, evolution, and ecology (Cook et al. 2014, Page et al. 2015, Guralnick et al. 2016, Lendemer et al. 2019, Johnston et al. 2018, Meineke et al. 2018, Kharouba et al. 2018, Hedrick et al. 2020). The vast majority of these records, at least for insects, presently come from digitized preserved specimens from natural history collections. However, we know that the specimens stored within collections are not evenly distributed throughout space and time and have many implicit biases intertwined with the history and methods used to accumulate them (Hortal et al. 2015, Johnston et al. 2018, Kharouba et al. 2018, Cooper et al. 2019, Whitaker and Kimmig 2020, Laney et al. 2021, Davis et al. 2022). Human observations have been rapidly increasing thanks to popular platforms such as iNaturalist which have their own slightly different biases, limitations, and strengths. We broadly consider fine-scale documentation of individual insects to be "collecting" for the purposes of this paper, though most of our recommendations are focused on traditional preserved-specimen based collections.

The goals of this study are twofold. First, we present an analysis of digitized insect occurrence data from the state of Arizona and compare the relative levels of sampling for different mountain ranges and ecoregions. Second, we address one example of an underexplored region and provide the first checklist of beetle species from the Sand Tank Mountains of central Arizona. We hope that these data and analyses can inform and bolster future insect collecting and survey work to improve our understanding of Arizona's biodiversity.

Arizona regionalization

Arizona encompasses a wide array of habitat types ranging from extreme deserts to mesic conifer forests. To efficiently classify these regions, different levels of the hierarchical ecoregions defined by Omernik and Griffith (2014) can be used. Level 3 of those ecoregions give a broad look at the state and are helpful to consider distributions and collecting efforts in broad strokes (Fig. 1a). However, this level of classification does not account for the fine scale habitat and plant community shifts that are seen especially in the mountainous parts of the state (see Brown (1978), Brown et al. (2007)).

Arizona can also be regionalized by its many mountain ranges. The Madrean Sky Islands are a series of discrete mountain ranges that arise from surrounding grasslands and are variously forested at their higher elevations (Fig. 1a area 12.1.1). These mountains are situated in the only gap of the North American Cordillera between the Rocky Mountain range to the north and the Sierra Madre Occidental range to the south and are a priority in insect conservation and phylogeographic research (Stock and Gress 2006, Ober et al. 2011, Moore et al. 2013, Halbritter et al. 2019, Yanahan and Moore 2019). Beyond the Madrean Sky Islands, the western and southern parts of Arizona are part of the Basin and Range Province of western North America which is characterized by a large number of mountain ranges that have formed as the earths crust stretched in this region (Morrison 1991) which covers the Sonoran and Mojave deserts (Fig. 1a areas 10.2.1 and 10.2.2). A final series of mountains occur in Arizona along the Mogollon Highlands region (Fleischner et al. 2017) which is a slightly oblique area of plateaus and associated mountains that generally separates northeastern Colorado Plateau from the southern Basin and Range Province (Fig. 1a area 13.1.1 in center of state).

Outlines of the 81 mountain ranges in Arizona with the highest peaks were geographically mapped for use in this study and are shown in Fig. 1b. The shapefiles of Arizona ecoregions and mountain ranges now allow for exploration of digitized insect occurrence records (Fig. 1c, d) to understand underlying patterns in bias and diversity of these areas.

Sand Tank Mountains

The Sand Tank Mountains, located in south central Arizona (Fig. 1b label 78, Fig. 2), cover a moderately large area in the Lower Colorado River Basin region of the Sonoran Desert (Brown 1978). The mountain range is situated with roughly its northern half on the Sonoran Desert National Monument bounded by US Interstate 8 to the north and its southern half on the Barry M. Goldwater Air Force Range. The mountains are therefore nearly entirely on public land, though access and collecting largely requires permits from the latter two entities. The highest point in the range, Maricopa Peak, only reaches 1234 m in elevation. The mountains are named for a series of tanks or tinajas (natual stone water catchments) that were often largely filled with sand and typically available to wildlife and humans for most of the year (Bryan 1925: 224-228).

Very little is known about the fauna of the Sand Tank Mountains and the adjoining Sauceda Mountains to the southwest (Fig. 1b label 75) which are almost never mentioned in the scientific literature. Brown (1978) included the Sand Tank mountains in a list of lower-elevation Sonoran Desert ranges which had relictual patches of grassland and chapparal species on them. The Sand Tanks also are the location of a notable Jaguar (*Panthera onca* (Linnaeus, 1758), family Felidae) record from 1930 which represents the southwestern known limit of the species in the state and likely the furthest documented excursion of the species into the Sonoran Desert (Babb et al. 2022).

Prior to the study presented here, a total of 27 occurrence records representing 16 insect taxa were available online (GBIF 2022a). This includes only a single record for the order Coleoptera which represents nearly 25% of all described species on earth, from a photo voucher on iNaturalist. We were unable to find any other beetle records from the mountains in the published scientific literature or in our own work in Arizona natural history collections.

Materials and methods

Evaluating collection bias across Arizona

Occurrence records for insects (Fig. 1) were downloaded from the online aggregator Global Biodiversity Information Facility (GBIF). Records were downloaded from GBIF (GBIF 2022a) by searching for every record that had geographic coordinates, contained 'Arizona' in the stateProvince data field and that belonged to Class Insecta. Note that the GBIF taxonomy is an integral part of the data discovery and download process and in the following analyses. The GBIF taxonomy is strongly, albeit understandably, influential for insect data since there are so many taxonomic names that are not reliably incorporated into the taxonomy. This may affect as much as 75% of records and names for major insect orders (Waller 2022). The occurrence records were imported into qGIS 3.24 (qGIS Development Team 2022) and checked against shape files with polygons representing ecoregions from the United States EPA (Omernik and Griffith 2014) and mountain ranges within Arizona. The list of mountain ranges was generated primarily by consulting online resources for mountain climbers. A curated list of mountain ranges and their highpoints (Anonymous 2022) was used as the starting point and each range was verified by through a combination of United States Geological Survery (USGS) topographic maps, Google Maps searches, and consulting regional gazeteers and atlases. Polygons for each mountain range were drawn by hand around geological formations as viewed in satellite imagery; topographic maps from the USGS, personal experience in the field, and mountain range and place names in google maps were used to ascertain a polygon that represented the footprint around the mountain range. Any occurrence found within the footprint of one of the included shapes as annotated as such. A custom script (Suppl. material 5) was written in R 4.0.2 (R Core Team 2020) to summarize the number of records by area metrics. Figures were produced in the same R script and utilized the packages dplyr (Wickham et al. 2022), ggplot2 (Wickham 2016), and cowplot (Wilke 2020).

Evaluating digitized records

For entomological field work, differences in occurrence records likely reveal a compilation of biological differences (e.g., increased insect biomass and population densities would increase the number of occurrence records), differences in survey effort (e.g., one area may have been visited by 100 researchers a year and another area by 10 researchers per year), and differences in social practices and research interests (e.g., one person may collect 100 of 200 observed individual insects at a particular event while another person may collect 5 of 200 observed individual insects at a different event). Insect occurrence records were therefore analyzed according to three different metrics, namely records, collecting events, and species. First, the total number of occurrence records for a given ecoregion or mountain range were tallied as a sum. Second, collecting effort was approximated by pooling records into putative collecting events. All insect records from a particular ecoregion or mountain range that had an identical date (using dwc:day, month, and year fields) and collector (dwc:recordedBy field) were considered to belong to a single collecting event. Third, putatively unique insect taxa were totalled for each ecoregion and mountain range by counting unique scientific names (dwc:scientificName field). These names correspond to the taxonomic interpretation according to the GBIF backbone taxonomy. This count may be considered an overestimate because different individuals of the same taxon may have been identified to different ranks (e.g., subspecies, species, genus, and family) and be counted multiple times. However, because so many taxa at the species level are not known to the GBIF taxonomy, many differently identified taxa are prone to being 'lumped' into a higher classification level (Waller 2022). For studies where the goal is to create a verified checklist of names, the original verbatim data from individual providers is included on GBIF but we deemed the taxon names as filtered by GBIF to be more standardized and at least easily comparable across ecoregions and mountain ranges. All data are made available as supplemental materials for annotated occurrence records (Suppl. material 1), summarized data for ecoregions (Suppl. material 2) and mountain ranges (Suppl. material 3).

Data were assessed for normality (Fig. 3) to determine suitability for the analyses presented below and to understand potential areas of bias in the occurrence data. Both untransformed and log-transformed data were assessed for normality via four metrics which include a boxplot, histogram and q-q plot for graphical analysis and a Shapiro-WIlk test (significant P-values of this test signify that the data are significantly different from a normal distribution). The distribution of insect occurrence records, collecting events, and taxon counts from ecoregions were all found to be normal in both untransformed and transformed forms (i.e. Shapiro-Wilk tests found their distributions to be indistinguishable from a normal distribution at the p = 0.05 level). For mountain ranges, insect occurrence records (Fig. 3a, b), collecting events (Fig. 3c, d), and taxon counts (Fig. 3e, f) were all non-normal in untransformed space but were all normal when log-transformed. The analyses shown below do not rely on normality, but these vizualizations and tests of the data are important to think about when considering sources of bias as discussed below.

Species-area relationships (SARs) were explored using linear regressions on both untransformed and transformed datasets as described above. There is some debate about what the most proper models are for SARs and growing evidence suggests that very small, intermediate, and very large areas operate under very different scaling parameters (Lomolino 2000, Lomolino and Weiser 2001, Stiles and Scheiner 2007, Dengler 2009, Storch et al. 2012, Storch 2016, Dengler et al. 2019). Our study is primarily focused on understanding the scale and bias of insect records in Arizona and therefore presents somewhat simplistic linear models to explore the data as a first step towards future studies which may employ more complex models to explore specific biological questions.

Species richness within areas was estimated using the R package iNEXT (Chao et al. 2014, Hsieh et al. 2020) to perform species rarefaction and extrapolation analyses. Counts were tabulated for the total number of records for each unique taxon within a region and these abundance data were given to iNEXT and analyzed using q=0 for the appropriate Hill number estimation for abundance data (Chao et al. 2014). Our analyses were primarily focused on exploring relative completeness of species richness sampling found within occurrence data but future studies primarily interested in modeling precise species richness would likely need to explore records in more detail to discern where there is and is not overlap at different taxonomic scales (e.g., how should records to the genus-level be counted if a single species from that genus is already counted from the area?). We analyzed taxa as unique name strings as described above for all analyses. We further re-analyzed several areas with a more conservative approach where we only used the subset of records that were identified to species (i.e., dwc:taxonRank = SPECIES) to explore how that changed extrapolation of total species richness. None of the rarefaction and extrapolation analyses presented here approach an assymptote within an estimated doubling of sampling effort and therefore have limitations in truly accounting for unobserved taxa in species richness estimates (Willis 2019); nevertheless, the rarefaction curves and estimates are still useful tools to understand uses and limitations of the underlying data.

Checklist of Sand Tank Mountains Coleoptera

Three collecting trips were made to the Sand Tank Mountains to survey for beetles. The first was on 29 April 2022 where blacklighting and night searches with headlamps were performed in a rocky basin near a paved wildlife water catchment basin (32.7868, -112.5177). Uncovered pitfall traps were set here and in a wide sandy wash (32.7982, -112.5112). The second trip was a single overnight visit from 3-4 June 2022 where the previously deployed pitfall traps were collected and night collecting was performed in the sandy wash site involving beating vegetation, blacklighting, and night searching. The third and final trip was on 15 July 2022 to a rocky canyon (32.6786, -112.3657) where blacklighting and night searches were performed. All beetle specimens were mounted and labeled and then identified to the lowest level possible. Full data for every voucher used in this study are fully digitized in the Ecdysis portal built on the Symbiota software (Gries et al. 2014), published to GBIF (GBIF 2022b), and in Suppl. material 4. Most specimens were deposited in the Arizona State University Hasbrouck Insect Collection (ASUHIC) with duplicates and focal research taxa deposited in the M. Andrew Johnston Research Collection (MAJC), Evan Waite Invertebrate Collection (EWIC) and Ethan Richard Wright Collection (ERWC), all of which are located in Tempe, Arizona, USA. Identifications were typically made using Arnett et al. (2002) to the level of family and genera. Species-level identifications were then performed by using appropriate primary literature or by consulting local taxonomic experts. The final identification resource for each species in the checklist is provided. For taxa identified by experts where a specific source is unknown, we attribute the identification to that person as unpublished data.

The checklist of species was built using the Ecdysis portal checklist tool from all of the digitized specimen records created as part of this project. The curated checklist was then exported for publication and inserted into the Arpha writing platform for this journal. Families are presented in alphabetical order and all species are presented alphabetically under their family. A total of 140 new species level records were identified anchored by 914 fully digitized pinned and labeled voucher specimens. When combined with the previously available record the following checklist enumerates 141 species of Coleoptera from the mountain range.

Sand Tank Mountains Coleoptera

Family Anthicidae

Duboisius arizonensis (Champion, 1916)

Notes: Identification reference: Abdullah 1964

Duboisius barri Abdulluh, 1964

Notes: Identification reference: Abdullah 1964

Notoxus calcaratus Horn, 1884

Notes: Identification reference: Chandler 1982

Vacusus confinis (LeConte, 1851)

Notes: Identification reference: Werner 1961

Family Bostrichidae

Amphicerus cornutus (Pallas, 1772)

Notes: Identification reference: Fisher 1950

Amphicerus teres Horn, 1878

Notes: Identification reference: Fisher 1950

Apatides fortis (LeConte, 1866)

Notes: Identification reference: Arnett et al. 2002

Dendrobiella aspera (LeConte, 1858)

Notes: Identification reference: Fisher 1950

Xyloblaptus quadrispinosus (LeConte, 1866)

Notes: Identification reference: Fisher 1950

Family Brachypsectridae

Brachypsectra fulva LeConte, 1874

Notes: Identification reference: Costa et al. 2006

Family Buprestidae

Chrysobothris micromorpha Fall, 1907

Notes: Identification reference: Arnett et al. 2002, N. Woodley personal communication to MAJ 2022

Gyascutus caelatus (LeConte, 1858)

Notes: Identification reference: iNaturalist

Melanophila atropurpurea (Say, 1823)

Notes: Identification reference: Sloop 1937

Family Carabidae

Apristus sp

Notes: This genus is in need of revision and we were unable to identify our specimens beyond genus.

Bembidion impotens Casey, 1918

Notes: Identification reference: Lindroth 1963

Calosoma prominens LeConte, 1853

Notes: Identification reference: Gidaspow 1959

Chlaenius orbus Horn, 1871

Notes: Identification reference: Bell 1960

Cymindis punctigera LeConte, 1851

Notes: Identification reference: Horn 1882

Discoderus obsidianus Casey, 1914

Notes: Identification reference: Casey 1914

Elaphropus conjugens (Notmann, 1919)

Notes: Identification reference: Erwin 1974

Lebia tuckeri (Casey, 1920)

Notes: Identification reference: Madge 1967

Notiobia terminata (Say, 1823)

Notes: Identification reference: Noonan 1973

Schizogenius pygmaeus Van Dyke, 1925

Notes: Identification reference: Whitehead 1972

Selenophorus aeneopiceus Casey, 1884

Notes: Identification reference: Messer and Raber 2021

Selenophorus concinnus Schaeffer, 1910

Notes: Identification reference: Messer and Raber 2021

Tetragonoderus pallidus Horn, 1868

Notes: Identification reference: Horn 1881

Family Cerambycidae

Anelaphus albofasciatus (Linell, 1897)

Notes: Identification reference: F.W. Skillman unpublished data

Anelaphus brevidens (Schaeffer, 1908)

Notes: Identification reference: F.W. Skillman unpublished data

Anelaphus piceus (Chemsak, 1962)

Notes: Identification reference: F.W. Skillman unpublished data

Anelaphus submoestus Linsley, 1942

Notes: Identification reference: F.W. Skillman unpublished data

Anoplocurius canotiae Fisher, 1920

Notes: Identification reference: F.W. Skillman unpublished data

Eustromula validum (LeConte, 1858)

Notes: Identification reference: F.W. Skillman unpublished data

Methia brevis Fall, 1929

Notes: Identification reference: F.W. Skillman unpublished data

Moneilema gigas (LeConte, 1873)

Notes: Identification reference: F.W. Skillman unpublished data

Sternidius centralis (LeConte, 1884)

Notes: Identification reference: F.W. Skillman unpublished data

Family Chrysomelidae

Colaspis viridiceps Schaeffer, 1933

Notes: Identification reference: Blake 1976

Coleorozena sp

Notes: This genus needs revision and we were unable to identify our specimens beyond genus.

Coleothorpa axillaris (LeConte, 1868)

Notes: Identification reference: Moldenke 1970

Diorhabda carinulata (Desbrochers, 1870)

Notes: Identification reference: TRACY and ROBBINS 2009

Glyptina sp

Notes: This genus needs revision and we were unable to identify our specimens beyond genus.

Pachybrachis connexus Fall, 1915

Notes: Identification reference: Barney 2019

Pachybrachis mellitus Bowditch, 1909

Notes: Identification reference: Fall 1915

Pachybrachis vigilans Fall, 1915

Notes: Identification reference: Barney 2019

Pachybrachis wickhami Bowditch, 1909

Notes: Identification reference: Barney 2019

Pachybrachis xanti Crotch, 1873

Notes: Identification reference: Barney 2019

Saxinis saucia LeConte, 1857

Notes: Identification reference: Moldenke 1970

Family Cleridae

Araeodontia peninsularis (Schaeffer, 1904)

Notes: Identification reference: B.H. Reily unpublished data

Cymatodera latefascia Schaeffer, 1904

Notes: Identification reference: B.H. Reily unpublished data

Cymatodera oblita Horn, 1876

Notes: Identification reference: B.H. Reily unpublished data

Cymatodera punctata Leconte, 1852

Notes: Identification reference: B.H. Reily unpublished data

Enoclerus quadrisignatus (Say, 1835)

Notes: Identification reference: B.H. Reily unpublished data

Lecontella gnara Wolcott, 1927

Notes: Identification reference: B.H. Reily unpublished data

Phyllobaenus discoideus (LeConte, 1852)

Notes: Identification reference: B.H. Reily unpublished data

Family Coccinellidae

Hyperaspis pleuralis Casey, 1899

Notes: Identification reference: Gordon 1985

Scymnus sp

Notes: Identification of this genus requires examination of male terminalia. Our single putatively female specimen was only identified to the subgenus *Scymnus (Pullus)*, of which there are a number of species known from this region.

Family Curculionidae

Eucyllus unicolor Van Dyke, 1936

Notes: Identification reference: Pelsue and Sleeper 1972

Ophryastes sp.

Notes: This diverse genus is difficult to identify without genitalic dissections and we were unabe to identify our specimen to species

Rhinostomus frontalis (LeConte, 1874)

Notes: Identification reference: Morrone and Cuevas 2002

Sibinia simplex (Casey, 1892: 421)

Notes: Identification reference: Clark 1978

Sibinia transversa (Casey, 1897: 665)

Notes: Identification reference: Clark 1978

Smicronyx sp

Notes: This speciose genus is difficult to identify and we were unable to identify our single specimen beyond genus.

Family Dascillidae

Anorus parvicollis Horn, 1894

Notes: Identification reference: Johnston and Gimmel 2020

Family Dermestidae

Anthrenus lepidus LeConte, 1854

Notes: Identification reference: Beal 1998

Family Dytiscidae

Eretes sticticus (Linnaeus, 1767)

Notes: Identification reference: Miller 2002

Family Elateridae

Agrypnus illimis (Horn, 1894)

Notes: Identification reference: Arnett 1952

Anchastus bicolor LeConte, 1866

Notes: Identification reference: Van Dyke 1932

Esthesopus parcus Horn, 1884

Notes: Identification reference: Horn 1884

Horistonotus lutzi Van Dyke, 1933

Notes: Identification reference: Wells 2000

Horistonotus simplex LeConte, 1863

Notes: Identification reference: Wells 2000

Mulsanteus arizonensis (Schaeffer, 1916)

Notes: Identification reference: B. Mathison unpublished data

Family Histeridae

Xerosaprinus coerulescens (LeConte, 1851)

Notes: Identification reference: W.B. Warner unpublished data

Xerosaprinus martini (Fall, 1917)

Notes: Identification reference: W.B. Warner unpublished data

Family Meloidae

Epicauta lauta (Horn, 1885)

Notes: Identification reference: Werner et al. 1966

Epicauta tenebrosa Werner, 1949

Notes: Identification reference: Werner et al. 1966

Epicauta tenuilineata (Horn, 1894)

Notes: Identification reference: Werner et al. 1966

Epicauta virgulata (LeConte, 1866)

Notes: Identification reference: Werner et al. 1966

Pyrota trochanterica Horn, 1894

Notes: Identification reference: Werner et al. 1966

Family Melyridae

Attalus serraticornis Fall, 1917

Notes: Identification reference: Marshall 1951

Trichochrous ferrugineus (Gorham, 1886)

Notes: Identification reference: M.L. Gimmel unpublished data

Trichochrous varius Casey, 1895

Notes: Identification reference: M.L. Gimmel unpublished data

Family Mordellidae

Mordellina sp

Notes: This genus has limited identification resources available. Our two specimens resemble *Mordellina testacea* (Blatchley, 1910) - a species only reported from the eastern United States.

Family Mycetophagidae

Typhaea stercorea (Linnaeus, 1758)

Notes: Identification reference: Arnett et al. 2002

Family Oedemeridae

Oxacis cana (LeConte, 1866)

Notes: Identification reference: Arnett 1951

Oxacis laevicollis Horn, 1896

Notes: Identification reference: Arnett 1951

Oxycopis mariae (Arnett, 1951)

Notes: Identification reference: Arnett 1951

Oxycopis sp

Notes: A moderate series of this *Oxycopis* species likely represent an undescribed species which we were unable to associate with any currently known from the western United States.

Family Phengodidae

Distremocephalus opaculus (Horn, 1895)

Notes: Identification reference: Zaragoza Caballero 1986

Family Ptinidae

Niptus ventriculus LeConte, 1859

Notes: Identification reference: Aalbu and Andrews 1992

Ptinus paulonotatus Pic, 1904

Notes: Identification reference: Papp 1962

Tricorynus sp

Notes: This speciose genus is in need of a modern revision. Our single specimen has elytra that lack discernable striae and may be near *Tricorynus lentus* (Fall, 1905).

Family Pyrochroidae

Cononotus bryanti Van Dyke, 1939

Notes: Identification reference: Van Dyke 1939

Family Salpingidae

Dacoderus striaticeps LeConte, 1858

Notes: Identification reference: Aalbu et al. 2005

Family Scarabaeidae

Acoma arizonica Brown, 1929

Notes: Identification reference: W.B. Warner unpublished data

Ataenius desertus Horn, 1871

Notes: Identification reference: W.B. Warner unpublished data

Ataenius hirsutus Horn, 1871

Notes: Identification reference: W.B. Warner unpublished data

Ataenius lobatus Horn, 1871

Notes: Identification reference: W.B. Warner unpublished data

Diplotaxis fissilabris Fall, 1909

Notes: Identification reference: W.B. Warner unpublished data

Diplotaxis moerens LeConte, 1856

Notes: Identification reference: W.B. Warner unpublished data

Diplotaxis planidens Fall, 1909

Notes: Identification reference: W.B. Warner unpublished data

Diplotaxis rufiola Fall, 1909

Notes: Identification reference: W.B. Warner unpublished data

Haroldiataenius lucanus (Horn, 1871)

Notes: Identification reference: W.B. Warner unpublished data

Oxygrylius ruginasus (LeConte, 1856)

Notes: Identification reference: W.B. Warner unpublished data

Phyllophaga scoparia (LeConte, 1856)

Notes: Identification reference: W.B. Warner unpublished data

Family Scraptiidae

Allopoda sp

Notes: This genus lacks a comprehensive key to species but genitalic dissections indicate that our series of specimens likely represent an undescribed species.

Diclidia greeni Liljeblad, 1918

Notes: Identification reference: Liljeblad 1945

Naucles pusio (LeConte, 1858)

Notes: Identification reference: Liljeblad 1945

Family Silvanidae

Ahasverus sp

Notes: Our specimens somewhat resemble *Ahasverus rectus* (LeConte, 1854) but differ in several characters from the holotype of that species. We have seen conspecific specimens to ours labeled as "*Ahasverus n.sp.*" in collections and think it is likely that it is indeed an undescribed species.

Family Staphylinidae

Philonthus sp

Notes: We were unable to identify our single specimen of this species beyond the level of genus in this speciose group.

Family Tenebrionidae

Alaephus macilentus Casey, 1891

Notes: Identification reference: M.A. Johnston unpublished data

Anepsius delicatulus LeConte, 1851

Notes: Identification reference: Doyen 1987

Araeoschizus decipiens Horn, 1890

Notes: Identification reference: Papp 1981

Araeoschizus regularis Horn, 1870

Notes: Identification reference: Papp 1981

Argoporis bicolor (LeConte, 1851)

Notes: Identification reference: Berry 1980

Asbolus mexicanus subsp. *angularis* (Horn, 1894)

Notes: Identification reference: Aalbu 2005

Batuliodes rotundicollis (LeConte, 1851)

Notes: Identification reference: Doyen 1987

Chilometopon helopioides (Horn, 1870)

Notes: Identification reference: MacLachlan and Olson 1990

Conibius opacus LeConte, 1866

Notes: Identification reference: M.A. Johnston unpublished data

Craniotus pubescens LeConte, 1851

Notes: Identification reference: Arnett et al. 2002

Cryptoglossa muricata (LeConte, 1851)

Notes: Identification reference: Aalbu 2005

Cryptoglossa variolosa (Horn, 1870)

Notes: Identification reference: Aalbu 2005

Edrotes ventricosus LeConte, 1851

Notes: Identification reference: Doyen 1968

Eleodes armata LeConte, 1851

Notes: Identification reference: Johnston et al. 2015

Eleodes tribula Thomas, 2005

Notes: Identification reference: Johnston 2016

Eupsophulus castaneus (Horn, 1870)

Notes: Identification reference: Spilman 1959

Eurymetopon rufipes Eschscholtz, 1831

Notes: Identification reference: M.A. Johnston unpublished data

Eusattus dubius LeConte, 1851

Notes: Identification reference: Doyen 1984

Hymenorus papagonis Fall, 1931

Notes: Identification reference: Fall 1931

Hymenorus punctatissimus LeConte, 1866

Notes: Identification reference: Fall 1931

Hymenorus spinifer Horn, 1894

Notes: Identification reference: Fall 1931

Latheticus oryzae Waterhouse, 1880

Notes: Identification reference: Arnett et al. 2002

Nocibiotes caudatus Casey, 1895

Notes: Identification reference: M.A. Johnston unpublished data

Nocibiotes granulatus (LeConte, 1851)

Notes: Identification reference: M.A. Johnston unpublished data

Statira defecta Schaeffer, 1905

Notes: Identification reference: Parsons 1975

Statira pluripunctata Horn, 1888

Notes: Identification reference: Parsons 1975

Steriphanus subopacus (Horn, 1870)

Notes: Identification reference: M.A. Johnston unpublished data

Telabis longipennis (Casey, 1890)

Notes: Identification reference: M.A. Johnston unpublished data

Triorophus laevis LeConte, 1851

Notes: Identification reference: M.A. Johnston unpublished data

Zophobas subnitens (Horn, 1874)

Notes: Identification reference: M.A. Johnston unpublished data

Family Trogidae

Omorgus carinatus Loomis, 1922

Notes: Identification reference: W.B. Warner unpublished data

Family Trogossitidae

Temnoscheila chlorodia (Mannerheim, 1843)

Notes: Identification reference: Barron 1971

Family Zopheridae

Hyporhagus gilensis Horn, 1872

Notes: Identification reference: Freude 1955

Rhagodera costata Horn, 1867

Notes: Identification reference: Stephan 1989

Analysis

Notes on the Sand Tank Mountains Coleoptera

The checklist provided herein significantly raises the entomological knowledge of this mountain range. Our surveys unfortunately were limited in their comprehensiveness as they did not include sampling during the peak flowering season that typically occurs between late February and April or in the winter which has a distinct insect fauna that often does not overlap with the taxa found during the warmer times of year. We also were unable to access a number of distinct habitats, including the relictual chaparral plant communities, that likely would have greatly increased our taxon count.

Many of the species reported from this study occur throughout the Lower Colorado River Basin subregion of the Sonoran Desert but are often poorly represented in natural history collections or in digitized occurrence records. Six species recorded by us had no prior digitized records from the state of Arizona even though they are known in the literature (

Diclidia greeni, *Horistonotus lutzi*, *Mulsanteus arizonensis*, *Niptus ventriculus*, *Oxycopis mariae*, and *Ptinus paulonotatus*). Many more represent the second digitized record or the first preserved specimen, as opposed to a human observation, from the state. These are notable in that they demonstrate specific examples of how digitized records both fall short of representing the full knowledge of the states fauna as well as the limited distibutional information available for many species. It is also notable that three collecting events produced likely three undescribed species (*Ahasverus sp*, *Allopoda sp*, and *Oxycopis sp*).

The actual number of coleoptera species that inhabit the Sand Tank Mountains is surely much higher than what is recorded here. Based on our experience in the region we presume this list is no more than 30% of the actual diversity and recommend future studies should focus on flower-feeding taxa and employ other trapping techniques such as flight-intercept traps and lindgren funnels. Estimating species richness using rarefaction and extrapolation (Fig. 4) estimates a total richness of 193 species which would mean we have sampled roughly 72% of the diversity so far. The lower estimate found in this analysis may actually be due to us employing similar collection methods on all our trips and perhaps this is a better reflection of the total number of species we could collect given the same techniques while not accounting for taxa that diversifying techniques would add.

Collection bias across ecoregions

Insect records and diversity for the ecoregions of Arizona are summarized in Fig. 5. The number of occurrence records are not very well correlated with the geographic area of the regions (Fig. 5a), but when transformed do start to show an expected increasing trend (Fig. 5b). When distinct collecting events are compared to geographic area (Fig. 5c, d) a trend of slightly more even distribution of sampling effort per area is observed. It seems clear that, relative to all the ecoregion in the state, the Madrean Archipelago is disproportionately highly samples while the Arizona/New Mexico Plateau is comparatively weakly sampled.

The number of taxa recorded from each ecoregion as compared to geographic area (Fig. 5 e, f) follows a similar trend as seen above and somewhat expectedly tends towards a linear relationship when log-transformed. Unsurprisingly the areas that are comparatively more densely sampled tend to have a comparatively higher number of taxa. It is likely there are other biological factors driving species distibutions in these areas but the strong heterogeneity in sampling level must be factored in to make any interpretations of these data.

Collection bias across mountain ranges

Insect records and diversity for Arizona mountain ranges by geographic area are summarized in Fig. 6. In contrast to the data for ecoregions presented above, mountain ranges show a much less even distribution of collecting records. Both individual occurrence records by area (Fig. 6a, b) and collecting events by area (Fig. 6c, d) are highly skewed by a few very disproportionately well collected mountain ranges and a large number of ranges with almost no sampling. Insect taxa by mountain range area (Fig. 6e, f) show a nearly identical trend to the overall occurrence records and collecting events, which indicates that the data on taxonomic richness for the mountain ranges is highly affected by the disproportionate sampling efforts.

The most distant outlier by far are the Chiricahua Mountains (label 5 in Fig. 6) which are located in the extreme southeastern corner of the state and represent 117,396 (40%) out of 296,421 total occurrence records which were mapped to all 81 mountain ranges examined here. This high sampling rate is in large part due to an active research station located withinthe range and likely other social mechanisms like word-of-mouth discussed below. The following four mountain ranges were also incredibly highly sampled, though nowhere near the sampling effort seen in the Chiricahuas. The Huachuca Mountains (label 6 in Fig. 6) are located along the Mexican border of Arizona and are home to many classical collecting localities and popular canyons such as Ramsey Canyon, Miller Canyon, and Carr Canyon. The Santa Rita Mountains (label 7 in Fig. 6) are just south of Tucson and have good access by roads,a university experimental station, and are home to the very popular Madera Canyon. The Santa Catalina Mountains (label 9 in Fig. 6) are located just north of Tucson and are very easily accessed by paved roads from that city with classic collecting localities such as Sabino Canyon and Mount Lemmon. The Atascosa/Pajarito Mountains (label 44 in Fig. 6) are also located along the middle of the Mexican border with Arizona and are home to the very well visited Pena Blanca Canyon and lake. Together, these five ranges represent 221,815 (75%) of the 296,421 total occurrence records from mountains reported here.

Species richness estimates

The disproportionate levels of data among mountain ranges discussed above demonstrate that it is too soon to accurately model insect diversity from occurrence records for most ranges. However, the Chiricahua Mountains are so disproportionately highly collected that they offer an important case study into what we can infer about insect diversity from occurrence records. Analysis of species richness for the Chiricahuas (Fig. 7) indicate that we are fairly far from reaching a plateau or accurate assessment of the actual taxonomic diversity. The preliminary estimate for all taxa (Fig. 7a) suggests 9,600 unique taxa are present while more conservative estimate of species (Fig. 7b) suggests 6,500 species are present. Perhaps more important than the total numbers, both estimates suggest that current digitized data at best account for 70% of the actual diversity from those mountains.

Scaling up to ecoregions, species richness is similarly incompletely sampled by current collecting efforts (Fig. 8). The Madrean Archipelago, the proportionately highest sampled region by area (Fig. 5), boasts the largest recorded taxonomic diversity of the six ecoregions with just over 15,300 taxa which falls well short of a preliminary estimate of over 21,700. All ecoregions apparently require more than double the current sampling effort to begin to find a plateau and accurate species richness estimate.

Species richness estimates for the entire state of Arizona again fail to plateau with the available data (Fig. 9). Preliminary species richness estimates are much higher than those observed with all taxa (Fig. 9a) predicting roughly 36,000 total taxa and species-only data

(Fig. 9b) predicting just over 21,600 species. As with the Chiricahua Mountains and ecoregions discussed above, both Arizona richness estimates imply that the current data only represent around 70% of predicted diversity, and similarly demonstrate that online data will need to be greatly expanded before accurate estimates can be made.

Discussion

Species richness estimates

All rarefaction and extrapolation estimates of species (or taxonomic) richness failed to plateau and provided very similar results that only 70% of the full estimated species richness were observed. Because all the analyses across the three scales explored here gave these similar proportional results, it seems clear that the estimates are strongly affected by incomplete sampling. We again urge readers to be cautious with the absolute numbers presented here. However, given our knowledge of the Sand Tank Mountains coleoptera study and its limitations along with the slopes of all rarefaction curves, the species richness estimates presented here seem to be extremely conservative counts and might be useful as a lowest-end predictor of what the true diversity is.

Factors driving collecting bias

The analyses presented here clearly demonstrate that, according to available data, insect collecting has not been done evenly throughout the state. The underlying factors that drive the biases seen in the data are likely numerous and difficult to fully ascertain. We hypothesize that two of the primary drivers are habitat accessibility and social interactions.

Habitat access for insect collectors is very important and has many facets. Perhaps the most important factors include road quality and quantity, proximity to population centers, and land ownership and management. For example, the Chiricahua Mountains excel in all three categories and have roads accessible to passenger cars that go to the highest elevations. The mountains are almost entirely on public lands and there are nearby towns with accommodations and stores as well as a popular research station. In contrast, all sites visited in the Sand Tank Mountains involved rugged back-country roads requiring high clearance and four-wheel drive vehicles in areas where it is unlikely to encounter other people in the event of an emergency. Habitat access is not equal at the large scale of ecoregions either. The majority of the Madrean Archipelago is covered by public lands (U.S. Forest Service and Bureau of Land Management) while large swaths of the Sonoran Desert and especially the Arizona/New Mexico Plateaus regions are Native American Reservations. Different sovereign tribal lands, private property, and various public land management agencies all have unique regulations and permitting processes which affect collecting insects. In our experience, insect collectors will often prefer accessing areas that have the least regulations and required permits. The Mohave Basin and Range ecoregion is an interesting example where most of the lands are public but the terrain is very rugged and roads and population centers are limited which is likely why there are so few insect records from the region.

Social aspects of the insect collector community are harder to quanitfy but are undoubtedly just as important as habitat access. When talking with colleagues at conferences or planning trips with enthusiastic collectors from far-flung locations, the first places talked about are "classic" collecting localities that have appeared in the published literature, printed on insect labels in collections, and spread by word-of-mouth between collectors. This invariably includes the canyons and sites discussed in the highly collected mountain ranges above. In our experience, this seems to lead to a positive feedback loop which drives an ever increasing focus on a small number of popular localities.

The Patagonia Picnic Table Effect (Laney et al. 2021), named after the town of Patagonia, Arizona, is a term from the birdwatching community to describe how one sighting of a rare species leads to increased birdwatching effort in the immediate region which in turn produces more sightings of other rare species in the same area. The equivalent in the insect world would be one collector finding a very rare or showy species which promts future collectors to either go and re-collect a similarly important specimen of their own where they may find something rare in their own taxonomic speaciality and continue to amplify interest in the location. Laney et al. (2021) analyzed 10 years of birdwatching data and demonstrated that there is an increase of activity following the initial discovery but there was no increased likelihood to find additional rare species in that area compared to any other. It seems clear that, despite its potential lack of utility in rare species documentation, it is a social phenomenon in natualist communities.

Recommendations for future collecting

The full scale of insect diversity has been underdocumented for the state of Arizona, its consituent ecoregions, or even its most popular mountain ranges. It is important that the entomological community continues to survey for and collect insects everywhere in the state. Continuing and increasing efforts to mobilize specimen data from natural history collections also remains a high priority and will likely help account for many species which are not currently represented in online data. We would recommend that gap analyses be done on digitized insect data when the number of records approximately doubles from its current state since none of the species richness estimation curves reported here approached an asymptote.

We urge collectors to make a concerted effort to go to new places and consider targeting specifically undercollected regions and mountain ranges. Small and targeted studies can exponentially improve our understanding of Arizona insect fauna and are likely the best way to increase knowledge of species distributions and may be curcial to understanding the entire state fauna. Our example of the Sand Tank Mountains beetles highlights how a modest collecting effort can still provide new occurrence records for species from the state and report on new localities for taxa that are otherwise considered rare in collections. We do not recommend that collectors avoid the classic and popular sites, indeed we still need to sample those, but we would advocate that entomologists consider dividing their time in the field and and only spend part of their efforts in the well-known habitats and spend the next day somewhere new.

The paucity of insect data from so many mountain ranges in the state strongly limit our ability to adequately protect and conserve insect biodiversity. Local, state, and federal land management agencies should partner with entomologists to increase insect sampling throughout the state. Opportunites for occurrence-data driven estimates for species diversity are in their infancy, even for a biodiversity hotspot that is accessible and popular. Nevertheless, the growing availability of occurrence data is an important resource to continue to develop to understand the diversity and distributions of insects in Arizona.

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References

- Aalbu R, Andrews F (1992) Revision of the spider beetle genus *Niptus* in North America, including new cave and phoeophile species (Coleoptera: Ptinidae). The Pan-Pacific Entomologist 68 (2): 73-96.
- Aalbu R (2005) The pimeliine tribe Cryptoglossini: classification, biology and inferred phylogeny (Coleoptera: Tenebrionidae). Annales Zoologici 55 (4): 677-756.
- Aalbu R, Andrews F, Pollock D (2005) Revision of western hemisphere Dacoderinae with a phylogenetic analysis of world taxa (Coleoptera: Salpingidae). The Coleopterists Bulletin 59 (mo4): 1-40.
- Abdullah M (1964) New Nearctic Eurygeniini (Coleoptera, Anthicidae, Pedilinae). Annals and Magazine of Natural History 7 (74): 81-94. https://doi.org/10.1080/00222936408651443
- Anonymous (2022) Arizona Mountain Ranges Highpoints List, 204 peaks, Revised May 14, 2020. http://www.peakbagging.com/Peak%20Lists/AZRange1.htm. Accessed on: 2022-1-04.
- Arnett R (1951) A revision of the Nearctic Oedemeridae (Coleoptera). American Midland Naturalist 45: 257-391.
- Arnett R (1952) A review of the Nearctic Adelocerina (Coleoptera: Elateridae, Pyrophorinae, Pyrophorini). Wassmann Journal of Biology 10 (1): 103-126.
- Arnett R, Thomas M, Skelley P, Frank J (2002) American Beetles, Volume II: Polyphaga: Scarabaeoidea through Curculionoidea. CRC Press, Boca Raton. [ISBN 0849309549]

- Babb R, Brown D, Culver M, Childs J, Thompson R, Kohls R, Taylor T (2022) Updates of historic and contemporary records of jaguars (*Panthera onca*) from Arizona. Journal of the Arizona-Nevada Academy of Science 49 (2). https://doi.org/10.2181/036.049.0205
- Barney R (2019) Definition and revision of the *pubescens* species-group of North American *Pachybrachis* Chevrolat (Coleoptera: Chrysomelidae: Cryptocephalinae), including descriptions of three new species. The Coleopterists Bulletin 73 (4). https://doi.org/10.1649/0010-065x-73.4.1017
- Barron J (1971) A revision of the Trogositidae of America north of Mexico (Coleoptera: Cleroidea). Memoirs of the Entomological Society of Canada 75: 1-143.
- Beal R (1998) Taxonomy and biology of Nearctic species of *Anthrenus* (Coleoptera: Dermestidae). Transaction of the American Entomological Society 124 (3+4): 271-332.
- Bell R (1960) A revision of the genus *Chlaenius* Bonelli (Coleoptera: Carabidae) in North America. Miscellaneous Publications of the Entomological Society of America 1: 97-166.
- Berry R (1980) A revision of the North American genus *Argoporis* (Coleoptera: Tenebrionidae: Cerenopini). Ohio Biological Survey Bulletin New Series 6 (1): 1-106.
- Blake D (1976) The brown semicostate and costate species of *Colaspis* in Mexico and Central America (Coleoptera: Chrysomelidae). United States Deartment of Agriculture, Technical Bulletin (1534)1-40.
- Bossart J, Carlton C (2002) Insect conservation in America: Status and perspectives. American Entomologist 48 (2): 82-92. https://doi.org/10.1093/ae/48.2.82
- Brown D (1978) The vegetation and occurrence of chaparral and woodland flora on isolated mountains within the Sonoran and Mojave Deserts in Arizona. Journal of the Arizona-Nevada Academy of Science 13 (1): 7-12. URL: https://www.jstor.org/stable/40021812
- Brown D, Unmack P, Brennan T (2007) Digitized map of biotic communities for plotting and comparing distributions of North American animals. The Southwestern Naturalist 52 (4): 610-616. https://doi.org/10.1894/0038-4909(2007)52[610:dmobcf]2.0.co;2
- Bryan K (1925) The Papago country, Arizona, a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places. Water-Supply Paper 499 https://doi.org/10.3133/wsp499
- Casey T (1914) Memoirs on the Coleoptera. Vol. 5. The New Era Printing Company, Lancaster, PA, 378 pp.
- Chandler D (1982) A revision of North American *Notoxus* with a cladistic analysis of the New World species (Coleoptera: Anthicidae). Entomography 1: 333-438.
- Chao A, Gotelli N, Hsieh TC, Sander E, Ma KH, Colwell R, Ellison A (2014) Rarefaction and extrapolation with Hill numbers: a framework for sampling and estimation in species diversity studies. Ecological Monographs 84 (1): 45-67. https://doi.org/10.1890/13-0133.1
- Clark W (1978) The weevil genus *Sibinia* Germar: natural history, taxonomy, phylogeny, and zoogeography, with revision of the New World species (Coleoptera: Curculionidae). Quaestiones Entomologicae 14 (2): 91-387.
- Cook J, Edwards S, Lacey E, Guralnick R, Soltis P, Soltis D, Welch C, Bell K, Galbreath K, Himes C, Allen J, Heath T, Carnaval A, Cooper K, Liu M, Hanken J, Ickert-Bond S (2014) Natural history collections as emerging resources for innovative education. BioScience 64 (8): 725-734. https://doi.org/10.1093/biosci/biu096

- Cooper N, Bond A, Davis J, Portela Miguez R, Tomsett L, Helgen K (2019) Sex biases in bird and mammal natural history collections. Proceedings of the Royal Society B: Biological Sciences 286 (1913). https://doi.org/10.1098/rspb.2019.2025
- Costa C, Vanin S, Lawrence J, Ide S, Branham M (2006) Review of the family Brachypsectridae (Coleoptera: Elateroidea). Annals of the Entomological Society of America 99 (3): 409-432. https://doi.org/10.1603/0013-8746(2006)99[409:rotfbc]2.0.co;2
- Davis C, Guralnick R, Zipkin E (2022) Challenges and opportunities for using natural history collections to estimate insect population trends. Journal of Animal Ecology https://doi.org/10.1111/1365-2656.13763
- Dengler J (2009) Which function describes the species-area relationship best? A review and empirical evaluation. Journal of Biogeography 36 (4): 728-744. https://doi.org/10.1111/j.1365-2699.2008.02038.x
- Dengler J, Matthews T, Steinbauer M, Wolfrum S, Boch S, Chiarucci A, Conradi T, Dembicz I, Marcenò C, García-Mijangos I, Nowak A, Storch D, Ulrich W, Campos JA, Cancellieri L, Carboni M, Ciaschetti G, De Frenne P, Dolezal J, Dolnik C, Essl F, Fantinato E, Filibeck G, Grytnes J, Guarino R, Güler B, Janišová M, Klichowska E, Kozub Ł, Kuzemko A, Manthey M, Mimet A, Naqinezhad A, Pedersen C, Peet R, Pellissier V, Pielech R, Potenza G, Rosati L, Terzi M, Valkó O, Vynokurov D, White H, Winkler M, Biurrun I (2019) Species–area relationships in continuous vegetation: Evidence from Palaearctic grasslands. Journal of Biogeography 47 (1): 72-86. https://doi.org/10.1111/jbi.13697
- Doyen J (1968) The phylogenetic position of *Edrotes* and a new species of the genus (Coleoptera: Tenebrionidae). The Pan-Pacific Entomologist 44 (3): 218-227.
- Doyen J (1984) Systematics of *Eusattus* and *Conisattus* (Coleoptera; Tenebrionidae; Coniontini; Eusatti). Occasional Papers of the California Academy of Sciences 141: 1-104.
- Doyen J (1987) Review of the tenebrionid tribe Anepsiini (Coleoptera). Proceedings of the California Academy of Sciences 44 (15): 343-371.
- Erwin T (1974) Studies of the subtribe Tachyina (Coleoptera: Carabidae: Bembidiini) supplement A: lectotype designations for New World species, two new genera, and notes on generic concepts. Proceedings of the Entomological Society of Washington 76: 123-155.
- Fall F (1915) A revision of the North American species of *Pachybrachis*. Transactions of the American Entomological Society 41: 291-486.
- Fall H (1931) The North American species of *Hymenorus* (Coleoptera: Alleculidae). Transactions of the American Entomological Society 57 (2): 161-247.
- Fisher W (1950) A revision of the North American species of beetles belonging to the family Bostrichidae. United States Department of Agriculture Miscellaneous Publications (698)1-157.
- Fleischner T, Hanna D, Floyd-Hanna L (2017) A preliminary description of the Mogollon Highlands ecoregion. Plant Press 40 (2): 3-6.
- Freude H (1955) Die Monommiden der Welt: II. Teil: Die Monommiden der amerikanischen Region. Entomologische Arbeiten aus dem Museum G. Frey 6: 684-763.
- Gaston K (1991) The magnitude of global insect species richness. Conservation Biology 5 (3): 283-296. https://doi.org/10.1111/j.1523-1739.1991.tb00140.x

- GBIF (2022a) GBIF Occurrence Download. Global Biodiversity Information Facilit. Release date: 2022-3-24. URL: https://doi.org/10.15468/dl.z4crnr
- GBIF (2022b) GBIF Occurrence Download. Global Biodiversity Information Facility. Release date: 2022-12-02. URL: https://doi.org/10.15468/dl.5dthvr
- Gidaspow T (1959) North American caterpillar hunters of the genera *Calosoma* and *Callisthenes* (Coleoptera, Carabidae). Bulletin of the American Museum of Natural History 116 (3): 225-344.
- Gordon R (1985) The Coccinellidae (Coleoptera) of America North of Mexico. Journal of the New York Entomological Society 93 (1): 1-912.
- Gries C, Gilbert E, Franz N (2014) Symbiota – A virtual platform for creating voucher-based biodiversity information communities. Biodiversity Data Journal 2 https://doi.org/10.3897/bdj.2.e1114
- Guralnick R, Zermoglio P, Wieczorek J, LaFrance R, Bloom D, Russell L (2016) The importance of digitized biocollections as a source of trait data and a new VertNet resource. Database 2016 https://doi.org/10.1093/database/baw158
- Halbritter D, Storer C, Kawahara A, Daniels J (2019) Phylogeography and population genetics of pine butterflies: Sky islands increase genetic divergence. Ecology and Evolution 9 (23): 13389-13401. https://doi.org/10.1002/ece3.5793
- Hedrick BP, Heberling JM, Meineke EK, Turner KG, Grassa CJ, Park DS, Kennedy J, Clarke JA, Cook JA, Blackburn DC, Edwards SV, Davis CC (2020) Digitization and the future of natural history collections. BioScience 70 (3): 243-251. https://doi.org/10.1093/biosci/biz163
- Horn G (1881) Synoptic tables of Coleoptera. Bulletin of the Brooklyn Entomological Society 4 (7+8): 39-40.
- Horn G (1882) Synopsis of the species of the tribe Lebiini. Transactions of the American Entomological Society 10: 126-163.
- Horn G (1884) A study of some genera of Elateridae. Transactions of the American Entomological Society 12: 33-52.
- Hortal J, de Bello F, Diniz-Filho J, Lewinsohn T, Lobo J, Ladle R (2015) Seven shortfalls that beset large-scale knowledge of biodiversity. Annual Review of Ecology, Evolution, and Systematics 46 (1): 523-549. https://doi.org/10.1146/annurev-ecolsys-112414-054400
- Hsieh TC, Ma KH, Chao A (2020) iNEXT: iNterpolation and EXTrapolation for species diversity. URL: http://chao.stat.nthu.edu.tw/wordpress/software-download/
- Johnston MA, Fleming D, Franz N, Smith A (2015) Amphidorini Leconte (Coleoptera: Tenebrionidae) of Arizona: Keys and species accounts. The Coleopterists Bulletin 69: 27-54. https://doi.org/10.1649/0010-065x-69.mo4.27
- Johnston MA (2016) Redefinition of the *Eleodes* Eschscholtz subgenera *Tricheleodes* Blaisdell and *Pseudeleodes* Blaisdell, with the description of a new species (Coleoptera: Tenebrionidae). Annales Zoologici 66 (4): 665-679. https://doi.org/10.3161/00034541anz2016.66.4.018
- Johnston MA, Aalbu R, Franz N (2018) An updated checklist of the Tenebrionidae sec. Bousquet et al. 2018 of the Algodones Dunes of California, with comments on checklist data practices. Biodiversity Data Journal 6 https://doi.org/10.3897/bdj.6.e24927
- Johnston MA, Gimmel M (2020) Review of North American Dascillidae (Coleoptera: Dascilloidea), with descriptions of dramatic female wing reduction. The Coleopterists Bulletin 74 (4). https://doi.org/10.1649/0010-065x-74.4.731

- Kharouba HM, Lewthwaite JMM, Guralnick R, Kerr JT, Vellend M (2018) Using insect natural history collections to study global change impacts: challenges and opportunities. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences 374 (1763). https://doi.org/10.1098/rstb.2017.0405
- Laney J, Hallman T, Curtis J, Robinson WD (2021) The influence of rare birds on observer effort and subsequent rarity discovery in the American birdwatching community. PeerJ 9 https://doi.org/10.7717/peerj.10713
- Lendemer J, Thiers B, Monfils AK, Zaspel J, Ellwood ER, Bentley A, LeVan K, Bates J, Jennings D, Contreras D, Lagomarsino L, Mabee P, Ford LS, Guralnick R, Gropp RE, Revelez M, Cobb N, Seltmann K, Aime MC (2019) The Extended Specimen Network: A strategy to enhance US biodiversity collections, promote research and education. BioScience 70 (1): 23-30. https://doi.org/10.1093/biosci/biz140
- Liljeblad E (1945) Monograph of the fmaily Mordellidae (Coleoptera) of North America, north of Mexico. Miscellaneous Publications Museum of Zoology, University of Michigan 62: 1-229.
- Lindroth C (1963) The ground-beetles (Carabidae, excl. Cicindelinae) of Canada and Alaska. Part 4. Opuscula Entomologica Supplementum 34: 945-1192.
- Lomolino M (2000) Ecology's most general, yet protean pattern: the species-area relationship. Journal of Biogeography 27 (1): 17-26. https://doi.org/10.1046/j.1365-2699.2000.00377.x
- Lomolino MV, Weiser MD (2001) Towards a more general species-area relationship: diversity on all islands, great and small. Journal of Biogeography 28 (4): 431-445. https://doi.org/10.1046/j.1365-2699.2001.00550.x
- MacLachlan W, Olson C (1990) A revision of the Trimytini of America north of Mexico (Coleoptera: Tenebrionidae). The Coleopterists Bulletin 44 (1): 69-82.
- Madge R (1967) A revision of the genus *Lebia* Latreille in America north of Mexico. Quaestiones Entomologicae 3: 139-242.
- Marshall M (1951) Studies in the Malachiidae. III. Proceedings of the California Academy of Sciences, 4th series 27: 77-132.
- Mayhew P (2007) Why are there so many insect species? Perspectives from fossils and phylogenies. Biological Reviews 82 (3): 425-454. https://doi.org/10.1111/j.1469-185x.2007.00018.x
- Meineke E, Davies TJ, Daru B, Davis C (2018) Biological collections for understanding biodiversity in the Anthropocene. Philosophical Transactions of the Royal Society B: Biological Sciences 374 (1763). https://doi.org/10.1098/rstb.2017.0386
- Messer P, Raber B (2021) A Review of Nearctic Selenophorus Dejean (Coleoptera: Carabidae: Harpalini) North of Mexico with New Species, New Synonyms, Range Extensions, and a Key. The Coleopterists Bulletin 75 (1). https://doi.org/10.1649/0010-065x-75.1.9
- Miller K (2002) Revision of the genus *Eretes* Laporte, 1833 (Coleoptera: Dytiscidae). Aquatic Insects 24 (4): 247-272.
- Moldenke A (1970) A revision of the Clytrinae of North America north of the Isthmus of Panama. Stanford University, Stanford, 310 pp.
- Moore W, Meyer WM, Eble JA, Franklin K, Wiens JF, Brusca RC (2013) Introduction to the Arizona Sky Island Arthropod Project (ASAP): Systematics, biogeography, ecology, and population genetics of arthropods of the Madrean Sky Islands. Proceedings RMRS 2013: 144-168.

- Morrison R (1991) Quaternary geology of the southern Basin and Range Province. Quaternary Nonglacial Geology: Coterminus US353-371. https://doi.org/10.1130/dnag-gna-k2.353
- Morrone J, Cuevas P (2002) Cladistics of the pantropical genus *Rhinostomus* (Coleoptera: Curculionoidea: Dryophthoridae), with nomenclatural notes. Journal of the New York Entomological Society 110: 376-388. https://doi.org/10.1664/0028-7199(2002)110[376:cotpgr]2.0.co;2
- Noonan G (1973) The anisodacylines (Insecta: Coleoptera: Carabidae: Harpalini): classification, evolution and zoogeography. Quaestiones Entomologicae 9 (4): 266-480.
- Ober K, Matthews B, Ferrieri A, Kuhn S (2011) The evolution and age of populations of *Scaphinotus petersi* Roeschke on Arizona Sky Islands (Coleoptera, Carabidae, Cychrini). ZooKeys 147: 183-97. https://doi.org/10.3897/zookeys.147.2024
- Omernik J, Griffith G (2014) Ecoregions of the Conterminous United States: Evolution of a hierarchical spatial framework. Environmental Management 54 (6): 1249-1266. https://doi.org/10.1007/s00267-014-0364-1
- Page L, MacFadden B, Fortes J, Soltis P, Riccardi G (2015) Digitization of biodiversity collections reveals biggest data on biodiversity. BioScience 65 (9): 841-842. https://doi.org/10.1093/biosci/biv104
- Papp C (1962) An illustrated and descriptive catalogue of the Ptinidae of North America. Deutsche Entomologishe Zeitschrifte 5: 367-423.
- Papp C (1981) Revision of the genus *Araeoschizus* LeConte (Coleoptera: Tenebrionidae). Entomologische Arbeiten aus dem Museum G. Frey 29: 273-420.
- Parsons C (1975) A key to nearctic *Statira* and *Arthromacra* (Lagriidae). The Coleopterists Bulletin 29 (4): 211-226.
- Pelsue F, Sleeper E (1972) A review of *Eucyllus* Horn (Coleoptera: Curculionidae, Brachyrhininae, Peritelini). Bulletin of the Southern California Academy of Sciences 71: 80-91.
- qGIS Development Team (2022) QGIS Geographic Information System. 3.24. Open Source Geospatial Foundation Project. URL: http://qgis.osgeo.org
- R Core Team (2020) R: A language and environment for statistical computing. 4.0.2. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/
- Sloop K (1937) A revision of the North American buprestid beetles belonging to the genus *Melanophila* (Coleoptera, Buprestidae). University of California Publications in Entomology 7: 1-20.
- Spilman T (1959) Notes on *Edrotes*, *Leichenum*, *Palorus*, *Eupsophulus*, *Adelium*, and *Strongylium* (Tenebrionidae). The Coleopterists Bulletin 13 (2): 58-64.
- Stephan K (1989) The Bothrideridae and Colydiidae of America north of Mexico (Coleoptera: Clavicornia and Heteromera. Occassional Papers of the Florida State Collection of Arthropods 6: 1-65.
- Stiles A, Scheiner S (2007) Evaluation of species-area functions using Sonoran Desert plant data: not all species-area curves are power functions. Oikos 116 (11): 1930-1940. https://doi.org/10.1111/j.0030-1299.2007.15703.x
- Stock SP, Gress J (2006) Diversity and phylogenetic relationships of entomopathogenic nematodes (Steinernematidae and Heterorhabditidae) from the Sky Islands of southern Arizona. Journal of Invertebrate Pathology 92 (2): 66-72. https://doi.org/10.1016/j.jip.2006.02.001

- Storch D, Keil P, Jetz W (2012) Universal species–area and endemics–area relationships at continental scales. Nature 488 (7409): 78-81. https://doi.org/10.1038/nature11226
- Storch D (2016) The theory of the nested species-area relationship: geometric foundations of biodiversity scaling. Journal of Vegetation Science 27 (5): 880-891. https://doi.org/10.1111/jvs.12428
- TRACY J, ROBBINS T (2009) Taxonomic revision and biogeography of the *Tamarix*-feeding *Diorhabda elongata* (Brullé, 1832) species group (Coleoptera: Chrysomelidae: Galerucinae: Galerucini) and analysis of their potential in biological control of Tamarisk. Zootaxa 2101 (1): 1-152. https://doi.org/10.11646/zootaxa.2101.1.1
- Van Dyke E (1932) Miscellaneous studies in the Elateridae and related families of Coleopterea. Proceedings of the California Academy of Sciences 20 (9): 291-465.
- Van Dyke E (1939) New species and subspecies of west American Coleoptera. The Pan-Pacific Entomologist 15: 15-20.
- Waller J (2022) Finding data gaps in the GBIF backbone taxonomy. Biodiversity Information Science and Standards 6 https://doi.org/10.3897/biss.6.91312
- Wells S (2000) Two new species of *Horistonotus* Candeze (Coleoptera: Elateridae), new synonymies, and a key to the species of the United States and Canada. Proceedings of the Entomological Society of Washington 102 (2): 412-420.
- Werner F, Enns W, Parker F (1966) The Meloidae of Arizona. Technical Bulletin - Agricultural Experimental Station, the University of Arizona (175)1-96.
- Werner FG (1961) A Revision of the Genus *Vacusus* Casey (Coleoptera: Anthicidae). Annals of the Entomological Society of America 54 (6): 798-809. https://doi.org/10.1093/aesa/54.6.798
- Whitaker A, Kimmig J (2020) Anthropologically introduced biases in natural history collections, with a case study on the invertebrate paleontology collections from the middle Cambrian Spence Shale Lagerstätte. Palaeontologia Electronica https://doi.org/10.26879/1106
- Whitehead D (1972) Classification, phylogeny, and zoogeography of *Schizogenius* Putzeys (Coleoptera: Carabidae: Scaritinae). Quaestiones Entomologicae 8: 131-348.
- Wickham H (2016) ggplot2: Elegant graphics for data analysis. Springer-Verlag New York. URL: https://ggplot2.tidyverse.org
- Wickham H, François R, Henry L, Müller K (2022) dplyr: A grammar of data manipulation. URL: https://CRAN.R-project.org/package=dplyr
- Wilke C (2020) cowplot: Streamlined plot theme and plot annotations for 'ggplot2'. URL: https://CRAN.R-project.org/package=cowplot
- Willis A (2019) Rarefaction, alpha diversity, and statistics. Frontiers in Microbiology 10 https://doi.org/10.3389/fmicb.2019.02407
- Yanahan A, Moore W (2019) Impacts of 21st-century climate change on montane habitat in the Madrean Sky Island Archipelago. Diversity and Distributions 25 (10): 1625-1638. https://doi.org/10.1111/ddi.12965
- Zaragoza Caballero S (1986) El genero *Distremocephalus* Wittmer en Mexico (Coleoptera: Phengodidae; Mastinocerini). Annales del Instituto de Biologia Universidad Nacional Autonoma de Mexico 56: 933-938.

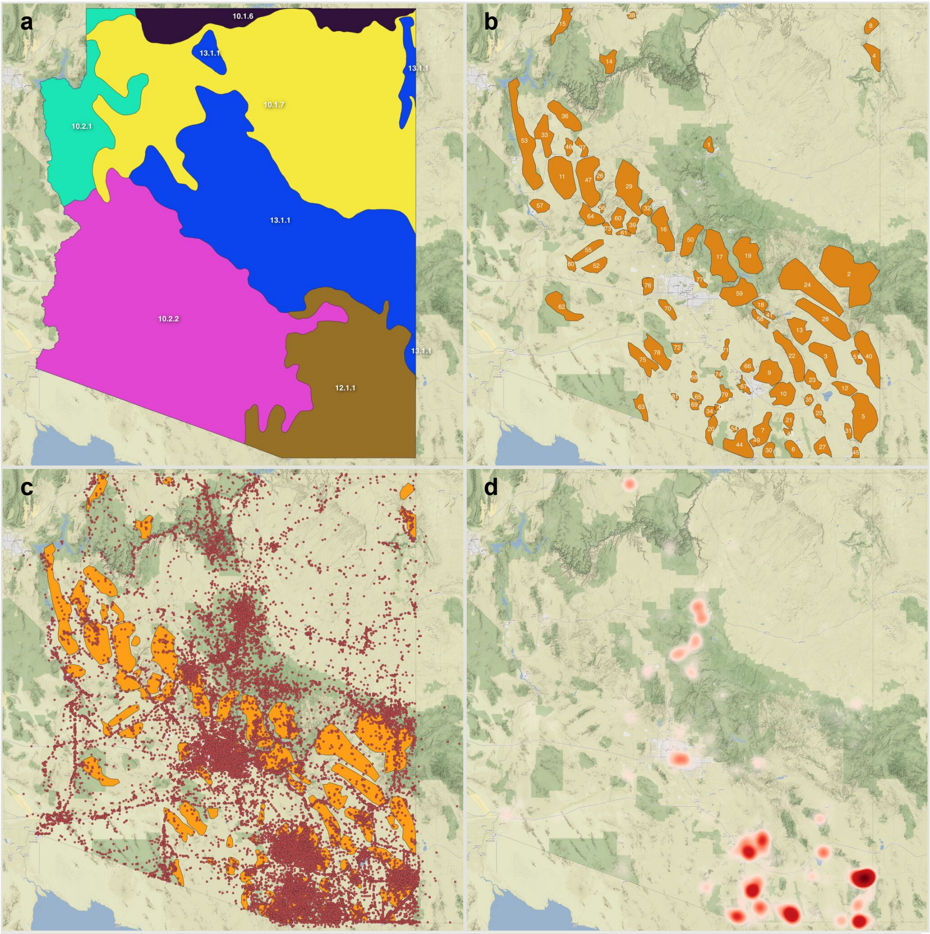

Figure 1.

Maps of the state of Arizona showing geographic regions and occurrence records.

a: Ecoregions of Arizona. Labels correspond to ecoregion codes with matching names as follows: 10.1.6 = Colorado Plateaus; 10.1.7 Arizona/New Mexico Plateau; 10.2.1 = Mojave Basin and Range; 10.2.2 = Sonoran Desert; 12.1.1 = Madrean Archipelago; 13.1.1 = Arizona/ New Mexico Mountains.

b: Arizona mountain ranges. Labels refer to mountain range details in Suppl. material 3.

c: Georeferenced insect records from Arizona. Shapes underneath are outlines of mountain ranges shown in B.

d: Heatmap of georeferenced insect records from Arizona.

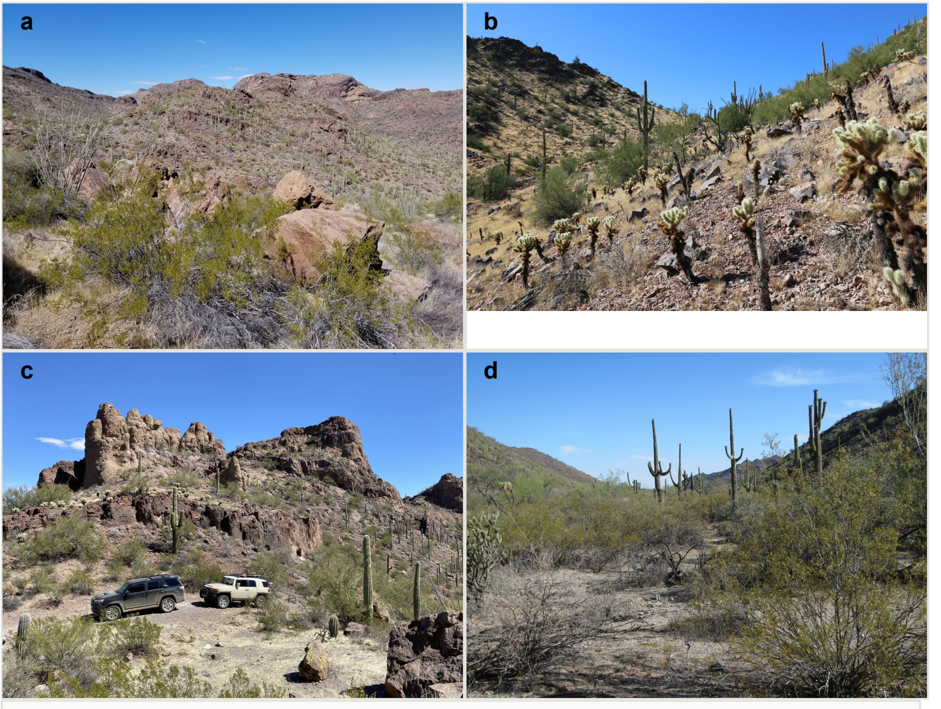

Figure 2.

Sand Tank Mountains with views of terrain and habitat.

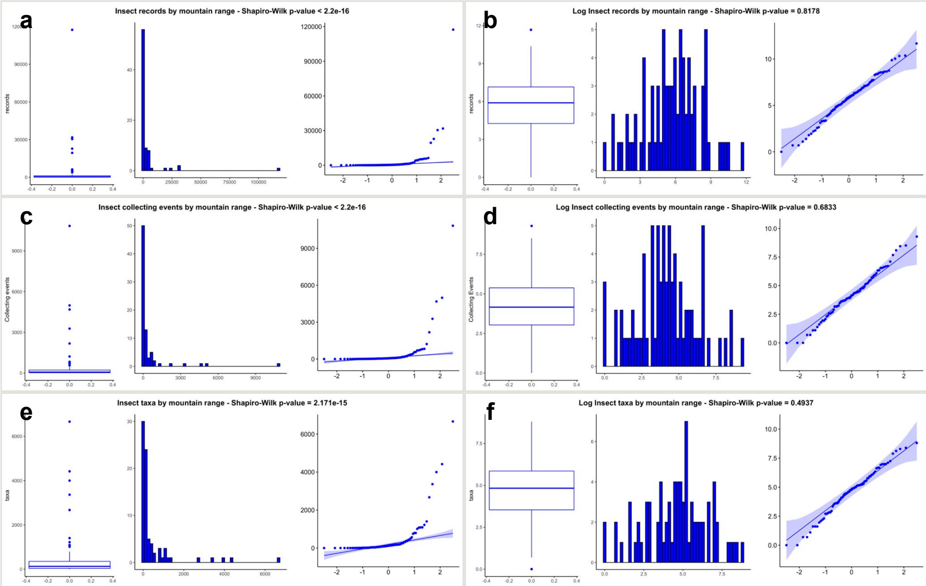

Figure 3.

Normality and distribution of digitized records of insects from Arizona. Each dataset shows a grouping of three vizualizations: (1) boxplot, (2) histogram, and (3) q-q- plot. The Shapiro-Wilk p-value is given for each dataset where a significant p-value represents a statistical difference from normality.

a: Insect records by mountain range
b: Log insect records by mountain range.
c: Collecting events by mountain range.
d: Log collecting events by mountain range.
e: Insect taxa by mountain range.
f: Log insect taxa by mountain range

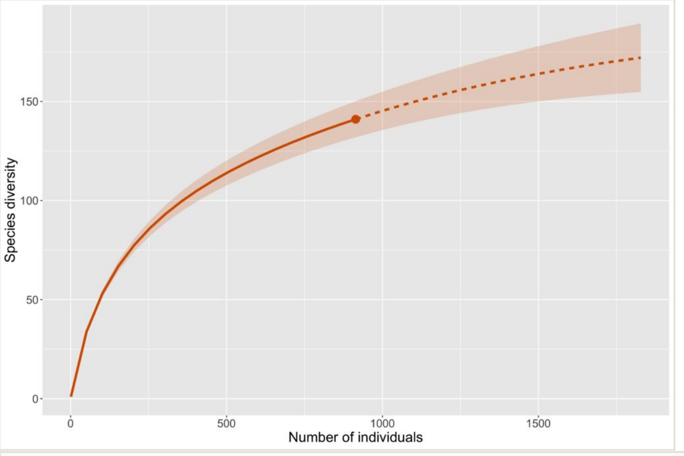

Figure 4.

Species richness estimated by rarefaction and extrapolation for the Sand Tank Mountain coleoptera fauna.

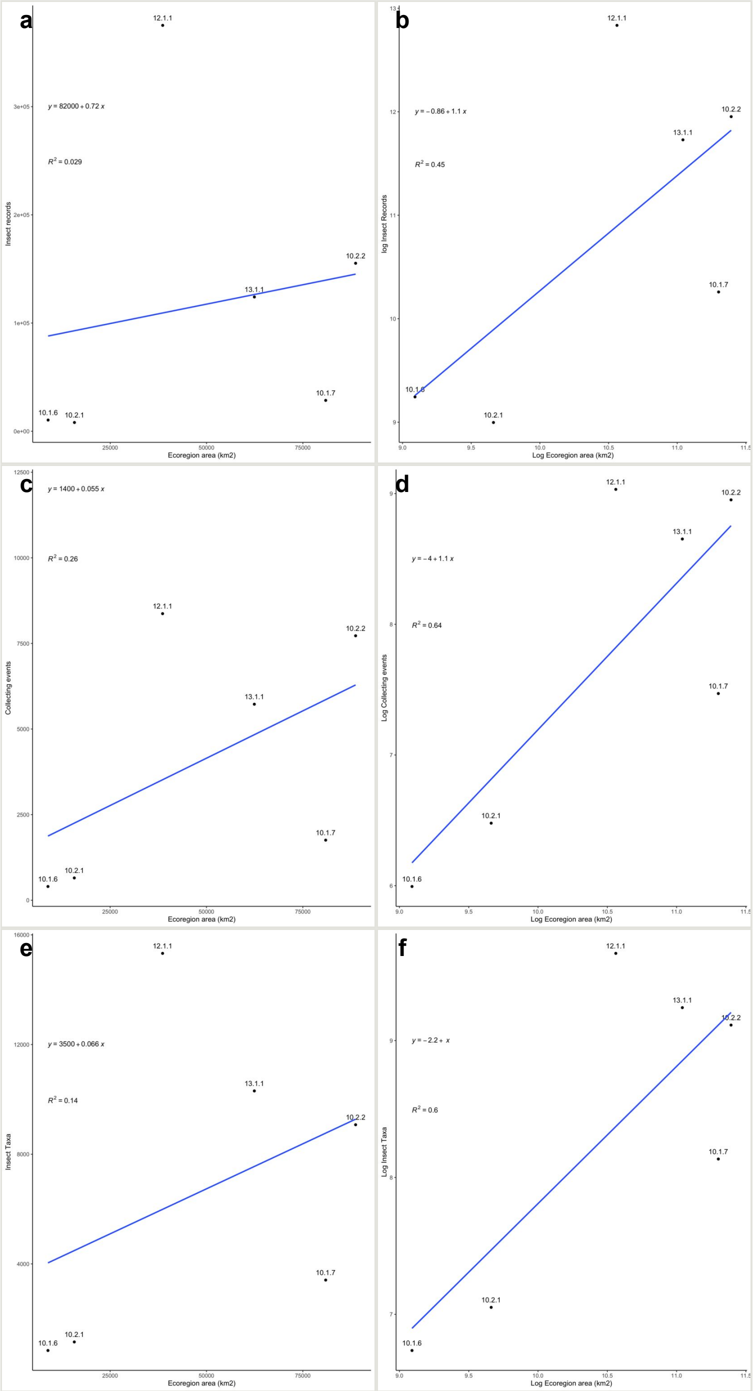

Figure 5.

Occurrence records by ecoregion from the state of Arizona. Ecoregion labels match Fig. 1a and Suppl. material 2.

a: Digitized insect records by geographic area (km^2) of ecoregions in Arizona.
b: Log-log transformed digitized records by ecoregion area (log number of records by log ecoregion area []).
c: Collecting events by ecoregion in Arizona. A single collecting event corresponds to all specimens with the same collector (DWC:recordedBy) and date (DWC:day, month, year).
d: Log-log transformed collecting events by ecoregion area (log collecting events by log ecoregion area []).
e: Insect taxa by geographic area () of ecoregions in Arizona.
f: Log-log transformed taxa by ecoregion area (log tax by log ecoregion area [km^2]).

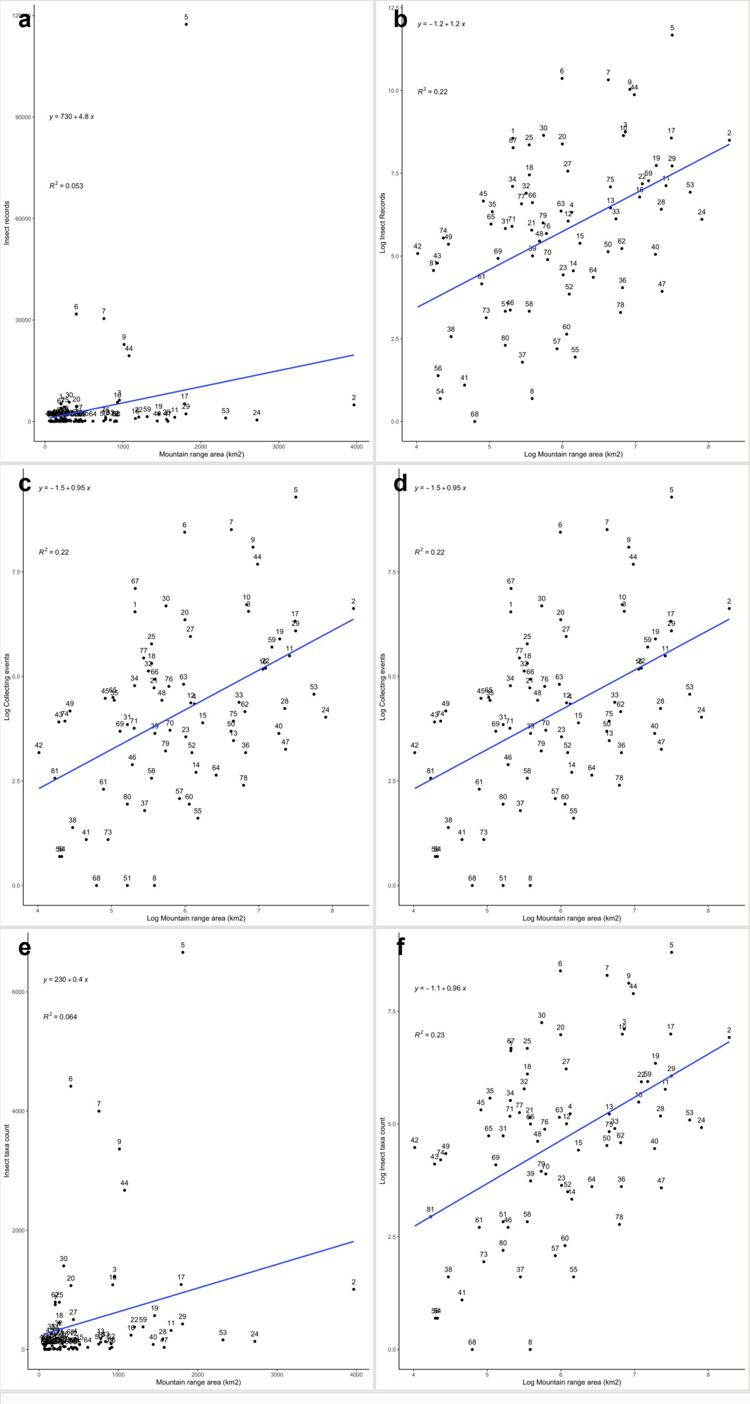

Figure 6.

Occurrence records by mountain range from the state of Arizona. Point labels match mountain ranges in Fig. 1b and Suppl. material 3.

a: Digitized insect records by geographic area () of mountain ranges in Arizona.
b: Log-log transformed insect records by mountain range area in Arizona (log insect records by log geographic area [] of mountain ranges).
c: Insect collecting events by geographic area () of mountain ranges in Arizona.
d: Log-log transformed collecting events by mountain range area in Arizona (log icollecting events by log geographic area [] of mountain ranges).
e: Insect taxa by geographic area () of mountain ranges in Arizona.
f: Log-log transformed insect taxa by mountain range area in Arizona (log insect taxa by log geographic area [] of mountain ranges).

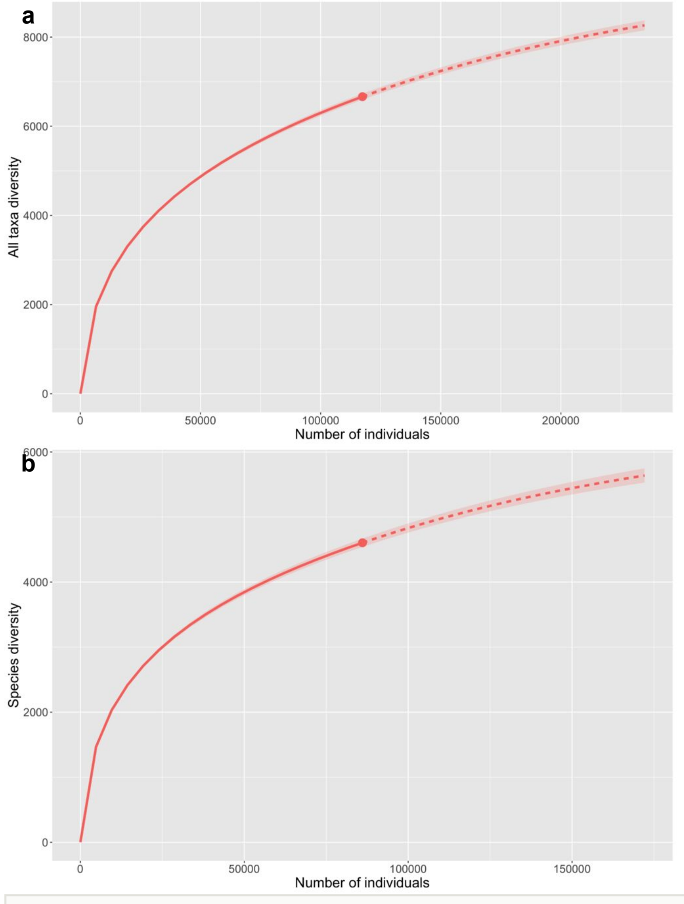

Figure 7.

Species richness estimation curve for the Chiricahua Mountains in Arizona by rarefaction and extrapolation.

a: Rarefaction and estimation curve for all taxa from all ranks for the Chiricahua Mountains (6,663 distinct taxon names observed).
b: Rarefaction and estimation curve for species level taxa for the Chiricahua Mountains (4,604 distinct taxon names observed).

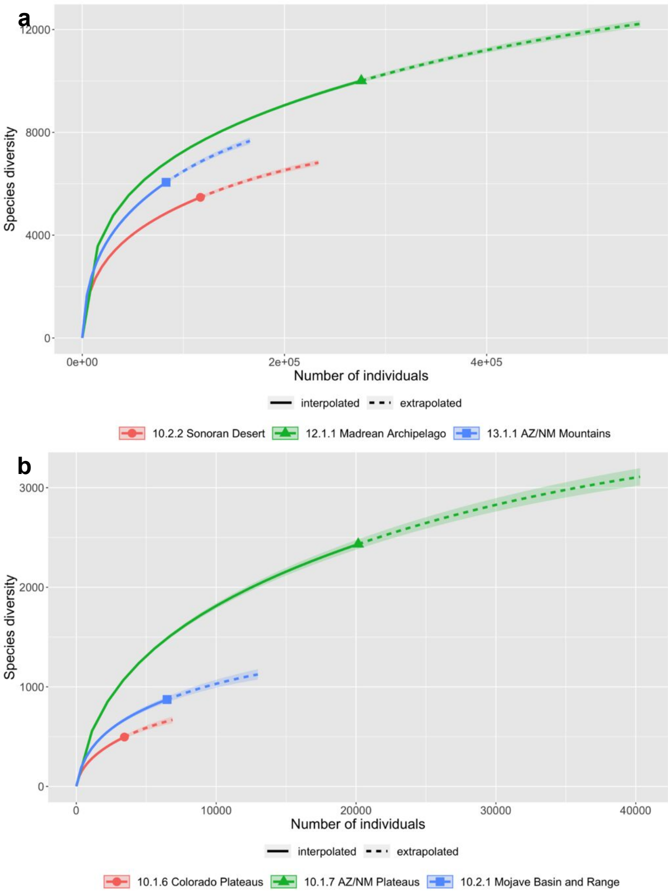

Figure 8.

Species richness estimation curve for the ecoregions of Arizona by rarefaction and extrapolation.

a: Sonoran Desert, Madrean Archipelago, and Arizona/New Mexico Mountains ecoregions.
b: Colorado Plateaus, Arizona/New Mexico Plateaus, and Mojave Basin and Range ecoregions.

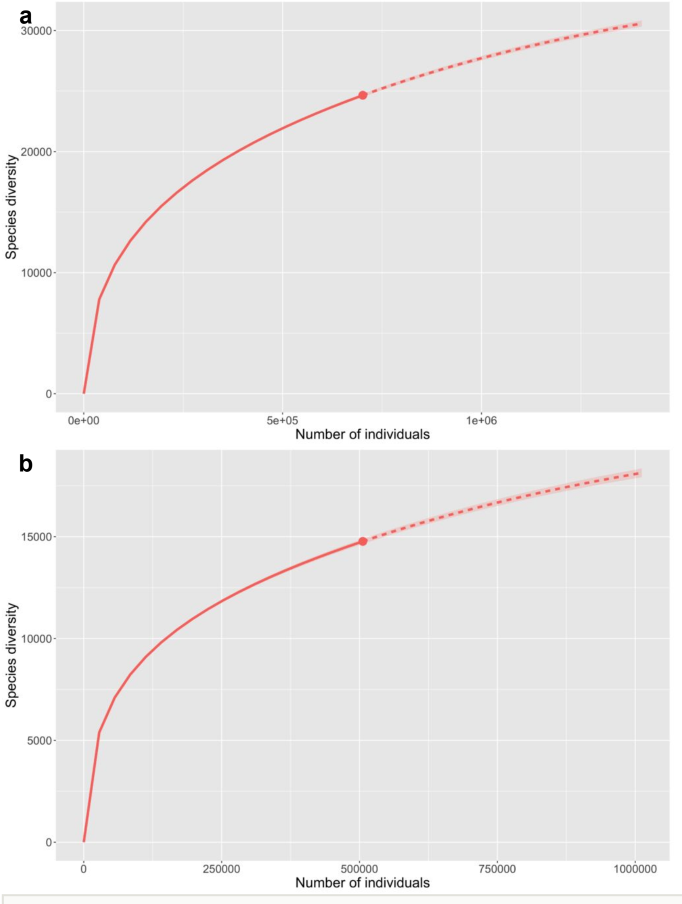

Figure 9.

Species richness estimation curves for the entire state of Arizona by rarefaction and extrapolation.

a: Rarefaction and estimation curve for all taxa from all ranks for Arizona (24,651 distinct taxon names observed).
b: Rarefaction and estimation curve for all species level taxa for Arizona (14,769 distinct species names observed).

Supplementary materials

Suppl. material 1: Arizona insect occurrence data annotated by which ecoregion or mountain range they occur within

Authors: M.A. Johnston
Data type: occurrences
Brief description: Zip archive of two occurrence recordsets for Arizona insects. The first file contains occurrence records annotated by which ecoregion they fall within and the second file contains annotated records by which mountain range they fall within.
Download file (53.24 MB)

Suppl. material 2: Arizona ecoregion data

Authors: M.A. Johnston
Data type: Geographical and biodiversity metrics of ecoregions
Brief description: This table includes data for all Arizona ecoregions including their geographic size and the number of insect records, collecting events, and taxa found within them.
Download file (1.20 kb)

Suppl. material 3: Arizona mountain range data

Authors: M.A. Johnston
Data type: Geographic and biodiversity metrics for mountain ranges
Brief description: This table includes information about the tallest mountain ranges in Arizona. A polygon in WKT format, the geographic area, prominence, and height of each mountain range is given. Totals for insect occurrence records, collection events, and taxa are also given.
Download file (46.53 kb)

Suppl. material 4: Sand Tank Coleoptera specimen records

Authors: M.A. Johnston
Data type: occurrences
Brief description: Darwin Core Archive of new records
Download file (31.68 kb)

Suppl. material 5: Data analysis and figure generation script

Authors: M. Andrew Johnston
Data type: R script used for data analysis and for generating all the statistical figures used in this paper.
Download file (24.19 kb)