Mapping selected endemic species and solar energy potential in the arid Southwest for future sustainable development (#104727)

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Mapping selected endemic species and solar energy potential in the arid Southwest for future sustainable development

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The need for renewable energy has become increasingly evident in response to the climate change crisis, presenting a paradoxical challenge to biodiversity conservation. The Southwest United States is desirable for large-scale Solar Energy Development (SED) due to its high Global Horizontal Irradiance (GHI) values and vast open landscapes. However, this region is also rich in unique ecological and biological diversity. Several distinct species have garnered special attention as human population growth, habitat alteration, and climate change have accelerated in recent decades (i.e,; LeConte's Thrasher (Toxostoma lecontei), Bendire's Thrasher (Toxostoma bendirei), Sonoran Desert Tortoise (Gopherus morafkai), Mojave Desert Tortoise (Gopherus agassizii), and the southwestern population of the Burrowing Owl (Athene Cunicularia). As the United States prepares to increase its development in renewable energies, particularly solar energy, there has been a growing concern about how this development will further impact these species. In this study, we propose a novel combined approach to find areas of high habitat suitability for endangered species within areas of high SED potential. Specifically, we employed species distribution modeling (SDM) to identify areas with suitable habitats and likely species presence, and we conducted a site suitability analysis for potential SED locations within the southwest. As a result, we found significant overlap between potential SED locations and the high-priority habitats of all target species, thus underlining the importance of prioritizing conservation efforts as more solar projects go under review in these southwestern states. Our study aims to inform conservationists and developers in making sustainable decisions for the region's future development.

Mapping Selected Endemic Species and Solar Energy Potential in the Arid Southwest for Future Sustainable Development

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Abstract

The need for renewable energy has become increasingly evident in response to the climate change crisis, presenting a paradoxical challenge to biodiversity conservation. The Southwest United States is desirable for large-scale Solar Energy Development (SED) due to its high Global Horizontal Irradiance (GHI) values and vast open landscapes. However, this region is also rich in unique ecological and biological diversity. Several distinct species have garnered special attention as human population growth, habitat alteration, and climate change have accelerated in recent decades (i.e,; LeConte's Thrasher (*Toxostoma lecontei),* Bendire's Thrasher (*Toxostoma bendirei),* Sonoran Desert Tortoise (*Gopherus morafkai),* Mojave Desert Tortoise (*Gopherus agassizii),* and the southwestern population of the Burrowing Owl (*Athene Cunicularia*). As the United States prepares to increase its development in renewable energies, particularly solar energy, there has been a growing concern about how this development will further impact these species. In this study, we propose a novel combined approach to find areas of high habitat suitability for endangered species within areas of high SED potential. Specifically, we employed species distribution modeling (SDM) to identify areas with suitable habitats and likely species presence, and we conducted a site suitability analysis for potential SED locations within the southwest. As a result, we found significant overlap between potential SED locations and the high-priority habitats of all target species, thus underlining the importance of prioritizing conservation efforts as more solar projects go under review in these southwestern states. Our study aims to inform conservationists and developers in making sustainable decisions for the region's future development.

Keywords: Renewable Energy, Species Distribution, Species Conservation, Climate Change, Spatial Analysis

1-Introduction

As countries adapt to the escalating climate crisis, the urgency to transition toward renewable energy sources has become more apparent. Among the various renewable energy options, solar energy is a highly promising and practical solution (Devabhaktuni et al., 2013). However, if done improperly, solar energy development (SED) can negatively impact important conservation areas and threaten biodiversity (Rehbein et al. 2019). The initial step in minimizing this impact is to identify where SEDs and areas for conservation overlap.

Although the variables used to determine a suitable location for large-scale SEDs can be nuanced and project-specific, it can be argued that several key variables are universally desired; 1) High Global Horizontal Irradiance (GHI), a measure of irradiation received by a horizontal surface on the ground and widely used as a value to build grid-connected photovoltaic power systems (GHI, Gbémou 2021, Global Solar Atlas, 2021), 2) Little to no vegetative land cover (Doljak & Stanojević 2017, Mierzwiak & Calka, 2017, Bukhary et al. 2018, Nebey et al. 2020), 3) limited slope (Charabi & Gastli, 2011, U.S. Department of Energy 2015, Alami Merrouni, Mezrhab, & Mezrhab 2016, Sabo et al., 2017, Rodrigues et al. 2017), 4) proximity to substations (Katkar et al., 2021, Goh et al., 2022), and 5) Land outside of protected areas.

The Southwestern United States (Figure 1) has been identified as a key region for solar development as it is a part of the Western Solar Plan (Bureau of Land Management Solar Program Environmental Impact Statement, 2023) ~~because~~ it ranks among the highest in the United States for GHI (Agha et al., 2020, Sengupta et al., 2018). In addition, the region's arid and semi-arid climates and the availability of flat and unobstructed terrains make it desirable for installing utility-scale solar power plants (Prăvălie et al., 2019).

However, the Southwest has also been recognized as a "hotspot" for threatened and endangered species within the United States (Flather et al., 1998). It is home to several arid-adapted species identified as "Species of Greatest Conservation Need", whose general habitat requirements resemble the characteristics associated with high solar development potential (Arizona Game and Fish Department 2022). Among the endangered species, the following are of critical interest: the LeConte's Thrasher (*Toxostoma lecontei),* Bendire's Thrasher (*Toxostoma bendirei),* Sonoran Desert Tortoise (*Gopherus morafkai),* Mojave Desert Tortoise (*Gopherus agassizii),* and the southwestern population of the Burrowing Owl (*Athene Cunicularia).* The overlap between SEDs and endangered species distribution may present a paradoxical challenge, putting SED's once-perceived "environmentally friendly" nature in potential conflict with identified species of special concern.

The impacts of SED on ecosystems and biodiversity are primarily related to habitat loss and alteration, both recognized as major threats to biodiversity (Tsoutsos et al., 2005; Gasparatos et al., 2017; Hernandez et al., 2014). Landscape changes caused by SED extend beyond the solar facilities themselves, encompassing supporting infrastructure such as access roads and equipment, which can result in an altered area approximately 2.5 times larger than the footprint of the panels (Gasparatos et al., 2017). Furthermore, the construction and decommissioning of SED facilities may lead to the destruction and modification of wildlife habitat, with soil disturbances acting as pathways for invasive species, potentially out-competing native ones (Turney & Fthenakis, 2011; Gasparatos et al., 2017; Lovich & Ennen, 2011). Lastly, extensive solar energy infrastructure may serve as both a physical and visual barrier, hindering the natural movement patterns of certain species.

Ignoring the potential impacts of SED on biodiversity could result in negative consequences for threatened species and ecosystems, leading to potential legal challenges, public opposition, and interventions that could jeopardize future SED operations (Damon Turney & Vasilis Fthenakis, 2011). With the rapid shift towards renewable energy, particularly in the Southwest, developers must thoroughly assess and consider the potential ecological and biological impacts on biodiversity (Sekercioglu et al., 2011). Mitigation strategies, although available, can be costly and less effective in preserving biodiversity (Phalan et al., 2017). Therefore, an avoidance approach to sensitive areas is crucial. By identifying sites where high SED potential and priority habitat overlap, developers can pinpoint priority areas for conservation that can be avoided, minimize ecological harm, and ensure sustainable development through this proactive approach.

Herein, we propose a combined approach to find areas of high habitat suitability for endangered species within areas of high SED potential. The specific goals of this study were to (1) identify the locations that are highly suitable for potential SED within the Southwest region, (2) investigate the geographical distribution of each of the selected species habitat suitability, and (3) identify the degree of overlap of areas of high SED potential and the selected species habitat suitability. To accomplish this, we analyzed photovoltaic, environmental, and structural features to identify areas of high suitability for SED. We used species distribution modeling (SDM) to identify areas of high habitat suitability (hereafter (hotspots of habitat suitability) within their known geographical range. SDMs are frequently used to elucidate species distribution and to support conservation decision-making (Addison et al., 2013). Next, we performed an overlay analysis to evaluate the overlap between potential SED locations and high-priority habitats for each target species.

2- Methods and Materials

2.1- Study area

The study area encompasses the arid regions of the Southwestern United States, spanning California, Nevada, Utah, Colorado, Arizona, New Mexico, and Texas (**Figure 1**). It is rich in habitat and biodiversity, encompassing topographic extremes and wide climate diversity. Notably, it includes the country's highest point, Mount Whitney, at 14,494 feet, and the lowest, Death Valley, at -282 feet (Science Research, 2023). Extreme topography variation can significantly influence various climatic parameters, such as temperature, precipitation, soil characteristics, and other ecological factors (Dillon et al., 2011). The Southwest is home to several ecosystems, including deserts, grasslands, woodlands, chaparral, tundra, wetlands, and various forested environments (Dahms & Geils, 1997). The region also supports extensive human activities and is home to some of the nation’s most productive agricultural land and urban areas, thus making this region an intriguing intersection of ecological complexity and human influence.

2.2- Species of Greatest Conservation Need

The LeConte's Thrasher (*Toxostoma Lecontei*) and Bendire's Thrasher (*Toxostoma Bendirei*) are experiencing significant declines, making them among the fastest-declining species in the southwest (Ammon et al., 2020). These birds are native to desert flats with sparse vegetation, such as saltbush, cholla cactus, and low shrubs (Sheppard, 2020; England & Laudenslayer, 1993). Both species are particularly vulnerable to habitat alteration and loss due to their preference for specific vegetation types (Sheppard, 2020; England & Laudenslayer, 1993). The risk is further exacerbated because SED projects often target landscapes with low-growing shrubs that can be easily removed during construction (Mierzwiak & Calka, 2017).

The Mojave Desert Tortoise (*Gopherus Agassizii*) and the newly distinguished Sonoran Desert Tortoise (*Gopherus Morafkai*) (Murphy et al., 2011) are biologically similar. Both species are characterized by their fossorial behavior; they construct burrows, creating microhabitats that provide shelter for themselves and many other desert inhabitants (Lovich & Ennen, 2011). The conservation status of *G. agassizii* is listed as critically endangered as it faces many threats, including those arising from renewable energy development (Berry et al., 2021).

The population of Burrowing Owl (*Athene Cunicularia*) within the southwest has steadily declined for many years, prompting valiant conservation efforts to preserve this species (U.S. Fish and Wildlife Service, 2023). The resident population within the southwest is valuable to the long-term persistence of the species, considering its unique genetic diversity (Hughes, Daily, & Ehrlich, 2000).

2.3- SED and SDM preparation

The combined approach to find areas of high habitat suitability for endangered species within areas of high SED potential included two major steps: (1) the use of abiotic variables to identify areas with the highest potential for SED and (2) the use of environmental variables and machine learning models to find ~~suitable~~ habitat of Species of Greatest Conservation Need.

2.3.1- Identifying sites with the highest potential for SED

We selected five variables often associated with solar energy development: global horizontal irradiance (Solargis, 2022), land cover (Doljak & Stanojević 2017, Mierzwiak & Calka, 2017, Bukhary et al. 2018, Nebey et al. 2020), slope (Charabi & Gastli, 2011, U.S. Department of Energy 2015, Alami Merrouni, Mezrhab, & Mezrhab 2016, Sabo et al., 2017, Rodrigues et al. 2017), proximity to substations (Katkar et al., 2021, Goh et al., 2022), and the exclusion of any listed protected areas (UNEP-WCMC and IUCN, 2024).

We obtained GHI from Solargis, 2022. GHI represents the sum of direct and indirect diffuse solar irradiation received and is used as a first approximation of photovoltaic power production (ESMAP 2020). We acquired the land cover data from the North American Land Change Monitoring System (Commission for Environmental Cooperation, 2020). To refine the analysis, we excluded land cover classes considered unsuitable for large-scale solar energy development: urban/built-up areas, wetlands, open water, forested areas, and snow/ice areas

(Mierzwiak & Calka, 2017; Nebey, Taye, & Workineh, 2020; Doljak & Stanojević, 2017; Bukhary, Ahmad, & Batista, 2018). We finally reclassified each pixel representing suitable land classes as one. We obtained slope values from EarthEnv (Amatulli et al., 2018). We excluded slope values that exceeded five degrees through reclassification to focus on slope values suitable for solar energy development. The remaining slope values were assigned one value (Alami Merrouni et al., 2016; Charabi & Gastli, 2011; Sabo et al., 2017; Rodrigues et al., 2017). We acquired the substation data from the U.S Energy Atlas (Energy Information Administration, n.d.). To estimate the distance between focal points, i.e., potential SED areas, we created a 5-mile buffer around each substation (Goh et al., 2022; Katkar et al., 2021). The resulting buffer zones served as a spatial indicator for identifying potential sites with high solar energy development potential. Next, we assigned each pixel within the buffer zone as one.

We obtained the protected areas from UNEP-WCMC and IUCN (Protected Planet, 2023). We excluded any areas classified as protected lands by the IUCN from our analysis. This process allowed us to ensure that our study did not include any areas where SED would conflict with protected areas. By excluding protected areas, we can focus our analysis on identifying sites with the highest potential for SED while minimizing negative impacts on the environment and sensitive species in the region. We assigned a value of one to the non-protected areas. All variables were upscaled to the same spatial resolution as the habitat suitability maps.

Finally, we overlaid the processed environmental and structural maps to calculate the areas with high SED suitability. Since the suitable areas for each fact were reclassified to one, we produced a summed map. We considered value four (100% overlap) to be suitable for environmental and structural areas – the SESA map. We overlaid the SESA map with the GHI map to mask SESA areas within the GHI map – sites suitable for potential SED development.

2.3.2- SDM preparation and evaluation

2.3.2.1- Occurrence and environmental data

We used occurrence data for the selected species obtained from GBIF (GBIFa-d, 2023), as well as solar and bioclimatic data from BioClim (WorldClim, 2020), and topography data from EarthEnv (Amatulli et al.,2018). To ensure high data quality and accuracy, the occurrence data underwent a thorough cleaning process, which included reducing spatial aggregation, removing duplicate occurrences and records with missing values, and incorporating pseudo-absences and background data. To mitigate the potential impacts of sampling bias and improve the quality control of the data, we first removed duplicate records and those with incomplete or inaccurate geographic positions (e.g., in the ocean). We then created a grid with the same resolution of the environmental variables to randomly select one site per site (Hijmans 2012).

2.3.2.2- Variable Selection

To minimize potential multicollinearity in the model, we used the *VarSel* function from the *SDMTune* package (Vignali et al., 2020) to remove highly correlated variables. This step helps to ensure that only variables with the most significant influence are included in the analysis, thereby improving the accuracy and reliability of the results. We generated 10,000 background locations using the *dismo* package in R (Hijmans et al. 2021). The data was then split into training and testing data sets, with a 20% allocation for testing. Then, a Maxtent model (Phillips et al., 2004) was employed, containing all variables (Elith et al., 2011). Maxent is successfully used to estimate species' habitat suitability (Elith et al., 2021). The *varSel* function was applied to perform data-driven variable selection. Starting from the provided model, it iterates through all the variables, starting from the one with the highest contribution (permutation importance or maxent percent contribution). The method used for assessing variable correlation was Spearman's rank correlation coefficient, and the threshold used was 0.7 (Vignali et al. 2020). The *varSel* function selects the least correlated variables based on the specified correlation threshold (Vignali et al., 2020). This process was performed for each target species.

2.3.2.3- Model Evaluation & Prediction

First, we prepared presence and background locations and split the data into 80% for training and 20% for testing. Then, we used the subset of variables indicated by the variable selection process, the training dataset, and Maxent to estimate habitat suitability for each species. We restricted the produced habitat suitability to the known geographical ranges of the target species described by the IUCN (**Figures 3 and 4**). Once we estimated habitat suitability, we applied the specificity/sensitivity threshold to transform suitability maps into binary (presence/background) (Liu et al. 2005). Lastly, we calculated the AUC (Area Under the Curve) and TSS (True Skill Statistics) values to evaluate each model. AUC and TSS are commonly used metrics for evaluating the performance of species distribution models, such as Maxent models (Elith et al., 2011). The AUC measures the model's ability to distinguish between presences and absences. AUC scores range from 0 to 1, meaning higher AUC values indicate better model performance in determining suitable and unsuitable habitats (Elith et al., 2011). The TSS is another evaluation metric that combines specificity and sensitivity into a single statistic. TSS scores range from -1 to 1, meaning higher TSS values indicate better model performance in correctly identifying suitable and unsuitable habitats (Elith et al., 2011).

2.4- Identifying high-priority habitats

We calculated the overlap between the species presence produced by the SDM and the potential SED locations to identify overlapping areas. We considered areas where the potential SED locations and species presence had a value of 1 while assigning N.A. values to any cells with values other than 1. To express the overlap quantitatively, we calculated the percentage of overlap as the ratio of the sum of cells with overlapping values to the sum of cells with presence data (excluding N.A. values). The overlap percentage was reported as *critical areas for SED development*, i.e., areas where solar energy development could be pursued while considering the selected species' habitat.

3- Results

3.1- SED Analysis

The sites identified through the site suitability analysis are depicted in **Figure 2**. These selected locations exhibit consistent traits, including a slope of less than five degrees, proximity within five miles of an existing substation, classification within one of four land cover categories (barren land, shrubland, grassland, or cropland), and a prominent Global Horizontal Irradiance (GHI) value ranking within the top 30%. The geographic distribution of these sites indicates that the sites suitable for potential SED development are mainly distributed in the Southwest United States, especially in Texas (all over the state), California, and Colorado (**Figure 2**). A major portion of suitable sites was also observed outside of urban areas of Arizona and Colorado.

3.2- SDM Results

The Species Distribution Modeling (SDM) outcomes for each target species are presented in **Figures S.1** and **S.2**. These figures show the habitat suitability and presence patterns for each species. These findings provide valuable insights into the specific variables that strongly influence the distribution and suitability of habitat for each target species. The high AUC and TSS values emphasize the reliability and accuracy of the SDM results. Values ranged from 0.89-0.98 for AUC and 0.63-0.91 for TSS (*Athene cunicularia:* AUC = 0.87, TSS = 0.6*, Toxostoma lecontei*: AUC = 0.98, TSS = 0.89: *Toxostoma bendirei,* AUC = 0.98, TSS = 0.89: *Gopherus agassizii*, AUC = 0.98, TSS = 0.89, *Gopherus morafkai:* AUC = 0.98, TSS = 0.92).

The spatial distribution of habitat suitability of *A. cunicularia*, the more widespread species, showed high values in the southwest of the United States, especially in California, Colorado, New Mexico, and Texas. These patterns were most influenced by precipitation and solar radiation. Major suitability values for *G. agassizii* and *T. lecontei* were found in California. Temperature, solar radiation (*G. agassizii*), precipitation, and temperature (*T. lecontei*) were affected by suitability patterns. For *G. morafkai* and *T. bendirei* the highest suitability values were observed in Arizona. The most influential variables were temperature and solar radiation.

3.3- High-priority habitats

The geographic patterns of areas with high habitat suitability for endangered species within regions of high SED potential are illustrated in **Figures 5** and **6**. For the Burrowing Owl (*A. cunicularia*), the most critical areas are distributed along the southwestern United States, especially in Texas, California, and Arizona. For LeConte's Thrasher (*T. lecontei*), Bendire's Thrasher (*T. bendirei*), the Mojave Desert Tortoise (*G. agassizii*), and the Sonoran Desert Tortoise (*G. morafkai*), the most critical areas are observed in California and Arizona (**Figures 5 and 6**).

Regarding the overlap between areas of high habitat suitability and SED potential for non-migratory species, the highest values are observed for the Sonoran Desert Tortoise (*G. morafkai*, 46.36%) and LeConte's Thrasher (*T. lecontei*, 35.81%), while the lowest is observed for the Mojave Desert Tortoise (*G. agassizii*, 16.69%).

For migratory species, the overlap of high-suitability areas and SED potential for Bendire's Thrasher (*T. bendirei*) is 31.44% for resident extant individuals, who are present year-round, and 6.38% for breeding individuals, who migrate for a portion of the year. Similarly, for the Burrowing Owl (*A. cunicularia*), the overlap is 6.76% for resident extant individuals and 13.63%

for breeding individuals. This distinction is important as it highlights the different conservation needs and potential impacts of SED projects on species that have both migratory and resident populations.

4- Discussion

This study aims to connect the knowledge gap between the long-term implications SED may have on biodiversity by employing a multifaceted approach that combines established methodologies and decision-making processes. Specifically, we integrated the outcomes of a site suitability analysis and SDM, widely recognized and utilized within the scientific research community. Doing so allows us to gain a new perspective and understanding of areas of critical importance for sensitive species' habitats and future SED projects. This approach contributes to our knowledge of renewable energy and conservation planning.

4.1- SED Suitability Analysis

The site suitability analysis identifies several promising regions for large-scale solar energy developments (SED), offering valuable insights for future initiatives including (a) California Central Valley: This region's high potential for future solar projects is primarily due to its relatively flat terrain and extensive agricultural land. The flat terrain facilitates easier installation and maintenance of solar panels, while agricultural land may offer large, open spaces suitable for SED (Doljak & Stanojević 2017, Mierzwiak & Calka, 2017, Bukhary et al. 2018, Nebey et al. 2020); (b) Greater Phoenix Valley, Arizona: The dense cluster of potential sites in this area is highly attractive due to the combination of flat topography and exceptionally high Global Horizontal Irradiance (GHI) levels. High GHI levels indicate abundant solar radiation, which is necessary for maximizing the efficiency and energy output of solar panels (Gbémou 2021, Global Solar Atlas, 2021, Doljak & Stanojević 2017), (c) Texas: The analysis reveals numerous suitable locations throughout Texas. The widespread potential in Texas is attributed to high GHI levels and ideal land cover, including shrublands, croplands, and grasslands. These types of land cover are often well-suited for SED because they can provide large, relatively unobstructed areas for panel installation. (Mierzwiak & Calka, 2017, Bukhary et al. 2018, Nebey et al. 2020). By identifying these regions, the analysis highlights where solar energy projects can be most effective and efficient, guiding future investments and development efforts toward areas with the highest potential for success. This targeted approach helps optimize resource allocation, improve project feasibility, and enhance the overall impact of solar energy initiatives.

4.2- SDM Results

Our findings indicate a significant correlation between habitat suitability for each of the five target species and climate and environmental variables, albeit with some variation. Notably, three key climatic and environmental variables exhibited the most substantial influence, consistently shared across all five target species. Precipitation emerged as a top influential factor for *T. lecontes*, *T. bendirei*, *G. morafkai*, and *A. cunicularia*. This correlation can be attributed to their dietary reliance on arthropods and small rodents, populations of which frequently correlate with precipitation levels and the overall health of vegetation (Desmond & Sutton; McDonald, Korfanta, & Lantz, 2004). Temperature played a crucial role for *T. lecontes*, *G. agassizii*, and *G. morafkai*, with temperature shifts impacting activity levels, feeding patterns, and species survivorship (Meyer, 2008; Sheppard, 1970). Topographic variables like elevation and Topographic Roughness Index (TRI) significantly impacted *T. bendirei*, *A. cunicularia*, and *G. agassizii*, influencing habitat preferences, distribution, and adaptation to specific landscapes (Desmond & Sutton; Meyer, 2008).

The influence of these variables on the species' habitat suitability emphasizes their critical importance in shaping the ecological conditions for each target species. Consequently, any significant or prolonged alterations in the environmental or climatic variables could directly affect the target species. For instance, precipitation's impact on food source availability reveals concerns about these species' ability to find sufficient sustenance, potentially hindering reproductive success and population health (Desmond & Sutton; McDonald, Korfanta, & Lantz, 2004). Temperature's influence on activity levels and survivorship highlights these species' adaptations to cope with extreme heat conditions, with different responses seen in burrowing owls and desert tortoises (Meyer, 2008; Sheppard, 1970). The connection between topography and habitat preferences also showcases the importance of specific landscape characteristics for *T. bendirei* and *A. cunicularia*, influencing their presence in landscapes with features like exposed ground patches or open flat land (Desmond & Sutton; Meyer, 2008).

The Southwest has been identified as a climate change "hotspot," with projected increases in air temperature, aridity, and seasonal variability (Gutzler & Robbins, 2011). Arid environments, such as deserts in the southwest, are particularly vulnerable to the impacts of climate change, supported by abundant evidence (Archer & Predick, 2008; MacDonald, 2010; Garfin, 2013). For instance, the region is expected to experience fewer frost days, more frequent unusually high temperatures, increased water demand, and a higher frequency of extreme weather events like droughts, heatwaves, and floods (Archer & Predick, 2008; MacDonald, 2010; Garfin, 2013). While changes in precipitation hold a higher degree of uncertainty, likely, both precipitation and temperature variations will directly impact vegetation and ecosystem processes throughout the southwest. (Archer & Predick, 2008). Nevertheless, it's important to acknowledge that these findings are grounded in current data, and future changes in these variables due to factors such as climate change and future urban expansion may introduce additional complexities to these species' habitat suitability and species welfare. Given the strong correlation between temperature, precipitation, and the overall fitness of target species, the suitable habitat is subject to change based on future environmental and climate changes.

4.3- Overlap Results – Implications for conservation

Our analysis considered both species presence and habitat suitability to gain insights into the potential impacts of future SED locations. Species presence refers to documented occurrences of a particular species within a specific geographic area. At the same time, habitat suitability assesses the environmental conditions and resources necessary for a species to thrive and persist. It's important to note that the percentages of species presence and habitat suitability provided in our analysis were determined within the ranges specified by the IUCN, and they are approximations. Additionally, these percentages may be subject to change based on currently available data, and the data used in our analysis is subject to change over time.

4.3.1 Target Species and SED Overlap estimations -

The spatial overlap between potential SED sites and selected species habitats underlines the significance of prioritizing species conservation and habitat preservation within the Southwest. Certain species, such as those studied here, overlap substantially with prospective SED locations, indicating potential risks to their habitats and populations. Considering the average percentages of overlap and variations among different species, it becomes evident that careful consideration and mitigation measures are necessary to balance renewable energy goals with preserving biodiversity and ecosystem integrity.

While the long-term impacts of large-scale SED remain a subject of ongoing research, a recent study by Bennun et al. (2021) provides crucial insights into some potential impacts. Their study highlights that habitat loss, resulting from vegetation clearance and ongoing facility maintenance and management, directly affects surrounding biodiversity. Additionally, their results highlighted additional adverse effects, including avian collisions with solar panels or transmission lines, the creation of barrier effects, and increased light and noise pollution (Bennun et al., 2021). Recognizing the interconnected challenges, it's noteworthy that both habitat loss and fragmentation pose significant threats to terrestrial biodiversity (Rogan & Lacher, 2018).

By addressing areas of overlap, we inherently identify regions where SED development can potentially occur without significant conflict. However, when refraining from SED in overlapping areas is unfeasible, mitigation becomes essential. **Figure S.3** exemplifies the availability of potential SED sites while still considering the priority habitat of the target species. Mitigation strategies can take various forms to overcome potential habitat loss and fragmentation problems, including proactive measures during SED project design and operational phases. Project design adjustments, such as altering SED layouts to avoid critical migratory corridors and nesting/roosting sites for specific species or rerouting and burying power lines to reduce avian collisions, play a crucial role in minimizing environmental impacts (Bennun et al., 2021). Additionally, operational mitigation efforts encompass modifying perimeter fencing to minimize barrier effects by creating passageways for smaller species (Bennun et al., 2021).

4.4- Limitations

Although our study provides valuable insights into the similarities between high-priority habitats and suitable SED locations, it is crucial to acknowledge certain limitations. Firstly, the site suitability analysis relies on existing substation data, and any future substation and transmission line availability are not accounted for. This limitation may affect the long-term viability and feasibility of the identified sites suitable for potential solar energy development sites. Secondly, the focus on the species' range within the United States Southwest, while providing valuable information, may not fully capture the complete spatial distribution or habitat suitability, as the range of each target species extends beyond our study area.

Furthermore, it's important to recognize that our spatial overlap analysis provides an approximation of the interaction between the potential SED sites and the target species' habitat. The actual spatial dynamics at a finer scale may differ, and the species' habitat suitability could change over time due to factors like climate change, impacting distribution and habitat availability. It is also important to note that the percentages of species presence and habitat suitability provided in our study were determined within the ranges specified by the IUCN, and they are approximations. Additionally, these percentages may be subject to change based on currently available data, and the data used in our analysis will be subject to change over time.

However, our study does provide a unique perspective that analyzes the potential interaction between future SED and high-priority habitats. We envision that similar analyses could prove valuable in guiding future conservation decisions. By recognizing these limitations, we aim to inspire further studies and conservation efforts that actively address potential changes and uncertainties tied to substation availability and environmental conditions.

5- Conclusion

As countries transition to renewable energy sources to combat the escalating climate crisis, a growing focus is on identifying suitable areas for renewable energy development, such as SED. As identified by multiple studies, the Southwest is undoubtedly the most ideal location for SED in the United States. However, the potential long-term implications on biodiversity remain under studied in this pursuit of renewable energy.

In an era characterized by the urgent need to address the climate crisis and transition to renewable energy sources, the importance of mitigating the impacts of SED on surrounding ecosystems and wildlife cannot be overstated. Our primary objectives of this study included identifying highly suitable locations for potential SEDs in the Southwest, identifying suitable habitats for the target species, understanding the intricate relationship between habitat suitability and environmental variables, and identifying suitable SED sites within each species' range. By employing diverse methodologies, such as site suitability analysis and species distribution modeling, to identify shared critical areas, we hope this information can help inform future conservation and decision-making in the transition towards sustainable and renewable energy.

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References

Addison, P. F. E., Rumpff, L., Bau, S. S., Carey, J. M., Chee, Y. E., Jarrad, F. C., McBride, M. F., & Burgman, M. A. (2013). Practical solutions for making models indispensable in conservation decision-making. Diversity and Distributions, 19, 490–502.

Arizona Game and Fish Department. 2022. The Arizona Wildlife Conservation Strategy. https://azgfd-wdw.s3.amazonaws.com/awcs-2022/documents/AWCS_Final_Approved_11-22.pdf

Agha, M., et al. (2020). Impacts of climate change on groundwater resources: A review. Environmental Research Letters, 15(7), 075004.

Alexandros Gasparatos, Christopher N.H. Doll, Miguel Esteban, Abubakari Ahmed, Tabitha A. Olang, Renewable energy and biodiversity: Implications for transitioning to a Green Economy, Renewable and Sustainable Energy Reviews, Volume 70, 2017, Pages 161-184, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.08.030.

Alami Merrouni, A., Mezrhab, A., & Mezrhab, A. (2016). P.V. sites suitability analysis in the Eastern region of Morocco. Sustainable Energy Technologies and Assessments, 18, 6-15. https://doi.org/10.1016/j.seta.2016.09.006

Archer, S. R., & Predick, K. I. (2008). Climate Change and Ecosystems of the Southwestern United States. Rangelands, 30(3), 23-28. ISSN 0190-0528. DOI: 10.2111/1551-501 https://www.sciencedirect.com/science/article/pii/S019005280850160X]

Arizona Bird Conservation Initiative and Sonoran Joint Venture. 2019. LeConte's Thrasher (Toxostoma lecontei) Species Account. Available at https://sonoranjv.org/accounts/lecontes-thrasher.pdf. Accessed on May 16, 2023.
Bureau of Land Management Solar Program Environmental Impact Statement. (2023). Solar Programmatic Environmental Impact Statement (Solar PEIS) - 2023. Retrieved from https://blmsolar.anl.gov/solar-peis-2023/

Bennun, L., van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., & Carbone, G. (2021). Mitigating biodiversity impacts associated with solar and wind energy development. IUCN, Global Business and Biodiversity Programme, The Biodiversity Consultancy. URL: https://doi.org/10.2305/IUCN.CH.2021.04.en

Berry, K.H., Allison, L.J., McLuckie, A.M., Vaughn, M. & Murphy, R.W. 2021. Gopherus agassizii. The IUCN Red List of Threatened Species 2021: e.T97246272A3150871. https://dx.doi.org/10.2305/IUCN.UK.2021-2.RLTS.T97246272A3150871.en. Accessed on 08 May 2023.

Borderlands Restoration Network. "Desert Thrasher Project." Borderlands Birds. Available at: https://borderlandsbirds.org/projects/desert-thrasher/. Accessed May 16, 2023.

Bivand, R., Keitt, T., & Rowlingson, B. (2022). rgdal: Bindings for the 'Geospatial' Data Abstraction Library. R package version 1.5-28. Retrieved from https://cran.r-project.org/package=rgdal

Bird, D. M., Jackson, W. M., & Fahrig, L. (2013). Habitat loss and fragmentation: Ecological, behavioral, and cognitive effects in songbirds. Studies in Avian Biology, 45, 35-54.

BirdLife International. 2016. Athene cunicularia. The IUCN Red List of Threatened Species 2016: e.T22689353A93227732. https://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22689353A93227732.en. Accessed on 23 June 2024.

BirdLife International. 2020. Toxostoma bendirei. The IUCN Red List of Threatened Species 2020: e.T22711108A179833350. https://dx.doi.org/10.2305/IUCN.UK.2020-3.RLTS.T22711108A179833350.en. Accessed on 23 June 2024.

BirdLife International. 2018. Toxostoma lecontei. The IUCN Red List of Threatened Species 2018: e.T22711121A131112198. https://dx.doi.org/10.2305/IUCN.UK.2018-2.RLTS.T22711121A131112198.en. Accessed on 23 June 2024.

Bukhary, S., Ahmad, S., & Batista, J. (2018). Analyzing land and water requirements for solar deployment in the Southwestern United States. Renewable and Sustainable Energy Reviews, 82(Part 3), 3288-3305. https://doi.org/10.1016/j.rser.2017.10.016

Charabi, Y., & Gastli, A. (2011). P.V. site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation. Renewable Energy, 36(9), 2554-2561. https://doi.org/10.1016/j.renene.2010.10.037

Commission for Environmental Cooperation (CEC). 2023. "2020 Land Cover of North America at 30 Meters". North American Land Change Monitoring System. Canada Centre for Remote Sensing (CCRS), U.S. Geological Survey (USGS), Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), Comisión Nacional Forestal (CONAFOR), Instituto Nacional de Estadística y Geografía (INEGI). Ed. 1.0, Raster digital data [30-m]. Available at http://www.cec.org/north-american-environmental-atlas/land-cover-30m-2020/

Creutzig, F., Agoston, P., Goldschmidt, J. et al. The underestimated potential of solar energy to mitigate climate change. Nat Energy 2, 17140 (2017). https://doi.org/10.1038/nenergy.2017.140

Dahms, C. W., & Geils, B. W. (1997). An assessment of forest ecosystem health in the Southwest (General Technical Report RM-GTR-295). U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Damon Turney, Vasilis Fthenakis, Environmental impacts from the installation and operation of large-scale solar power plants, Renewable and Sustainable Energy Reviews, Volume 15, Issue 6, 2011, Pages 3261-3270, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2011.04.023.

Denholm, P., & Margolis, R. M. (2008). Land-use requirements and the per-capita solar footprint for photovoltaic generation in the United States. Energy Policy, 36(9), 3531-3543.

Desmond, M. J., & Sutton, C. B. (Final Report to New Mexico Department of Game & Fish). Breeding Habitat Requirements and Territory Size of Bendire's Thrasher (Toxostoma bendirei). Department of Fish, Wildlife and Conservation Ecology, New Mexico State University, Las Cruces, NM 880. Retrieved from: https://borderlandsbirds.org/wp-content/uploads/2017/08/Breeding-Habitat-Requirements-and-Territory-Size-of-Bendires-Thrasher.pdf

Devabhaktuni, V., Alam, M., Depuru, S. S. S. R., Green, R. C., Nims, D., & Near, C. (2013). Solar energy: Trends and enabling technologies. Renewable and Sustainable Energy Reviews, 19, 555-564. ISSN 1364-0321. https://doi.org/10.1016/j.rser.2012.11.024

Dillon, G. K., Z. A. Holden, P. Morgan, M. A. Crimmins, E. K. Heyerdahl, and C. H. Luce. 2011. Both topography and climate affected forest and woodland burn severity in two regions of the western US, 1984 to 2006. Ecosphere 2(12):130. doi: 10.1890/ES11-00271.1

Doljak, D., & Stanojević, G. (2017). Evaluation of natural conditions for site selection of ground-mounted photovoltaic power plants in Serbia. Energy, 127, 291-300. https://doi.org/10.1016/j.energy.2017.03.140

England, A. S., & Laudenslayer, W. F., Jr. (1993). Bendire's Thrasher (Toxostoma bendirei). In A. Poole & F. Gill (Eds.), The Birds of North America, No. 71. Philadelphia, PA: The Academy of Natural Sciences; Washington, D.C.: The American Ornithologists' Union.

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ESMAP. 2020. Global Photovoltaic Power Potential by Country. Washington, DC: World Bank. Available at https://documents1.worldbank.org/curated/en/466331592817725242/pdf/Global-Photovoltaic-Power-Potential-by-Country.pdf. Accessed on August 2022.

El Chaar, L., & Lamont, L. A. (2010). Global solar radiation: Multiple on-site assessments in Abu Dhabi, UAE. Renewable Energy, 35(7), 1596-1601. https://doi.org/10.1016/j.renene.2009.10.007.

Energy Information Administration. (n.d.). Power Plants. EIA Atlas. Retrieved (08 February 2023) from https://atlas.eia.gov/datasets/eia::power-plants/explore?filters=eyJTdGF0ZU5hbWUiOlsiQXJpem9uYSJdfQ%3D%3D&location=33.344406%2C61.504000%2C4.00&showTable=true.

Flather, C. H., Knowles, M. S., & Kendall, I. A. (1998). Threatened and Endangered Species Geography. BioScience, 48(5), 365–376. https://doi.org/10.2307/1313375

Garfin, G. (2013). Assessment of Climate Change in the Southwest United States. ISBN: 9781610914468.

Gbémou, S.; Eynard, J.; Thil, S.; Guillot E.; Grieu S. A Comparative Study of Machine Learning-Based Methods for Global Horizontal Irradiance Forecasting. Energies 2021, 14, 3192. https://doi.org/10.3390/en14113192

GBIF-a (08 February 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.wnu773

GBIF-b (08 February 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.5zb66t

GBIF-c (08 February 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.teygbt

GBIF-d (08 February 2023) GBIF Occurrence Download https://doi.org/10.15468/dl.kfygaz

Global Solar Atlas 2021. Global P.V. Potential Study. IRENA and Solargis, 2021. Available at: https://globalsolaratlas.info/global-pv-potential-study.

Gutzler, D.S., Robbins, T.O. Climate variability and projected change in the western United States: regional downscaling and drought statistics. *Clim Dyn* 37, 835–849 (2011). https://doi.org/10.1007/s00382-010-0838-7

Goh, H.H., Li, C., Zhang, D. et al. Application of choosing by advantages to determine the optimal site for solar power plants. Sci Rep 12, 4113 (2022). https://doi.org/10.1038/s41598-022-08193-1

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., et al. (2014). Environmental impacts of utility-scale solar energy. Renewable and Sustainable Energy Reviews, 29, 766-779. doi: 10.1016/j.rser.2013.08.041

Hijmans, R.J., van Etten, J., Sumner, M., Cheng, J., Baston, D., Bevan, A., Bivand, R., Busetto, L., Canty, M., Fasoli, B., Forrest, D., Ghosh, A., Golicher, D., Gray, J., Greenberg, J.A., Hiemstra, P., Hingee, K., Ilich, A., Institute for Mathematics Applied Geosciences, Karney, C., Mattiuzzi, M., Mosher, S., Naimi, B., Nowosad, J., Pebesma, E., Perpinan Lamigueiro, O., Racine, E.B., Rowlingson, B., Shortridge, A., Venables, B., Wueest, R. (2022). raster: Geographic Data Analysis and Modeling. R package version 3.6-20. URL: https://CRAN.R-project.org/package=raster

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., and Hijmans, M.R.J. (2021). dismo: Species Distribution Modeling. R package version 1.4-5. URL: https://cran.r-project.org/package=dismo.

Hughes, Jennifer B., Gretchen C. Daily, and Paul R. Ehrlich. "The loss of population diversity and why it matters." *Nature and human society* (2000): 71-83.

International Finance Corporation. (2015). Handbook for developing solar power plants. Retrieved from https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/publications/publications_handbook_solarpowerplants

Jane Elith, Steven J. Phillips, Trevor Hastie, Miroslav Dudik, Yung En Chee, Colin J. Yates, 2011. A statistical explanation of MaxEnt for ecologists. Diversity and Distributions 17:43-57. doi: 10.1111/j.1472-4642.2010.00725.x

Jeffrey E. Lovich, Joshua R. Ennen, Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States, BioScience, Volume 61, Issue 12, December 2011, Pages 982–992, https://doi.org/10.1525/bio.2011.61.12.8

Komac, Benjamin & Esteban, Pere & Trapero, L. & Caritg, Roger. (2016). Modelization of the Current and Future Habitat Suitability of Rhododendron ferrugineum Using Potential Snow Accumulation. PloS one. 11. e0147324. 10.1371/journal.pone.0147324.

Katkar, V. V., Sward, J. A., Worsley, A., & Zhang, K. M. (2021). Strategic land use analysis for solar energy development in New York State. Renewable Energy, 173, 861-875. https://doi.org/10.1016/j.renene.2021.03.128

Lovich JE Bainbridge D . 1999. Anthropogenic degradation of the southern California desert ecosystem and prospects for natural recovery and restoration. Environmental Management 24: 309–326.

MacDonald, G. M. (2010). Water, climate change, and sustainability in the southwest. Proceedings of the National Academy of Sciences, 107(50), 21256-21262. DOI: 10.1073/pnas.0909651107. [https://www.pnas.org/doi/abs/10.1073/pnas.0909651107]

McDonald, D., N.M. Korfanta, and S.J. Lantz. (2004, September 14). The Burrowing Owl (Athene cunicularia): a technical conservation assessment. [Online]. USDA Forest Service, Rocky Mountain Region. Available: http: //www.fs.fed.us/r2/projects/scp/assessments/burrowingowl.pdf [2023, July 23].

Meyer, Rachelle. 2008. Gopherus spp. In: Fire Effects Information System, [Online]. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: www.fs.usda.gov/database/feis/animals/reptile/goph/all.html [2023, July 23].

Murphy RW Berry KH Edwards T Leviton AE Lathrop A Riedle J.D. 2011. The dazed and confused identity of Agassiz's land tortoise, Gopherus agassizii (Testudines, Testudinidae) with the description of a new species, and its consequences for conservation. ZooKeys 113: 39–71.

Mierzwiak, M., & Calka, B. (2017). Multi-criteria analysis for solar farm location suitability. Reports on Geodesy and Geoinformatics, 104(1), 20-32. https://doi.org/10.1515/rgg-2017-0012

National Audubon Society. "LeConte's Thrasher." Audubon Field Guide. Available at: https://www.audubon.org/field-guide/bird/lecontes-thrasher. Accessed May 16, 2023.

Nebey, A., Taye, B., & Workineh, T. (2020). Site suitability analysis of solar P.V. power generation in South Gondar, Amhara region. Journal of Energy, 2020, 1-15. https://doi.org/10.1155/2020/3519257

Phalan, B., Hayes, G., Brooks, S., Marsh, D., Howard, P., Costelloe, B., Vira, B., Kowalska, A., & Whitaker, S. (2017). Avoiding impacts on biodiversity through strengthening the first stage of the mitigation hierarchy. Oryx, 52, 316 - 324. https://doi.org/10.1017/S0030605316001034.

Phillips, S. J., Dudik, M., & Schapire, R. E. (2004). A maximum entropy approach to species distribution modeling. Proceedings of the Twenty-First International Conference on Machine Learning. P. 655–662.

Prăvălie, R., Patriche, C., & Bandoc, G. (2019). Spatial assessment of solar energy potential at global scale. A geographical approach. Journal of Cleaner Production, 209, 692-721. https://doi.org/10.1016/j.jclepro.2018.10.239

Pebesma E (2018). "Simple Features for R: Standardized Support for Spatial Vector Data." The R Journal, 10(1), 439–446. doi:10.32614/RJ-2018-009, https://doi.org/10.32614/RJ-2018-009.

Rehbein, José A.; Watson, James E. M.; Lane, Joe L.; Sonter, Laura J.; Venter, Oscar; Atkinson, Scott C. y Allan, James R. (2020). Renewable energy development threatens many globally important biodiversity areas. Global Change Biology, 26(5), 3040-3051. https://doi.org/10.1111/gcb.15067

Rogan, J. E., & Lacher, T. E. (2018). Impacts of Habitat Loss and Fragmentation on Terrestrial Biodiversity. In Reference Module in Earth Systems and Environmental Sciences (pp. 10913-3). Elsevier. ISBN 9780124095489. doi: 10.1016/B978-0-12-409548-9.10913-3.

Rodrigues, S. & Coelho, M.B. & Cabral, Pedro. (2017). Suitability analysis of solar photovoltaic farms: A Portuguese case study. International Journal of Renewable Energy Research. 7. 244-254.

Sabo, M. L., Mariun, N., Hizam, H., Mohd Radzi, M. A., & Zakaria, A. (2017). Spatial matching of large-scale grid-connected photovoltaic power generation with utility demand in Peninsular Malaysia. Applied Energy, 191, 663-688. https://doi.org/10.1016/j.apenergy.2017.01.087

Sandia National Laboratories. (n.d.). Global horizontal irradiance (GHI). P.V. Performance Modeling Collaborative. Retrieved April 6, 2023, from https://pvpmc.sandia.gov/modeling-steps/1-weather-design-inputs/irradiance-and-insolation-2/global-horizontal-irradiance/

Sheppard, J. M. (2020). LeConte's Thrasher (Toxostoma lecontei), version 1.0. In Birds of the World (P. G. Rodewald, Editor). Cornell Lab of Ornithology, Ithaca, NY, USA. https://doi.org/10.2173/bow.lecthr.01

Sheppard, J. M. (1970). A Study of the Le Conte's Thrasher. California Birds, 1(3), [Page 83-94].

Sekercioglu, C. H., Daily, G. C., Ehrlich, P. R., & Ehrlich, A. H. (2011). Disappearance of insectivorous birds from tropical forest fragments. Proceedings of the National Academy of Sciences, 108(48), 20415-20420.

Sengupta, M., Y. Xie, A. Lopez, A. Habte, G. Maclaurin, and J. Shelby. 2018. "The National Solar Radiation Data Base (NSRDB)." Renewable and Sustainable Energy Reviews 89 (June): 51-60.

Southwest Climate Adaptation Science Center. (2023). Science Research. https://www.swcasc.arizona.edu/science

Solargis. (2022). Longterm average of global horizontal irradiation - Global Solar Atlas (Version 1.0) [GHI - LTAy_AvgDailyTotals (GeoTIFF)]. Solargis. https://globalsolaratlas.info/

Theocharis Tsoutsos, Niki Frantzeskaki, Vassilis Gekas, Environmental impacts from the solar energy technologies, Energy Policy, Volume 33, Issue 3, 2005, Pages 289-296, ISSN 0301-4215, https://doi.org/10.1016/S0301-4215(03)00241-6.

The White House. "Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies." The White House Briefing Room. Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/. Accessed May 15, 2023.

Taherdoost H, Madanchian M. Multi-Criteria Decision Making (MCDM) Methods and Concepts. *Encyclopedia*. 2023; 3(1):77-87. https://doi.org/10.3390/encyclopedia3010006

Vignali, S, Barras, AG, Arlettaz, R, Braunisch, V. SDMtune: An R package to tune and evaluate species distribution models. Ecol Evol. 2020; 00:1– 18. https://doi.org/10.1002/ece3.6786

UNEP-WCMC and IUCN (2023), Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], April 2023, Cambridge, UK: UNEP-WCMC and IUCN. Available at: www.protectedplanet.net.

U.S. Energy Information Administration. (n.d.). How much electricity does a nuclear power plant generate? Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

U.S. Department of Commerce, International Trade Administration. "Mexico - Renewable Energy." Country Commercial Guides. Available at: https://www.trade.gov/country-commercial-guides/mexico-renewable-energy. Accessed May 15, 2023.

U.S. Department of Energy. (2015). 5-step project development overview. https://www.energy.gov/sites/default/files/2015/08/f25/5-Step%20Project%20Development%20Overview.pdf

U.S. Fish and Wildlife Service. "Burrowing Owl (Athene cunicularia)." U.S. Fish and Wildlife Service Species Profile. Available at: https://www.fws.gov/species/burrowing-owl-athene-cunicularia. Accessed May 15, 2023.

Figure 1

Study Extent of the United States Southwest, including California, Nevada, Colorado, Arizona, New Mexico, and Texas.

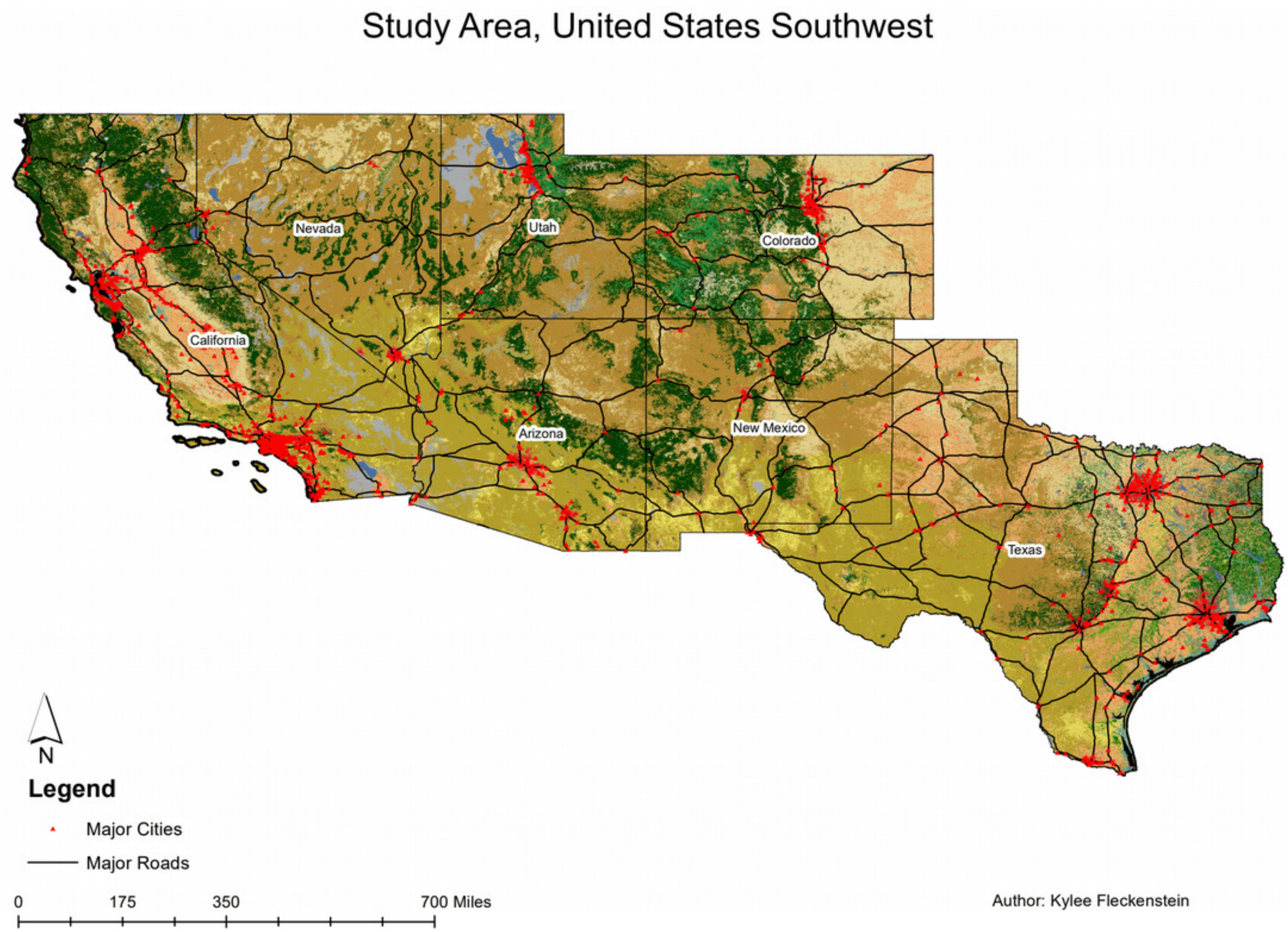


Figure 2

Spatial Distribution of Suitable Sites for Potential Solar Energy Development (SED) in the Southwest Region.

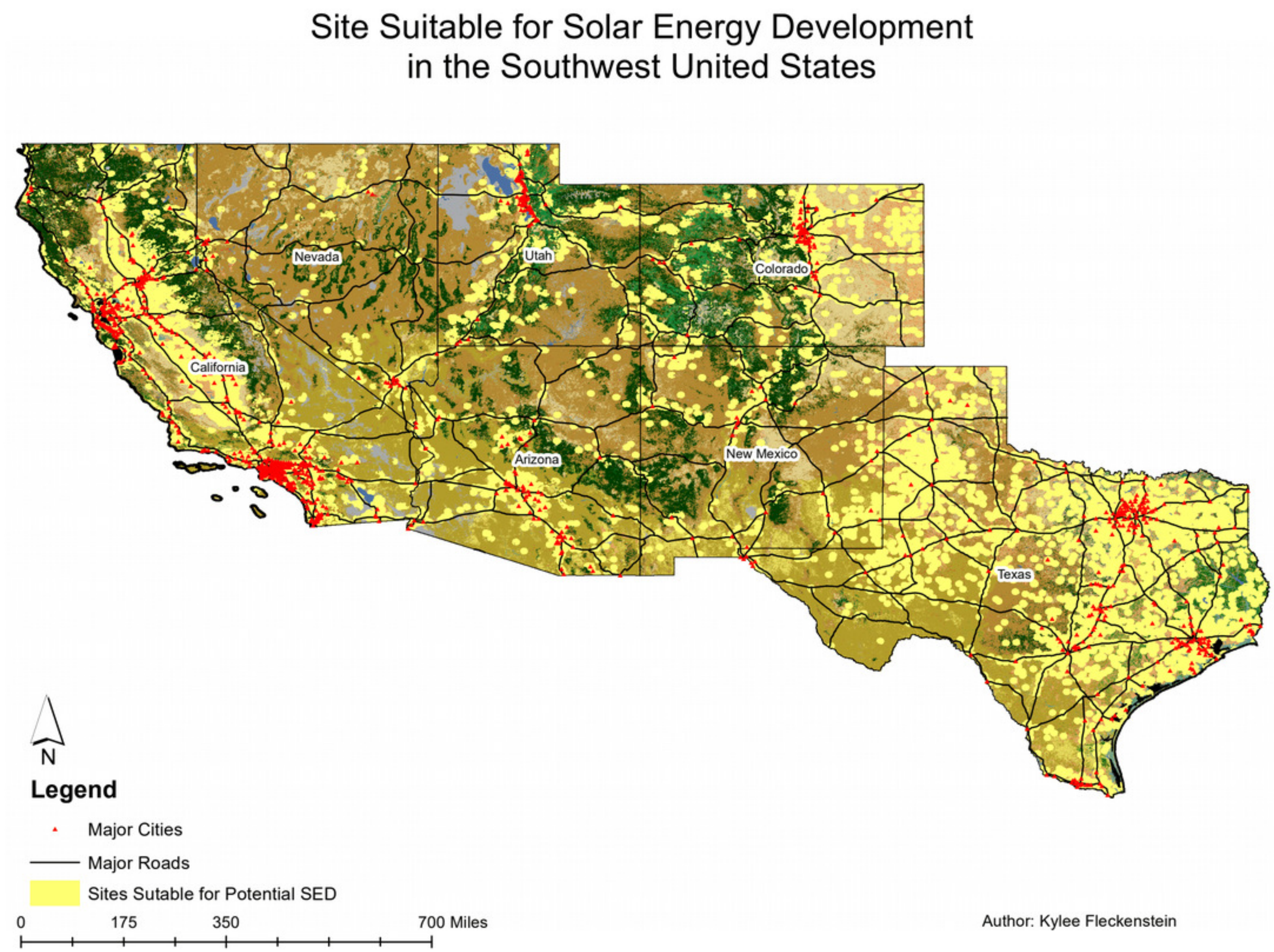


Figure 3

Habitat Suitability Mapping for Each Target Species within the IUCN breeding and resident extant.

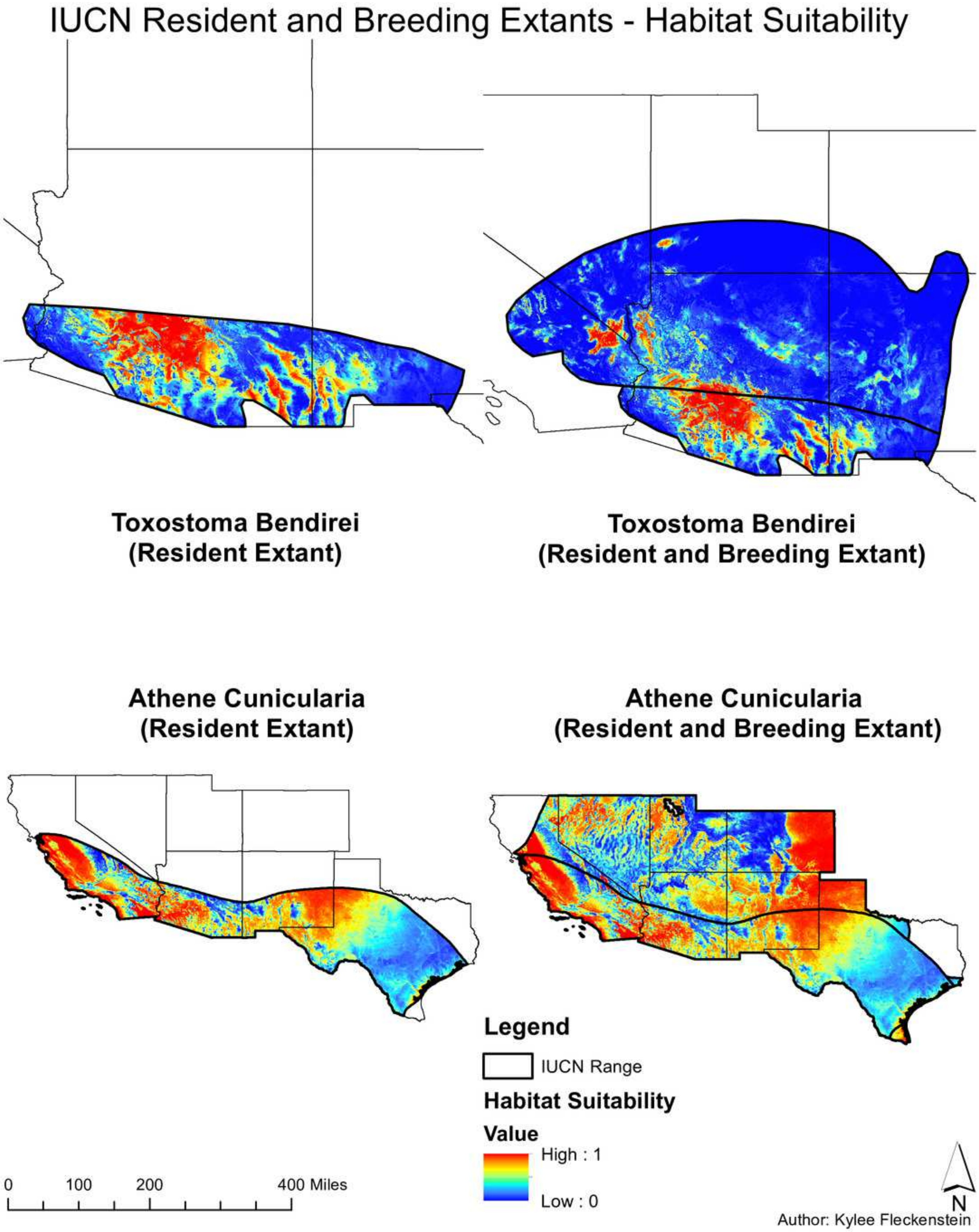

IUCN Resident and Breeding Extants - Habitat Suitability
Toxostoma Bendirei
(Resident Extant)
Toxostoma Bendirei
(Resident and Breeding Extant)
Athene Cunicularia
(Resident Extant)
Athene Cunicularia
(Resident and Breeding Extant)
Legend
IUCN Range
Habitat Suitability
Value
High : 1
Low : 0
0 100 200 400 Miles
N
Author: Kylee Fleckenstein

Figure 4

Habitat Suitability Mapping for Each Target Species within the IUCN resident extant.

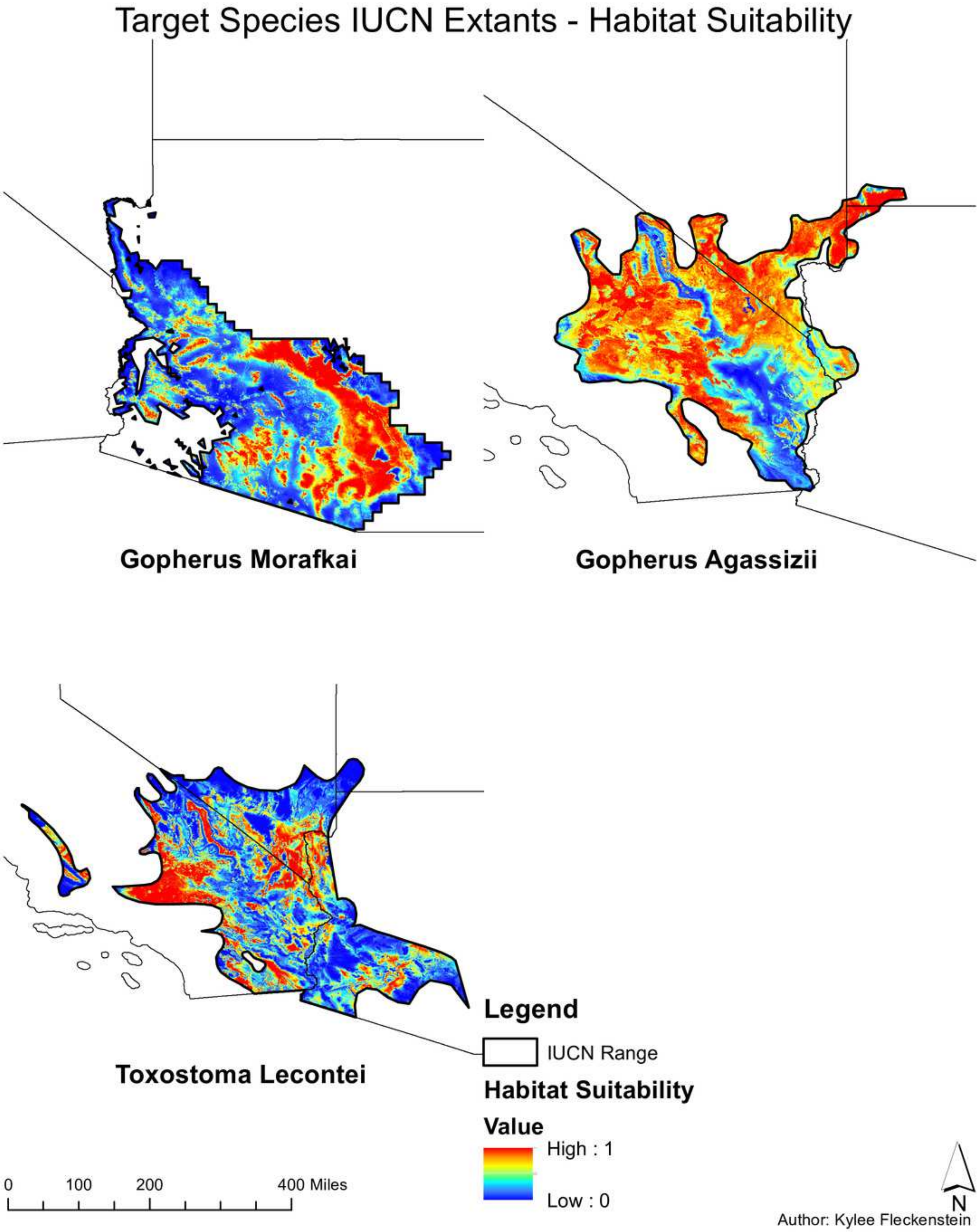

Target Species IUCN Extants - Habitat Suitability
Gopherus Morafkai
Gopherus Agassizii
Toxostoma Lecontei
Legend
IUCN Range
Habitat Suitability
Value
High : 1
Low : 0
0
100
200
400 Miles
N
Author: Kylee Fleckenstein

Figure 5

Overlap Analysis: Potential Solar Energy Development (SED) Sites and Target Species Presence with IUCN breeding and resident extant.

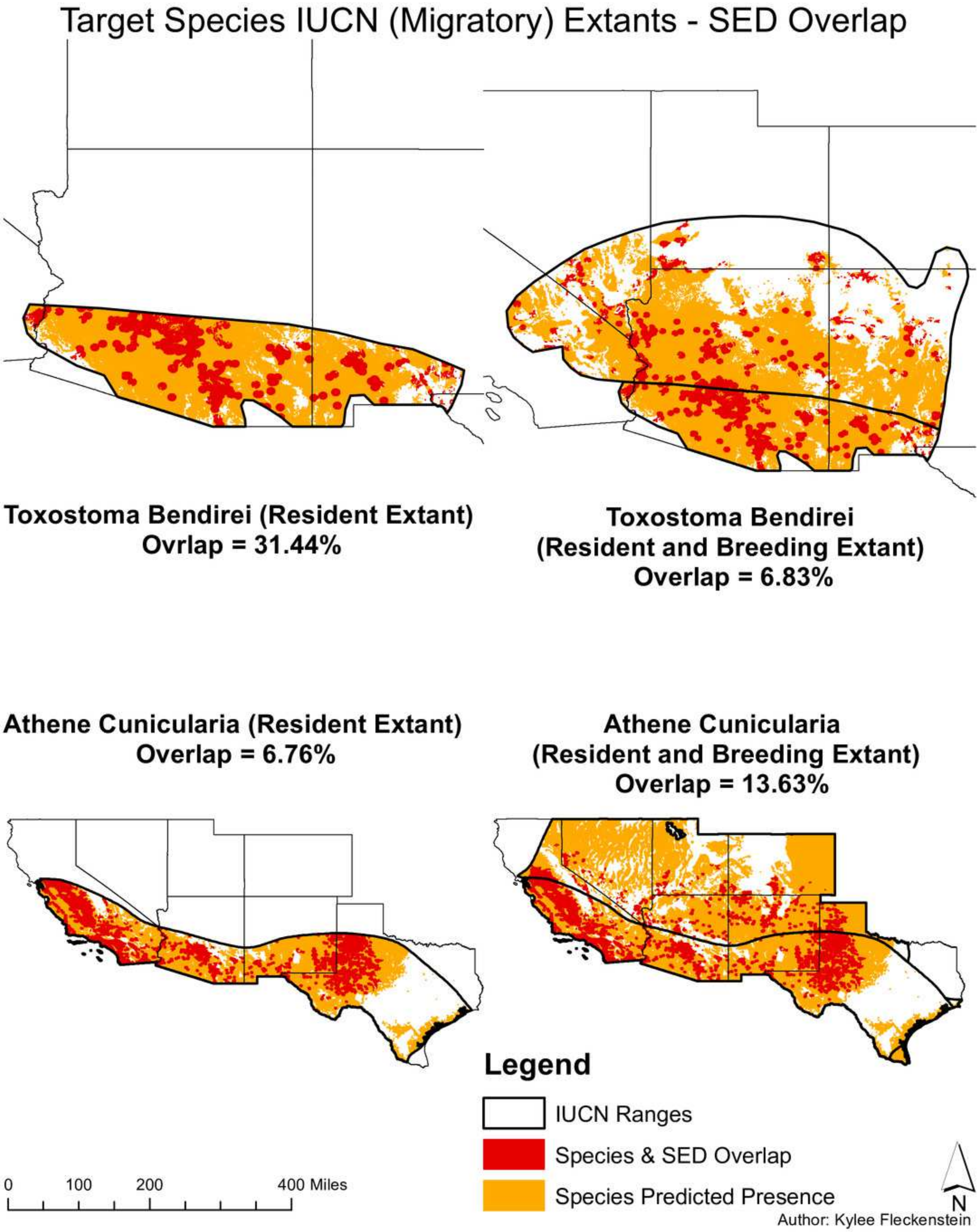
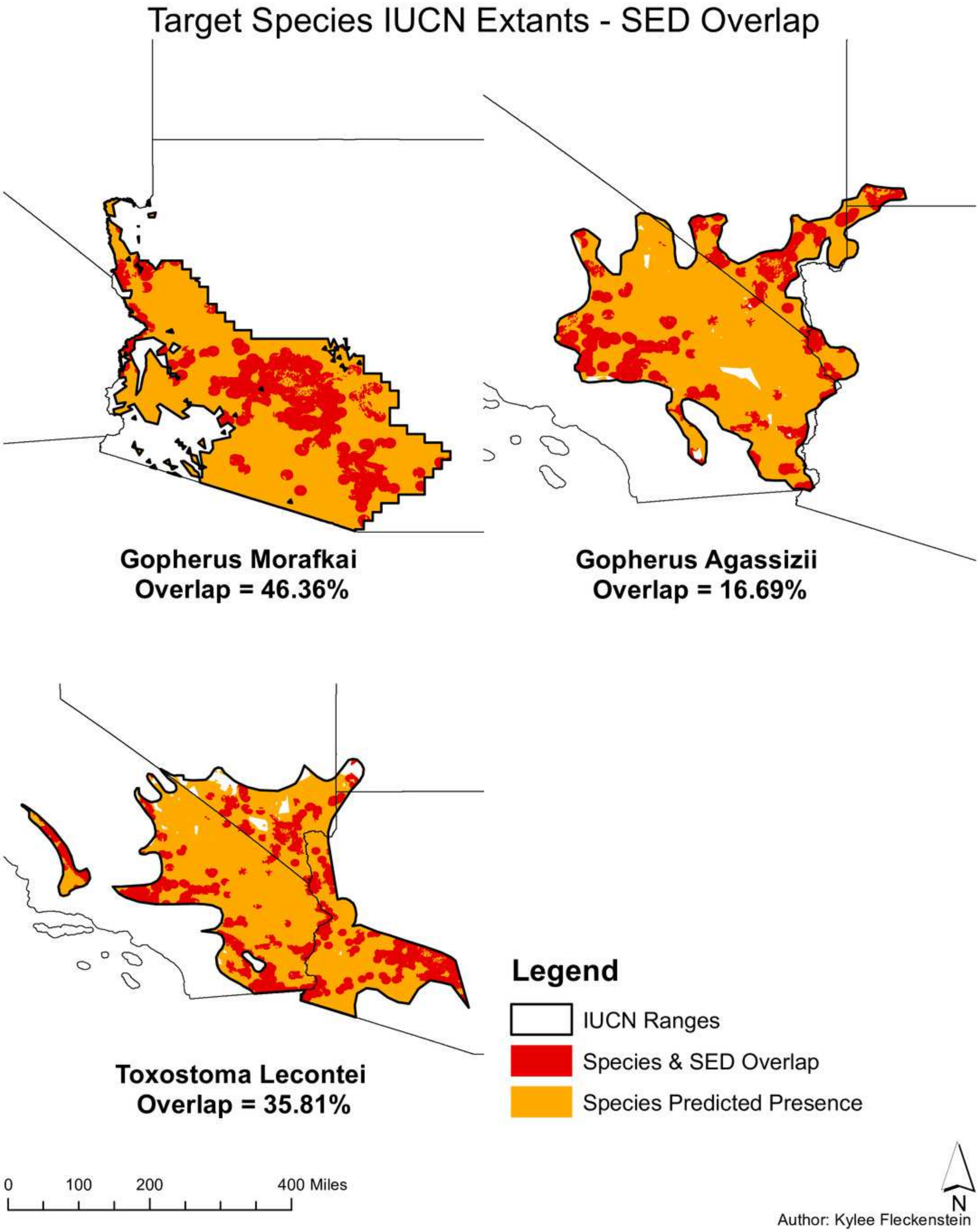

Target Species IUCN (Migratory) Extants - SED Overlap
Toxostoma Bendirei (Resident Extant)
Ovrlap = 31.44%
Toxostoma Bendirei
(Resident and Breeding Extant)
Overlap = 6.83%
Athene Cunicularia (Resident Extant)
Overlap = 6.76%
Athene Cunicularia
(Resident and Breeding Extant)
Overlap = 13.63%
Legend
IUCN Ranges
Species & SED Overlap
Species Predicted Presence
0 100 200 400 Miles
N
Author: Kylee Fleckenstein

Figure 6

Overlap Analysis: Potential Solar Energy Development (SED) Sites and Target Species Presence with IUCN resident extant.


Target Species IUCN Extants - SED Overlap
Gopherus Morafkai
Overlap = 46.36%
Gopherus Agassizii
Overlap = 16.69%
Toxostoma Lecontei
Overlap = 35.81%
Legend
IUCN Ranges
Species & SED Overlap
Species Predicted Presence
0
100
200
400 Miles
N
Author: Kylee Fleckenstein