



**INSTITUTO POTOSINO DE INVESTIGACIÓN
CIENTÍFICA Y TECNOLÓGICA, A.C.**

POSGRADO EN CIENCIAS AMBIENTALES

**Overwintering ecology in migratory grassland
birds of a grassland priority conservation area at
the highland plateau, Central Mexico.**

Tesis que presenta

Francisco Vega Reyes

Para obtener el grado de

Maestro en Ciencias Ambientales

Codirectores de la Tesis:

Dr. Leonardo Chapa Vargas

Dra. Elisabeth Huber-Sannwald

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Constancia de aprobación de la tesis

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Dr. Leonardo Chapa Vargas
Dra. Elisabeth Huber-Sannwald
Director/Codirectores de la tesis

Dr. Michael P. Ward
Miembro del Comité Tutorial

Dr. Antonio Celis Murillo
Miembro del Comité Tutorial



Créditos Institucionales

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CARTA DE EXAMEN PREVIO

División de Ciencias Ambientales
Maestría en Ciencias Ambientales

DEPARTAMENTO DEL POSGRADO
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CIENTÍFICA Y TECNOLÓGICA
PRESENTE

Los suscritos profesores investigadores se integran como jurado con el objeto de proceder a revisar el documento titulado Overwintering ecology in migratory grassland birds of a grassland priority conservation area at the highland plateau, Central Mexico del alumno Francisco Vega Reyes, que como requisito presenta para concluir los estudios de Maestría en Ciencias Ambientales del propio Instituto.

El resultado de la deliberación del jurado fue la siguiente:

Aprobarlo

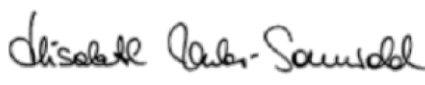
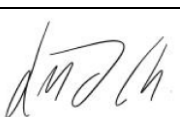
Comentarios sobre el trabajo de investigación:

Debe considerar replantear su discusión y conclusiones acerca del nomadismo de la especie que se estudió. Para la presentación final, integrar más los dos capítulos de acuerdo a las recomendaciones que se le dieron durante el examen previo

Comentarios sobre el documento de tesis:

Se recomienda trabajar la tesis para publicar este trabajo que es de muy buena calidad

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NOMBRE Y FIRMA DE LOS SINODALES	
Dra Elisabeth Huber-Sannwald	
Dr, Leonardo Chapa Varas	

Dr Michael P. Ward	
Dr Antonio Celis Murillo	

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Resumen

Overwintering ecology in migratory grassland birds of a grassland priority conservation area at the highland plateau, Central Mexico.

PALABRAS CLAVE: Ecología del movimiento, Lark Bunting, Biología de la conservación, Mapeo participativo, ARU.

Muchas especies de aves presentan estrategias de movimiento migratorio para mejorar su éxito reproductivo al encontrar el mejor hábitat y las mejores condiciones ambientales posibles durante todo el año. La ecología de invierno ha sido poco estudiada y se ha propuesto como un área de investigación prioritaria con un alto potencial para impactar significativamente las estrategias de conservación. La ecología de invierno puede incluir interacciones sociales, uso del hábitat, patrones migratorios, adquisición de recursos y estrategias de supervivencia, entre otros, durante la etapa no reproductiva del ciclo de vida. Esto es particularmente importante para las aves de pastizal de América del Norte; ya que estas han tenido algunas de las disminuciones poblacionales más pronunciadas en los últimos 50 años. Para este proyecto, la pregunta principal aborda si la ecología del movimiento y la presencia de los Lark Bunting, un ave de pastizal amenazada, a lo largo de su tiempo en el desierto del sur de Chihuahua varía a través del espacio y el tiempo sin territorios fijos, y cuál es el contexto socioecológico del paisaje que habitan. Esta tesis describe sus movimientos a través del espacio y el tiempo, junto con el aprendizaje de los habitantes del ejido sobre cómo ha cambiado el paisaje a lo largo de los últimos 60 años. Para lograr esto, se recopiló un año de datos y se utilizó para estudiar los movimientos locales de los Lark Bunting durante el invierno de 2023 mediante radiotelemetría autónoma. Para abordar los cambios en el tiempo, se analizaron los datos de 4 inviernos para evaluar las fluctuaciones de presencia/ausencia y las variables que causan estos cambios en la presencia; teniendo la hipótesis de que la precipitación y el índice de verdor de la vegetación del suelo (a través de SAVI), son los principales impulsores de estas fluctuaciones. Para tener una comprensión más amplia sobre dónde viven los Lark Bunting y cuáles podrían ser posibles amenazas de su hábitat, realizamos entrevistas semiestructuradas y un mapeo participativo en el sitio de estudio. Encontramos una baja revisita del sitio por parte de los Lark Bunting mediante radiotelemetría autónoma dentro de un invierno. Además, la presencia de Lark Bunting en nuestro sitio de estudio se asoció principalmente como una respuesta a la temperatura y SAVI. Por último, aprendimos sobre cómo el uso de la tierra y las prácticas agrícolas han cambiado en los últimos 60 años en nuestro sistema socioecológico. Encontramos preocupación de los agricultores locales sobre las áreas donde los Lark Bunting hibernan y una importancia atribuida a esas mismas áreas en términos de biodiversidad. Nuestros datos sugieren una respuesta de los Lark Bunting a variables ambientales y a una ausencia de territorios. Estos movimientos ocurren en el contexto de un sistema socioecológico semiárido donde la precipitación, y por lo tanto los recursos, pueden variar a través del tiempo y el espacio. Además,

este sistema socioecológico fue reportado por todos los residentes locales como un cambio en los patrones de precipitación, aunque nuestros datos climáticos no pudieron dilucidar estos cambios; pero sí se presentaron fluctuaciones de 40 años en la precipitación. Se espera que las conclusiones de este trabajo generen un análisis integrador relacionado con el estado de hibernación de esta ave que constituya la base para la implementación de estrategias de conservación realistas para este complejo sistema socioecológico.

Abstract

Overwintering ecology in migratory grassland birds of a grassland priority conservation area at the highland plateau, Central Mexico.

KEY WORDS. Movement ecology, Lark Bunting, Conservation Biology, Participatory mapping, ARU.

Many avian species present migratory movement strategies to improve their fitness by finding the best possible habitat and environmental conditions throughout the year. Overwintering ecology has been largely understudied and has been proposed as a priority research area having high potential to significantly impact integrative conservation strategies. Overwintering ecology may include social interactions, habitat use, migratory patterns, resource acquisition and survival strategies, among others during the non-reproductive, wintering stage of the life cycle. This is particularly important for North American grassland birds; since these are threatened species having some of the most pronounced population declines in the last 50 years. For this project, the main question addresses if the movement ecology and presence of Lark Buntings, a threatened grassland bird, over their time in the Southern Chihuahuan desert varies through space and time without fixed territories, and what is the socio-ecological context of the landscape they inhabit. This thesis describes their movements through space and time, together with learning from the inhabitants of the ejido about how the landscape has change in through the last 60 years. To achieve this, one year of data was gathered and used to study the local movements of Lark Buntings over 2023 winter through autonomous radio-telemetry. To address changes in time, data from 4 winters were analyzed to evaluate presence/absence fluctuations and the variables causing these changes in presence; having the hypothesis of precipitation and ground vegetation greenness index (through SAVI), being the major drivers of these fluctuations. To have a broader understanding on where Lark Buntings live and what could be possible threads to their habitat, we conducted semi-structured interviews and participatory mapping on the study site. We found low site revisiting from Lark Buntings through autonomous radio-telemetry within one winter. Additionally, presence of Lark Buntings on our study site were mainly associated as a response to temperature and SAVI. Lastly, we learned about how land use and agricultural practices have changes on the last 60 years in our socio-ecological system. We found concern from local farmers on areas where Lark Buntings overwinter and an attributed importance to those same areas in terms of biodiversity. Our data suggest a response of Lark Buntings to environmental variables and an absence of territories. This movements occurs in the context of a semi-arid socio-ecological system where precipitation, and therefore resources, can vary through time and space. In addition, this socio-ecological system was reported from all local residents to be going through a shift in precipitation patters, although our climatic data could not elucidate these changes; but 40-year fluctuations in precipitation were present. It is hoped that the conclusions of this work were to generate an integrative analysis related to the overwinter status of

this bird that would constitute the basis for implementation of realistic conservation strategies for this complex social-ecological system.

Introduction

Biodiversity loss is one of the major challenges in our century; birds of North America count to some of the most threatened species in our times (Ceballos et al., 2020; Dirzo et al., 2014). Many North American birds are migrants that spend the breeding season in highly productive regions in Canada and the United States and the winter in southern United States, Mexico, Central and South America and (H. Berlanga et al., 2010). It has been estimated that during the last 50 years there has been a loss of 3 billion individual North American birds (27-30% of the total population, (Rosenberg et al., 2019). This loss has been steepest for grassland birds; grasslands *per se* are among the most threatened ecosystems in North America due to their conversion to agriculture and fragmentation (Monroe et al., 2021; Rosenberg et al., 2019; Skagen et al., 2005; Van Auken, 2009; Wimberly et al., 2018). There are several factors responsible for the decline of North American avifauna. The evidence thus far suggests that the most important factors influencing grassland bird population trends are high mortality from pesticides, farm equipment incidents, and high nest predation rates (R. Stanton et al., 2017; R. L. Stanton et al., 2018). Nest predation in degraded habitats is significantly higher than in pristine grasslands. This is a consequence of native vegetation loss from many North American grasslands (it has been estimated that only 4% of the United States plains are covered by native vegetation)(Augustine et al., 2021; Samson & Knopf, 1994). However, most of the information regarding population trends and grassland bird ecology has been documented in studies from breeding sites (Rosales et al 2022). On the other hand, regarding winter ecology, information about basic ecology, population trends, mortality rates and even location of wintering sites is largely unknown, especially for the Mexican portion of the wintering grounds. Although this stage of the life cycle of migratory birds has been regarded as an important gap to be evaluated, and some recent studies have targeted this issue, many fundamental aspects of wintering birds should be evaluated (CB Wilsey et al., 2019; Mattsson et al., 2020; Smith & Gahbauer, 2017).

The Lark Bunting (*Calamospiza melanocorys*) is a neotropical migratory grassland bird that winters in Mexico. This granivorous species is listed as one of

the Common Species at Steep Decline (Rosenberg et al., 2016). Additionally, it is listed as a Species at Risk Act in Canada (Fraser, 2006; Smith & Gahbauer, 2017). It has been estimated that the global population of this species has declined as much as 80% since 1970; and half of the remaining population could be lost by 2032 (Rosenberg et al., 2016). Furthermore, the species has been studied very little during winter, both from a demographic and an ecological perspective. Its threatened status, and the limited information available about basic ecological aspects make them an important species to study. The current study centers on Lark Bunting winter ecology, including individual movement and activity patterns and the socioecological context and perspectives of the landscape they inhabit; this work intends to fill part of the gap on the current knowledge of this species. Conservation ecology is the result of science, landowners, society, and decision makers with the common effort to protect nature. To achieve a holistic conservation strategy, this work has the approach of first, learn about the natural system through studying and understanding the seasonality of overwinter movements of Lark Buntings. Based on preliminary results from the working group, the question of why the Lark Bunting movements patterns resemble a Seasonal Nomadic strategy is the axis of chapter one. Understanding if these movements truly resemble a nomadic strategy overwinter will impact the approach on conservation strategies for this species between single large patches in a specific region or several small patches across a bigger landscape. Once understanding the biological context of this threatened species, understanding the socioecological context where Lark Buntings spend almost half of their lifetime turns as important for their conservation. Grassland management, plus climatic variables, strongly influences the diversity and abundance of North American grassland species (Askins et al., 2007; With et al., 2008). Thus, is important to understand and learn from the perspectives and strategies of landowners and local farmers. By coproducing knowledge about how local stakeholders conceptualize the value of an increasingly heterogenous rangeland landscape, which is both the source of their livelihoods and the habitat of a highly endangered migratory bird; we hope to find if areas where Lark Bunting have a preference had a particular management,

and if so, if these management are replicable over long periods of time in similar areas. Thus, it is the intention of the author that the results of this work make an impact on future conservation strategies.

Chapter 1: Overwintering movement ecology of the threatened Lark Bunting (*Calamospiza melanocorys* Stejneger, 1885) at a North American grassland priority conservation area

Introduction

Migratory animals face challenges pertaining to intra annual variation in environmental conditions by moving between habitats. This movement behavior allows the migrating organisms to obtain “the best of both worlds” (CB Wilsey et al., 2019; Marra et al., 2005). Two main stages of the annual cycle of a migrant animal are the reproductive phase in spring/summer and the overwintering phase (non-breeding phase), where individuals search for suitable habitats and resources for their winter survival. Birds engage in a variety of behavioral, physiological, and even epigenetic changes along their migratory lifecycle (Johnson et al., 2019; McWilliams et al., 2020). For overwintering birds, these changes may include a switch in habitat preference, flocking behavior, molting (change in plumage), among others (McWilliams et al., 2020; Piersma et al., 2022). These changes are the result of the absence of reproductive competition. Although few recent studies have started to focus on the study of birds in their wintering grounds (Macías-Duarte et al., 2009; Parejo et al., 2021), assessments made on the course of the last two decades have pointed to the lack of information related to migratory bird ecology at the non-breeding grounds (Albert et al., 2020; Schmaljohann et al., 2022). The current information from conservation assessments arises from concerns due to decreases observed on North American avifauna (CB Wilsey et al., 2019). For North American migratory birds, especially grassland species, significant population declines for the last 50 years have been documented (Mineau & Whiteside, 2013; Pool et al., 2014; Rosenberg et al., 2019). Their conservation represents an important challenge because coordinated cross-countries efforts are often required to achieve success (Mason et al., 2020). Therefore, understanding ecological processes overwintering birds are experiencing is important to propose adaptive conservation strategies.

The Lark Bunting (*Calamospiza melanocorys* Stejneger, 1885) is one of the North American grassland species that spend the winter in the southern United

States and Mexico. It exhibits the steepest decline among the grassland bird species, such that it has been listed as a “Common Bird Species at Steep Decline” by the network for the conservation of birds Partners in Flight (Rosenberg et al., 2016). With an estimated population loss from 1970 to 2020 of 80%, and an estimated decrease of its current population to 50%, this species is of major conservation concern (Smith & Gahbauer, 2017). Just like for other grassland species, overwintering information is still missing. Because of the lack of information for *C. melanocorys* on their wintering sites and their population declines, it is important to understand fundamental aspects about their wintering ecology including their home range and territory. Particularly, it is important to understand how the species move through and use the landscape from both an ecological and conservation perspective (Runge & Tulloch, 2017). Like many other wintering migrants in Mexico, *C. melanocorys* needs resources and refuge to survive the winter season. Manual telemetry studies on this species recorded variability in flocks both in size (from 5 to >60 individuals) and movement distances (from <100 mts to >8 km), in both single and mixed flocks (Rosales Acosta, 2021). For the flocks with the largest movements across the landscape a core area of movement was not evident, and the results suggested that this species has movement strategies characteristic of nomadic birds. Similarly, for the breeding grounds, it has been recently proposed that both the Lark Bunting and the Chestnut-collared Longspur (*Clacarius ornathus*) have nomadism based on the finding that these species show high turnover rates (Green et al., 2019). Moreover, the presence of Lark Buntings increases with higher NDVI (Normalized Difference Vegetation Index) values, a remote-sensing measure associated with the amount of greenness (productivity) in the vegetation.

Nomadism is not unique to birds; it is an adaptation present across different taxa. However, all nomadic movements have the same characteristics; nomadism is defined as an animal movement strategy characterized by high frequency of movements between locations without a determined time and/or direction (Teitelbaum & Mueller, 2019). Nomadism is suspected to be an adaptation to environmental conditions on avian species such as: 1) Nomadic species tend to be

specialized in a particular feeding resource (generalist species have the least representation in number of species in nomadic classifications); 2) Nomadic species tend to inhabit habitats with a high variability in resources both in space and time (i.e., resources are ephemeral) (Dean 2004). 3) Nomadism can appear in species as a predator abundance strategy (Szymkowiak & Kuczyński, 2015) 4) Intra-specific competition could potentially drive individuals within a population to adopt nomadic strategies which could ultimately impact resource distribution between sexes (Basso et al., 2023) or 6) a mix of some of the previous mentioned (Mettke-Hofmann, 2017)

Although there are several definitions for nomadism, it is still a topic with several overviewed aspects. With the help of recent and accessible technologies, the classification of many avian species as nomadic, migrant, or resident has emerged during the last couple of years (Gibson et al., 2022). Bird species that were considered as residents of broad areas have been reported to behave as nomadic during seasons of severe drought or during specific life stages, either for complete populations or a fraction of them. Now there has been a change in the classification of nomads in five main subcategories: 1) full nomads, 2) seasonal nomads, 3) phase nomads, 4) irruptive nomads, and 5) partial nomads (Teitelbaum & Mueller, 2019). Birds are among the most representative taxa for nomadism, having at least one representative in each type of nomadism. However, due to the high degree of movement and the unpredictability of the areas occupied each year, there is still a lot to know about many potential nomadic birds that are probably misclassified.

Based on previous findings (Rosales-Acosta 2021), one of the objectives of this work was to determine if *C. melanocorys* is a nomadic species during winter. Because *C. melanocorys* is a North American migratory bird that migrates to the breeding sites each year in a predictive way, it cannot be considered into a fully nomadic classification. However, because previous reports have shown they may move over large extensions during both the winter and the reproductive season; the species could be a seasonal nomadic. Species under this classification include the Trumpeter Hornbill (*Bycanistes bucinator*), this frugivorous bird from South-east

Africa extends its home range during winter in erratic broad areas for foraging (Lenz et al., 2015).

As mentioned before, nomadic species associate to habitats with a high variability in resources both in space and time, such as the Chihuahuan semi-deserts. One of the major climatic oscillations that influence weather in North America is El Niño Southern Oscillation (ENSO). ENSO is characterized by the oscillation in precipitation patterns depending on the ocean temperatures around the equatorial pacific coast. Together with ENSO, the Pacific Decadal Oscillation and the North Atlantic Oscillation have been reported to have an impact on avian fitness and survivorship (McArthur, 2013). In the context of birds inhabiting semi-arid deserts, where resources are heterogeneous in space and time, summer precipitation together with Fall vegetative cover have been addressed as major drivers of bird abundance (Macías-Duarte & Panjabi, 2013). ENSO may affect precipitation and thus ultimately food availability. This could be a major driver in the presence of Lark Buntings and could partially explain their absence in parts of the Chihuahua desert during certain years. However, the effect of long-term fluctuations in temperature and specially in precipitation and vegetative cover on Lark Bunting presence in Mexican landscapes has not been evaluated.

Nomadic birds represent an extra challenge from a conservation perspective. In contrast to territorial birds, they may be more vulnerable to ecosystem, population, and community processes (Mettke-Hofmann, 2017; Sitters et al., 2014). With a broader potential distribution than other migrants, these species need wider and spaced protected areas where there could be higher chances of finding the resources, they need for a given period of their life cycle (Runge & Tulloch, 2017). Therefore, understanding the movement patterns for this species represents an important step in improving current knowledge of its overwintering ecology.

General research question

Why are the Lark Bunting movements patterns resembling a Seasonal Nomadic strategy during its wintering phase in México?

Specific research question

How are Lark Bunting movement patterns during the winter at an overwintering site in the Chihuahuan desert?

How environmental variables influence Lark Bunting presence in the southern portion of the Chihuahuan desert over the course of four years? And in what direction?

General objective

- Determine if the movement and activity patterns of *C. melanocorys* during the winter season present high variation through space and time, corresponding to a seasonal nomadic bird.

SPECIFIC OBJECTIVES

- Describe *C. melanocorys* movement patterns to determine winter territory and home range (as a non-nomadic bird) or if the species present a nomadic behavior.
- Report overwinter activity patterns of *C. melanocorys* individuals for the first-time using telemetry.
- Determine if the preferred landscapes of *C. melanocorys* flocks are specific to grassland communities or a mix of landscapes.
- Understand changes in presence and abundance patterns of *C. melanocorys* at El Salado during four winter periods and determine what are the climatic variables that influence their presence or absence on these sites.

Hypothesis

Based on the unpredictability of resources in semi-arid environments, it is expected that Lark Buntings would behave as a seasonal nomadic bird at winter

sites with no specific territories during winter or at least not measurable through a three tower telemetry system. This behavior will translate in high variation in activity, and low number of days detected throughout the wintering time at the Mexican semi-desert on the Lark Bunting. It was expected that during that same time, Lark buntings would spend most of their time foraging in patches of grassland.

The influence of precipitation and temperature has significant impact on primary productivity which directly impacts the greenness values (here evaluated with the Soil Adjusted Vegetation Index) from remote sensing, and ultimately the presence of Lark Buntings during different years.

METHODS

Study Site

The research was carried out in the northern region of the Potosí highlands, in the Ejidos (Communities with shared land) of El Salado and Noria de Cedros. The joint extension of these ejidos is more than 40,000 ha. The study was surveyed on one portion of the ejidos (24°20'54.89"N, 100°41'34.79"W). The study area is located in the southern portion of the Chihuahuan Desert bioregion. The landscape is characterized by heterogeneous vegetation patches consisting of yuccas (*Yucca spp*), creosote bush (*Larrea tridentata*), or perennial halophytic grasses (*Sporobolus spp*, *Bouteloua spp*), however there is also the presence of mesquites (*Prosopis velutina*) and different cacti species (Granados-Sánchez et al., 2011, Rzedowski, J. 1965.). The main economic activities in the region are extensive livestock production (mainly caprine and bovine), subsistence rainfed agriculture and, to a lesser extent for El Salado, beekeeping. The number of inhabitants of these ejidos is 210 and 183, respectively (INEGI 2018).

VEGETATION AND LAND COVER MAPPING

SENTINEL-2 satellite images with a resolution of up to 10 m per pixel were used. Land Cover/ vegetation estimations were made in the SCP extension (semi classification plug-in) of the QGIS (Quantum GIS) program (Colgado L. 2019). The bands 2-8A, 11, and 12 were used for multispectral analyzes to generate a land cover classification map. The ROI tool on SCP was used to train the program about the spectral signatures for the different vegetations. Spectral signatures were calculated for different training inputs and using the maximum probability algorithm and the “Classify” tool, the map was generated. A total of 3 Macroclasses (Water, Humans & Vegetation), 8 Land cover Micro Classes (Figure 1) and 16 training inputs were uploaded and used for the classification. The resulting classification map has a finer scale than the government products such as CONABIO land cover raster layer of 200 mts per pixel (CONABIO 2024), whereas SENTINEL-2 images

may have a resolution up to 10 m per pixel for some of their layers (ESA 2024). We used this information for a more precise understanding of the movement patterns and landscape use of *C. melanocorys* from the UTM data obtained.

CLIMATIC DATA

TEMPERATURE AND PRECIPITATION

Due to the loss of the nearest meteorological station (18 km away from the study site) in 2010 from the National Agency of Water (CONAGUA), data from the NASA POWER (Prediction of Worldwide Energy Resources) project were used. This project is part of NASA's MERRA-2 project. Mean daily data from March 2019 to March 2023 were considered. Data requested was mean temperature at 2 meters from surface (T2M), mean specific air humidity at 2 meters height (QV2M), relative air humidity at 2 meters (RH2M), precipitation corrected (PRECTOTCORR), wind speed at 2 meters (WS2M), wind direction at 2 meters (WD2M), surface soil wetness (GWETTOP) and soil profile moisture (GWETPROF). To confirm the assumption that the study site falls into the classification of heterogeneous and non-predictable resources the data for a 40-year timeframe were analyzed.

ENSO REPORT

The Cold & Warm Episodes by Season report from the National Weather Service's Climate Prediction Center (NWS) was used. The report allows visualizing deviations from the mean oceanic temperature. Deviations >0.5 within 3 consecutive months are indicative of an El Niño event, which are translated to an increase in precipitation in the Mexican drylands. On the other hand, deviations <0.5 within 3 consecutive months from the mean ocean temperature result in a La Niña event, with a reduction in precipitation for the areas previously mentioned. Data for January 2019 to March 2023, as well as data from January 1982 to March 2023 were reviewed. Since ENSO influences the wet-dry conditions at the Chihuahuan desert (Zolotokrylin A. et al 2015), and thus resource availability for

birds (LaManna et al., 2012) this should be considered when evaluating presence/absence of a bird expected to be nomad (Dean 2004).

VEGETATION INDEX DATA AND LARK BUNTING PRESENCE/ABSENCE MODEL

Since determination of nomadic behavior of birds may require long term monitoring, 4 years of climate data were used to correlate with Lark Buntings presence / absence. Data on Lark Buntings from January 2019 to March 2023 was available from our study site from the Ornithology research lab from the IPICYT. The USGS ESPA (EROS Science Processing on Demand Interface) portal was used to request NDVI (Normalized Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index) images. SAVI is presented as a modification of the Original NDVI, it takes into account the reflectance of bare soil by dividing the Near Infrared and red values from the original formula with a soil brightness correction value (L). This produces a more accurate measurement of the greenness of an area where vegetation is not dense or dominant; where bare soil could generate overestimation due to light reflection in a large surface area (Olmos-Trujillo et al 2020, Wang Z et al 2020).

To obtain these data, the same codename as the one in the USGS Earth Explorer portal was considered. At least one and up to three images per month were obtained, however due to weather conditions and cloud cover percentages, this was not possible for 9 of the 51 months (Table 1). The ESPA program sent processed NDVI and SAVI raster images. Due to the extent of these images, the QGIS (Quantum GIS) program clip tool was used on the images based in both: I) the area within the sociopolitical borders of the study site, and II) the area where most avian monitoring efforts were concentrated. The final area covered by each image was the same, about 2,600 hectares. With all the environmental data, different generalized linear mixed effect models (glmm`s) were run. Data were categorized by years and by winters, i.e. winter 2022 from November 2021 until March 2022. The model that best explained presence of Lark Buntings was selected based on the Akaike Information Criterion (AIC) and on graphic

characteristics such as the distribution of residual values and actual vs expected probabilities.

RADIO-TAGGING AND RADIOTELEMETRY

Tagging

Mist nets (12 x 3 m) were used at sites visited by migratory grassland birds (open grass areas and water sources including wildlife and livestock wells). Most of the capture effort focused on Lark Buntings, however other grassland birds (Brewer's Sparrows, *Spizella brewerii*; and *Pooecetes gramineous*) were captured and radio tagged as well. The captures were made during the winter of 2023 considering the time between the end of October 2022 to the beginning of April 2023. Once a bird was captured, it was banded with a metallic bird band with a unique number and a unique ring color combination using plastic bands. This allowed identification of each individual in recaptures or resighting. Once the bird was banded, morphological data such as weight, total length, wing length and tarsus length were collected, and a radio transmitter was placed on with a Leg loop harness. Radio transmitters had a useful life of 45 days in which the activity and movement of a total of 24 birds were monitored. Transmitters emitted a signal approximately every two seconds. The radio transmitters were placed and secured using a leg-loop harness made of elastic thread. To avoid compromising the ability of the bird to fly and thus survive, the harnesses did not exceed 3% of the bird's weight.

Telemetry

Once the radio transmitters were in place, birds were monitored through an autonomous telemetry system, which consists of set of three towers previously installed (Figure 1). Each tower supported 6 antennas plugged into an Autonomous Receiving Unit (ARU). The tower system had an effective detection area of 53 ha. Whenever two or more antennas were able to detect the same bird, triangulation was possible. The towers were programmed to track each transmitter's unique signal and record the time (dd:mm:yyyy) and direction (in degrees, north being 0°) with respect to the tower that originally detected the signal. Information registered

from the three towers was merged and analyzed with the ARU package in the RStudio program (R core team), the position of the bird was triangulated each time it was registered by at least two towers. Activity through the day around each tower was also obtained from the ARU package. Additionally, on-foot behavioral observations between 7am and 6pm were conducted for overwintering flocks over the course of 4 days. For each observation, the following information was registered: time, number of individual/s with transmitter, number of individuals in the flock, UTM coordinates of the flock, vegetation category (Grassland, shrubland, mixture), number of individuals perched in shrubs and not foraging (here classified as “guards”) and behavior (perched, foraging, flying). Information about vegetation category was also compared with semi-automatic classification data obtained from remote sensing.

Once the useful life of the radio expired, activity graphs and maps of each individual and each species were generated based on UTM locations calculated from triangulation. Nomadic strategies are characterized by random movements through space and time. To determine detectability through space for one year of data (determine winter territory and home range, as a non-nomadic bird, or if the species present a nomadic behavior), daily detections (number of detections / number of monitoring days) and dates detected (0 = not detected, 1 = detected) were extracted from the processed data and analyzed in RStudio. Detection probabilities for each of the 22 migratory birds through the winter were calculated using the “glm” package in RStudio. We used generalized linear mixed models to calculate if the probability of detection changed as time (transformed to numeric variable) advanced. Testing a null hypothesis of the absence in strong periodic movement patterns over one winter season (randomness) in the overwinter grounds would suggest a nomadic behavior (McEvoy, 2014; Tseng et al., 2017). Date and number of detections were used as fixed variables and, since nomadism could also be present in a subset of individuals but not the whole population (Basso et al., 2023), individual's ID was used as random variable. This model was compared with a null model of detection over time (as numeric date) test and AIC comparison was used to determine which model best explained the variance in

detectability. Due to the high number of zeros in the database, a gamma distribution was used for the modeling (Singh et al., 2012).

To address random movements through time, the approach was to understand changes in presence patterns of Lark Buntings at our study site during a four winter periods. The objective was to determine what are the climatic variables that influence Lark Buntings presence or absence on these sites. A total of eight models were compared (Table 5), the models included either numerical values or standardized values for the independent variables: Temperature, Cumulative precipitation, Daily precipitation, Mean SAVI value, Max SAVI value, Min SAVI value and Standard deviation SAVI value. These variables represent seasonality (through temperature), rainfall in a period of time (through cumulative and daily precipitation), and vegetation cover (through SAVI statistics); the main variables proposed to influence presence and abundance of grassland birds in México (Macias-Duarte et al 2018). Two columns for categorical variables were included: Year and Winter. Year was assigned based on the date of the presence or absence. We evaluated the effects by year and by winter because effects of precipitation in a given calendar year strongly correlates with grass production of the following year(s), which has been correlated to grassland bird densities (Lipsey & Naugle, 2017; Macías-Duarte et al., 2009; Peterson et al., 2014) Therefore, to account for the effects on summer precipitation, categorical variable “Winter” included observations from the end of July from one year to the end of July of the following year.

Results

LAND COVER CLASSIFICATION

A high resolution (avg 20 m per pixel) raster image for the area was obtained from the Land cover classification (Figure 1). The final raster image covers more than the total study area and include neighboring the ejidos south from the study site. A total of 9 micro classes (categories) of vegetation were used in our classified image. Unclassified pixels comprised 8.2% of the total raster image and 3.8% of the study area. In the area where Lark Buntings were tagged and tracked the most abundant vegetation type was Grass and shrub mosaics, representing 49.47% of the area, followed by Mezquite (*Prosopis velutina*) dominated Microphyllous desert scrubs covering 19.23% of the site. For the ejido El Salado, the most abundant land cover classification was Grass and shrub mosaics vegetation covering 32.25% of the land, followed by Mezquite (*Prosopis velutina*) dominated Microphyllous desert scrubs covering 18.07% of the land. For the ejido Noria de Cedros, the two most abundant land cover classifications were Bare Soil and Grass and shrub mosaics vegetation covering 26.65% and 18.09% of their land, respectively (Table S2). The extent and usage of this map exceed the boundaries of the study area. This map could also be used in other landscape studies and correlate with grassland densities in long term monitories (i.e. Pool et al., 2014).

PRECIPITATION AND TEMPERATURE

The maximum temperature over the four winters was 17.28°C, Minimum temperature was 3.49°C and maximum temperature was 25.23 (Figure 4). Temperature was statistically different between 2019 and 2020, 2020 being lower (Wilcox test, $p < 0.01$; Figure S1). Annual precipitation considering the study area presented different annual mean for the last 40 years (Kruskal-Wallis test; $p < 0.001$; 5-year mean = 450.62, std err= 139.77mm; Figure SX Chapter 2). 2019 presented three days with daily precipitation > 20mm (55.53 mm, 27.66 mm and 24.5mm) in late October (25th) and early September, whereas 2021 and 2022

presented no days with such characteristics. 2020 presented July 26 & 27 together with January 1 also presented precipitations >20 mm (Figure 3). 2022 was the year with the lowest annual precipitation (314.19 mm; Figure S2). 2019 and 2022 were years where late precipitation occurred (17.72 mm in November 2019 and 19.75 mm in October 2022).

ENSO REPORT

Reports from the National Weather Service's Climate Prediction Center showed the presence of ENSO in several years. For the years that this study was conducted (2021 to 2023), La Niña phenomena was present, having a minimum deviation from the mean sea temperature of -1.3 and a maximum deviation from mean sea temperature of -0.7 (Table 3). On the other hand, accounting for this and previous studies conducted in the area both El Niño and La Niña were present during bird monitoring. El Niño was present at the beginning of 2019, second half of 2019 and 2020 were considered a transition year followed by years of La Niña from the second half of 2020 until the beginning of 2023 (2019 to 2023).

SAVI CHANGES AMONG YEARS

The cropping of the original USGS image to the study area reduced the standard deviation on 32.71%. SAVI values ranged from 0 to 0.52 (being possible SAVI values 0 - 1); the mean value for the four years was 0.18. The year 2019 had the highest SAVI yearly mean value (Mean SAVI score = 0.16). With a highest mean value within a day in the year of 0.22 and a maximum pixel value of 0.52 (Figure 5). The months having the highest maximum SAVI values were July 2019 (SAVI score = 0.52) and September-August 2022 (SAVI score = 0.51 & 0.44). Months with the lowest mean SAVI values were April 2022 (SAVI score = 0.116) and March 2023 (SAVI score = 0.118). Standard deviation was higher within the months having the highest maximum SAVI values (July 2019, SD dev = 0.04 and September-August 2022, SD dev = 0.032) and August 2021 (SD dev = 0.033).

Autonomous Radio Unit (ARU) Activity

Over the course of 5 months (October 2022 to March 2023), a total of 24 migratory birds were radio tagged, including 19 Lark Buntings (*Calamospiza melanocorys*), four Brewer's Sparrows (*Spizella brewerii*) and one Vesper's

Sparrow (*Pooecetes gramineus*). A total of 16,487 Lark Bunting detections were obtained from the 3-tower system; and 15,793 detections were obtained for the other bird species. For the 24 radio tagged birds, 18 had constant detections from at least one tower for 24 hours for a total period ranging from 15 to 20 days. Only a total of 30 locations were triangulated for the Lark Buntings, 18 for Brewer's Sparrows and 20 for the Vesper's Sparrow. In other words, only 68 (30 + 18 + 20) times two towers detected the same individual at the same time in our tower system. The proportion of detections per day was not equivalent between individuals. Whereas 18 individuals had activity patterns from 6 am to 7 pm (i.e. Figure 6a), four individuals showed nocturnal activity, from 9 pm to 5 am. No visual confirmation allowed evidencing predation. Resighting of one individual with some nocturnal activity (individual with tag frequency 164.898) >5 km apart from the tower where it had consistent detections (Figure 6b) was possible. Due to the limited sample size for Brewer's Sparrows and Vesper's Sparrows, statistical analyses could not be conducted for these two species.

Habitat Preference

65.5% (95 out of 145) of the UTM locations obtained from the automated telemetry system correspond to pixels classified as Halophytic grassland communities (a mixture of grasses and small, <10 cm, shrubs). The second most visited land cover types by birds was *Sporobolus* dominated pixels representing 8.9% (13 out of 145). The remaining 25% of the locations correspond to unclassified pixels, yucca forest, microphyllus shrubland and bare soil (Figure 7). The most distant point detected by the telemetry system was 1,500 m away from the nearest tower.

Manual Telemetry

A total of 116 observations for a total of 4 individuals and their flocks were made over the course of 4 days, three in December 2022 and one March 2023. 73.28% of the observations (86 observations) correspond to foraging behavior for the whole flock. 67.24% of the observations correspond to pixels classified as Grass and shrub mosaics. All 4 observed individuals were associated with flocks of Lark Buntings from 4 to 34 individuals. However, in sites having water accessible for birds, additional flocks gathered from different directions, reaching > 100

individuals flying together. During the course of the tracking, individuals from other species (Black throated sparrows and Brewer Sparrow mainly) interacted and joined the Lark Bunting flocks, which could have an implication on foraging behavior, ultimately an important driver for the adaptation of Nomadism (Grzybowski, 1983).

Change in detection probabilities throughout a year

The model with the lowest AIC score was model 6 (Table 4), which consisted of the logarithmic transformation of data. An important, yet not significant ($p=0.07$) negative interaction between number of detections and the date when birds were tagged was detected. Substantial variation among individuals (Random effect) in number of detections was recorded ($p = 0.05$) for 5 of our 18 individuals. Number of detections depending on the bird tagged varied from 0.08 detections/day vs 53.7 detections/day: Figure 8). After the two weeks of tag deployment, resighting of any bird was almost null, however a single female (bird 164.898) was spotted with flocks of over 100 individuals around a cattle tank, around 3 km southeast to the nearest tower and its tagging location. Probability of detecting a bird decreased as time advanced, but not statistically significant (Estimate = -0.06181, $p = 0.077$. TABLE S2). Date thus did not have a significant effect based on the model, and variation was mostly attributed to differences in individual movements.

Presence/absence model for Lark Buntings in four years at El Salado Study Site

In all models, the categorical variable Winter explained more variation than the variable Year (Table 5). Model 1.7 (Table 5) best explained the variability of presence/absence in Lark Buntings for the four years (AIC = 32.71). The variable with the most impact on the presence was Daly mean temperature (Estimate = -264, $p = 0.001$) followed by Standardized Mean SAVI and Standardized SAVI Standard deviation (Estimate = 43.836, $p = 0.04$ and Estimate = -73.24, $p = 0.02$; Figure S4). Standardized accumulated Precipitation did not represent a significant factor for the presence of Lark Buntings ($p = 0.07784$; Table S3).

Discussion

Lark Bunting, a suspected nomadic migratory bird, presents the conservation challenge of steep population declines in recent years. Part of the lack of accurate estimations on population trends and conservation strategy effectiveness derives from its proposed nomadic behavior (Green et al 2019). In our study, Lark Buntings showed responses on their presence in four winters of surveys to environmental variables such as temperature and vegetation index (Model 1.7, Table S2), and in movement activity within one year (Figure S3). Changes in abundances among years for migratory species in a region can be explained by shifts in their migratory route due to meteorological events such as El Niño/La Niña Oscillation (Mallon et al., 2021), lack of resources in a given place (Teitelbaum et al., 2023), more recently due to climate change (Culp et al., 2017), or as a result of a high behavioral plasticity that leads individuals to search for overwintering sites that are optimal in terms of resource availability (Sagario et al., 2020). Plasticity in shifting overwintering locations among years is a major characteristic among nomadic birds that translates in random movements through space and time (Teitelbaum & Mueller, 2019). It represents a behavioral advantage in environments such as deserts where resources are heterogeneously distributed both, in time and in space (Curtin et al., 2002; Eichinger & Moriarty, n.d.; Macías-Duarte & Panjabi, 2013). Most studies on nomadism in birds have collected data for more than 10 years and analyzed presence/absence patterns for such extended time periods (Dean 2004). The relatively recent appearance and increase in accessibility to telemetry technologies, however, have allowed reducing the timespan needed to determine if a species shows such a behavior (Goymann et al., 2010; Poessel et al., 2018). This is the first study conducted in the Mexican Chihuahuan desert examining movement patterns of a grassland bird species through autonomous radio telemetry.

In spite of the relatively large area sampled and the intensive sampling effort, the current study gathered a relatively moderate number of records for the timespan of the study (five months; October 2022 to March 2023). This is not the first time a study has faced difficulties attempting to determine Lark Bunting home

ranges (Runge & Tulloch, 2017; Teitelbaum & Mueller, 2019). For instance, large sampling efforts from Green et al (2023) combined with the use of multiscale occupancy models have been recently used to elucidate habitat preferences for this species over vast territories. Earlier studies also faced challenges estimating territory sizes and home ranges due to the lack of consistency in yearly Lark Bunting presence and estimated territory sizes ranging from 0.2 to 2 ha (Finch et al. 1987; Dechant et al. 2002). In the current study, a limited number of UTM points was obtained per individual (min 20, max 450). A minimum of 40 UTM points was expected to be achieved for statistically robust calculations of the home range (Macías-Duarte & Panjabi, 2013; Wells et al., 2008), and ARU studies achieve a sample size up to 400 UTM points (Celis-Murillo et al., 2017; Schofield et al., 2018). Taking into account that high detectability over a large area may equal high mobility of tagged individuals (Jeltsch et al., 2013; Mettke-Hofmann, 2017; Wells et al., 2008), the current study prioritized detectability over point triangulation. However, individual detectability among towers was not equal, and most of the radio-tagged individuals spent most of the time near one of the towers (Tower 3 with 24,266 detections) followed by Tower 1 (6,624 detections). Tower 3 was embedded in a landscape of small hills with patches of medium-sized *Larrea tridentata* shrubs at the lower parts between the hills. Peak of the hills (max altitude 1,706.5 m a.s.l.) were primarily covered by short-statured halophytic grasses (Figure 10). Lark Bunting is reared as a non-obligate grassland species that can distribute also in landscapes with shrub densities of 10 to 30% (Smith & Gahbauer, 2017). Although little is known about the possible impacts of shrub presence on both breeding and non-breeding grounds, this is an important issue to address since one of the factors impacting grassland population declines is the low nesting success due to nesting in non-proper habitat (Drum et al., 2015; R. L. Stanton et al., 2018). Without the pressure of mating in the wintering grounds, however, the presence of shrubs may not represent an ecological threat to this species. Indeed, shrubs were used by Lark bunting individuals in the study area. Shrubs could be used for roosting as it was observed during manual tracking.

Access to water is probably critical for overwintering survival. Tower 1 was near a cattle well. While many species of North American Grassland Birds (particularly granivorous birds) fulfill their physiological water needs from seeds (Holmes & Johnson, 2005), this applies mainly for the breeding grounds. In the course of this and other studies conducted in the same area, bird visits to cattle wells to obtain water has been registered on a common basis (Vargas-Facundo 2022, Rosales-Acosta 2022, Personal obs.). Previous studies examined avian density around cattle wells and found significant correlations between distance to a water source and avian abundance (Abdu et al., 2018; Lee et al., 2021; Tanner et al., 2017). Thus, the detections on Tower 1 might be skewing the hypothetical home range of the focal species and biasing the results onto a broader area where the birds overwinter. Yet, long term resighting of individuals was uncommon (3 resightings after 3 weeks of transmitter deployment), and the number of detections within the battery life of the transmitter (aprox 28 days) was not equal between individuals.

Other studies with a similar ARU sampling design have found a more constant detection for radio tagged birds (Crewe et al., 2019; Wright et al., 2018), although those studies were not conducted on Lark Buntings. In addition, Rosales-Acosta et al. (2021) reported different movement patterns for Lark Buntings within one winter at El Salado using manual radio-telemetry only. The authors found a combination of strategies, having radio-tagged individuals in flocks with a constant home range around cattle wells, and others having a more nomadic movement pattern with sightings at various locations of the study site being separated by up to 6 km. Individuals showing different movement patterns within the same species have been reported in other populations of other bird species as well (Basso et al., 2023) and could be a strategy to improve foraging by segregating the use of complementary ecological niches, which may be particularly advantageous in years with low ecosystem productivity (Gibson et al., 2022; Lenz et al., 2015). The current study increases the body of knowledge on Lark Bunting movement strategies overwinter at the Chihuahuan Desert. By using a combination of manual and autonomous telemetry for one year without the same results in the same study

site but similar trends in high mobility of Lark Buntings around the site. This could be due to the variability in climatic (precipitation) and/or resource availability (inferred indirectly from SAVI mean and maximum values) among years. To address the response of Lark Buntings to resource availability, more than one year of data was needed and the last part of this chapter aimed to address the possible factors influencing Lark Bunting's presence in the study site.

Taking into account four winters of studying Lark Buntings in the Mexican Semi-desert, variation in SAVI was negatively correlated to cumulative and daily precipitation which at first might seem counterintuitive. However, legacy effects and a delay between precipitation and the development of plants resulting in a higher SAVI value might be involved (Cuddington, 2011). In our study, SAVI has proven to be an important environmental condition to understand and predict the presence of Lark Bunting in our study area ($p = 0.02$), and a more even distribution (negative value on SAVI Standard Deviation estimate) of the SAVI value on the study site also was significant on Lark Buntings Presence. A continuous survey through a longer timeframe may help present more robust and consistent information about the correlation between vegetation indices and nomadic bird behavior. However, finding different responses from Lark Bunting populations at a site with conditions varying through time (variable yearly precipitation and SAVI values), aligns with the hypothesis that this species has a nomadic strategy, and their presence is a response to resource availability with these resources being unpredictable between years. Therefore, the hypothesis that Lark Bunting exhibits nomadic behavior due to conditions varying through time is validated to some extent with this study. On the other hand, although with a smaller scale, this result coincides with those from Green et al. (2019) elucidating that the presence of Lark Bunting at the breeding grounds was correlated to higher NDVI, an equivalent to SAVI values in our study site.

Though the current study had a small sample size ($n = 5$ individuals) for the non-Bunting tagged individuals, these species yielded more consistent detections (16,487 detections for Lark Bunting vs 15,763 detections for non-buntings) and were mostly detected next to the tower that was closest to their capture location.

This result was expected, since non-nomadic grassland birds have well defined territories and home ranges (Askins et al., 2007; McEvoy, 2014; Mettke-Hofmann, 2017). Indeed, home ranges have been estimated for these species (e.g., Macías-Duarte & Panjabi 2013). However, even in studies on grassland species known to have shorter movements throughout the landscape, home ranges have not been successfully estimated for the total of tagged individuals (Crewe et al., 2019; Macías-Duarte & Panjabi, 2013; Schofield et al., 2018). This could be the result of either mortality from individuals due to uncertain factors, though this is not likely since survival in the Chihuahuan desert appears to be high based on the high re-sighting rate and lack of reports of mortality from this and previous studies by the same research group or the presence of several movement strategies within the population such as recently shown in Hudsonian Godwits (Basso et al., 2023). As tracking technologies have become more accessible, researchers have reported a variety of movement strategies of birds with highly complex behaviors in terms of foraging (Ginter & Desmond, 2005; Sparling & Krapu, 1994) and reproduction (Celis-Murillo et al., 2017), together with responses to precipitation and vegetation cover (Macías-Duarte et al., 2018), etc. The results of the current study illustrate the opportunities and research needed on the overwintering and movement ecology of species; a knowledge gap that should be filled within the following years. Such research is crucial in the context of declining species. Particularly for the Lark Bunting, so much is still unknown on the overwintering ecology which could elucidate and help to implement more integral conservation strategies. Information such as multiscale (between Mexican states and between the US and Mexico) movement patterns, migration timing, survival rates, dietary preferences, flocking behavior, and migratory routes are some of the most important questions to address before population declines reach a tipping point.

Conclusions

The Lark Bunting shows high mobility rates on the semi-arid Chihuahuan desert during winter, and patterns of presence that are inconsistent among winters; thus, behaving as a seasonal nomadic during winter. This high mobility is likely the response to a landscape with high heterogeneity in resource distribution both in space and in time. After temperature, standardized mean SAVI was positively correlated with the presence of Lark Bunting on the southern portion of the Chihuahuan desert. The response to this environmental variable and the variability observed within four winters of study support the idea of previous authors that Lark Bunting exhibits a nomadic strategy. It was also observed that the Lark Bunting tends to be a nuclear species within flocks of semi-arid grassland species, and that information from ecological factors such as predation, dietary composition, and migratory patterns are important to be addressed in the near future.

Figures

Table 1: Image codes requested for the ESPA program to conduct analyses of NDVI and SAVI

DATE	Month	Year	Product_Name	Satellite	collection
11/1/2019	1	2019	LC08_L2SP_028043_20190111_20200829_02_T1	LANDSAT-8	LEVEL-2
27/1/2019	1	2019	LC08_L2SP_028043_20190127_20200829_02_T1	LANDSAT-8	LEVEL-2
28/2/2019	2	2019	LC08_L2SP_028043_20190228_20200829_02_T1	LANDSAT-8	LEVEL-2
17/4/2019	4	2019	LC08_L2SP_028043_20190417_20200829_02_T1	LANDSAT-8	LEVEL-2
05/19/2019	5	2019	LC08_L2SP_028043_20190519_20200828_02_T1	LANDSAT-8	LEVEL-2
4/6/2019	6	2019	LC08_L2SP_028043_20190604_20200828_02_T1	LANDSAT-8	LEVEL-2
6/7/2019	7	2019	LC08_L2SP_028043_20190706_20200827_02_T1	LANDSAT-8	LEVEL-2
10/10/2019	10	2019	LC08_L2SP_028043_20191010_20200825_02_T1	LANDSAT-8	LEVEL-2
26/10/2019	10	2019	LC08_L2SP_028043_20191026_20200825_02_T1	LANDSAT-8	LEVEL-2
13/12/2019	12	2019	LC08_L2SP_028043_20191213_20201022_02_T1	LANDSAT-8	LEVEL-2
14/1/2020	1	2020	LC08_L2SP_028043_20200114_20200823_02_T1	LANDSAT-8	LEVEL-2
2/3/2020	3	2020	LC08_L2SP_028043_20200302_20200822_02_T1	LANDSAT-8	LEVEL-2
18/3/2020	3	2020	LC08_L2SP_028043_20200318_20200822_02_T1	LANDSAT-8	LEVEL-2
3/4/2020	4	2020	LC08_L2SP_028043_20200403_20200822_02_T1	LANDSAT-8	LEVEL-2
21/5/2020	5	2020	LC08_L2SP_028043_20200521_20200820_02_T1	LANDSAT-8	LEVEL-2
22/6/2020	6	2020	LC08_L2SP_028043_20200622_20200823_02_T1	LANDSAT-8	LEVEL-2
8/7/2020	7	2020	LC08_L2SP_028043_20200708_20200912_02_T1	LANDSAT-8	LEVEL-2
25/8/2020	8	2020	LC08_L2SP_028043_20200825_20200905_02_T1	LANDSAT-8	LEVEL-2
26/9/2020	9	2020	LC08_L2SP_028043_20200926_20201006_02_T1	LANDSAT-8	LEVEL-2
12/10/2020	10	2020	LC08_L2SP_028043_20201012_20201105_02_T1	LANDSAT-8	LEVEL-2
28/10/2020	10	2020	LC08_L2SP_028043_20201028_20201106_02_T1	LANDSAT-8	LEVEL-2
15/12/2020	12	2020	LC08_L2SP_028043_20201215_20210314_02_T1	LANDSAT-8	LEVEL-2
31/12/2020	12	2020	LC08_L2SP_028043_20201231_20210308_02_T1	LANDSAT-8	LEVEL-2
16/1/2021	1	2021	LC08_L2SP_028043_20210116_20210306_02_T1	LANDSAT-8	LEVEL-2
17/2/2021	2	2021	LC08_L2SP_028043_20210217_20210302_02_T1	LANDSAT-8	LEVEL-2
5/3/2021	3	2021	LC08_L2SP_028043_20210305_20210312_02_T1	LANDSAT-8	LEVEL-2
21/3/2021	3	2021	LC08_L2SP_028043_20210321_20210401_02_T1	LANDSAT-8	LEVEL-2
6/4/2021	4	2021	LC08_L2SP_028043_20210406_20210415_02_T1	LANDSAT-8	LEVEL-2
8/5/2021	5	2021	LC08_L2SP_028043_20210508_20210518_02_T1	LANDSAT-8	LEVEL-2
24/5/2021	5	2021	LC08_L2SP_028043_20210524_20210529_02_T1	LANDSAT-8	LEVEL-2
9/6/2021	6	2021	LC08_L2SP_028043_20210609_20210615_02_T1	LANDSAT-8	LEVEL-2
27/7/2021	7	2021	LC08_L2SP_028043_20210727_20210804_02_T1	LANDSAT-8	LEVEL-2
12/8/2021	8	2021	LC08_L2SP_028043_20210812_20210819_02_T1	LANDSAT-8	LEVEL-2
13/9/2021	9	2021	LC08_L2SP_028043_20210913_20210924_02_T1	LANDSAT-8	LEVEL-2
29/9/2021	9	2021	LC08_L2SP_028043_20210929_20211013_02_T1	LANDSAT-8	LEVEL-2
15/5/2021	10	2021	LC08_L2SP_028043_20211015_20211025_02_T1	LANDSAT-8	LEVEL-2

31/10/2021	10	2021	LC08_L2SP_028043_20211031_20211109_02_T1	LANDSAT-8	LEVEL-2
16/11/2021	11	2021	LC09_L2SP_027043_20211116_20220119_02_T1	LANDSAT-9	LEVEL-2
2/12/2021	12	2021	LC08_L2SP_028043_20211202_20211209_02_T1	LANDSAT-8	LEVEL-2
26/12/2021	12	2021	LC09_L2SP_028043_20211226_20220121_02_T1	LANDSAT-9	LEVEL-2
3/1/2022	1	2022	LC08_L2SP_028043_20220103_20220113_02_T1	LANDSAT-8	LEVEL-2
19/1/2022	1	2022	LC08_L2SP_028043_20220119_20220127_02_T1	LANDSAT-8	LEVEL-2
12/2/2022	2	2022	LC09_L2SP_028043_20220212_20220214_02_T1	LANDSAT-9	LEVEL-2
20/2/2022	2	2022	LC08_L2SP_028043_20220220_20220301_02_T1	LANDSAT-8	LEVEL-2
8/3/2022	3	2022	LC08_L2SP_028043_20220308_20220315_02_T1	LANDSAT-8	LEVEL-2
24/3/2022	3	2022	LC08_L2SP_028043_20220324_20220330_02_T1	LANDSAT-8	LEVEL-2
1/4/2022	4	2022	LC09_L2SP_028043_20220401_20220405_02_T1	LANDSAT-9	LEVEL-2
17/4/2022	4	2022	LC09_L2SP_028043_20220417_20220419_02_T1	LANDSAT-9	LEVEL-2
25/4/2022	4	2022	LC08_L2SP_028043_20220425_20220503_02_T1	LANDSAT-8	LEVEL-2
3/5/2022	5	2022	LC09_L2SP_028043_20220503_20220505_02_T1	LANDSAT-9	LEVEL-2
19/5/2022	5	2022	LC09_L2SP_028043_20220519_20230416_02_T1	LANDSAT-9	LEVEL-2
27/5/2022	5	2022	LC08_L2SP_028043_20220527_20220603_02_T1	LANDSAT-8	LEVEL-2
12/6/2022	6	2022	LC08_L2SP_028043_20220612_20220617_02_T1	LANDSAT-8	LEVEL-2
6/7/2022	7	2022	LC09_L2SP_028043_20220706_20230408_02_T1	LANDSAT-9	LEVEL-2
22/7/2022	7	2022	LC09_L2SP_028043_20220722_20230406_02_T1	LANDSAT-9	LEVEL-2
24/9/2022	9	2022	LC09_L2SP_028043_20220924_20230328_02_T1	LANDSAT-9	LEVEL-2
2/10/2022	10	2022	LC08_L2SP_028043_20221002_20221012_02_T1	LANDSAT-8	LEVEL-2
3/11/2022	11	2022	LC08_L2SP_028043_20221103_20221114_02_T1	LANDSAT-8	LEVEL-2
11/11/2023	11	2022	LC09_L2SP_028043_20221111_20230322_02_T1	LANDSAT-9	LEVEL-2
27/11/2023	11	2022	LC09_L2SP_028043_20221127_20230320_02_T1	LANDSAT-9	LEVEL-2
13/12/2023	12	2022	LC09_L2SP_028043_20221213_20230411_02_T1	LANDSAT-9	LEVEL-2
6/1/2023	1	2023	LC08_L2SP_028043_20230106_20230110_02_T1	LANDSAT-8	LEVEL-2
14/1/2023	1	2023	LC09_L2SP_028043_20230114_20230314_02_T1	LANDSAT-9	LEVEL-2
30/1/2023	1	2023	LC09_L2SP_028043_20230130_20230311_02_T1	LANDSAT-9	LEVEL-2
15/2/2023	2	2023	LC09_L2SP_028043_20230215_20230310_02_T1	LANDSAT-9	LEVEL-2
3/3/2023	3	2023	LC09_L2SP_028043_20230303_20230308_02_T1	LANDSAT-9	LEVEL-2
11/3/2023	3	2023	LC08_L2SP_028043_20230311_20230321_02_T1	LANDSAT-8	LEVEL-2
27/3/2023	3	2023	LC08_L2SP_028043_20230327_20230405_02_T1	LANDSAT-8	LEVEL-2

Table 2: Land cover classification (according to J. A. Zavala-Hurtado and M. Jiménez 2019). Values correspond to the study area (split in Noria de Cedros and El Salado), and the whole processed image (portion of the Northern High Plateau of San Luis Potosí) with their respective percentage and area (ha) cover for January 4th 2023.

Study site land-cover types				
Classification	Raster Value	Pixel Sum	Percentage cover [%]	Area [ha]
Unclassified	0	4230	3.28	42.3
Water	1	334	0.26	3.34

Rosetophilus scrub	3	4660	3.61	46.6
Microphyllous desert scrub	4	8314	6.44	83.14
Mezquite (<i>Prosopis velutina</i>) dominated Microphyllous desert scrubs	5	24812	19.23	248.12
Halophytic grasslands (<i>Sporobolus</i> dominated)	6	8750	6.78	87.5
Grass and shrub mosaics	7	63827	49.47	638.27
Crops	8	1	0.0007	0.01
Bare soil	10	14103	10.93	141.03
		Total = 100	Total =1	290.31

Trimonth	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
DJF	0.6	-0.9	0.7	-1.6	-0.8	1.5	-1.4	-0.9	-0.4	-0.4	0.5	2.5	-0.3	-0.9	0.7	0.5	-1	-1	-0.7
JFM	0.6	-0.8	0.2	-1.5	-0.8	1.2	-1.2	-0.7	-0.4	-0.5	0.5	2.1	-0.2	-0.9	0.7	0.5	-0.9	-0.9	-0.4
FMA	0.4	-0.6	-0.1	-1.3	-0.6	0.8	-0.9	-0.6	-0.3	-0.3	0.5	1.6	0.1	-0.7	0.7	0.4	-0.8	-1	-0.2
MAM	0.4	-0.4	-0.3	-1	-0.3	0.4	-0.7	-0.5	-0.3	0	0.7	0.9	0.2	-0.5	0.7	0.2	-0.7	-1.1	
AMJ	0.3	-0.1	-0.4	-0.8	0	-0.2	-0.6	-0.3	-0.4	0.2	0.9	0.4	0.3	-0.2	0.5	-0.1	-0.5	-1	
MJJ	0.1	0	-0.5	-0.6	0.3	-0.7	-0.4	0	-0.4	0.2	1.2	-0.1	0.3	0	0.5	-0.3	-0.4	-0.9	
JJA	-0.1	0.1	-0.6	-0.4	0.5	-1	-0.5	0.2	-0.4	0	1.5	-0.4	0.1	0.1	0.3	-0.4	-0.4	-0.8	
JAS	-0.1	0.3	-0.8	-0.2	0.6	-1.3	-0.6	0.4	-0.3	0.1	1.9	-0.5	0.2	0.2	0.1	-0.6	-0.5	-0.9	
ASO	-0.1	0.5	-1.1	-0.2	0.7	-1.6	-0.8	0.4	-0.3	0.2	2.2	-0.6	0.5	0.5	0.2	-0.9	-0.7	-1	
SON	-0.3	0.8	-1.3	-0.4	1	-1.6	-1	0.3	-0.2	0.5	2.4	-0.7	0.8	0.8	0.3	-1.2	-0.8	-1	
OND	-0.6	0.9	-1.5	-0.6	1.4	-1.6	-1.1	0.1	-0.2	0.6	2.6	-0.7	0.9	0.9	0.5	-1.3	-1	-0.9	
NDJ	-0.8	0.9	-1.6	-0.7	1.6	-1.6	-1	-0.2	-0.3	0.7	2.6	-0.6	0.8	0.8	0.5	-1.2	-1	-0.8	

Table 3: Data from the National Weather Service's Climate Prediction Center. Each row represents a year, each column the mean difference of sea temperature for data from three months. Blue numbers represent months when La Nina was present whereas red numbers represent months when El Nino was present.

Table 4: List of detection probability models. Model 6 presented the best AIC value thanks to a prior log transformation and elimination of 0 values.

id	Formula	AIC value	Notes
model	glm(detections ~ DATE*individual, data = data2, family = "gaussian")	22195	
model 2	glm(detections ~ DATE, data = data2, family = "gaussian")	22925	
model 3	glm(detections ~ DATE*individual, data = data2, family = "poisson")	14900	
model 6	glm(detections ~ DATE*individual, data = data3, family = "gaussian")	1012. 7	Log transformed data

Table 5: List of models used to explain the presence/absence of Lark Buntings at our study site based on environmental variables. Models 1.7 and 1.9 were considered the optimal ones based in AIC and Delta AIC values reflecting parsimony.

id	Formula	AIC value	df	Delta AIC	K
model0.5	glmer(LarkBuntingsPresence ~ Temperature + CumulativePrecipitation + DailyPrecipitation +MeanSAVI_2 + MaxSAVI_2 + MinSAVI_2 + StdDevSAVI_2 + (1 Year), data = modelo, family = binomial(link = "logit"))	878.81076	9	0	5

model1	glmer(LarkBuntingsPresence ~ Temperature + CumulativePrecipitation + DailyPrecipitation + MeanSAVI + MaxSAVI + MinSAVI + StdDevSAVI + (1 Year), data = modelo, family = binomial(link = "logit"))	66.00281	9	7.7954	7
model1.5	glmer(LarkBuntingsPresence ~ StandardizedTemperature + StandardizedCumulativePrecipitation + StandardizedDailyPrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI + StandardizedMinSAVI + StandardizedStdDevSAVI + (1 Year), data = modelo, family = binomial(link = "logit"))	65.99084	9	1344388	9
model1.7	glmer(LarkBuntingsPresence ~ StandardizedTemperature + StandardizedCumulativePrecipitation + StandardizedDailyPrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI + StandardizedMinSAVI + StandardizedStdDevSAVI + (1 Winter), data = modelo, family = binomial(link = "logit"))	32.71167	9	46.7179	9
model1.9	glmer(LarkBuntingsPresence ~ StandardizedTemperature + StandardizedCumulativePrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI + StandardizedStdDevSAVI + (1 Winter), data = modelo, family = binomial(link = "logit"))	28.46816	7	46.7299	9
model1.92	glmer(LarkBuntingsPresence ~ StandardizedCumulativePrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI + StandardizedStdDevSAVI + (1 Year), data = modelo, family = binomial(link = "logit"))	76.4886	6	46.73	9
model1.93	glmer(LarkBuntingsPresence ~ StandardizedCumulativePrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI + StandardizedStdDevSAVI + (1 Winter), data = modelo, family = binomial(link = "logit"))	59.55561	6	76.73	9
model2	glmer(LarkBuntingsPresence ~ StandardizedCumulativePrecipitation + StandardizedTemperature + StandardizedStdDevSAVI + (1 Winter), data = modelo, family = binomial(link = "logit"))	22.16953	5	856.1699	9

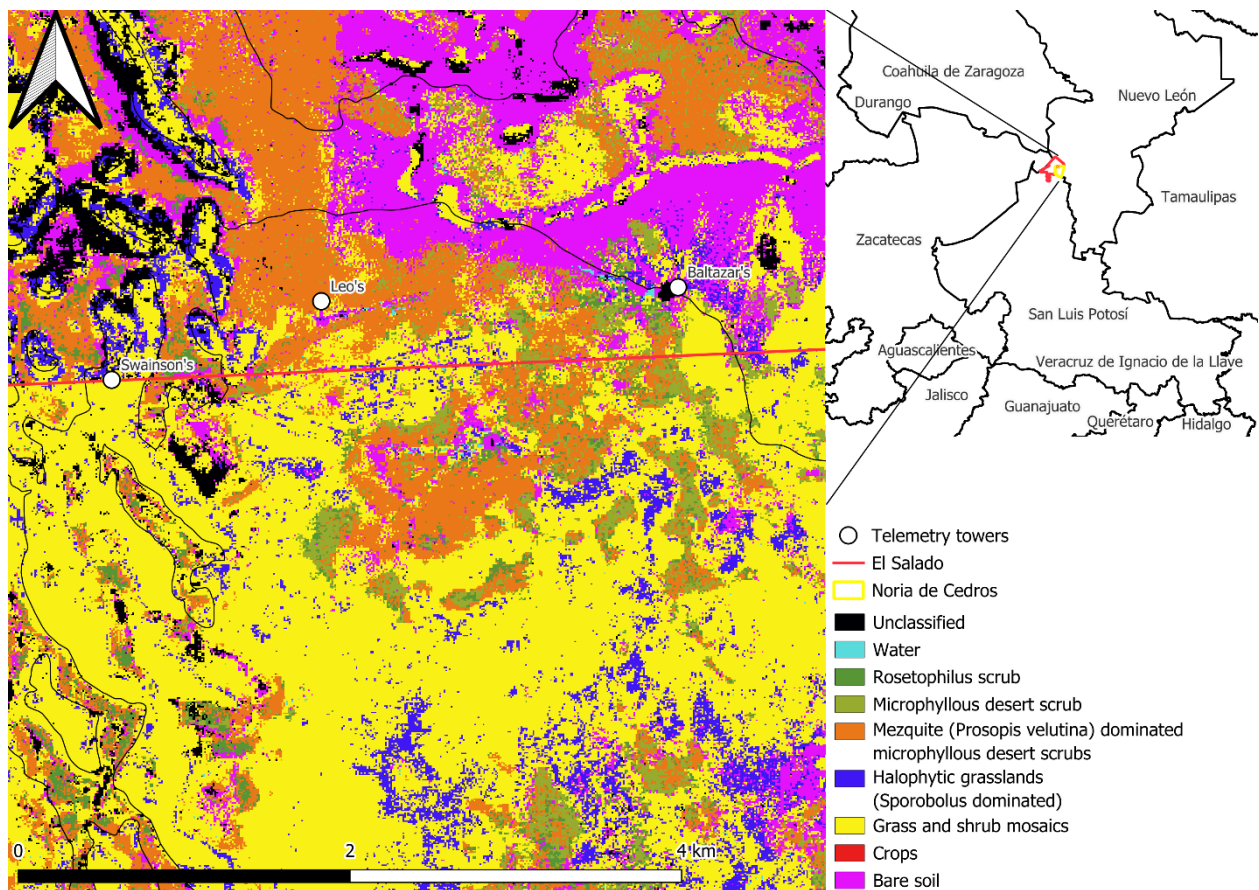


Figure 1: Land cover classification map of the study site El Salado according to J. A. Zavala-Hurtado and M. Jiménez 2019. Sentinel – 2 image was taken on January 4th, 2023. Red line represents the border between the two ejidos (North: El Salado, South: Noria de Cedros).

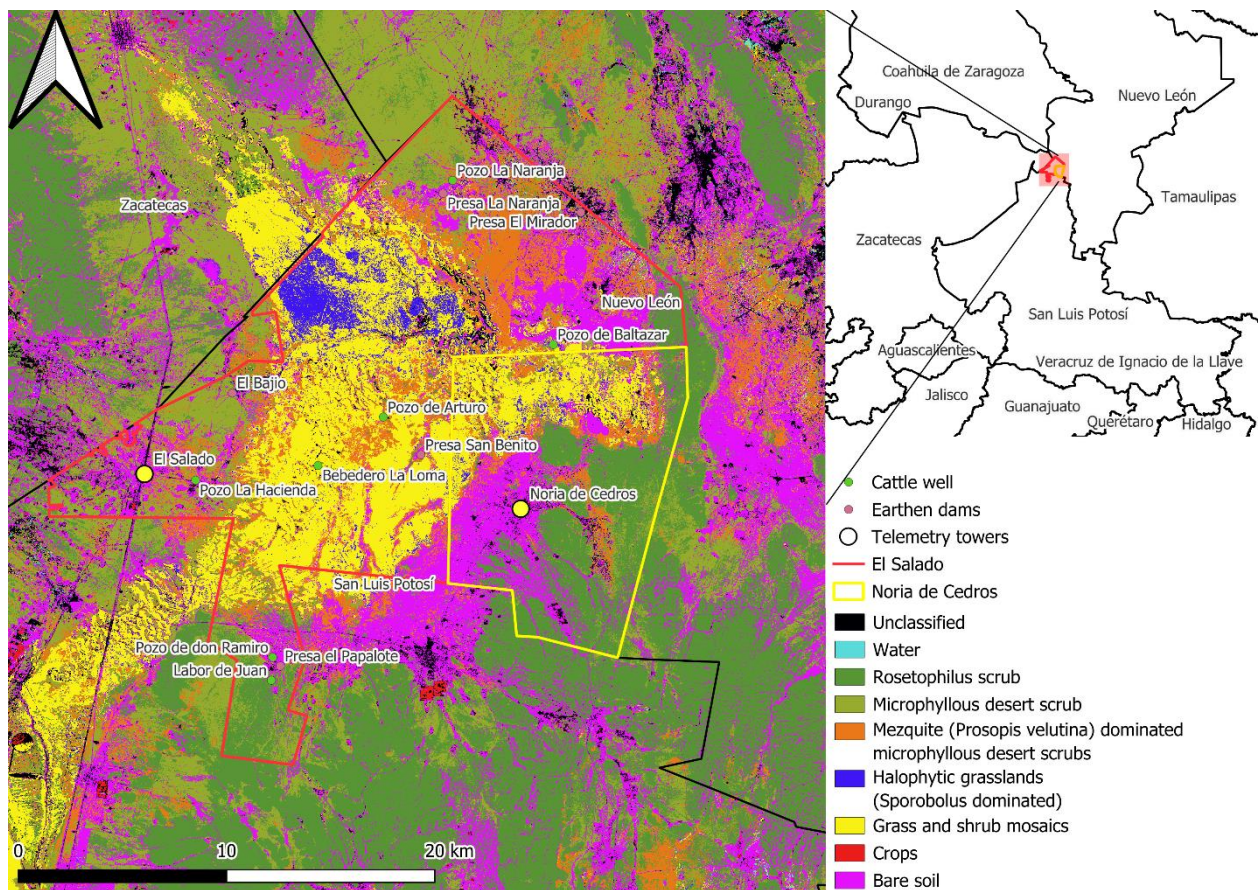


FIGURE 2: Map of the ejidos El Salado and Noria de Cedros and locations of main water resources for cattle; cattle wells represented by green dots and cattle dams represented by purple dots.

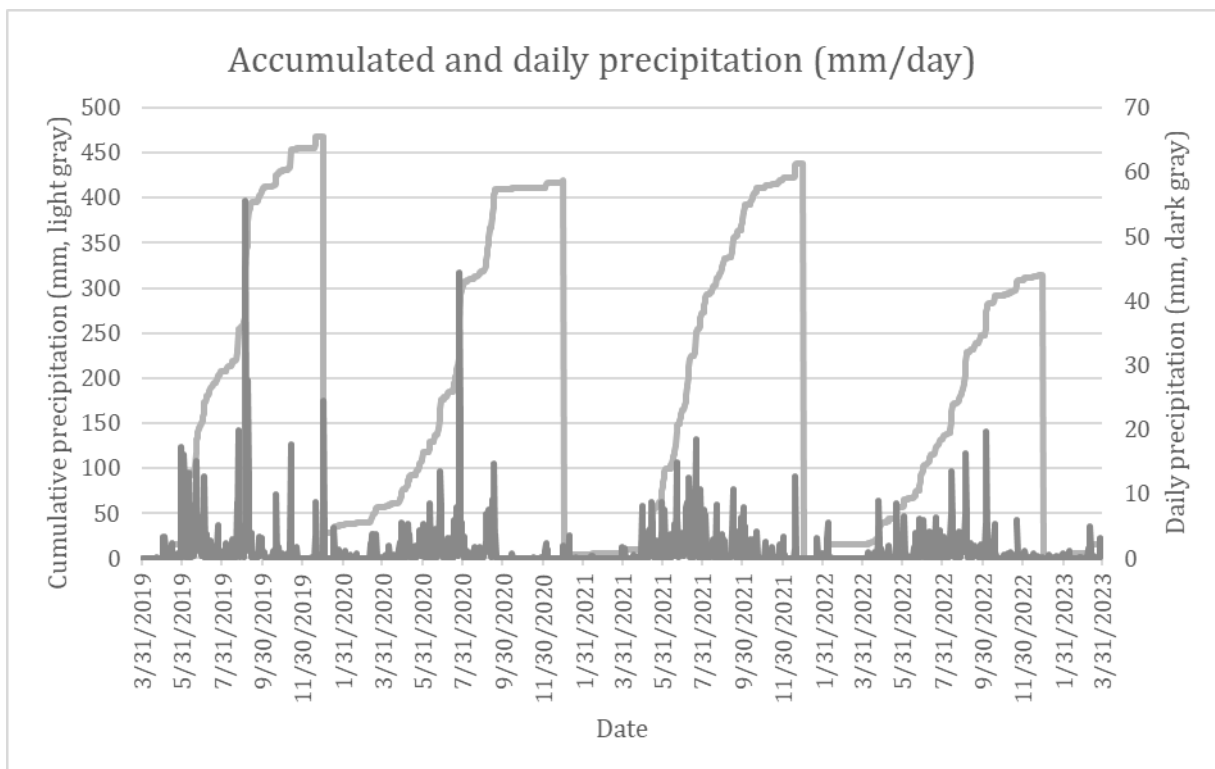


Figure 3: Cumulative and daily precipitation from 2019 to 2023 at a semiarid grassland region in Northern San Luis Potosí, Mexico. Dark gray bars represent daily precipitation and light gray lines represent accumulated precipitation

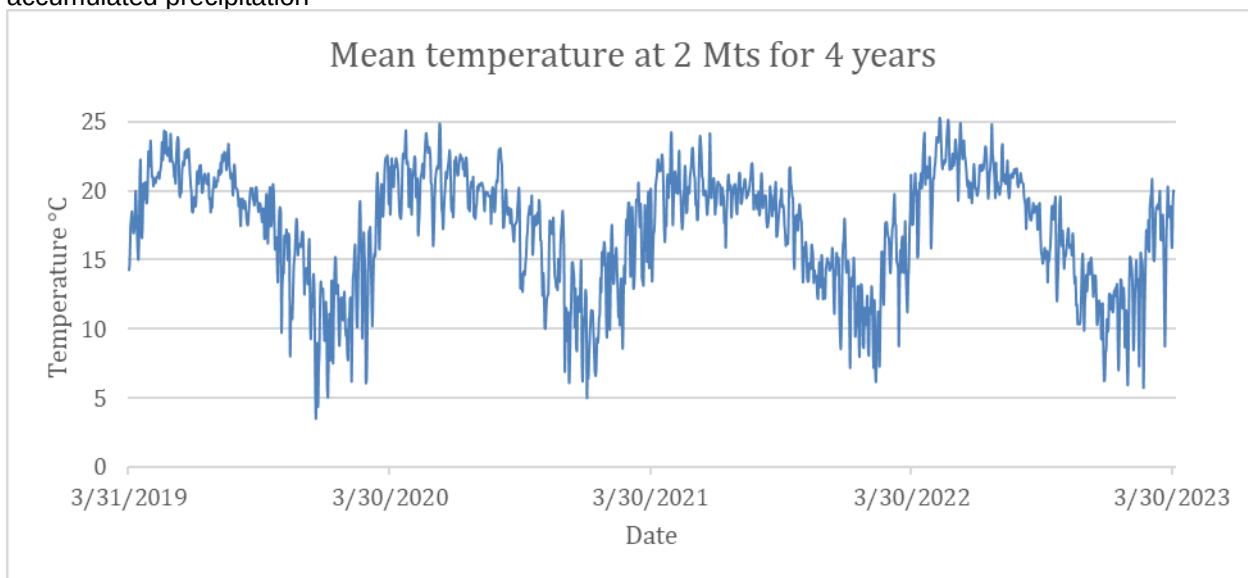


Figure 4: Mean daily temperature (°C) at two meters height between 2019 and 2023 at the study site in a semiarid grassland region in Northern San Luis Potosí, Mexico. The data was obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project funded through the NASA Earth Science/Applied Science Program.

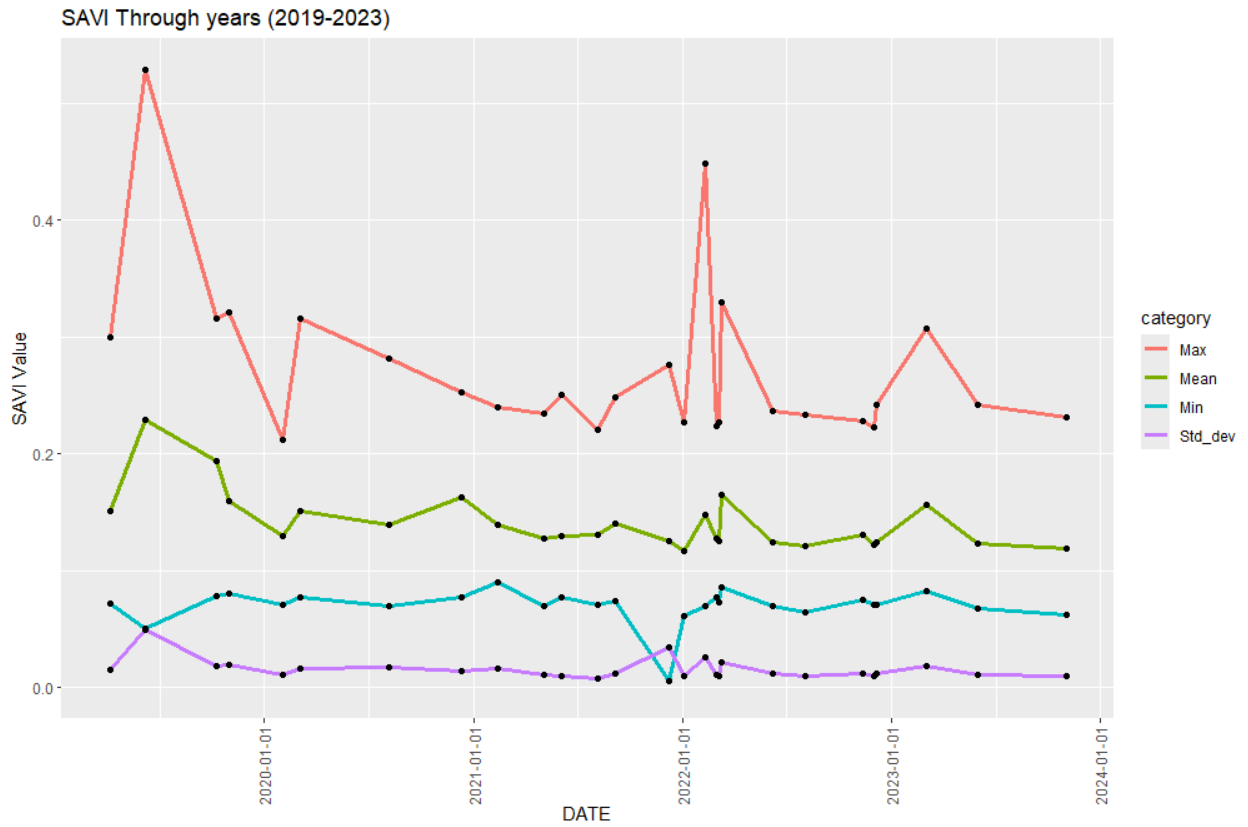
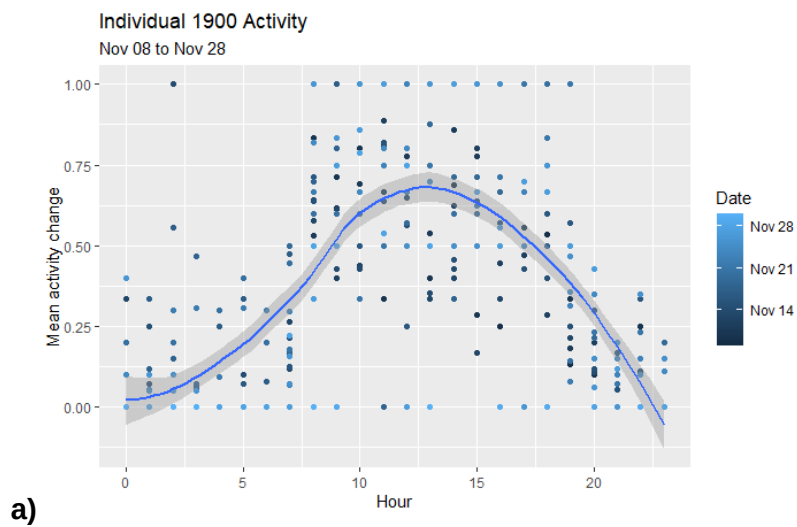


Figure 5: Soil Adjusted Vegetation Index (SAVI) metrics for at least one month from January 2019 to March 2023. Metrics included minimum and maximum values, mean and Standard deviation for every raster image.



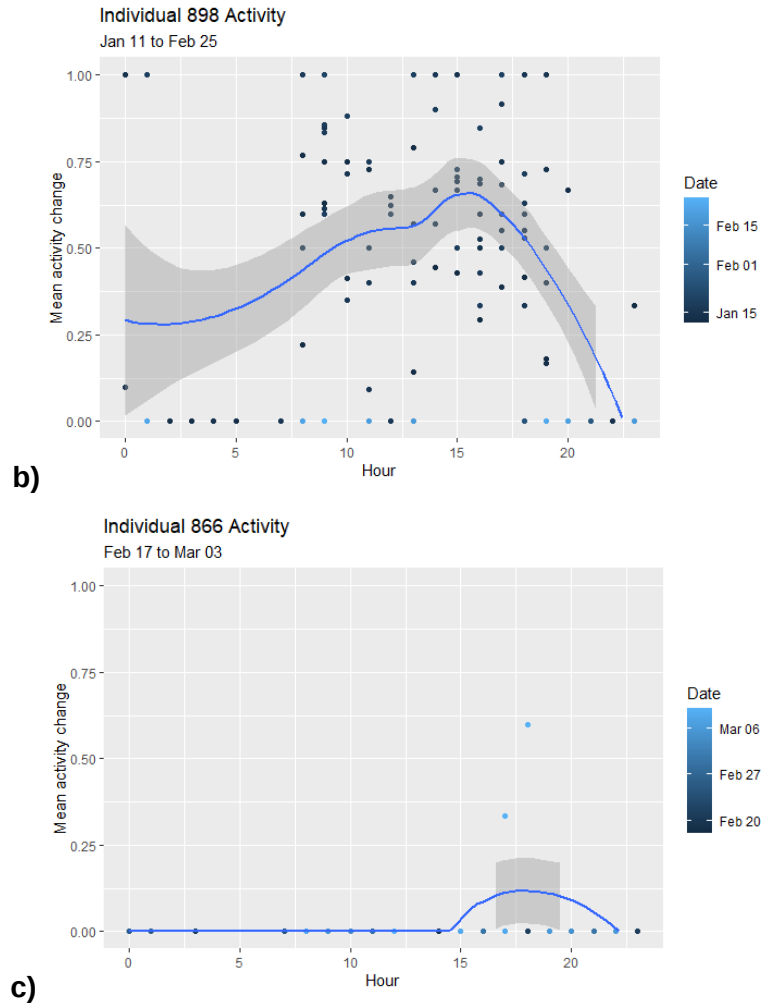


Figure 6 a): Average daily activity plot for a Lark Bunting at the beginning of the 2023 winter (November 2022) at Tower 3. b): Average daily activity plot for a Lark Bunting in the middle of the 2023 winter (January 2023) at Tower 1 c): Average daily activity plot for a Lark Bunting in late 2023 winter (March 2023). For all images, SE is presented in

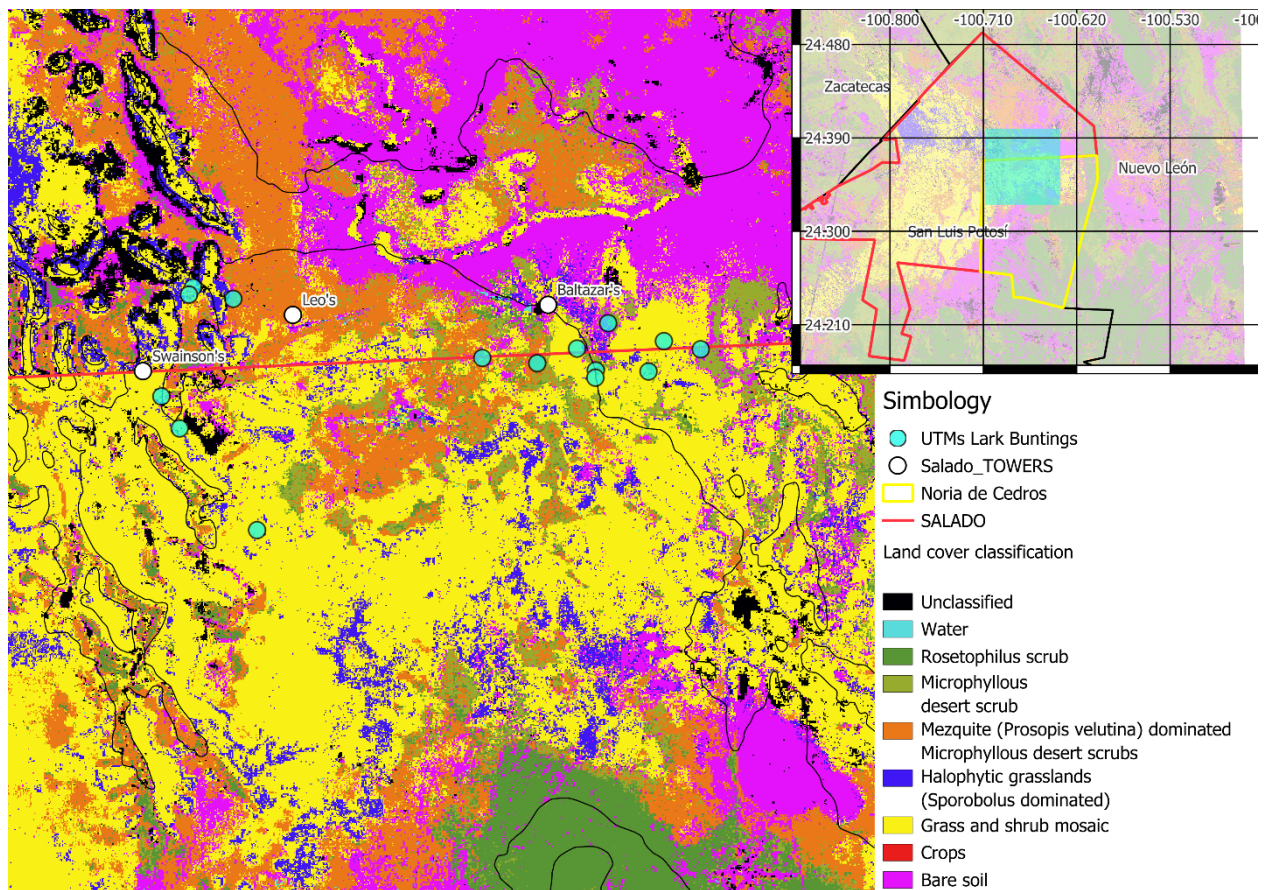


Figure 7: UTMs for the 19 Lark Buntings detected around the Telemetry system at the study site. Black lines represent elevation. Thick red line represents the border between the Ejidos of El Salado and Noria de Cedros, SLP. To visualize vegetation where triangulations occurred, land-cover classification is overlapped in the background. White dots show the location of the telemetry system towers.

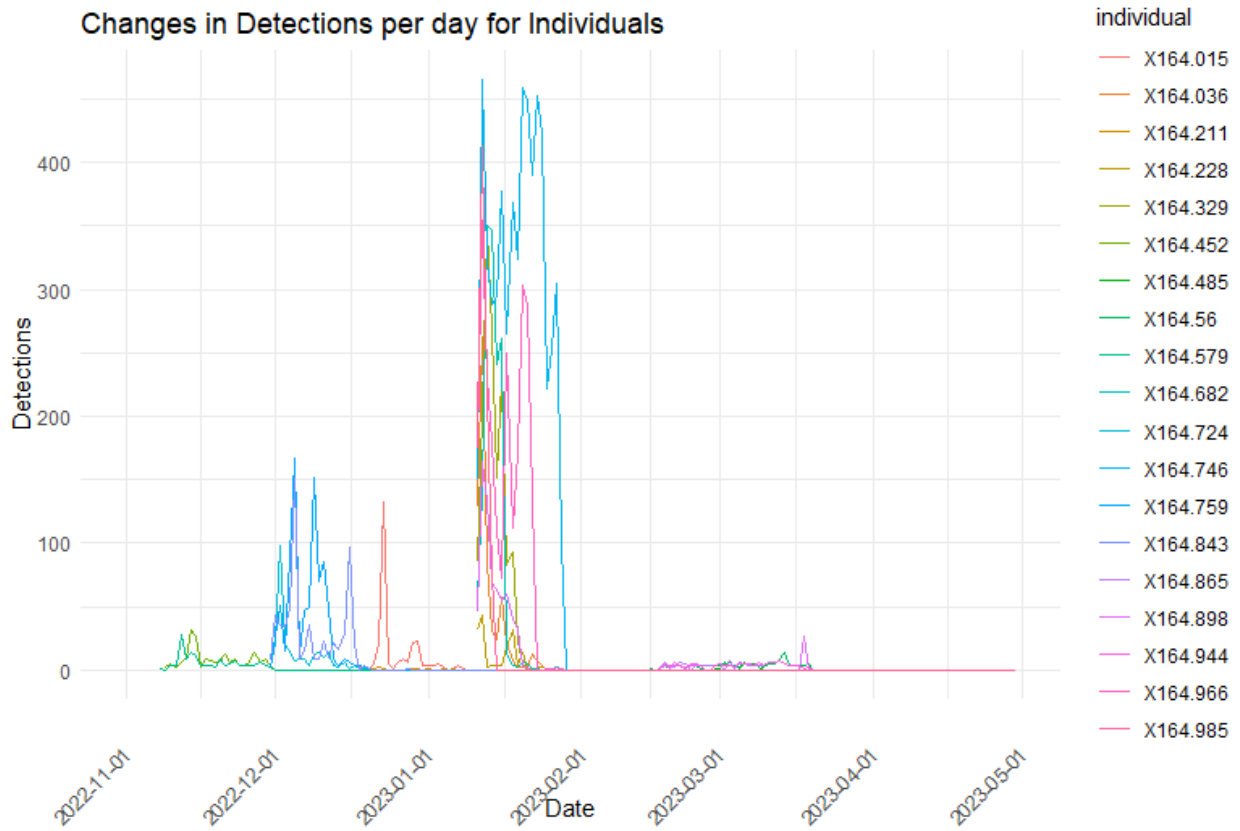


Figure 8: Total number of detections per day using radio-telemetry. Most of the detections were from the ARU system. Due to fixed battery life of transmitters after 25 days detections dropped to 0, yet not all radio-tagged individuals presented the same number of detections.

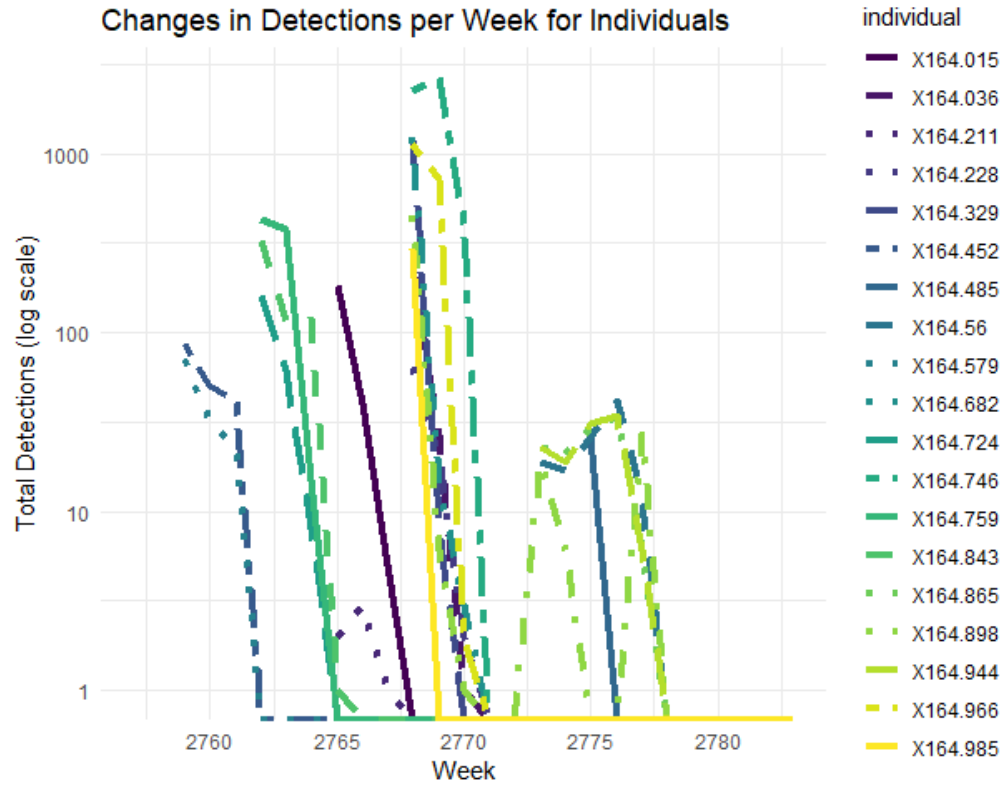


Figure 9: Log-transformed Number of detections per week for radio-tagged Lark Buntings. For representation purposes weeks were transformed into numerical variables. For representation purposes dates were transformed into numerical values, week 2760 corresponds to the second week of November.

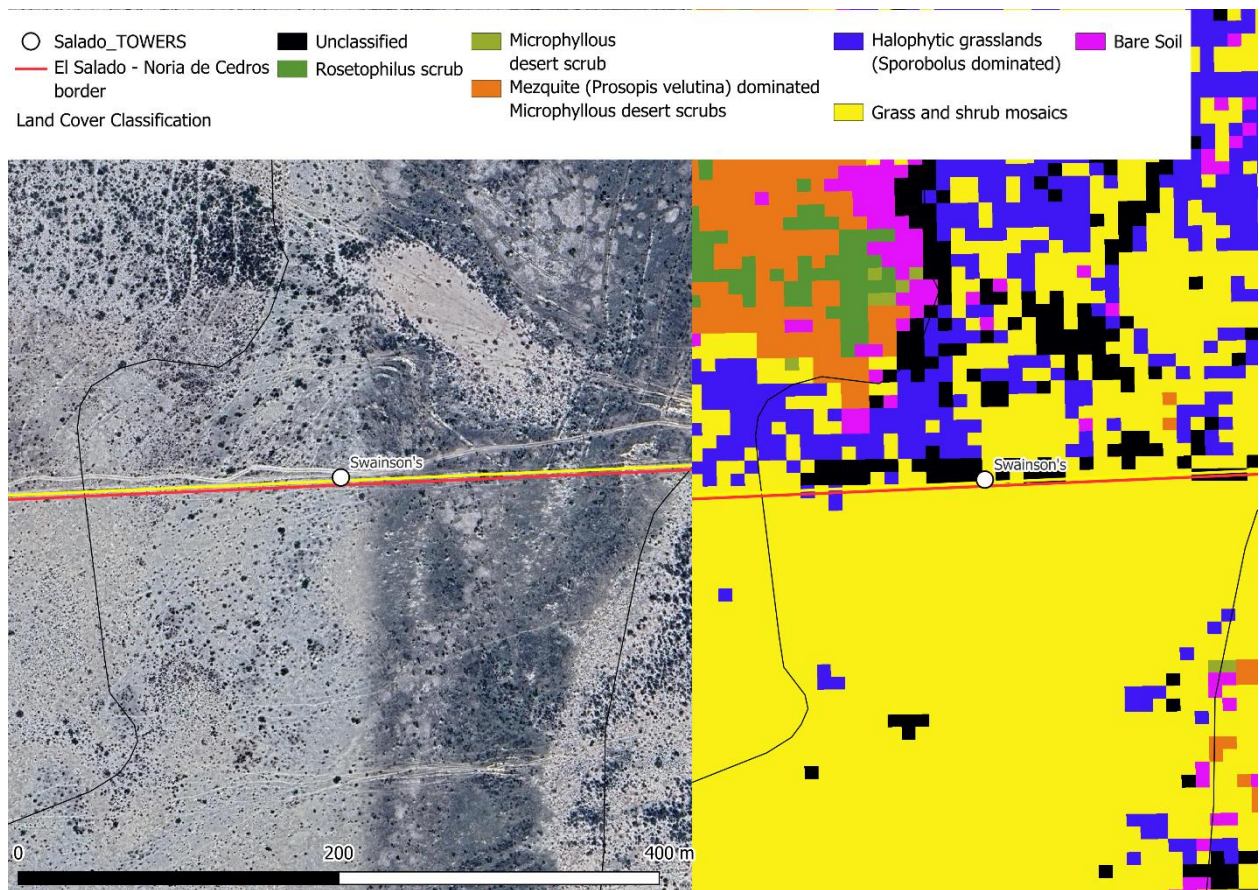


Figure 10: Swainson's tower surroundings from Satellite image (Left) and semi-automatic classified image (Right). Satellite image courtesy by Google Earth.

Supplementary information

Table S1: Land cover classification (according to J. A. Zavala-Hurtado and M. Jiménez 2019). Values correspond to the study area (split in Noria de Cedros and El Salado), and the whole processed image (portion of the Northern High Plateau of San Luis Potosí) with their respective percentage and area (ha) cover for January 4th 2023.

Noria de Cedros Land-cover types				
Classification	Raster Value	Pixel Sum	Percentage cover [%]	Area [ha]
Unclassified	0	36770	2.55	367.7
Water	1	2200	0.15	22
Rosetophilus scrub	3	497608	34.54	4 976.08
Microphyllous desert scrub	4	97673	6.78	976.73
Mezquite (Prosopis velutina) dominated Microphyllous desert scrubs	5	133988	9.3	1 339.88
Halophytic grasslands (<i>Sporobolus</i> dominated)	6	32991	2.29	329.91
Grass and shrub mosaics	7	280455	19.47	2 804.55
Crops	8	762	0.05	7.62
Bare soil	10	358239	24.87	3 582.39
			Total = 100	Total =14 406.86
El Salado Land-cover classification				
Classification	Raster Value	Pixel Sum	Percentage cover [%]	Area [ha]
Unclassified	0	110373	3.04	1 103.73
Water	1	15514	0.43	155.14
Rosetophilus scrub	3	288274	7.94	2 882.74
Microphyllous desert scrub	4	488838	13.47	4 888.38
Mezquite (Prosopis velutina) dominated Microphyllous desert scrubs	5	657641	18.12	6 576.41
Halophytic grasslands (<i>Sporobolus</i> dominated)	6	230771	6.36	2 307.71
Grass and shrub mosaics	7	1174291	32.35	11 742.91
Crops	8	1366	0.04	13.66
Bare soil	10	661411	18.22	6 614.11
			Total = 100	Total= 36 284.79

Northern Highland plateau of San Luis Potosí classification (images)				
Classification	Raster Value	Pixel Sum	Percentage cover [%]	Area [ha]
Unclassified	0	1123575	3.46	11 235.75
Water	1	177120	0.55	1 771.2
Rosetophilus scrub	3	11878322	36.59	118 783.22
Microphyllous desert scrub	4	5818156	17.92	58 181.56
Mezquite (<i>Prosopis velutina</i>) dominated Microphyllous desert scrubs	5	3074287	9.47	30 742.87
Halophytic grasslands (<i>Sporobolus</i> dominated)	6		1.08	3 506.24
Grass and shrub mosaics	7	2475075	7.62	24 750.75
Crops	8	72359	0.22	723.59
Bare soil	10	7495690	23.09	74 956.9
			Total = 100	Total = 324652.08

Table S2: Output from Model 6 showing no effect on date in detections.

```
Call:
glm(formula = detections ~ DATE * individual, family = "gaussian",
     data = data3)

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)    1.198e+03  6.746e+02   1.776  0.07672 .
DATE          -6.181e-02  3.485e-02  -1.774  0.07710 .
(Dispersion parameter for gaussian family taken to be 0.9195052)

Null deviance: 1084.38  on 353  degrees of freedom
Residual deviance: 290.56  on 316  degrees of freedom
(1880 observations deleted due to missingness)
AIC: 1012.7

Number of Fisher Scoring iterations: 2
```

Table S3: Output from Model 1.7 to evaluate Lark Buntings presence on different winter seasons.

```
Generalized linear mixed model fit by maximum likelihood (Laplace Approximation) [
glmerMod]
Family: binomial ( logit )
Formula:
LarkBuntingsPresence ~ StandardizedTemperature + StandardizedCumulativePrecipitation +
  StandardizedDailyPrecipitation + StandardizedMeanSAVI + StandardizedMaxSAVI +
  StandardizedMinSAVI + StandardizedStdDevSAVI + (1 | Winter)
Data: modelo

   AIC   BIC logLik deviance df.resid
  32.7  51.7  -7.4   14.7     52

Scaled residuals:
   Min     1Q   Median     3Q      Max
-0.19746  0.00000  0.00000  0.00000  0.09981

Random effects:
Groups Name      Variance Std.Dev.
Winter (Intercept) 2059    45.37
Number of obs: 61, groups: Winter, 4

Fixed effects:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)    -3.849    21.943  -0.175  0.8608
StandardizedTemperature    -264.000  108.051  -2.443  0.0146 *
StandardizedCumulativePrecipitation -12.293    7.544  -1.629  0.1032
StandardizedDailyPrecipitation   -67.990   42.242  -1.610  0.1075
StandardizedMeanSAVI         43.836   24.394   1.797  0.0403 *
StandardizedMaxSAVI         20.219   12.745   1.586  0.1126
StandardizedMinSAVI        -10.946   14.641  -0.748  0.4547
StandardizedStdDevSAVI       -73.240   37.420  -1.957  0.0201 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
optimizer (Nelder_Mead) convergence code: 0 (OK)
Model failed to converge with max|grad| = 0.0858967 (tol = 0.002, component 1)
```

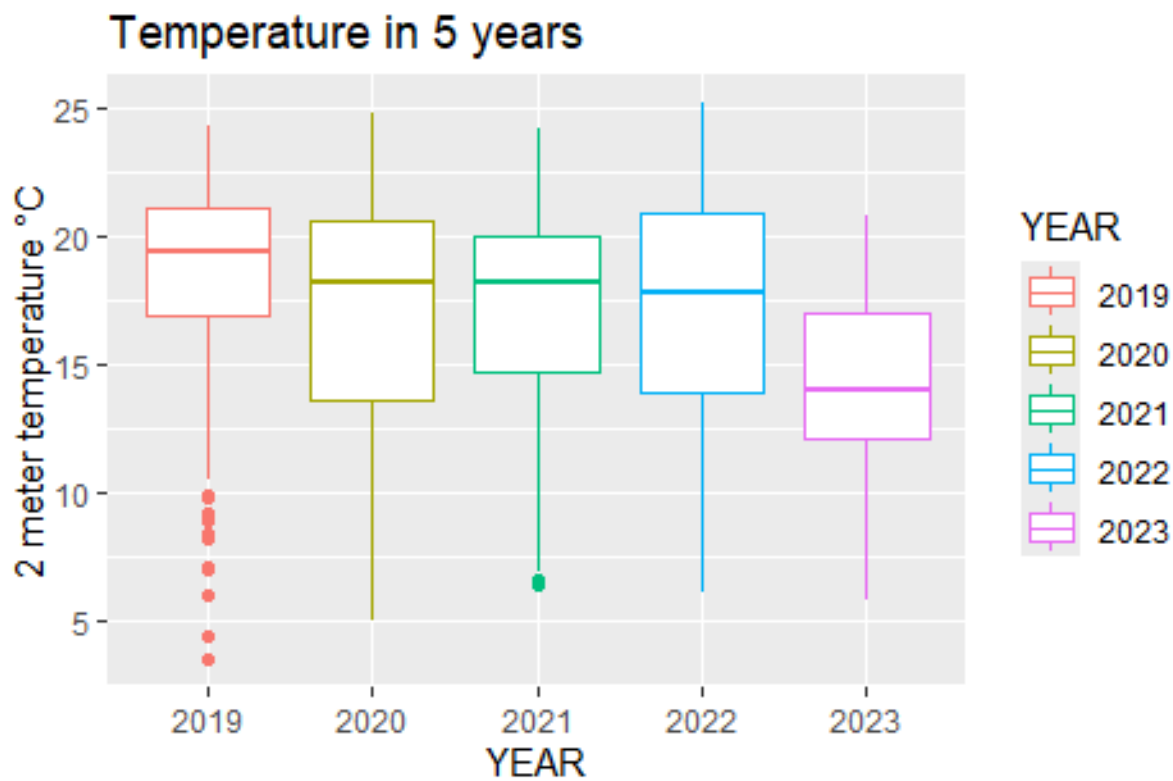


Figure S1: Mean annual temperature (°C) at 2 meters height (TM2) obtained from NASA's POWER site (<https://power.larc.nasa.gov/>). Temperature was statistically different between 2019 and 2020, 2020 being lower (Wilcox test, $p < 0.01$).

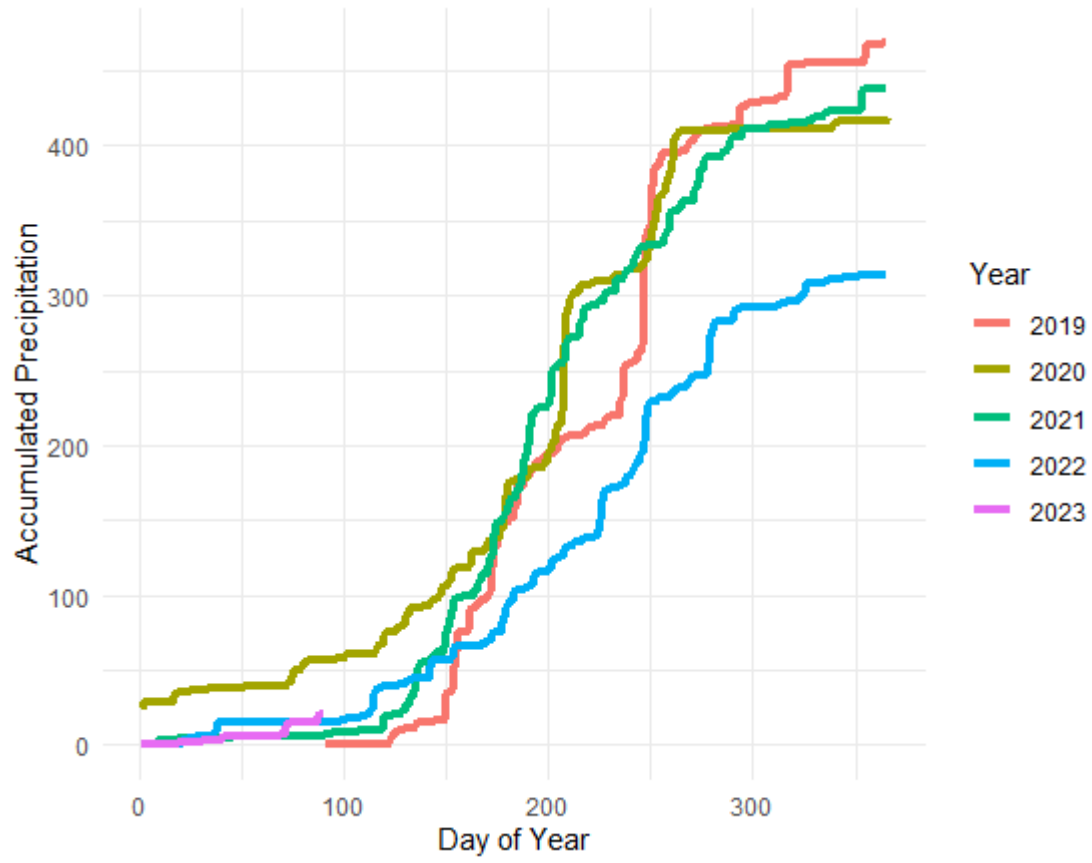


Figure S2: Accumulated precipitation for the five years at the study site from January 2019 until April 2023. Total accumulated precipitation was similar for 2019, 2020 and 2021, however the dates when precipitation occurred differed among years. Precipitation for 2022 was lower than the other years.

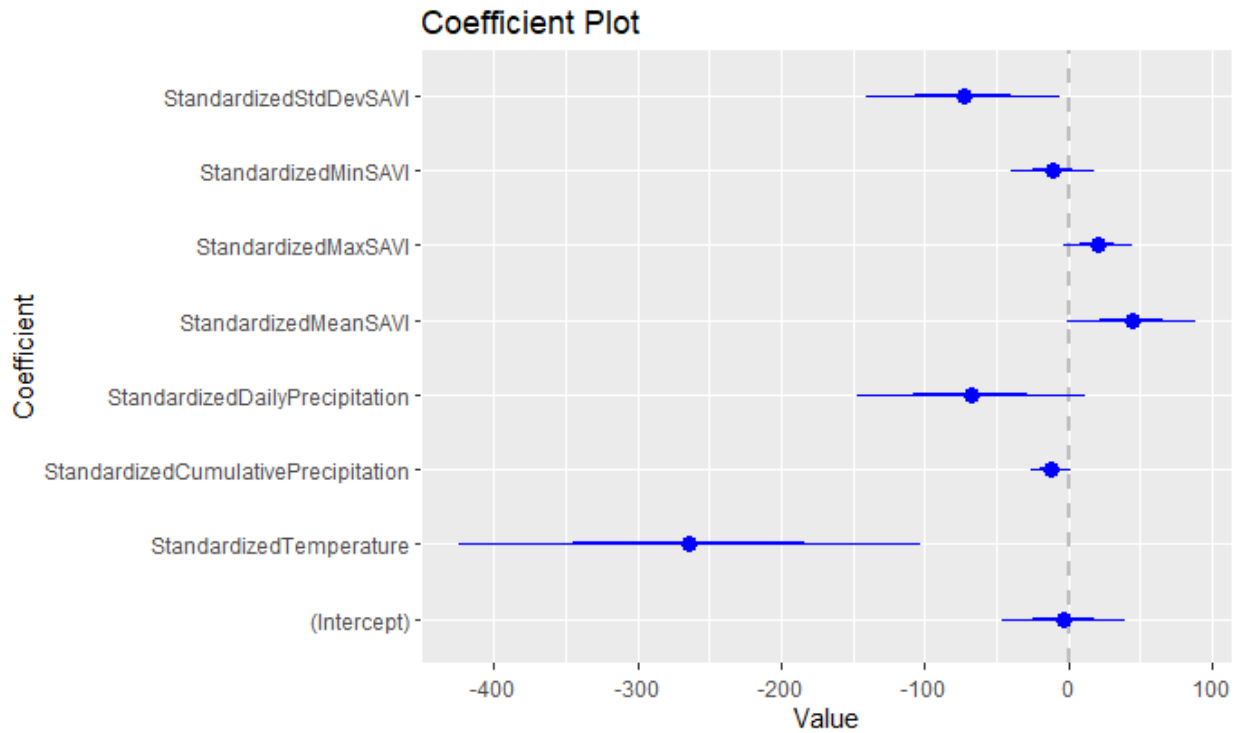


Figure S3: Coefficient plot for Model 1.7 showing the regression estimates and intervals of confidence for the variables used to predict Lark Buntings Presence at the study site.

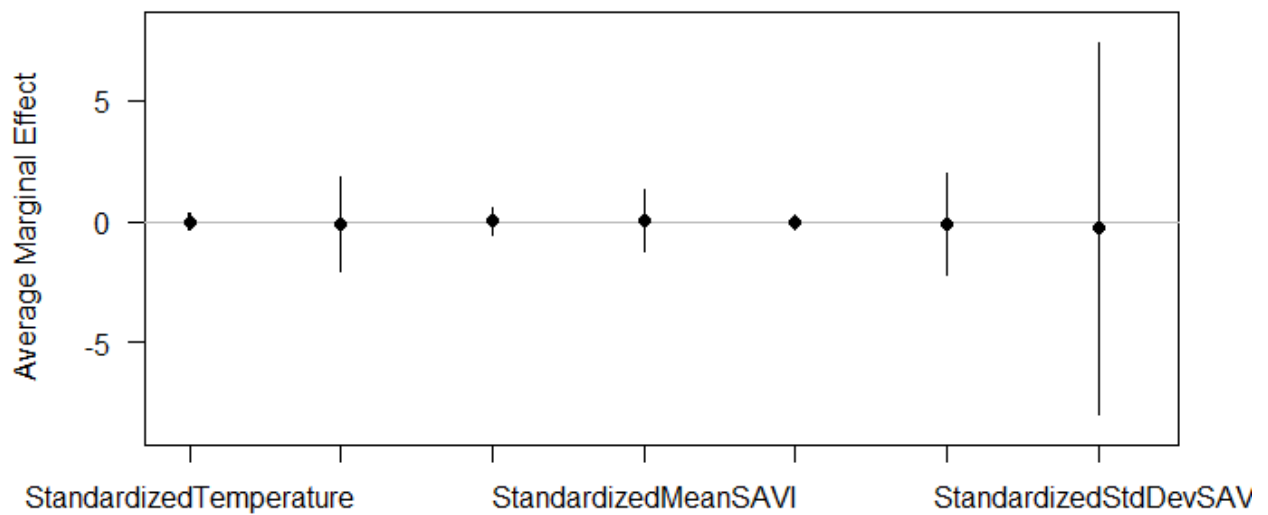


Figure S4: Average marginal effects (AME) for the 7 variables used in model 1.7. The AME from each of the variables the average effect of the predictor in the outcome, considering the variability induced by random effects

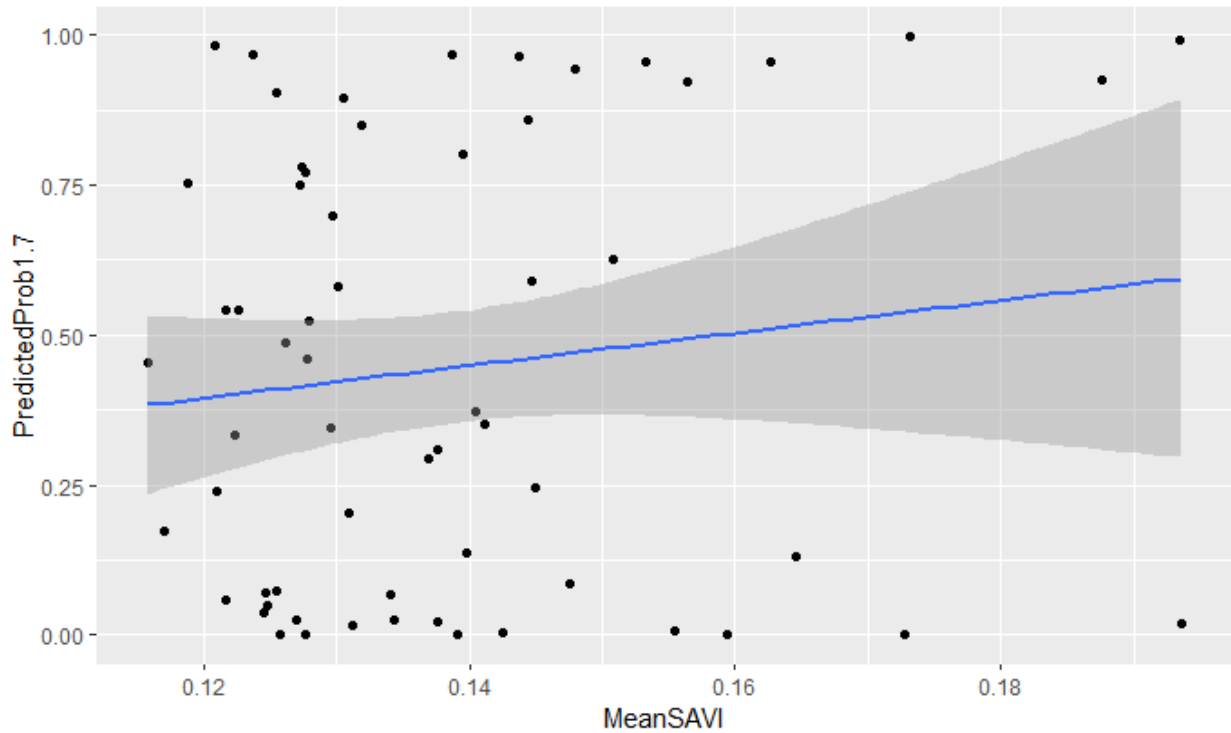


Figure S5: Isolated impact of Mean SAVI variable only in predicted probability of Lark Bunting presence based on model 1.7. Grey area represents the Standard Error.

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Chapter 2: Meaningful places and socioecological history of the last 80 years for a North American grassland priority conservation area.

Introduction

Grasslands are one of the most threatened ecosystems in North America and worldwide (Stanton et al., 2018). Some regions in North America have completely lost native prairies or have less than 10% of their original distribution (Pool et al., 2014; Samson & Knopf, 1994). The grasslands of arid and semi-arid regions have evolved under a complex natural disturbance regime characterized by nomadic grazing by large native ungulates, periodic wildfires, and high variability in precipitation (Sutter & Ritchison, 2005; Vázquez-Quintero et al., 2019; Wimberly et al., 2018). However, over the last century and in particular, recent decades sociopolitical, socioeconomic and climate change factors have led to transitions in land tenure, commodity markets and ecosystem integrity, respectively and thus altered the natural grassland disturbance regime with the introduction of domestic livestock, continuous often uncontrolled grazing, suppression of wildfires and increasing frequencies of droughts and torrential precipitation. Current disturbance regimes regulating grasslands are basically anthropogenically controlled (CEC 2003). Apart from these changes, land use change presents the most important threat to grassland communities (Nguyen et al., 2019), followed by the introduction of invasive forage species, shrub encroachment, land degradation and ongoing impacts of climate change (Pons et al., n.d.; Wimberly et al., 2018). The natural grassland biome used to cover almost 14% of the national territory; it has suffered a decline in 60% over the last 20 years (Ceballos et al., 2010, CONABIO 2022). A large diversity of threatened species depends on the North American grassland biome, some exhibiting one of the steepest population declines on the continent; for instance, grassland birds and the Mexican prairie dog (Castellanos-Morales et al., 2014; Rosenberg et al., 2019).

From a land use perspective, grassland ecosystems are rangelands. Mexican rangelands are large extensions of grasslands and shrublands dedicated mainly to extensive livestock production (Raufirad et al., 2018). Rangelands are one of the most abundant social-ecological systems in drylands. By definition,

dryland social-ecological systems are complex systems (Cabrera-García, 2008; Maestre 2012; Huber-Sannwald et al. 2012), as the livelihoods of local communities directly depend on the natural resources and other ecosystem services that these rangelands provide. Hence, human activities related to diverse land use practices generate system feedback that may keep the system in a particular social-ecological state (Yáñez-Chávez et al., 2018). Maintaining a particular (favorable) system state, i.e., with sustainable resource use in times of constant change, is challenging and requires adaptive management of various often interacting elements of the system (Kay, 2012; B. Williams, 2003). Hence, decision-making by local stakeholders together with fluctuations in the region's biodiversity and delivery of ecosystem services, and the social-ecological landscape context play key roles in the dynamics of land use systems (Kasprzyk et al., 2013). Abrupt changes such as extreme weather events, unsustainable agricultural practices or biodiversity loss (Ceballos et al., 2010) may lead to the loss of social-environmental resilience, that is, the capacity of rangelands to recover their structure and functions after disturbance events. Loss of resilience can result in crossing thresholds of key variables and the shift of a system to an alternative regime, from where there is no return (Kelly et al., 2015). Thus, understanding and incorporating the knowledge of local stakeholders and other key actors on rangeland dynamics is essential for the co-development of actions leading to the conservation of the grassland ecosystems, the species that inhabit these unique environments, and the livelihoods and traditions of local landowners (CEC, 2013).

Co-constructing the history of social-ecological systems with local stakeholders has the benefit of both the learning about technical and/or scientific knowledge by the local stakeholder and including local, traditional and/or indigenous knowledge into the recorded history of structural, functional and institutional characteristics of a social-ecological system. A more holistic approach to tackle complex conservation problems has been adopted in several studies (Johansson & Isgren, 2017). The main goal is to share knowledge among academics and other stakeholders in a horizontal approach and thereby to

generate a mutual responsibility towards the conservation of social-ecological systems. This way communities and all other stakeholders involved tackle jointly and in a participatory fashion conservation issue (Basupi et al., 2017; Eilola et al., 2021) thereby avoiding the imposition of often inadequate conservation policies (Eilola et al., 2021). Additionally, it promotes landowners' participation in conservation actions and acknowledges the importance of including local actors in the processes of conservation planning (Vázquez-Quintero et al., 2019).

One effective approach to reconstruct the history of land use and practices and to identify meaningful places to local stakeholders in a spatial context is participatory mapping (Cabrera-García, 2008). Sharing experiences, daily activities, and perspectives of both researchers and stakeholders through a standardized visual format (the participatory maps), can generate reference information when talking with academics, and representatives of governmental, and non-governmental organizations. Local stakeholders may contribute with complementary or multi-perspective understanding of local processes and concerns to be considered for joint future planning (Vukomanovic et al., 2019). Multi-stakeholder participation may generate maps with information on priority areas of economic relevance, conservation success, conservation concern, among others, ultimately co-generating integrative conservation strategies (Johansson & Isgren, 2017; Luizza et al., 2016). Critically important information in the context of conservation of land and participatory mapping are the identification and location of meaningful places. Meaningful places are those that represent a deep feeling of belonging and connection of individuals to a certain place of their land / territory (Bauer, 2009; Luizza et al., 2016). These connections may be related to religion, traditions, ancestry (Cervený et al., 2017; Cuerrier et al., 2015) all the way to important water sources for humans and wildlife, or important areas of pasture, scenic landscapes, among others (Vukomanovic et al., 2019). The feeling of belonging to certain important "meaningful" places may indicate directly what areas are of importance from a conservation perspective. Therefore, identifying and characterizing the meaningful places with different stakeholders of a region may be an inclusive and comprehensive approach to delimitate conservation areas with

high biological and social-ecological heritage (Balderas Torres et al., 2013; Cabrera-García, 2008).

Research question

How do local stakeholders conceptualize the value of an increasingly heterogenous rangeland landscape, which is both the source of their livelihoods and the habitat of a highly endangered migratory bird?

Hypothesis

The local knowledge of stakeholders of the ejidos complements scientific understanding of the social-ecological system, by incorporating multi-stakeholder priorities, conceptually reconstructing previous states of the system, and understanding the ample value of the system, its current context, and potential future changes.

General objective

- Weave local knowledge with current scientific understanding on the rangelands in the Northern high-plateau of San Luis Potosí as a basis for conservation planning taking a complex social-ecological system's approach.

Specific objectives

- Reconstruct and jointly learn with local stakeholders on the dynamics of the rangeland landscape in a social-ecological system's context.
- Identify if preferred areas for *C. melanocorys* flocks are threatened based on local knowledge.
- Co-define with participatory methods effective integral conservation strategies of these rangelands to achieve long-term protection of the migratory grassland bird *C. melanocorys*.

Methods

Study site

The high plateau in San Luis Potosi is characterized by an arid climate. The ejidos El Salado (24°18'41.25"N, 100°51'25.73"W; 37,000 ha) and Noria de Cedros (24°17'39.11"N, 100°40'52.70"W, 14,500 ha) are located in the North of the state San Luis Potosi, which delimits the border to Nuevo León and Zacatecas. An Ejido is a communal land tenure regime, where land is shared by members of a village or community (Kourí, 2020). The places where each ejido concentrates most of their populations (towns) are separated by about 19 km. The oldest records regarding human settlement in the ejido is the Hacienda El Salado, which according to the locals, was one of the most important economic centers of cattle and horse raising in the highland region. However, there are also traces of hunting materials made of bone and rock, probably of Chichimeca origin. There are records on conflicts between Spaniard landowners and the Chichimeca in the region (Ruíz & Orozco, 2023). After the Mexican revolution, the distribution of land (Reparto agrario) was carried out; this is when the land of the hacienda became the property of its former workers and when the current ejido (communal land tenure) regime appeared. A more recent change of medium impact in the ejido occurred with the abandonment of the railways since there was a railway station in the ejido, yet the railroad system is still in use by private companies. Currently, the main activities of the ejidos are related with agriculture and livestock production, followed by activities related with the manufacturing industry. The population at El Salado is of 201 individuals, for Noria de Cedros is 80 individuals (INEGI 2020).

These ejidos are located within the Chihuahua desert, characterized by arid climate with the main precipitation period occurring between the months of April to September (CEC, 2013). Although other works report the main precipitation period between the months of July to September with an annual cumulative precipitation between 250 – 400 mm (McIntosh et al 2019). It is estimated that for the bioregion 11% of the precipitation falls between December to February, together with the fall precipitation (17% between September and November) the precipitation accounts

for 28% of total rainfall throughout the year (REFF Robertson et al). This region includes part of the “Important Area for the Conservation of Birds: “Pradera del Tokyo”. The vegetation of the region is characterized by creosote bush scrubland and halophytic grassland, both ecosystem types include also species of the Crassulaceae and Cacti (Huenneke et al., 2001). The main economic activity in the region is extensive livestock production, particularly cattle, although there are also horses and goats (Curtin et al., 2002; Yeaton & Flores Flores, 2009). As an additional resource, wildlife hunting for subsistence purposes has been implemented in the ejido. Previously, the El Salado ejido was a hacienda, from which it has maintained its name. The neighboring ejidos have a territorial extension of approximately 40,000 hectares (Instituto Nacional de Estadística y Geografía; INEGI) where different economic activities are practiced by the ejidatarios.

Rangeland vegetation context

To have a detailed image and context about the landscape structure and heterogeneity in El Salado-Noria de Cedros system, SENTINEL-2 satellite images with a resolution of up to 10 m per pixel were used. The calculations were made in the SCP extension (semi classification plug-in) of the QGIS (Quantum GIS) program (Colgado L. 2019). The bands 2-8A, 11, and 12 were used for multispectral analyzes to generate a land cover classification map. The ROI tool on SCP was used to train the program about the spectral signatures for the different vegetation types. Spectral signatures were calculated for different training inputs and by using the maximum probability algorithm and the “Classify” tool, the map was generated. A total of 3 Macroclasses (Water, Humans & Vegetation), 8 Land cover Micro Classes (Figure 1) and 16 training inputs were uploaded and used for the classification of land cover types. The resulting classification map has a finer scale than the government products such as CONABIO land cover raster layer. Government products have a resolution of 200 mts per pixel, whereas SENTINEL-2 images have a resolution of up to 10 m per pixel for some of their layers.

Weather patterns for El Salado/Noria de Cedros Landscape

To have a broader perspective about possible changes in the ejido derived from shifts in weather patterns, particularly precipitation, weather data was obtained for a study site near the border of the two ejidos: El Salado South-East border and Noria de Cedros North-East Border. This information was also used as a reference to compare information provided by ejidatarios. Due to the lack of data from the nearest meteorological station (18 km away from the point selected) since 2010 (CONAGUA), data from the NASA POWER (Prediction of Worldwide Energy Resources) project was used. Mean daily data from March 2019 to March 2023 were considered. Data requested was mean temperature at 2 meters from surface (T2M) and precipitation corrected (PRECTOTCORR), from the PRECTOTCORR cumulative precipitation per year got calculated by the sum of daily values. Data for a 40-year timeframe was analyzed using RStudio 2023.09.1+494 (Posit software).

Scouting of the Ejidos

As part of the logistics for the installation of towers used in Chapter 1, two years before conducting interviews with the population, one full day was dedicated for each ejido to conduct a guided tour accompanied by one farmer from each of the ejidos. Together, the farmer and researchers covered the main roads in the ejido and registered the coordinates of cattle water wells and dams (Figure 2). Although the main goal of mapping the water wells and dams was to scout for sites to install antennas for a telemetry study, these sites are also considered important centers of activity since all farmers raising cattle visit them at least once a week and water sources are usually important landmarks for orientation by locals.

Local understanding and knowledge as entry point for multi-stakeholder collaboration

To understand and collectively gain a more complete perspective of the complex context and dynamics of rangelands as social-ecological systems, semi-structured interviews were carried out with key local actors of the two ejidos to learn about their experiences and knowledge on the use and management of their land. Interviews were conducted between May and July 2023. The questions

addressed four thematic axes: biodiversity, activities, water, and meaningful places considering the past (>50 years ago), the present and envisioned future of both ejidos. The interviews consisted of 24 open-ended questions and were recorded for later analysis (prior consent of the interviewee). Most of the interviews were conducted at the houses of the ejidatarios, where all household members were invited to join. 12 households were interviewed, with a total of 22 people responding to the semi-structured interviews.

To facilitate the interview, printed maps with a scale of 1:35 000 for El Salado and 1:24 000 for Noria de Cedris of the ejido were provided, where the participants were asked to indicate, draw, or mark areas of importance to them, to the ejido as a whole and those areas that have undergone significant changes as far as they remembered (on average between 20 to 60 years). Additionally, the participants were invited to identify meaningful places to them from a personal, cultural, social, economic, or environmental perspective. For sites that have been undergoing major changes, participants were asked to identify the main causes of these changes. At all times, an audio recording of the activities was conducted for further consultation and dissemination material (all with the prior consent of the people involved). All individuals agreed on sharing their personal information such as name, age, gender, etc. Information will be safely stored, and privacy of the interviewees will be protected for the next 5 to 10 years; after that personal information will be destroyed. Our sample size of interviewees is considered appropriate, since we covered most of the activities conducted in the territory. Selgrath & Gergel (2019) estimated optimal sample sizes for participatory mappings as low as 7% of the population to obtain information from communities that covers large extension of territory in a coastal social-ecological system with fishermen as the main interviewees. All information recorded was reviewed by the interviewer and used for the description and conceptual reconstruction of the system. Although information was requested in different conceptual blocks (activities, biodiversity, water and meaningful places) the conceptual reconstruction did not make these separations and described the system as a whole.

Digitalization and Rasterization

Maps were scanned and georeferenced to obtain a raster image of the map drawn by the members of the community. The areas drawn for the four categories were digitalized into Shapefile documents. Once all areas were digitalized rasterization was conducted. All digitalization and rasterization were conducted in QGIS ver 3.28.18 (QGIS Development team). A final map per category was created, representing the mayor areas and the ones mostly threatened, each ejido had their own set of maps. On the physical maps, information of past and present activities and characteristics of the landscape were placed with the same colors and symbology. However, interviewers make notes on activities that happened in the past and in the present. For the digitalization, a particular variable got added on QGIS to differentiate between past and present traits.

Results

Climate analysis at El Salado/Noria de Cedros

PRECIPITATION AND TEMPERATURE

The maximum temperature over the four winters analyzed was 17.28°C, Minimum temperature was 3.49°C and maximum temperature was 25.23 (Figure 3). Temperature lower in 2020 than 2019 (Wilcox test, $p < 0.01$; Figure S2). Based in 40 years of data mean temperature has been 16.34°C, median temperature 17.27°C, minimum temperature.

To evaluate differences in precipitation for every month of every year we ran a Standard Precipitation Index model (SPI, Figure S1.). SPI found an oscillation pattern regarding standardized differences in precipitation patterns compared to the mean. Based on SPI test, 2020 – 2023 were years with lower precipitation than the average. Neither with representation of cumulative precipitation nor with SPI a pattern and/or trend presenting a reduction on precipitation was found for the study site.

Social-ecological context of the rangeland landscape El Salado – Noria de Cedros

A total of 22 people were interviewed corresponding to 12 households, 14 individuals in 7 households for El Salado and 8 individuals for 5 households from Noria de Cedros. Interviewees ranged in age from 20 to 80 years, the majority (72%; 16 individuals) of respondents identified themselves as males. The group with least participants were young people (13.63%; 3 participants) ranging in age between 20 and 30 years. Interviews lasted between 45 and 100 minutes. Most of the interviewees identified themselves as ranchers (50%; 11 individuals). All interviewees remembered and shared information and knowledge that was passed down from the generation of their parents and in two cases even to their grandparents. We learned about every day and economic activities in and around the ejidos that have been practiced over the past 90 years. Long-term temporal

information has previously been used in studies assessing activities and learning about local knowledge in participatory mapping (Bauer 2009).

Reconstructing the history of the social-ecological systems at El Salado and Noria de Cedros together with local stakeholders

Historically, livestock production occurred in almost all the land area since its early beginnings as a Hacienda. However, the way production has occurred has not been constant through time. At El Salado, 35 years ago, a single family used to own most of the cattle in the Ejido and took the decisions regarding cattle rotation. On the other hand, until 20 years ago, Noria de Cedros focused predominantly on goat production and switched to cattle production since the early 2000s. Like in many semi-arid livestock production systems, livestock grazing congregated (and still does) around artificial water sources, a practice that has always occurred. Intergenerational knowledge transfer has been important in these ejidos. Information passed transferred by parents and relatives older than the interviewees provided a broader perspective of the activities with significantly more interactions within the rangeland systems. According to the elder generations, former activities at El Salado included goat husbandry and pastoralism as well as fiber extraction (“ixtle”) from plants such as *Yucca* sp. and *Agave lechuguilla*. Most of the people from El Salado switched from raising goats to cattle over the last 40 years. However, there are still some goat herders in the ejido. The ixtle extraction stopped when the oldest interviewees were already adults, about 40 years ago, mainly due to the lack of markets to sell. One of the major changes in recent years, although not an activity itself but with an important impact on the economy of the area, was the use of trains. Used either for personal transport or to connect with important economic centers such as larger cities, for instance, for the sale of goat products in San Luis Potosi or Monterrey. The termination of train transportation at the end of 20th century occurred when the Mexican railway company was sold to foreign companies as part of the adoption of the neoliberal economic model. The change in Mexican railway policies and the cancelation of passenger trains isolated the communities and stopped the exchange of goods and services among

populations. In the case of Noria de Cedros, subsistence activities have prevailed through time. These activities included livestock production, mainly goat pastoralism and rainfed agriculture. In both ejidos, subsistence rain-fed agriculture has been practiced by farmers since the beginning of the ejido. Currently, farmers produce corn (*Zea mays*) and beans (*Phaseolus vulgaris*) in small-scale agricultural plots associated with each household, they mostly cultivate local varieties. Agricultural practices including timing of seeding, crop planting, and harvesting, were similar in the two ejidos.

Farmers had and still monitor the equivalent of precipitation efficiency of the rangelands by seeing the duration of greenness of grassland plants after the rainy season. This information, however, is not registered in any written document. Besides, they distinguish drought from non-drought years by evaluating crop yield, which can vary since different crops with different water demands can be used in the area (i.e., range from maize to melons, being melons a more water-demanding crop). Major shifts in agriculture linked to changing climate conditions occurred in the recent past, as wheat and oat are no longer seeded, while according to testimonies of 40–50-year-old farmers these were standard crops in former times. According to their parents even watermelon was planted in the region. Former crop seeding schedules allowed farmers to grow two rounds of maize and beans with one of wheat in between within a year. Farmers commented frequently that years with higher precipitation resulted in a wider variety of plants in summer and winter over the grasslands.

Present

In current El Salado – Noria de Cedros system, Ejidatarios, vegetation, climate (particularly precipitation), water and the interactions between them have been and still are some of the major components identified in our system. The climate of the region is dry; interviewees, especially the oldest ones, commonly reported rain previously (>10 years ago) starting in the months of April to September. In our climate analysis for the area, we found a mean temperature of 17.27°C, a max temperature of 25.23°C, and a min temperature of -3.42°C; with a cumulative precipitation of 461.07 mm, std dev = +/- 123.76. Either way, the

current shortage in the amount of precipitation causes the availability of water for livestock to be a constant concern for both ranchers and farmers.

Based on our land cover classification (Figure 1) we found a complex heterogeneous landscape. Indeed, vegetation in the area consists of patches of yuccas (*Yucca spp*), creosote bush (*Larrea tridentata*), and perennial halophytic grasses (*Bouteloua chasei*, *Flourensia cernua*, *Dalea gypsophilas*, *Scleropogon brevifolius*) (Vargas-Facundo- 2022). There is also the presence of mesquites (*Prosopis velutina*) and different cacti species (*Cylindropuntia imbricata*, *Cylindropuntia leptocaulis*, *Ferocactus wislizenii*). Current distribution of plants and landscape configuration is the result of previous, intentional or unintentional, management. Grasslands are an important component of the system, influencing livestock farming as the main economic activity. The presence and configuration of this heterogeneous landscape influences the activities that farmers can conduct and the areas of the ejidos allocated to such activities. Due to the vast extension of the ejidos (about 37,000 ha together), there are fences within the ejido separating grazing areas among ejidatarios; each of these areas is treated as a management unit and farmers rotate cattle between the areas locally known as “pastas”. The pastas are used and visited by different members of the ejido, who decide how to invest in infrastructure in that area such as new fences, water wells or cattle enclosures. The land is not officially owned by any of the farmers nor privatized, but as generations have passed the farmers have spread along these areas based on kin relationships.

Participatory mapping of the activities related to subsistence farming, livestock (mainly cattle and goat) production, and informal activities for both current and former family members at El Salado revealed >90% of the ejido land and ~50% of the territory of Noria de Cedros is currently allocated to these activities (Figure 5). Although it did present some overlapping, farmers are not using all the regions within the ejido for livestock production at the same time. Currently, grassland areas are mostly used by different groups of farmers within the population actively having livestock production activities in the ejido. Livestock activities extended across roughly 50% of Noria de Cedros land, the rest of the

ejido was not actively used for farming or goat production. The southeastern portion of Noria de Cedros is located at higher altitudes and is not as suitable for cattle production on the farmers' vision. Additionally, information provided by the interviewees about their parents provided reports about ejido activities for the last 90 years. Regarding livestock production centers near water wells, most interviewees from Noria de Cedros did not identify water wells as key places for local activities.

In our interviews, water was regarded as the most important resource in the area by the interviewees, and water wells for livestock were identified as the places having the highest activity. Water for human activities such as housekeeping, laundry and hygiene at El Salado is provided from a neighboring ejido (El Gallo) pipeline 12 km apart; it is pumped one day a week and habitants fill containers and rationalize water use during the week. At some point about 50 years ago, water for the use in the houses of the ejido was brought by the railway in big containers from the city of San Luis Potosi. Nowadays drinkable water can only be acquired from local stores since well water has high salt concentrations. At Noria de Cedros, the inhabitants collect rainfall water for human activities such as hygiene and sanitation in containers through a collective cistern. Whenever dry years occur and no water is available in the cistern, ejidatarios must go to nearby towns with water containers to get water. Like in El Salado, water for human consumption is acquired at local stores or in nearby cities such as Matehuala (at 81 km from the Ejido).

Regarding water for livestock production, farmers constantly monitor the amount of water in their water wells and earthen dams, the two main sources for livestock production, and their water levels are a constant topic of conversation between them and with actors external from the ejido. Some water dams were established over 60 years ago. All members of the ejidos have free access to the water dams. However, due to the distance of certain wells to the ejidos and habits from each farmer, the livestock from a particular farmer is usually allocated to a specific dam (Figure 2). Although rare, dams can have water available throughout the whole year depending on the rainfall from a given year. Since not all pastas

contain dams, cattle wells are the only source of water throughout the year. Thus, usually when dams are filled, some ranchers tend to close the wells to reduce pressure on these resources. In addition, not all wells have been actively used for the same period of time. Indeed, the cattle wells “La Hacienda” and “El Bajio” (Figure 2) have been active for over 80 years. The spatial distribution of wells and dams and temporal availability of water translates into a heterogeneous distribution of cattle among grazing paddocks and thus on the nearby grassland vegetation. Participants referenced places during the interviews by using wells as a start point to draw the areas for grazing on participatory mapping, showing the cultural importance of water.

During the rainy season, which according to the farmers starts at Easter (from March/April) and lasts until August, cattle grazing is practiced across the full extent of the rangelands. The use of pastas aims to reduce grazing pressure and aims for grasses to recover. This has been reported to change in the last 40 – 60 years and until 15 years ago, when “temporales” started to be scarcer or even disappear. Temporales are described as small but reliable precipitation events that occur between October and March. There is a consensus between the landowners that precipitation has been diminishing through recent years. For the last 15 years the main rainy season has occurred between June, July and August, with high interannual fluctuation. Thus, the loss of crops in a year and the detection of bad conditions of grasslands, plus livestock death are strong indicators used by farmers of a reduction in precipitation on both Noria de Cedros and El Salado. Rainfall is reported to have decreased both in temporal length within the season and in volume by all our interviewees. Although the answers from landowners were usually related to their ejido, comparisons between ejidos were mentioned. Our data suggest that no significant reduction in precipitation has occurred in the last 40 years (Figure S3).

It was common to hear that the ejido Noria de Cedros suffered more severe droughts in recent years compared to El Salado; in particular, all landowners identified areas in the north-west part of the ejido as severely impacted by drought. This reduction in water availability has caused shifts in farmer’s activities, including

abandonment of agriculture, switch in the livestock production system from goat pastoralism to cattle production (particularly in Noria de Cedros, but also at El Salado), switch in cattle breeds from Charolais to Cebú, and migration to cities. The main explanation pattern consisting of a switch from goat pastoralism to cattle production was a tradeoff between time spent and profit. Farmers reported goat pastoralism to be an activity that requires a daily time investment, although more resistant to drought by cattle. Irrigated agriculture with water from a well is practiced only in one area of El Salado. The drilling and administration of the well was organized by a cooperative of ejidatarios (10 ejidatarios), who paid the cost of installation and are the only ones allowed to use this water for their crops (mainly alfalfa and oats as forage, but also maize). In light of the increasing aridity in the region, over the last 30 to 50 years, some farmers have been shifting to genetically modified crop varieties provided by SADER (Secretariat of Agriculture and Rural Development), through programs such as “PROCAMPO”. Current precipitation conditions allow if at all a single crop season of maize within a year. During the participatory mappings at El Salado all water wells were considered threatened, each interviewee reported at least one water well in bad shape. In contrast, not all farmers at Noria de Cedros reported at least one of the wells of the ejido as threatened, besides some wells from Noria de Cedros are not used by any of the interviewees. In addition to livestock production near the town there are areas dedicated to beekeeping of the European bee (*Apex mellifera*) and parcels for rain-fed agriculture, mainly corn, beans, chili, and forage (mainly alfalfa).

In recent years the absence of “temporales” have not only affected agricultural practices, but also is attributing to cause declines in species diversity. As an example, they mentioned the occurrence of “hierbas de invierno” (winter herbs); these are annual plant species that appear in response to winter precipitation and survive cold temperatures (-8 °C). However, over the last 10 years, winter annuals have been rare. In surveys from the last 2-3 years, both researchers and stakeholders did not see those herbs on their usual time reported. Additionally, Sandoval-Avilez and Ocaña-Feregrino in two independent vegetation surveys did not report these plants for 2023 (personal communication) but they

were present in the winter of 2024 (Rodriguez-Licea C.Y., personal communication). Farmers considered areas as threatened on the participatory mapping because of changes in animal or plant composition. Areas reported as important reservoirs of biodiversity (Figure 7) included zones with all types of land cover (including shrublands, Isotal, and grasslands). Farmers have noticed with great concern the increase in shrub encroachment over the past years. This invasion has centered in areas nearby two cattle wells and in the vicinity of the hacienda (Figure 6), where most of the farmers concentrate their livestock; usually the closest sites to the town (Figure 5).

Respondents coincided at indicating that animal species richness seem to have declined for the last 20 years as a response to shifts in precipitation patterns. In case of avian species, some farmers mentioned changes in avian composition, however these changes were only observed in the vicinity of towns but less so in nature. Another common observation by farmers was the decrease in sightings of animals such as hares, rabbits, and wild rats also attributed to the gradual diminishing in precipitation. However, some farmers mentioned that the hemorrhagic disease has caused a decimation in hare populations in 2021 and 2022. These observations were confirmed by alerts and reports from official national authorities (SEMARNAT 2020). In addition to environmental factors, an increase in the abundance of predators and herbivores have triggered unprecedented human conflicts with animals. Populations of Coyote (*Canis latrans*) and White-Collared Peccary (*Pecari tajacu*), for instance are considered a direct threat to livestock and crops, respectively. Farmers had no explanation for the increase in coyote population size, while in case of White-Collared Peccary they associated their population increase near human settlements as a consequence of droughts and search for food. Conflicts with these two species were reported both at Noria de Cedros and El Salado. For El Salado, according to stories told by relatives of the interviewees, biodiversity used to be higher considering the presence of large mammals such as Mountain lion (*Puma concolor*), Black bear (*Ursus americanus*), particularly at the Northern and Southern parts of the ejido. Most of these species are hard to spot nowadays by farmers because of a

decrease in their abundance. In terms of avian species inhabiting the grasslands, almost none of the farmers are familiar with their common names; they refer to most of them as either “birds” or in some cases just “sparrows. However, some interviewees related greater precipitation with greater abundance and probably diversity of birds on their grassland. Figure 6 shows the areas considered as threatened by farmers.

In addition to the “native” elements of the system, there are external elements that interact in the system which have the potential to inspire people from the community or bring resources through governmental agencies or via research grants. Different stakeholders have been collaborating with these ejidos; academics from research institutes such as IPICYT conduct research projects. Additionally, government sectors such as SEMARNAT, CONANP, SEGAM, CONAFOR, SAGARPA/SADER, among others, have interacted with the ejidos via government support programs. These programs, however, frequently target development and conservation from opposite ends. Civil societies like OVIS A.C. (Wildlife Non-government Organization) are directly involved in conservation projects; they have been collaborating with the ejidos for over six years. The interaction between these external actors and the community has derived in an increasing interest for knowing and understanding the local fauna by some of the farmers that are interested, for instance in learning about topics such as regional bird diversity, potential causes for the decrease of Mexican Prairie Dogs (*Cynomys mexicanus*) in the area, or how to better conserve grasslands. In recent years, the ejido El Salado has found additional sources of income by hunting use of some species such as coyote, lynx, or hares. Currently, El Salado is registered under the figure of Environmental Managing Unit, and in the process of becoming an Area Voluntarily Dedicated to Conservation (ADVC; acronym in Spanish), the first one in the state of San Luis Potosí. Hunting permits are given by SEMARNAT. Interaction with hunters may imply a change/restructure in the system of particular interest to analyze. At El Salado, there are conservation efforts consisting of cattle exclosures, and the implementation of reservoirs of forage for drought conditions by planting cacti (*Opuntia spp*). This last action was implemented during the last

years through to the support by NGOs and government programs at the state and federal level. Cacti plantations, however, are not considered effective by some ejidatarios. The government program known as “payments for environmental services” (PSA) directed by the National Commission of Natural Protected Areas (CONANP in Spanish) aims to recover grasslands and thus pays the ejido to generate areas of cattle exclusion (Figure 9).

Areas where conservation actions are being conducted were identified as beneficial in terms of biodiversity conservation during the participatory mapping. It is worth mentioning that the area at the border of El Salado with Noria de Cedros is considered highly threatened in terms of biodiversity loss. Farmers attributed this to the reduction on precipitation around the area and at the whole extension of the ejido Noria de Cedros. For ejidatarios of El Salado, another threat for this region is overgrazing by cattle and horses in the area of Noria de Cedros. Noria de Cedros farmers reported a reduction in both diversity of grasses and quality of forage for cattle in the North-eastern part of their ejido (Figure 6). Part of the area designated for cattle exclosure at El Salado was identified as a hotspot of biodiversity including a high diversity of grasses, shrubs, and mesquite (Figures 7 & 9). The area and the application of the program of payment for environmental services has been used for research by the IPICYT (Instituto Potosino en Investigación Científica y Tecnológica) and by OVIS for the protection and conservation of grasses and birds. Another goal for the area is the reduction on the pressure to the grasses in the area. Due to the short term on the PSA program some ejidatarios recognize the potential of this area as pastas and they believe that in the future these areas could be included as part of a rotational system program. Part of the efforts and attention to this area has led to the study of threatened migratory birds such as the Lark Bunting (*Calamospiza melanocorys*).

In a study conducted in parallel to the current reconstruction of the socioecological system, areas where Lark Buntings spend time over the winter were identified (Chapter 1). An overlap with this area in activities from current ejidatarios and relatives, areas with biodiversity considered as threatened, and activity of Lark Buntings was found. Lark buntings are moving in the hills, crossing

the border between the ejidos looking for food. We found that tagged buntings stayed in certain areas for up to 28 days, before moving to other areas in the surroundings. Buntings usually moved in flocks of 4 to 50 individuals, bouncing in the ground during the day in patches of *Bouteloua* spp. grasses and small (<10) shrubs, but staying the night at *Larrea tridentata* dominated shrublands (Figure 11). In general, ejidatarios consider areas dominated by gobernadora as threatened and as something not good for the landscape because it does not allow grasses to grow. Concern of ejidatarios about the PSA area is attributed to both the economic importance given through government programs and the inclusion of research programs to the ejido.

In general, all interviewees reported at least one meaningful place inside their ejido land in the categories of aesthetics, intrinsic value, subsistence, sense of belonging and memories. Although not common, some of the meaningful places were identified as threatened. In the case of meaningful places regarding grasslands, the most common concern was the lack of recovery in grasses (mainly attributed to the lack of rain). While for meaningful places associated to the towns, the common concern was the migration of community members (particularly young ones) to urban areas, in search for better opportunities. Figure 10 includes the areas of meaningful places, these places fitted mostly on the “Sense of belonging” category among interviewees. These same sites were mentioned and addressed as meaningful because of their contribution to subsistence. Meaningful places concentrated mainly in the surroundings of the towns, although places distant from towns were also identified. Specifically at El Salado, one of the most addressed meaningful sites was the former hacienda, being always associated to a cultural heritage place. Most of the interviewees expressed their interest to recover the space and to generate activities in the surrounding of the hacienda. Meaningful places far from the towns mostly belonged to the subsistence category, one belonged to “scenic” category and one to “sense of belonging”. Some wells were reported as meaningful sites that are threatened in terms of water conservation (Figure 10) because in recent years, groundwater levels in the wells have been dropping and thus have not been able to keep up with the high demand for

livestock production. In response to the question about potential places where the members of the community envisioned things to change in the future, most of the interviewees did not express any concern about any changes. In particular, all people aged 50 years and older believe that the way the ejidos were organized was good and nothing needed to be changed. Some of the younger people from El Salado expressed interest to recover and maintain the structure of the Hacienda El Salado, at 2.5 km distant from the community. Currently even the main building of the Hacienda is falling apart, only a few of the original structures have remained even though it is regarded as a “cultural heritage” meaningful site. For Noria de Cedros, no meaningful place was reported regarding intrinsic value or scenic value; however, the sites associated to subsistence were frequently mentioned as meaningful sites. In other words, sites important for providing the materials or food the farmers need and they visit almost daily were the only meaningful sites.

Discussion

Our dryland ejidos can be considered complex social ecological systems since they meet the requirements by presenting key elements that interact with each other and thereby generate inherent dynamics between them (Moore, 2018; Raymond et al., 2009). Participatory mapping together with semi-structured interviews allowed us to construct and analyze the history and current status of the ejidos from a social ecological systems perspective. The El Salado-Noria de Cedros social ecological system consists of a landscape with complex dynamics considering the tight human – nature interlinkages. Different social groups, both local and external (the influence governmental agencies, NGO's, and academia) influence the way the vegetation develops. In addition, precipitation patterns, both historical and recent, together with the plant and animal associations shape the landscape and the way it is used, the places where cattle could graze and the migratory birds that might visit the area. Throughout the years the system has gone through events at different times that shaped and changed interactions between elements of the system, something common and characteristic of complex environmental systems (Lee et al., 2021).

Changes in the system can go as far as the appearance of the Hacienda and the introduction of cattle and goats to the system at the beginning of the XVI century. The construction of the Mexican railway system also impacted the local economy of the region, increasing connectivity and allowing products from the region to go far to cities such as Monterrey and San Luis Potosí. The later disappearance of the railway system was another important event that changed the way people could earn money. More recently, the shift in precipitation patterns towards a drier climate is generating concern among ejidatarios and making elements of the system to shift in strategies, including humans, animals, and plants. These events have impacted households and the communities in different ways; one of the major consequences has been the abandonment or migration of members from the community to cities in Mexico and the United States in search for wage labor opportunities. This is a complex issue affecting many municipalities

in Mexico (Massey, 2020). An important consequence of the increase in migration on the region is the loss of ejidatarios to work the land, many of these ejidatarios were also members of the “Consejo ejidal”, which is the social structure in which ejidatarios democratically make decisions about work to do or money to be invested in the community. Based on reports from interviewees, about 25% of the registered ejidatarios still live in the ejidos, the rest migrated to other cities or countries. The recent abandonment of the ejidos, together with the shift in climate patterns are challenging the resilience of the system, and future years could generate either a recovery or a reorganization of the system considering the adaptive cycle that complex social-ecological systems go through (Schoon & Van Der Leeuw, 2015).

For all interviewees, but especially those from El Salado, water shortage was identified as a major issue. This results in an important problem to address since drylands are predicted to be severely affected by climate change, and precipitation regimes are expected to shift drastically in the next 50 years (Lee et al., 2021; McGowan et al., 2021). Forming a multisectoral partnership of ejidos, NGOs, governmental and academic sectors may allow to co-manage the grassland ecosystems to regenerate sustainable production systems as those mentioned by the elder interviewees. Alternatively, if the cattle stocking rate does not get adjusted to the carrying capacity of the rangeland system, shrub encroachment may further increase and a complete reorganization towards a dryland with increasingly limited possibilities for livestock productions may occur. Shrub encroachment has been reported as a major threat to local populations of protected species such as the Mexican Prairie dog (Truett et al 2004) or several grassland bird specialists.

The current state of the system is both a challenge and an opportunity for the ejidatarios living and depending on the rangelands. A shift towards a more sustainable and adaptive approach, by conducting activities that release pressure on the grasslands and water reservoirs may be implemented. The shift to activities considering future more severe drought scenarios is something some of the ejidatarios are already considering, and the technical counseling of external

institutions could help them achieve a more resilient system. El Salado-Noria de Cedros past activities such as intense grazing in areas closer to towns and the traditional livestock production with unregulated grazing over whole ejidos have left a handprint in tradition, way of living, shaping the present landscape into a mosaic of different land use types and hence vegetation types. Semi-arid grasslands are susceptible to overgrazing, fragmentation, and climate change (Bodner & Robles, 2017; Mendez-Estrella et al., 2016); they depend on specific regimes of disturbance to maintain grass species composition (Geiger & McPherson, 2005; Merou et al., 2013). Livestock production regulated only by fewer animals in the past due to the monopoly of the cattle from a few families seems to have contributed to maintaining the functioning of grassland ecosystems in the study area, as they were included in the list of Priority areas for the conservation of grasslands in Mexico (Rosenberg et al., 2016).

Habitat loss and degradation of grassland habitat for migratory birds is of increasing concern to governmental and civil organizations as it promotes high vulnerability to land-use change, unsustainable agricultural practices, overgrazing and changes in precipitation patterns all over North America (Rosenberg et al., 2019; Stanton et al., 2018). The steep decline of North American grassland birds has promoted concern and thus study of these understudied species has been implemented. Aspects such as overwinter survival, habitat use, and movement strategies are still moderately known for many decreasing grassland birds. For example, Balderas Torres et al., (2013) found important links between the threatened Sierra Madre Sparrow (*Xenospiza baileyi*) and the social ecological system it inhabits. By conducting participatory mapping and semi-structured interviews researcher described overlooked aspects of its breeding biology and attributed the loss of habitat to a disconnection between governmental programs (i.e. programs to reforest areas targeting native grasslands and ban prescribed fires from CONAFOR) and important traditional knowledge from local ejidatarios. In our study region, we found some inconsistencies between government programs and the traditional management of grasses, particularly with the “reforestation” of cacti (*Opuntia spp*) in a *Bouteloua* dominated area of the study area as it was

addressed as non-successful and harmful for the grasses. Surveys conducted over the last 4 years and sightings by ejidatarios of grassland birds in general at El Salado and Noria de Cedros have revealed that for areas marked by ejidatarios as both threatened and important for biodiversity are visited or used as habitat by threatened migratory birds.

The local understanding about the importance of the areas and recent projects developed in the area are bringing attention to unprotected places vital in the lifecycle of threatened bird species. In addition to the areas used for subsistence farming and where farmers conduct their activities, meaningful places outside the perimeter of the town and unrelated to subsistence farming are also visited and frequented by threatened species. Thus, learning about, identifying, and considering meaningful places even though they are not visited by threatened bird species will have a major impact and value when designing integrative conservation programs considering biodiversity and intrinsic locally important landscape values (Gottwald & Stedman, 2020; Soliva & Hunziker, 2009). Thus far, conservation efforts of grassland ecosystems have implications for carbon sequestration, economic subsistence (Hovick et al., 2014), habitat for migratory and resident avian species (De León-Mata et al., 2020; Hill et al., 2014), among others. Short- and long-term conservation challenges require collaboration among different stakeholders and sectors at different institutional scales and a multidisciplinary approach would increase success probabilities (Cheddadi et al 2021, Moon et al 2014).

We generated a total of 6 participatory maps together with local ejidatarios containing part of the history about previous ways of living and species present on the region and ways to obtain water for the region. In particular, the ejidatarios mentioned the recovery of *Yucca* dominated areas attributed to the abandonment on the activity of Ixtle crafting at El Salado. One of the biggest concerns from ejidatarios was related to recent changes in their ejido attributed to the change in precipitation patterns, which directly impacts several interactions and feedbacks in the system such as crop yield, and cattle capacity from rangelands. In addition, the interest from some of them to incorporate alternative or more resilient production

practices is something to be considered in future conservation strategies in the region. It is very important to identify and embrace stewardship in the area to try to achieve more success in conservation programs for drylands (Anammasiya Ayambire et al 2021). The Knowledge farmers shared extended to the overall landscape of the El Salado/Noria de Cedros system, a 52,000-ha landscape.

Both Ejidos coincided in having concerns about the reduction in precipitation during recent years. Most climate change scenarios predict more severe droughts and a lower frequency of precipitation events, which will be spaced less evenly through the year (Kamali et al., 2017). Farmers are not familiar with these findings; however, it may be helpful for them to learn about these scenarios since most of them imply different weather conditions and have important implications for landscape management strategies. Drought related, hence enforced, abandonment of agriculture is very common in drylands, both nationally and internationally (Escalante-Sandoval & Nuñez-Garcia, 2017; Herrera-Pantoja & Hiscock, 2015). While local farmers have multiple social-environmental sources of evidence for a clear reduction in precipitation, we could not corroborate the reduction in precipitation based on climate data from meteorological stations. Likely the database did not include sufficient years (more than 40 years), or the drought is a truly local phenomenon, or farmers do not address meteorological drought but an integrated concept of drought with productive, economic, and social consequences (Knapp CN & Fernandez-Gimenez ME 2009, Grey et al 2021).

Thanks to the knowledge of local farmers, we could identify areas of high within region biodiversity, and places where conservation efforts are having an impact. Rotational cattle management was seen positively by landowners under projects such as the payment of environmental services. Most farmers, however, are not encouraged to implement such strategies by themselves and would like support from other organizations, both private and public, to bring technical assistance for those projects. Rotational management of grassland paddocks on semi-arid grasslands has been reported as a positive action towards keeping or even recovering grassland communities and other associated species such as birds (Ghimire et al., 2019). In this study, we identified areas considered by farmers

to have medium to low grazing pressure as visited areas for a threatened grassland bird species (Figure 11). These same areas are under conservation strategies from farmers together with governmental and non-governmental agencies. The areas under PSA have an overall positive perception in terms of biodiversity, however without the financial support, an important short-term strategy will be to find other ways to keep managing more areas within a similar model, even without a payment itself; although new financial programs such as carbon credits could be an alternative (Jurado-Guerra et al 2021). However, land protection without management may not always be the best option (Davis et al 2019) as it does not target other issues such as shrub encroachment (Andersen & Steidl 2019).

Government programs such as payments for environmental services have been reported with contrasting results in other ejidos of Mexico. Balderas Torres et al., 2013 reported that different outputs were obtained due to the lack of continuity of the programs and the minimal training ejidatarios have received to develop these programs independently. Programs from other organizations that address other major issues such as technical capacity building and training on identifying and growing native, drought adapted forage grasses, together with prescribed burning management in the area should also be considered to pursue a more integrated approach towards conservation (Ling et al 2023).

The Challenge of participatory mapping

Although participatory mapping allows a horizontal exchange of knowledge and experiences, this exchange should also include other stakeholders and decision makers from governmental and non-governmental agencies in order to get a full picture of the multi-sectoral understanding of this complex region characterized by a rich social-environmental legacy. Our study attempted to contribute from a diagnostic perspective to the need of addressing these problems from a complex environmental system's perspective (Otero, 2022). Potential limitations may be related to a lack of cover regarding the whole spectrum of ejidal activities, yet other studies have addressed systems similar to the one evaluated through our study obtaining representative results (Selgrath & Gergel 2019). Participatory mapping with local actors and incorporating local knowledge in the decision-making process is an important way forward to generate more integrated conservation strategies (Clement & Standish, 2018).

Participatory mapping has been a very important tool in the diagnostic and sharing of local and traditional knowledge that can be translated and incorporated into conservation programs, helping in the identification of potential conflict zones (Selgrath & Gergel, 2019), landscape change and interest in managing ecosystem services (Weyer et al., 2019). The maps presented in this research attempt to serve as an integrated guide from both Ejidatarios and other key actors of the region (such as representors of the governmental agencies and NGOs; although these last actors were not interviewed, an important future step) to collectively identify and target areas with the highest threats in the region such as biodiversity loss or the positive impact achieved through previous programs like the PSA from CONAFOR and its importance for threatened migratory birds. All potential actions decided upon should also consider the continuous impacts of future climate change (Li et al., 2020; Qin et al., 2014), since actions planned to solve current problems might not be effective for future scenarios.

In this chapter, we aim to understand the vision of local decision makers (in our case local farmers) and their concerns, which together with an aspect of the

natural history of a threatened species such as the wintering ecology of the Lark Bunting (Chapter 1) would give a multidisciplinary approach for future conservation strategies. Examples of this kind of work in Mexico are the study of Cabrera-García (2008), where the researcher also linked the social and ecological aspects surrounding the environment of the Sierra Madre Sparrow. In comparison, another important limitation in our study is the lack of specificity in estimations about grassland bird species loss throughout the years, due to the lack of trained ejidatarios to identify grassland birds inhabiting the system. This is an identified opportunity to engage farmers with high potential of turning into stewards, if they are not already, of the land they inhabit. The training and formation of biodiversity stewards could be an effective strategy for the conservation of the landscape in general, having grassland birds as ambassadors of conservation actions in the social-ecological system. This initiative may have high potential in an area where ejidatarios are eager to conserve current ways of living and face the challenges of climate change.

Conclusions

El Salado and Noria de Cedros are complex environmental systems, each having their own elements and feedback even though they are neighboring dryland livestock-production systems. The main elements of these systems include a vast, heterogeneous landscape where local stakeholders have different visions for their land management, plus the impact from government and non-government organizations; with an increasing concern due to changes in surface and groundwater availability. The shift in precipitation patterns and the decrease in winter precipitation has had a major impact on the livelihoods and interactions of members from both ejidos. The main output of this change in interactions is the congregation of ejidatarios concerned in actions that could help increase the resilience of the system against more severe droughts in the future, and ejidatarios waiting for better days to come as the experience has shown them that there is high variability and temporal heterogeneity in precipitation throughout the years. The shift in precipitation patterns has also resulted in changes regarding the animals raised and the crop production. The subsistence activities within the ejido have not changed until very recently and some decision makers are not considering a more resilient approach, such as a reduction in cattle number and especially a constant grazing management, even though future climate estimations point towards more droughts.

Preferred areas for Lark Buntings currently present medium to low grazing pressure, are within areas considered host high numbers of flora and fauna, and present heterogenic vegetation compositions. As a result of this work, recommended conservation actions include I) A more holistic and participatory approach to incorporate all stakeholders from the conceptualization of the conservation project until the final reports, encouraging their participation during the whole process. II) Identify areas with similar descriptions from farmers used by Lark Buntings and target them for future conservation projects. III) Address not only the preservation of grasses but also other threats such as shrub encroachment, the most addressed threat by farmers in the interviews.

The participatory maps generated in this work are expected to help addressing major issues within the system in the future. In this project, we have identified high diversity in personal meaning of a shared land, and the necessity of a multi-stakeholder approach. This activity demonstrates that involving various stakeholders can lead to a win-win situation. By working together, we can develop conservation programs that not only protect endangered ecosystems but also ensure the well-being of local farmers. At El Salado and Noria de Cedros, if a proper conservation of grassland systems and the species inhabiting these biomes is expected, coordinated efforts from landowners and decision makers are imperative.

Figures

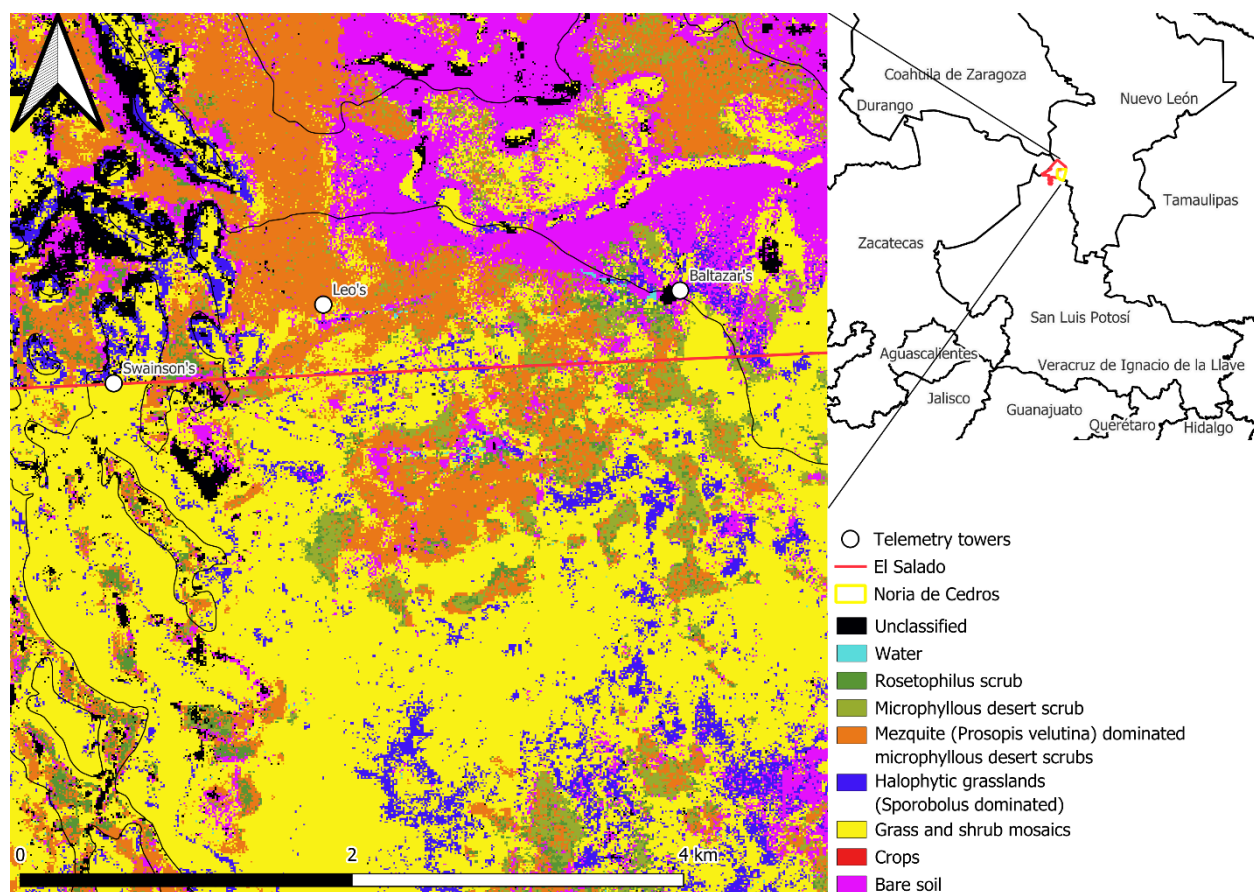


Figure 1: Land cover classification map of the study site El Salado according to J. A. Zavala-Hurtado and M. Jiménez 2019. Sentinel – 2 image was taken on January 4th, 2023. Red line represents the border between the two ejidos (North: El Salado, South: Noria de Cedros).

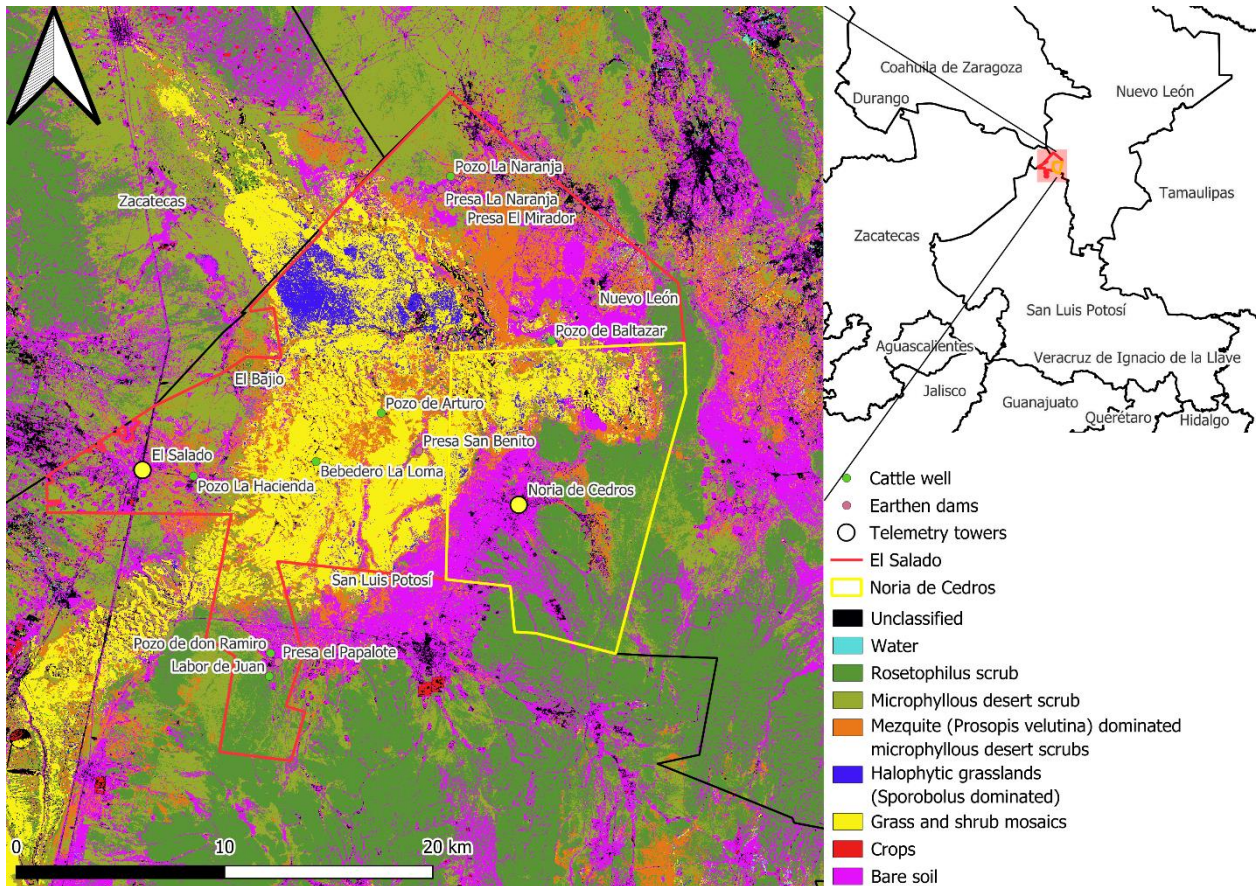


Figure 2: Map of the ejidos El Salado and Noria de Cedros and locations of main water resources for cattle; cattle wells represented by green dots and cattle dams represented by purple dots.

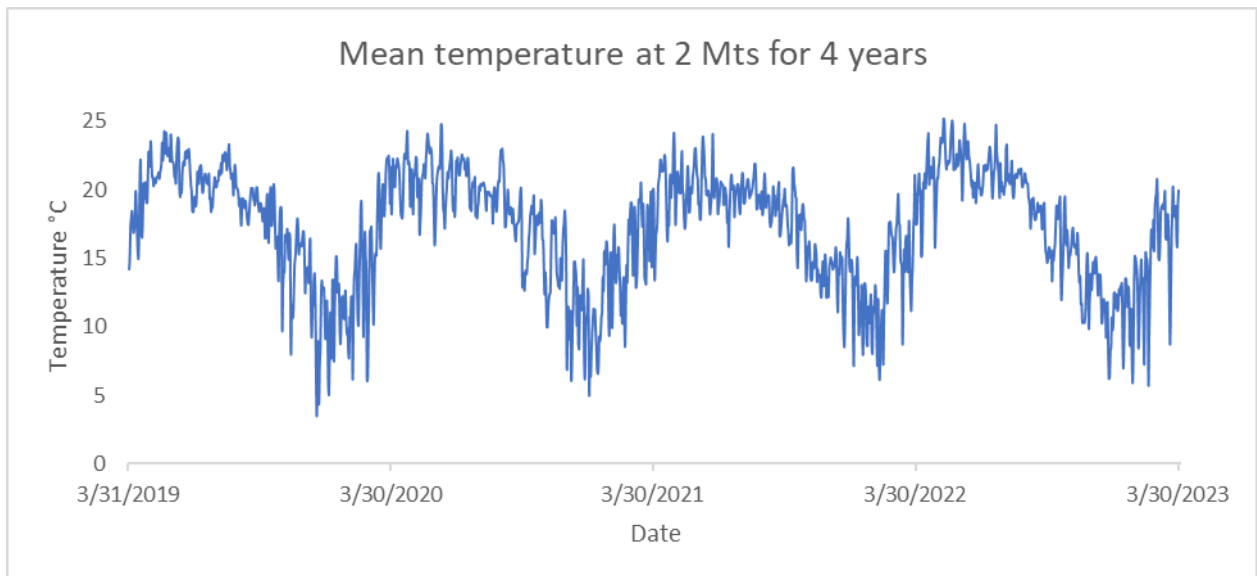


Figure 3: Mean daily temperature ($^{\circ}\text{C}$) at two meters height between 2019 and 2023 at the study site in a semiarid grassland region in Northern San Luis Potosí, Mexico. The data was obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Prediction of Worldwide Energy Resource (POWER) Project funded through the NASA Earth Science/Applied Science Program.

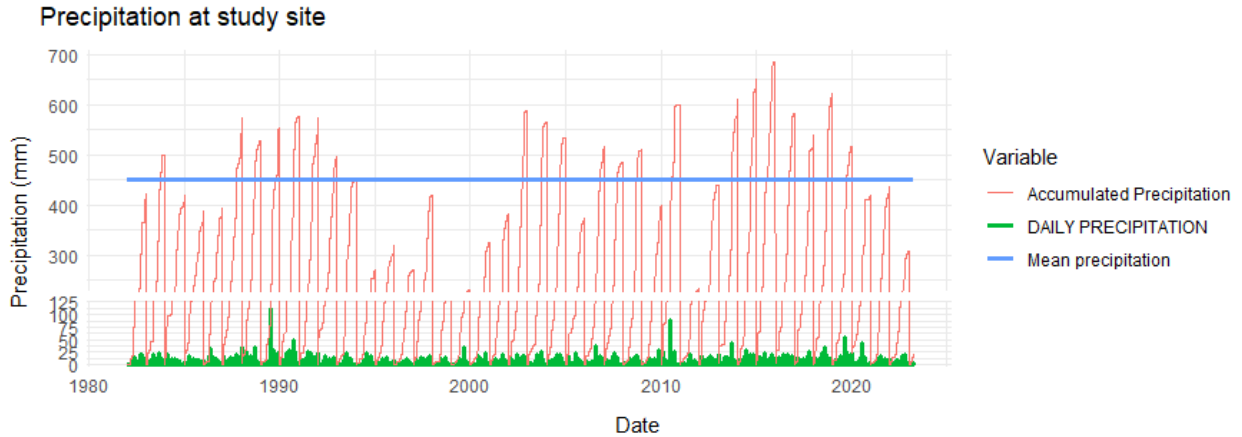


Figure 4: Cumulative precipitation (Red) and daily precipitation (blue) for the study area at El Salado – Noria de Cedros study site for the last 40 years (1983 - 2023). Cumulative precipitation tends to vary between years together with daily precipitation.

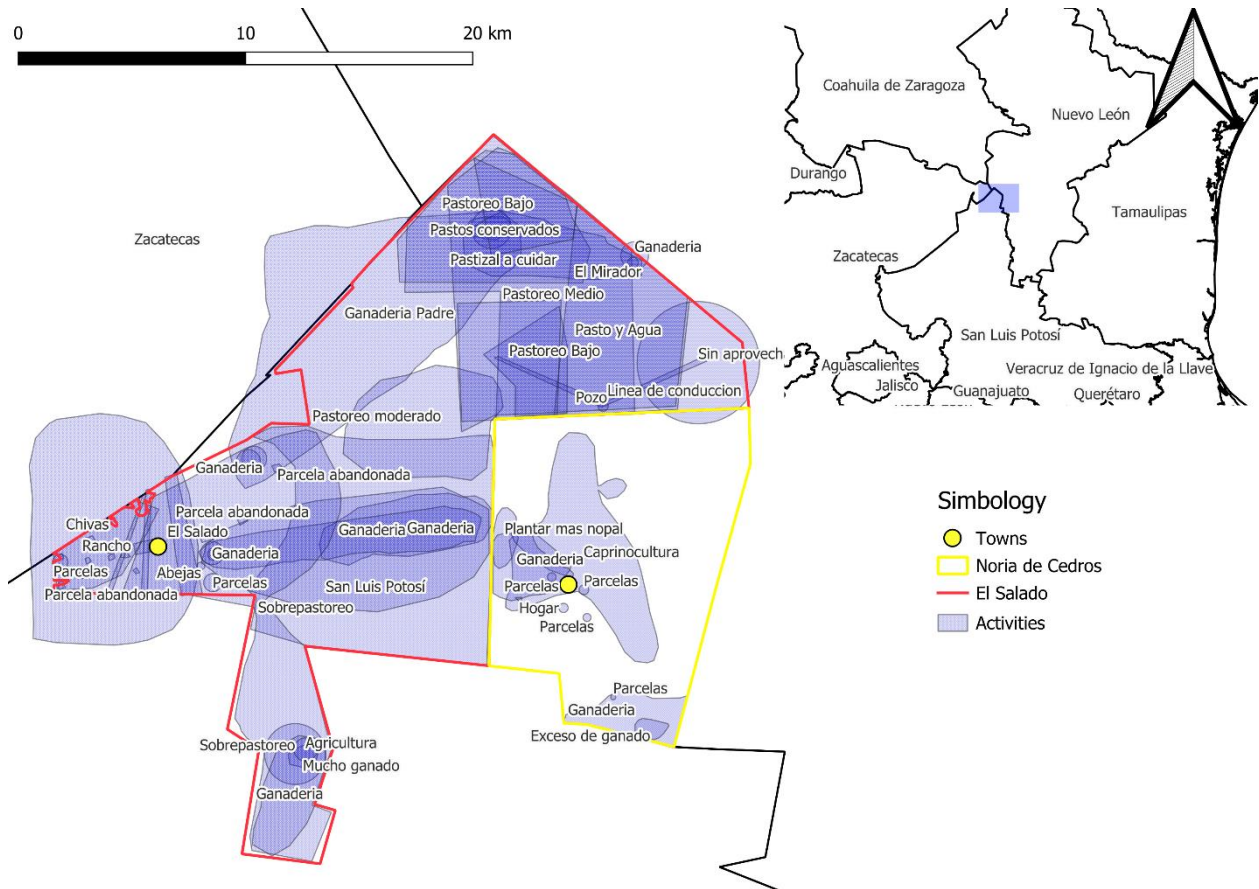


Figure 5: Participatory map generated from the responses of all interviewees (n=24) with the areas where subsistence farming and other productive activities were reported by ejidatarios of the ejidos El Salado (left) and Noria de Cedros (bottom right). Activities near the town, in isotal, shrublands and grasslands were reported. Darker color represents the overlap of areas in the ejido from different interviewees. El Salado border is represented with a green line, orange line represents the elevation lines.

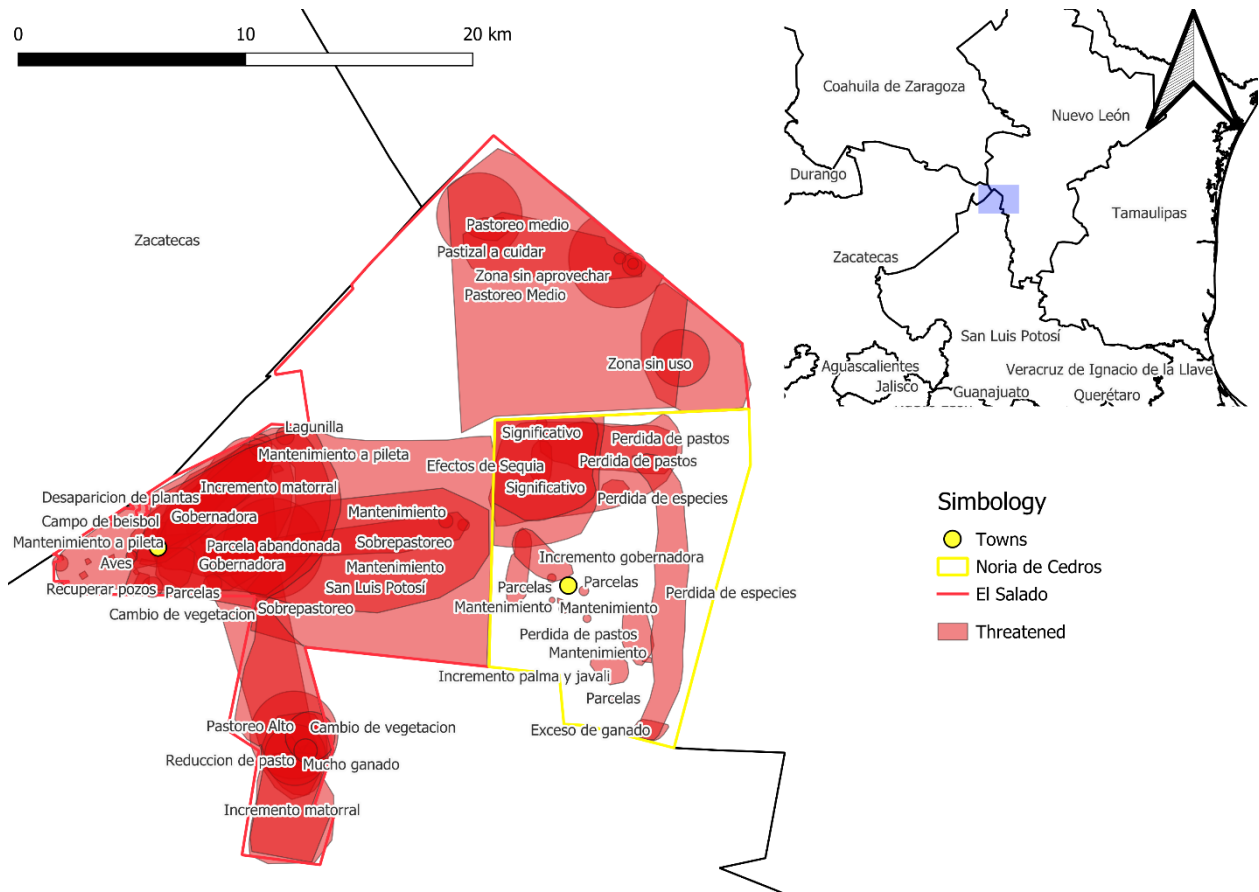


Figure 6: Participatory map generated from the responses of all interviewees ($n=24$) with the areas where subsistence activities, mainly grazing and crop growth are reported as threatened by the disappearance of grasses due to shrub encroachment (mainly) or impacted by severe drought in recent years of ejidos El Salado (left) and Noria de Cedros (right). All the areas near dams and wells in the El Salado area were reported as threatened by at least one interviewee. Darker color represents the overlap of areas in the ejido.

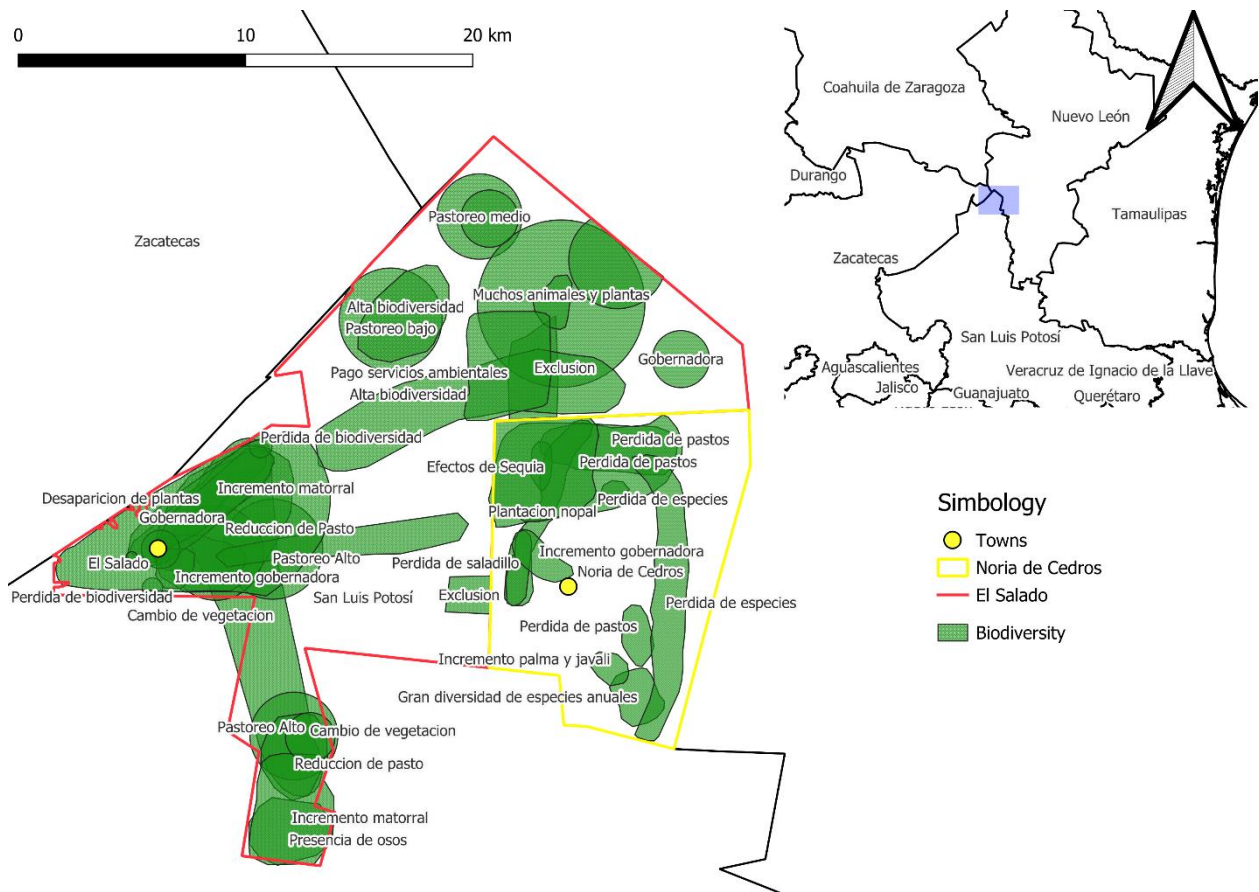


Figure 7: Participatory map generated from the responses of all interviewees (n=24) with the areas where high amounts of biodiversity (referred as species richness) are reported in ejidos El Salado (left) and Noria de Cedros (right). Darker color represents the overlap of areas in the ejido.

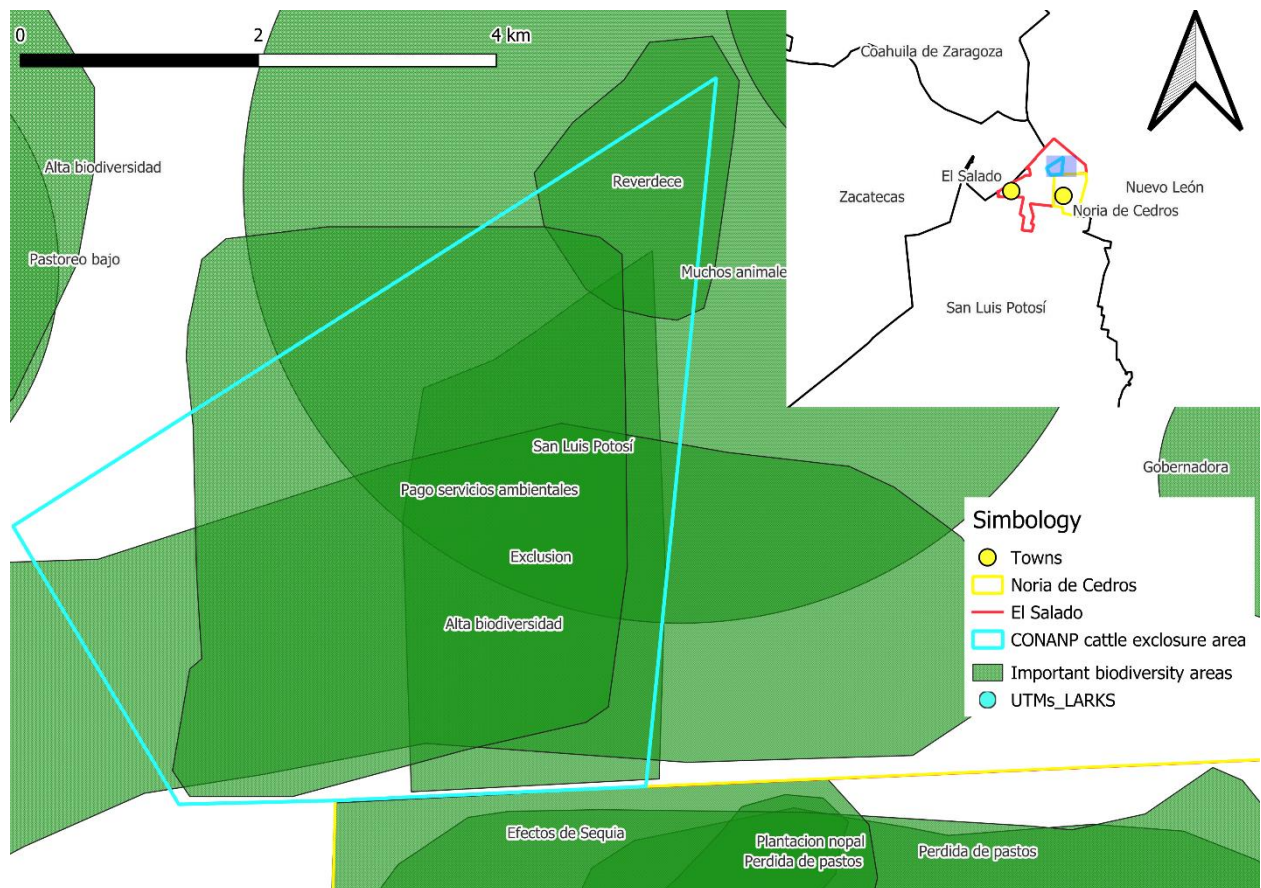


Figure 9: Cattle enclosure area established under the program Payment for Environmental Services from CONANP overlapped with zones considered as important for biodiversity or with high diversity of flora and/or fauna (green). Darker color represents the overlapping of areas in the ejido reported from different interviewees (n=24).

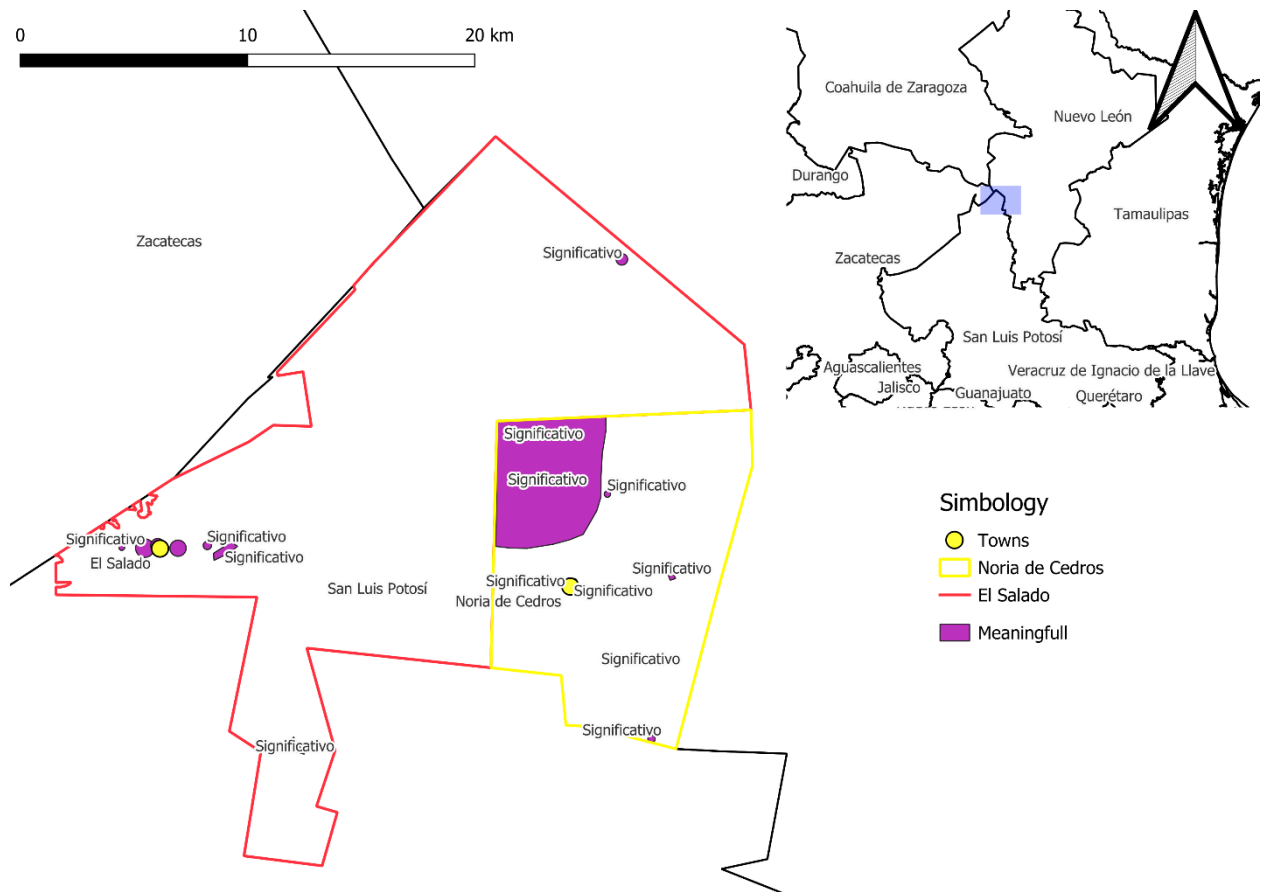


Figure 10: Participatory map generated from the responses of all interviewees (n=24) with the meaningful sites reported from the members of El Salado (left) and Noria de Cedros (right). El Salado border is represented with a red line, yellow line represents the border with Noria de Cedros.

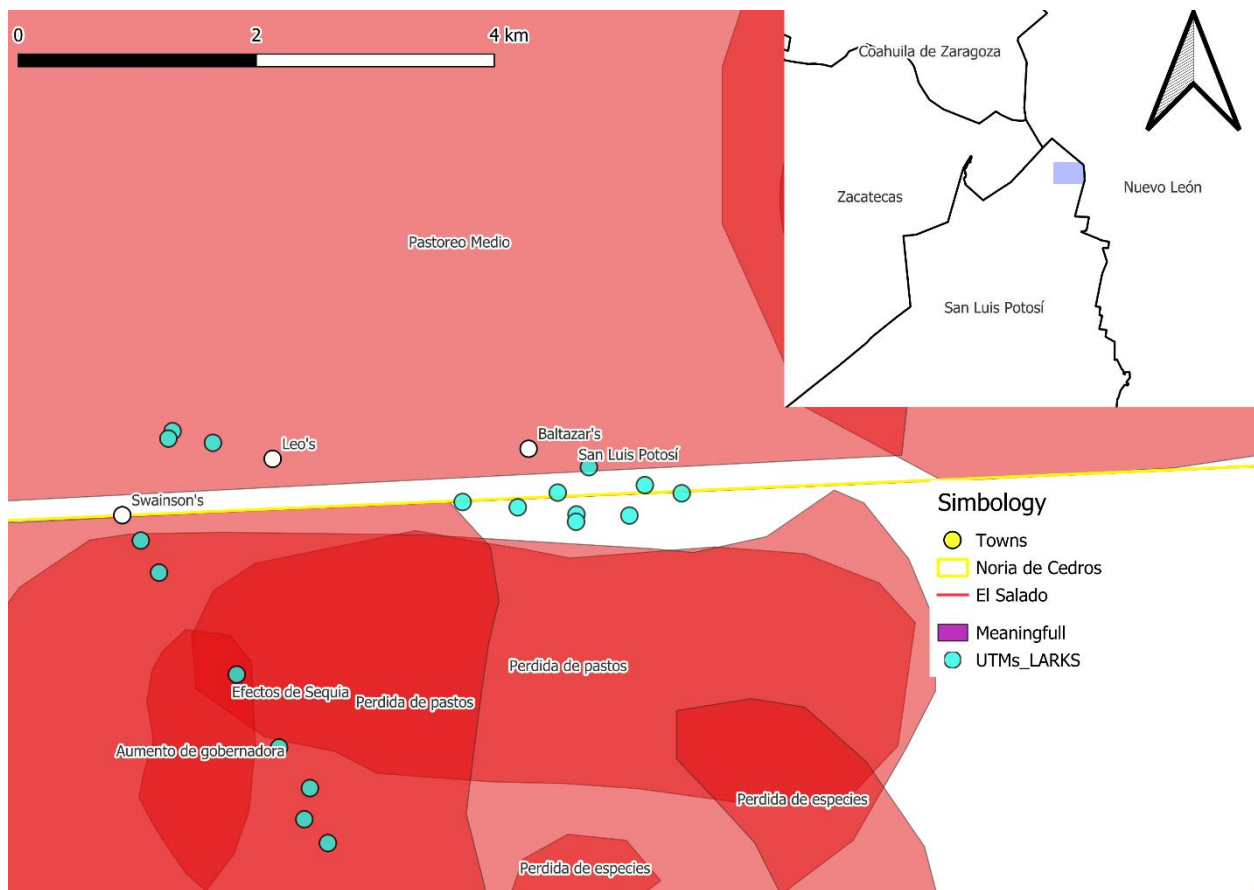


Figure 11: Overlapping map of Lark Bunting detections from Autonomous and manual radio telemetry and zones considered as threatened (red). Darker color represents the overlapping of areas in the ejido reported from different interviewees. Telemetry towers used in parallel study are represented in white dots.

SUPPLEMENTARY INFORMATION

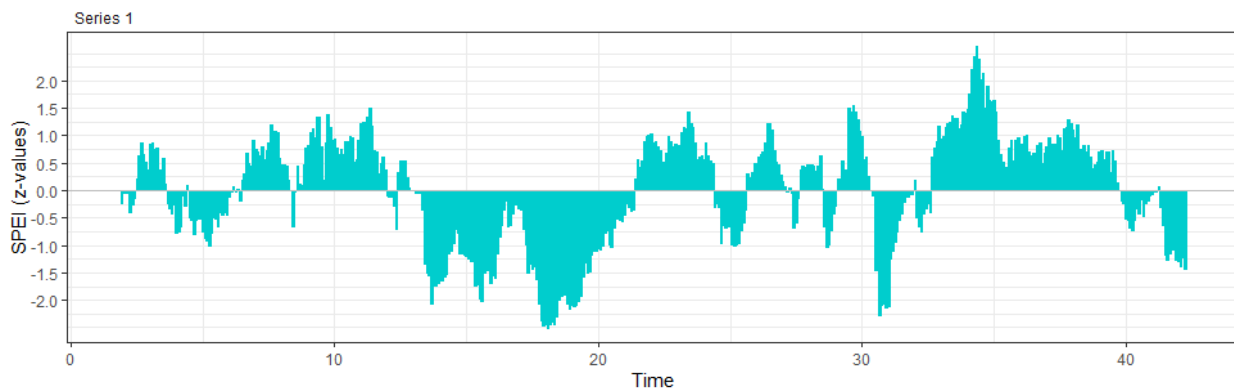


Figure S1: Standard Precipitation Index (SPEI) analysis conducted for El Salado – Noria de Cedros study site for 40 years of monthly deviations of the mean in precipitation. X axis represents time starting in 1982. Each individual bar corresponds to the SPEI value of each month within the year.

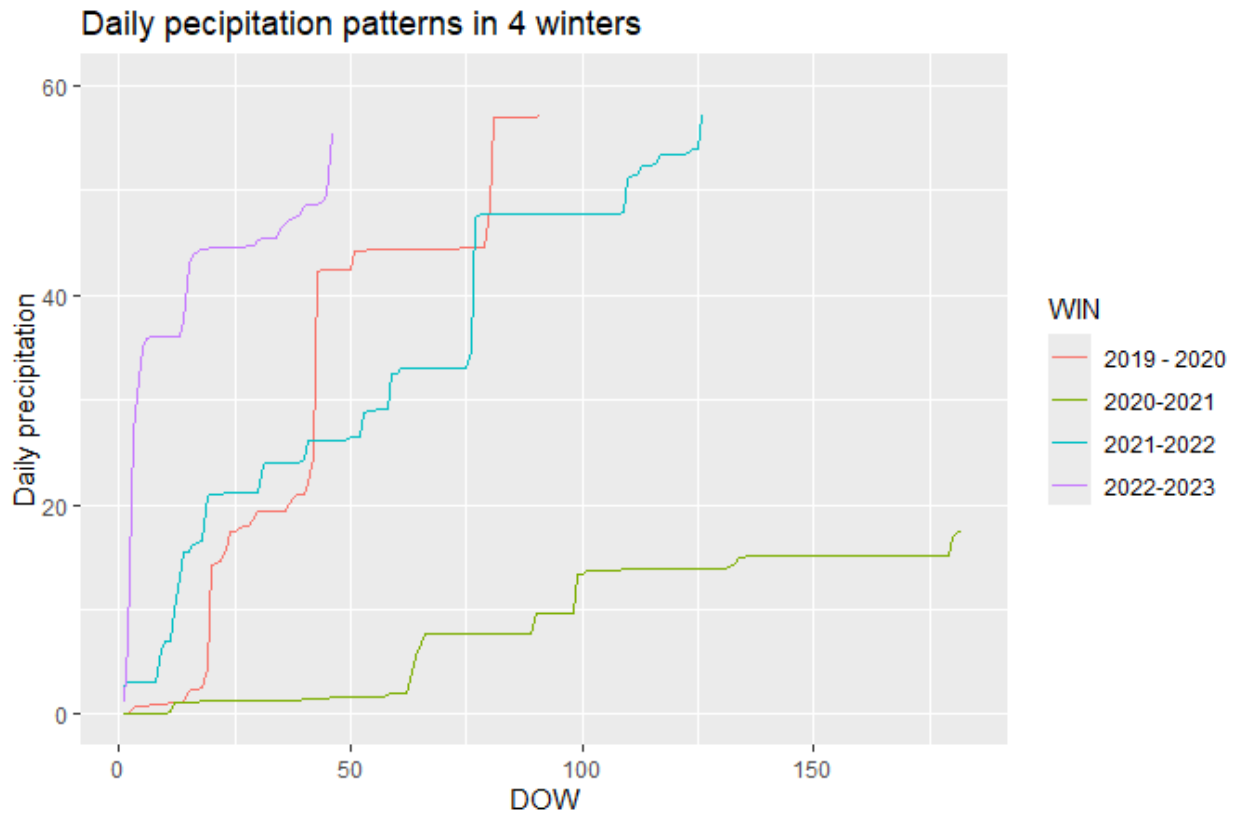


Figure S2: Cumulative winter precipitation for 4 winters at the study site. DOW represents Day of Winter. DOW 1 corresponds to Nov 4th, DOW 182 corresponds to April 1st of the following year

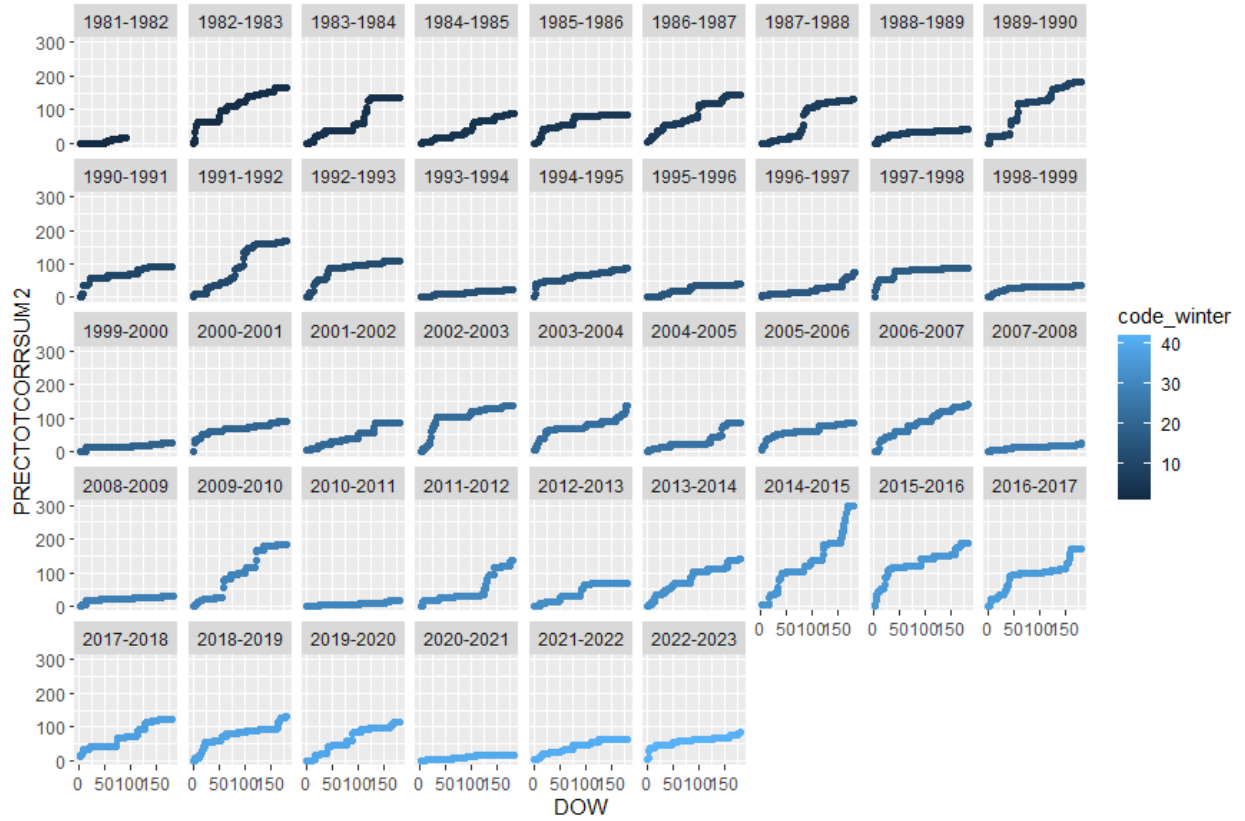


Figure S3: Cumulative winter precipitation for 42 winters at the study site. DOW represents Day of Winter. DOW 1 corresponds to Nov 4th, DOW 182 corresponds to April 1st of the following year. Code_winter represents the number of the winter starting in 1982.

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General Conclusions

Conservation through a multidisciplinary approach has the advantage of a broad perspective with high chances of success. Understanding not only the biological context under a threatened bird behaves in part of their lifecycle, but also the past and present of the landscape where they spend over one third of their life cycle is important to identify causes and target more specific areas towards recovering population declines. We worked with presence/absence data through five years containing four winters and one year of autonomous telemetry and found high variability within a year and a response to mean SAVI values. These responses are taking place in the context of a landscape with variable precipitations throughout the years. Within this same landscape, livestock practices for the last 90 years have changed and shaped the vegetation distribution in some areas; with increasing shrub encroachment and shifts in precipitation patterns for the last 20 years. Movements with high variability through time and space responding to environmental variables in an unpredictable environment are characteristic of nomadic birds. By focusing not only on the movement strategy of individuals, but also on the landscape, we intended to obtain a more comprehensive approach towards preventing this and other grassland populations continuing on steep declines. Based on our results, El Salado – Noria de Cedros is a site Lark Buntings use overwinter, as long as environmental conditions are favorable. If these conditions do not match, Lark Buntings can stay shorter amounts of time and move towards places where they might find better resources. The landscape presents conditions that Lark Buntings use, and a positive perception from the local farmers towards preserving biodiversity in the area and implementing more conservation efforts. However, there is a need for alternative subsistence activities and more sustainable agricultural practices to keep grasslands and the biodiversity they host in the face of climate change.

Finally, future conservation strategies should take into account the high mobility of the Lark Buntings and target several areas across the whole ejido but should be co-defined with local farmers. This will also generate a heterogeneous landscape with different grassland stages, which will benefit a wider taxa of

grassland birds. The conservation strategies should also be conducted alongside ejidatarios as this will expose them to the results and witness the results of the conservation actions. Finally, stewardship should be encouraged from current and future farmers to generate a more resilient system; this could be achieved by generating more vertical structures between farmers, NGOs and academia, i.e. including farmers in bird/vegetation surveys to share knowledge from both sides or have more frequent workshops about projects at the ejidos.