Final Report

WDFW 2024-25 Wildlife Diversity Grant

Project Title: Does habitat restoration in agroecosystems contribute to bat conservation? An assessment for Townsend's big-eared bat (*Corynorhinus townsendii*) in Eastern Washington

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Executive Summary:

Bats provide critical pest control services in agricultural landscapes, yet agriculture poses significant direct and indirect threats to bats, primarily through habitat alteration and driving insect declines. This project investigated how agroecological land use—including the types of crops, the amount of protected land, and habitat restoration through the USDA Conservation Reserve Program (CRP)—affects bat activity and diversity in the Columbia Plateau ecoregion of Eastern Washington, focusing on the state candidate species, Townsend's big-eared bat (*Corynorhinus townsendii*), and other bat species of conservation concern.

We deployed acoustic monitors to monitor bats and camera traps to monitor nocturnal flying insects across nine protected sites (BLM and WDFW) in Douglas County from July–October 2024 and March–June 2025, spanning 163 monitoring nights. These sites represented a gradient of surrounding land types—cropland, CRP restoration, and protected natural habitat. Using generalized linear mixed-effects models, we analyzed how bat activity, species richness, diversity, and feeding behavior were influenced by environmental variables including climate, land cover, water features, and nocturnal flying insect abundance.

Key Findings:

We recorded all 14 bat species expected in the region, including all Washington State Species of Greatest Conservation Need (SGCN) expected in the region. We detected *C. townsendii* 19 times across six of nine sites and all three study regions. Temperature emerged as the dominant environmental driver of bat activity, with both short-term nightly temperatures and long-term minimum temperatures strongly predicting bat diversity, activity, and feeding intensity.

Agricultural practices showed contrasting effects on bat communities. Insect-pollinated crops and greater crop diversity within 2–5 km were strongly associated with increased bat diversity and activity, particularly benefiting *C. townsendii* and other moth specialists, while more wind-pollinated crops at 20 km scales were associated with decreased bat diversity and activity. Bat activity, diversity, and foraging showed consistent negative relationships with CRP land across multiple spatial scales and CRP practices, including permanent grass plantings (CP1, CP2) and wildlife enhancements (CP38E).

Protected areas increased the chances of detecting several species, including *C. townsendii*. The presence of more springs and seeps had positive effects on total bat diversity and activity, underscoring the importance of water features for bats. Nocturnal insect abundance showed modest but significant effects on bat feeding activity, with fine-scale temporal correlations observed throughout the night.

Management Implications:

These findings indicate that diverse bat communities, including vulnerable species like *C. townsendii*, are an active and important component of the agricultural landscapes of eastern Washington. The positive associations between bats and diverse insect-pollinated crops suggests that diversified agricultural systems may provide more valuable foraging habitat than simplified agricultural systems composed primarily of cereal grains, and perhaps more even than grassland restoration through the CRP. Indeed, although they warrant further investigation, our results suggest that in order to better support bats, the CRP should strive to encompass habitat types and landscape features, such as water sources, that bats and their insect prey rely on. Furthermore, our results highlight that maintaining and expanding protected areas, particularly those that include water sources, is critical for the conservation of rare and vulnerable species like *C. townsendii* in agricultural landscapes.

Recommendations:

1. Expand protected areas in key habitat areas for *C. townsendii* and other rare and vulnerable bat species
2. Prioritize conservation efforts for *C. townsendii* in northern Douglas County, where the species mostly occurs
3. Prioritize protection and restoration of springs, seeps, and other point water sources in agricultural landscape conservation planning
4. Investigate additional factors (e.g., contract age) that may affect the value of CRP land to bats, and reevaluate CRP habitat management practices to incorporate habitat features that better support bats and their insect prey
5. Encourage diverse crop rotations that include insect-pollinated species
6. Implement long-term monitoring programs using validated passive acoustic and camera-based techniques

Introduction:

With 90% of species suffering population declines and 53% of species at risk of extinction in the next 15 years, bats are among the most threatened taxa in North America (Adams et al. 2024). Primary threats include climate change, problematic species (including diseases like white-nose syndrome), agriculture, and energy production (Adams et al. 2024). Collecting current diversity and distribution data is vital to conservation efforts as bat populations continue to be impacted by these interacting stressors (Adams et al. 2024). These data can help reveal how bats are affected by local and landscape factors, identifying threats and management priorities (Myers et al. 2024). This is especially important in heavily human-modified landscapes, like agricultural regions, where bats continue to forage and roost despite human disturbances (Adams et al. 2024).

Agriculture is the largest contributor to biodiversity loss globally (Dudley & Alexander 2017), and a primary threat to bats (Adams et al. 2024). At the same time, sustainable agricultural production depends on ecosystem services, including pollination and pest control, provided by diverse ecological communities (Klein et al. 2007; Power 2010). Indeed, insectivorous bats supply essential agricultural pest control services, often preferentially preying on pest species (Aizpurua et al. 2018; Russo et al. 2018; Kemp et al. 2019; Maslo et al. 2022). In a recent study, a reduction in bat pest control services led to a greater reliance on harmful chemical pesticides, which was associated with both lower farm crop revenue and higher human infant mortality (Frank 2024). Findings like these make clear that bats supply direct benefits to agriculture and human health. Thus, sustainable agriculture depends on ensuring that crop production does not come at the expense of supporting ecosystem service-providing organisms like bats (Tilman 1999; Scherr & McNeely 2008; Erisman et al. 2016).

Fortunately, there is evidence that sustainable land management can help maintain bat diversity and ecosystem services in agricultural regions (Wickramasinghe et al. 2004; Park 2015; Xavier et al. 2023). Indeed, bats are among the taxa that can benefit most from biodiversity-friendly agricultural practices (NERR138 2023). For example, maintaining a higher proportion of protected and restored habitat, as well as access to roosting sites and water sources, can increase bat diversity and foraging activity in agroecosystems (Henderson & Broders 2008; Lentini et al. 2012; Fuentes-Montemayor et al. 2013; Monck-Whipp et al. 2018; Slough et al. 2023; Li & White 2024; Dodd et al. 2008; Stahlschmidt et al. 2012; Nelson & Gillam 2020).

For insectivorous bat species, some of these benefits likely arise from the positive impacts of agroecological practices on insect populations. Many bats are moth specialists, preying almost entirely on moths. Given the negative effects of intensive agricultural practices on moths and other insects (e.g., via habitat loss and pesticide use: Wagner et al. 2021), bats with ranges that overlap major agricultural regions are particularly at risk of reductions to their insect prey (Hayes & Wiles 2013). However, lower-intensity agricultural practices and conservation interventions such as habitat restoration have been shown to increase both moth abundance and bat foraging activity in agroecosystems (Wickramasinghe et al. 2004; Olimpi & Philpott 2018; Peter et al. 2021; Chaperon et al. 2022).

Several state and federal conservation programs have been established to increase the diversity and abundance of insects in agricultural areas, in part because insects provide numerous agricultural ecosystem services including pollination, pest control, and soil maintenance (Klein et al. 2007; Schowalter et al. 2018). One example is the USDA Farm Service Agency Conservation Reserve Program (CRP), the largest private-lands conservation program in the country, which compensates growers to set aside a portion of their land for various conservation efforts including pollinator habitat restoration (Hellerstein 2017). While it is likely that these insect conservation efforts also impact insectivorous bats, to our knowledge no formal assessment of the CRP's impact on bat foraging activity has been conducted.

Townsend's big-eared bat (*Corynorhinus townsendii*) occurs across much of the Western US, including major agricultural regions in Washington state. Its diet is composed of over 90% moths, making it an extreme moth specialist (Ober & Hayes 2008; Hayes & Wiles 2013). *C. townsendii* is a species of conservation concern in the Western US and a candidate species for the WDFW. The species is also listed as a Species of Greatest Conservation Need (SGCN) under the State Wildlife Action Plan (SWAP), and a Priority Species under WDFW's Priority Habitat and Species (PHS) Program. *C. townsendii* is considered rare throughout its range, and has declined in Washington since the early 1900s (Senger 1973; Gruver & Keinath 2006). Major threats include the loss of roosting sites (including hibernacula) and agricultural expansion, including associated pesticide use which may indirectly effect *C. townsendii* by reducing the abundance of moths (Hayes & Wiles 2013). The species usually occurs in small, isolated populations where roosting locations, foraging sites, and water sources are in close proximity (Fellers & Pierson 2002; Gruver & Keinath 2006; Hayes & Wiles 2013). Although most habitats in Washington are suitable for foraging by *C. townsendii*, detailed range and habitat use information is lacking (Hayes & Wiles 2013). Furthermore, little is known about the effects of land management on their habitat use (Hayes & Wiles 2013). *C. townsendii* typically travel up to 5 km from roosts to foraging sites during the summer, potentially making them sensitive to landscape factors such as habitat connectivity (Hayes & Wiles 2013).

The majority of studies investigating bats in agricultural landscapes have found landscape structure and composition, including the proportion and distribution of protected and restored habitat, to be major factors influencing bat distribution and foraging activity (Henderson & Broders 2008; Lentini et al. 2012; Fuentes-Montemayor et al. 2013; Monck-Whipp et al. 2018; Slough et al. 2023; Li & White 2024). Locations of roosting sites and water sources also influence bat distributions and movement patterns (Dodd et al. 2008; Stahlschmidt et al. 2012; Nelson & Gillam 2020). The availability of insect prey may also influence bats' use of agricultural mosaics, particularly for specialists like *C. townsendii*.

Project Objectives:

We have three primary objectives in this study:

1. Evaluate the impacts of climate, land use, and insect abundance on bat diversity and foraging activity within protected habitat patches surrounded by varying compositions of protected land, restored CRP land, and cropland in Douglas County, Washington.
2. Provide updated information on the distributions, population densities, and habitat associations of *C. townsendii* and other bat species listed as SGCN to aid WDFW in assessing species conservation status, and inform land management in habitats (e.g., shrubsteppe) that are increasingly threatened by incompatible development, land use, and resource management.
3. Validate powerful, efficient, and non-invasive techniques for insect and bat monitoring to guide future conservation and monitoring efforts.

Methods:

Study Area:

We established nine sites within protected areas (BLM and WDFW) in Douglas County, Eastern Washington (Figure 1A), where *C. townsendii* has previously been detected with acoustic monitors, most recently in 2019 and 2020 (visualize.batamp.databasin.org/species/coto). The county is characterized by a mosaic of cropland, protected BLM/DNR/WDFW land, and restored CRP land, offering a unique opportunity to assess the impact of agroecological land use on bats and their insect prey. We selected sites based on accessibility and to encompass variation in the factors of interest including the amount of cropland, CRP land, and protected land in the surrounding landscape (Figure 1B and Figure S1). We chose three sites in each of three regions roughly in the North, Central, and South of Douglas County.

Douglas County encompasses Eastside Steppe and Shrubsteppe habitats, both listed on the PHS Program. These habitats are under significant pressure from development, land use, and resource management, and are also utilized as foraging and/or roosting sites for several bat SGCN, including *C. townsendii*, Hoary bat (*Lasiurus cinereus*), Silver-haired bat (*Lasionycteris noctivagans*), seven *Myotis* species, and Spotted bat (*Euderma maculatum*). The county also houses roosting concentrations of Big-brown Bat (*Eptesicus fuscus*) and Pallid bat (*Antrozous pallidus*), both listed on the PHS Program. These bats all feed on moths and other insects, and habitat degradation driven by agriculture and other land use change is a primary threat. Furthermore, the majority of these species lack adequate baseline data on migration patterns, habitat requirements and population status.

At each field site, we established a monitoring array consisting of three components: a camera trap to monitor nocturnal flying insects, an acoustic monitor to monitor bats, and a temp-RH data logger (Figure 1C). We affixed each of these to the top of an anchored U-post, such that the equipment was elevated 1.5 m above the ground. We placed equipment away from any tall vegetation to avoid interference with the acoustic monitors. We conducted monitoring for a total of 163 nights, from July to October 2024, and from March to June 2025. We replaced batteries and SD cards and cleaned equipment roughly every three weeks throughout this monitoring period.

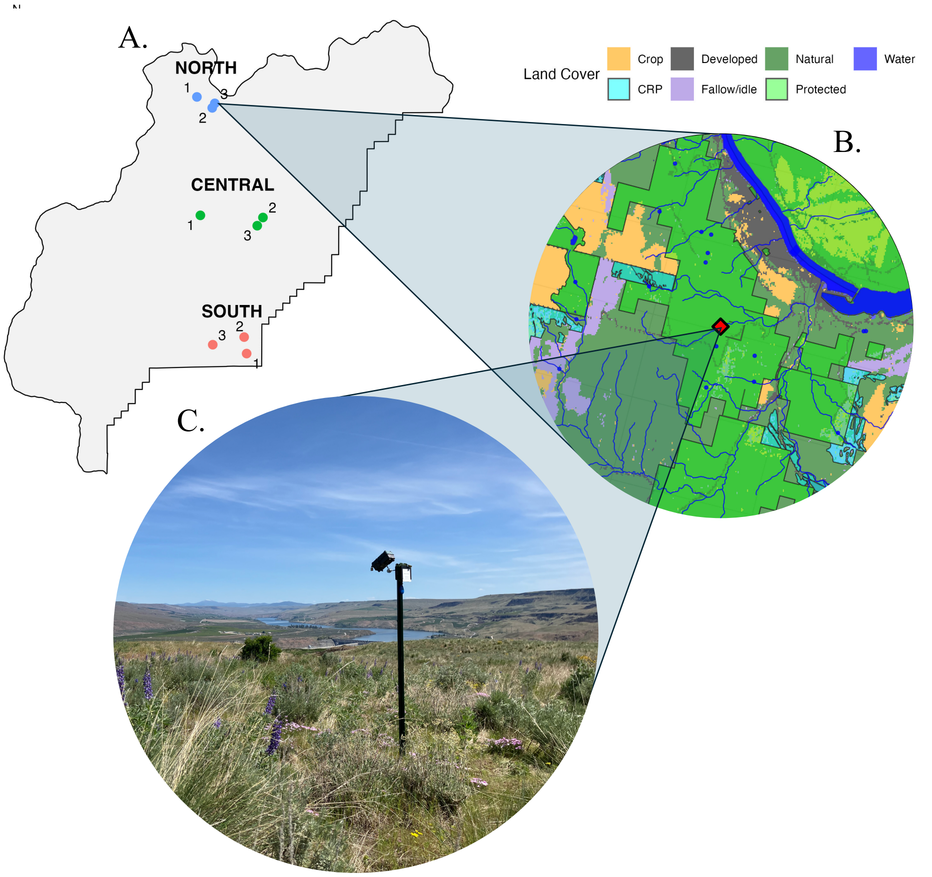

Figure 1. (A) The locations of each of the nine monitoring sites distributed across three regions in Douglas County, Washington. (B) An example map showing the landscape composition around one monitoring location (North region, site 3, 5km buffer). (C) The monitoring array set up at this same location.

Nocturnal Flying Insect Monitoring:

Following previous studies (Ruczyński et al. 2020; Wallace et al. 2023; Dietzer et al. 2024), we monitored nocturnal flying insect abundance using camera traps (Bushnell CORE DS-4K No Glow Trail Camera, Bushnell Outdoor Products, Overland Park, KS, USA) angled up at the sky and programmed to take time lapse photos with infrared flash every minute from sunset to sunrise. We quantified insect abundance in each image using open source, pre-trained machine learning software based on the Mask R-CNN deep learning framework (Camfi; Wallace et al. 2023). Each photographed insect appears as a white streak against a black background, with each "streak" analyzed by the Camfi model to determine the confidence that it is an insect (Figure 2A and 2B). This method provides a reliable approximation of relative insect abundance between sites (Ruczyński et al. 2020; Wallace et al. 2023).

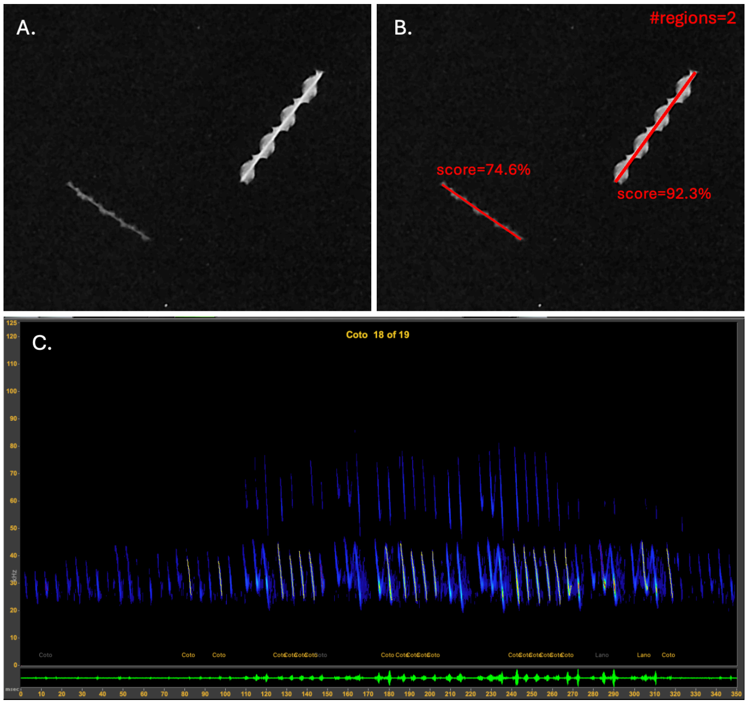

Figure 2. (A) Example camera trap image showing insect streaks. (B) Example output of the same image from the CamFI model, showing insect classifications. (C) Example sonogram analyzed on SonoBat software, showing species classification for *C. townsendii.*

Bat Acoustic Monitoring:

We monitored bats using broad-spectrum, passive acoustic monitors (Wildlife Acoustics Song Meter Mini Bat 2 AA, Wildlife Acoustics, Maynard, MA, USA), which can provide reliable estimates of bat diversity, population densities, habitat associations, and foraging activity (Milchram et al. 2020; Stowell & Sueur 2020; Hoggatt et al. 2024). *C. townsendii* uses relatively low-intensity calls when echolocating, which can make it difficult to detect with acoustic monitors. Nevertheless, due to its non-invasive nature, acoustic monitoring is noted as a preferred method in the WDFW conservation plan for *C. townsendii* (Woodruff & Ferguson 2005).

We recorded continuously from a half hour before sunset to a half hour after sunrise each night, using a sample rate of 256 kHz, minimum trigger frequency of 8 kHz (in order to detect low frequency callers like *E. maculatum*), maximum recording length of 6 sec, trigger window of 3 sec, and left channel gain of 12dB. We analyzed bat sonograms and assigned species classifications using SonoBat software version 30.1, with the "PacNW-Jefferson – eastern Washington" species classification pack, using the defaults of acceptable call quality set to 0.60, the sqnc decision threshold set to 0.90, and the max number of calls to consider set to 32 (Figure 2C). For all potential species classifications from the software for *C. townsendii* and *E. maculatum*, we relied on a regional bat expert, Ted Weller (USFS), to manually vet the classifications.

Weather, Climate, and Landscape Factors:

We logged temperature and relative humidity every 10 minutes at each site throughout the monitoring period using temp–RH loggers (Kestrel Drop 2, Kestrel Instruments, Boothwyn, PA, USA). Temperature and humidity are important predictors of both moth (Intachat et al. 2001) and bat activity (Tuneu-Corral et al. 2020). Using gridMET data (Abatzoglou 2013), we calculated mean temperature and precipitation at one month, four month, three year, 10 year, and 30 year periods before each monitoring date for each site. We quantified the landscape composition in four different buffer radii (2 km, 5 km, 10 km, and 20 km), using the latest versions of the following geospatial datasets: Cropland Data Layer, National Hydrography Dataset, National Land Cover Dataset, USDA CRP Lands, and Protected Areas Database. For each site, we calculated the proportion of each buffer area occupied by: (1) insect-pollinated crops, (2) wind pollinated crops, (3) fallow, (4) pasture/grassland, (5) open water (lakes, ponds), (6) natural habitat, (7) developed land, (8) mean CRP land enrollment between 2022-2024 (total and broken down by CRP practice), and (9) protected area by GAP status. We also calculated (10) the number of point water features (seeps and springs), and (11) the total length of linear water features (streams, rivers) in each buffer.

Data Analysis:

We conducted all statistical analyses and generated all visualizations in R version 4.5.0. Using the vegan package, we tested for variation in bat community composition between sites with PERMANOVA (function adonis2), and visualized with PCoA plots. We performed indicator species analysis (package indicspecies, function multipatt) to determine bat species significantly associated with each monitoring region. We performed redundancy analysis to determine which environmental factors (climate, landscape factors, and insect abundance) contributed to observed variation in bat community composition. Using the acoustic data, we calculated standardized ecological indices used in acoustic bat surveys (Tuneu-Corral et al. 2020) at hourly, nightly and weekly time periods: total detections, species richness ($q = 0$), exponential Shannon index ($q = 1$), and the number of detections per species. We also calculated the number of detections per species at each temporal resolution. We also quantified the number of feeding buzzes per call using SonoBat software, and calculated the proportion of calls containing feeding buzzes, a measure of feeding intensity. We quantified total insect abundance at each temporal resolution from the Camfi model output. We analyzed spatial differences among the nine monitoring sites using linear models followed by Tukey's HSD post-hoc tests to identify significant pairwise differences. To assess temporal variation, we used linear models to test for linear and quadratic trends across the sampling season for each site. We modeled count data (insect abundance, bat detections, species richness, feeding buzzes) using Poisson or negative binomial GLMs when overdispersion was detected, and used standard linear regression for continuous responses (Shannon diversity). We retained quadratic models when the quadratic term was significant, otherwise retaining the linear models.

To analyze the effects of weather, climate, landscape composition, and insect abundance on bat activity and diversity, we used a multi-stage variable selection and modeling framework designed to handle the high-dimensional predictor space and nested structure of our data. First, we organized environmental predictors into six groups: (1) insect abundance; (2) weather and climate; landscape composition within (3) 2 km buffers, (4) 5 km buffers, (5) 10 km buffers, and (6) 20 km buffers. We also included temperature x humidity interaction terms for weather, and precipitation x temperature interaction terms within matching temporal windows for climate. For each response variable and predictor group, we implemented a three-step variable selection approach to identify robust predictors from the high-dimensional predictor space. First, we applied LASSO regression with 10-fold cross-validation using the glmnet package, employing the "lambda.1se" criterion for conservative variable selection. Second, we conducted stability selection using the stabs package with a cutoff of 0.75, per-family error rate of 1, and 1000 bootstrap replicates. Third, we performed random forest analysis using the ranger package with 500 trees and variable importance based on node impurity. We retained variables selected by at least two of the three methods for final model fitting, using the union of all methods when no consensus emerged.

We then used selected predictors to fit generalized linear mixed-effects models (GLMMs) using the glmmTMB package. We employed a nested random effects structure to account for the non-independence of data collected from the same locations and time periods: (1|site) + (1|year) + (1|site:week_of_year), where site represents the nine monitoring locations, year accounts for interannual variation, and the interaction term captures site-specific seasonal patterns. After fitting models with each sub-group of predictors, we fitted global models for reach response combining all predictors selected across sub-models, allowing evaluation of cross-scale variable importance. We used identical random effects structures and model selection procedures for these global models. We chose model families based on response variable characteristics. We modelled continuous diversity indices (e.g., Shannon index) using gaussian distributions. We modelled count responses (detections, feeding buzzes) using Poisson or negative binomial distributions depending on overdispersion (variance-to-mean ratio > 3). We modelled proportion data (feeding buzz proportion) using beta regression after logit transformation. We modelled binary data (e.g., presence or absence of detections from specific species) using binomial distributions. We employed zero-inflated models when zero-inflation was significant. For models with multiple selected predictors, we conducted automated model selection using the MuMIn package with AICc ranking to identify the most parsimonious model structure. For all final models, we performed comprehensive validation using the DHARMa package to test for residual uniformity (Kolmogorov-Smirnov), overdispersion, zero-inflation, and outliers.

Results:

Spatiotemporal Variation in Bat Diversity and Insect Abundance:

Throughout the monitoring period and across all sites, we detected 14 bat species, all species expected in the region, and all of the bat species in Washington state except Keen's myotis (*Myotis keenii*). This included the state candidate species, *C. townsendii*, and all species listed as SGCN and expected in the region: Hoary bat (*Lasiurus cinereus)*, Silver-haired bat (*Lasionycteris noctivagans*), seven *Myotis* species, and Spotted bat (*Euderma maculatum*; Figure 3). There were 23,260 total bat detections assigned to species with the described SonoBat settings, averaging 17 detections per site and night. Total bat detections per species ranged from eight for the rarest species (*E. maculatum*) to 10,475 for the most common (*M. ciliolabrum;* Figure S2). Across the entire monitoring period, total species richness ranged from 10-14 across sites, with nightly species richness varying significantly between sites (Figure S3).

Bat detections, species richness, Shannon diversity, and feeding buzzes were generally highest in the North, followed by the South, and significantly lower in the Central region (Figure S3). Insect abundance did not vary significantly between sites or regions (Figure S4). There was substantial temporal variation in bat detections, species richness, Shannon diversity, and feeding buzzes, which generally peaked during late June-mid July (weeks 25-30; Figure S5). Insect abundance also varied significantly throughout the season, interestingly showing a mid-season lull around the same time that bat metrics peaked, then increasing sharply after July (Figure S6).

Weekly bat community composition differed significantly between the North, Central, and South regions of Douglas county (PERMANOVA: $F_{(2,195)} = 12.19$, $R^2 = 0.11$, $p = 0.001$; Figure 4A). Indicator species analysis revealed eight species significantly associated with the North region (*Myotis lucifugus, Eptesicus fuscus, Myotis thysanodes, Myotis evotis, Myotis yumanensis, Myotis californicus, Antrozous pallidus, Corynorhinus townsendii*), and two species significantly associated with the South (*Myotis ciliolabrum, Myotis volans*). RDA analysis revealed that variation in community composition was partially explained by climate, landscape factors, and insect abundance, with some species associated with wetter vs. warmer conditions, and other species associated with insect-pollinated agriculture and protected/natural land vs. CRP land (Figure 4B).

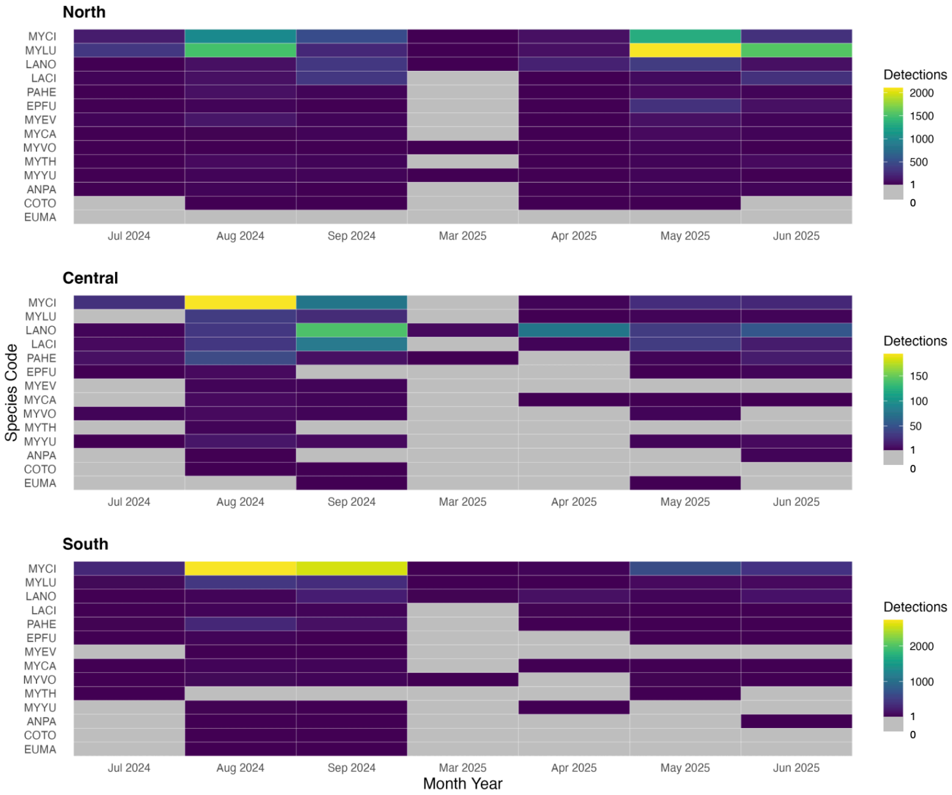

Figure 3. Monthly detections for each of 14 bat species in the North, Central, and South region of Douglas County, with three sites per region pooled. Cells are colored by the number of detections (gray = 0).

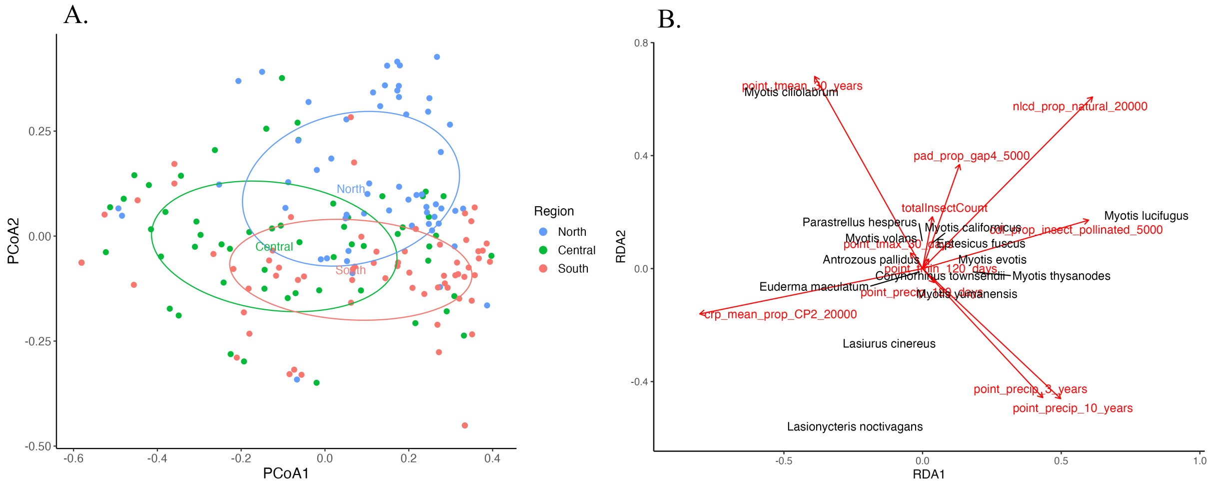

Figure 4. (A) PCoA plot visualizing variation in bat community composition between regions of Douglas County, with repeated samples representing distinct weeks. (B) RDA biplot visualizing environmental factors contributing to differences in community composition between sites. Red arrows represent environmental predictors, with arrow length indicating the strength of each variable's influence, and direction indicating the gradient along which species and sites vary. Black labels indicate species; species positioned closer to a given arrow are more strongly associated with that environmental variable.

Effects of Weather and Climate:

For all GLMM models, results were generally in agreement when using data summarized at nightly and weekly resolutions. Hereafter, we will focus on the results from the nightly models. Due to the number of models with significant terms, we are not displaying statistics and figures for all results, only for a representative sample. Tables of model summaries for all response-predictor combinations at nightly and weekly resolutions are included as supplementary information.

Temperature emerged as the dominant environmental driver across all bat responses, with significant positive effects in most models. Total bat detections ($\beta = 0.73$, 95% CI [0.59, 0.88], $p = < 0.001$; Figure 5A and Table S1), bat species richness, bat Shannon diversity, bat feeding buzzes, and the proportion of bat calls with feeding buzzes increased significantly with both warmer short term (nightly) temperatures, and long term (10 year) minimum temperatures (for total bat detections: $\beta = 0.86$, 95% CI [0.45, 1.27], $p = < 0.001$; Figure 5B and Table S1). Detections for most individual bat species, including *C. townsendii*, also increased significantly with warmer short and long term conditions. Insect abundance also increased significantly with warmer minimum temperatures in the short - medium term (nightly to four months).

Precipitation was a weaker predictor than temperature for bats, but we found that greater precipitation in the preceding four months was negatively correlated with bat Shannon diversity. Several *Myotis* species showed positive correlations with greater long-term precipitation (e.g., Fringed myotis (*Myotis thysanodes*) and Long-eared myotis (*Myotis evotis),* and Yuma myotis (*Myotis yumanensis*)). However, several *Myotis* species also showed negative correlations with greater nighttime relative humidity (Long-legged myotis (*Myotis volans*), California myotis (*Myotis californicus*), California myotis (*Myotis californicus*)).

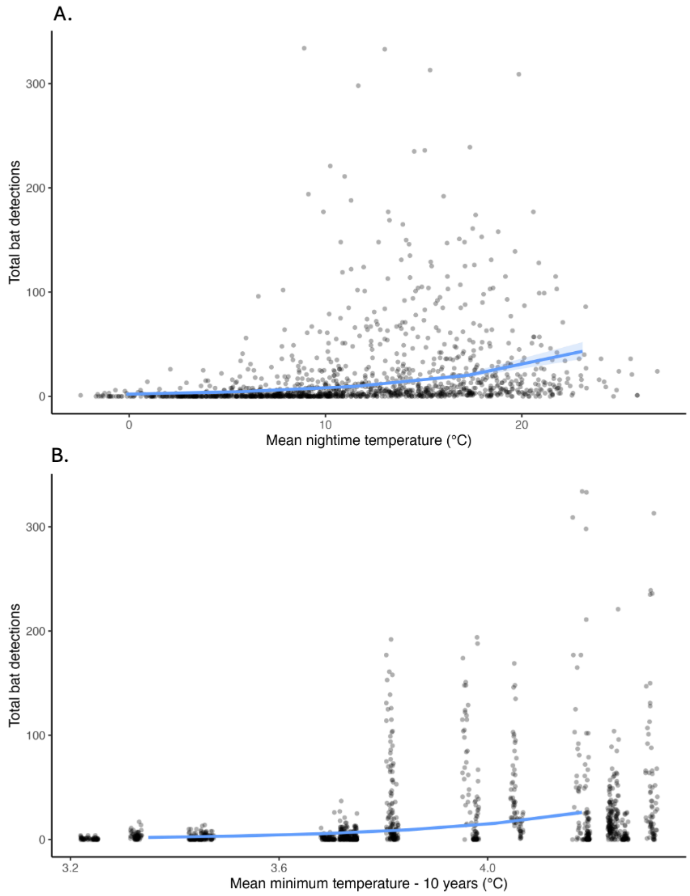

Figure 5. (A) The relationship between total bat detections and mean nighttime temperature. (B) The relationship between total bat detections and mean minimum temperature during the preceding 10 years. Gray points represent raw data while blue lines represent GLMM model fit and 95% CI.

Effects of Agriculture:

At smaller spatial scales (2-5 km), bat detections, species richness (β = 0.39 , 95% CI [0.13, 0.65], p = 0.003; Figure 6A and Table S2), and Shannon diversity all increased significantly with higher proportions of land occupied by insect-pollinated crops. At larger spatial scales (20 km), these metrics decreased significantly when more land was occupied by wind-pollinated crops (for species richness: β = -0.45, 95% CI [-0.65, -0.25], p = < 0.001; Figure 6B and Table S3). Detections for several individual bat species increased significantly with more insect-pollinated crops in the landscape and higher crop diversity, including *C. townsendii*, Silver-haired bat (*Lasionycteris noctivagans*), Fringed myotis (*Myotis thysanodes*), Hoary bat (*Lasiurus cinereus*), Long-eared myotis (*Myotis evotis*), Yuma myotis (*Myotis yumanensis*), and Little brown bat (*Myotis lucifugus*). Although pasture and grassland may have been conflated in the cropland data layer, total bat detections, the proportion of bat calls with feeding buzzes, and the chances of detecting several species (Canyon bat (*Parastrellus hesperus*), Hoary bat (*Lasiurus cinereus*), and Little brown bat (*Myotis lucifugus*)) all increased significantly with more pasture in the surrounding landscape at 10-20 km scales. Total bat feeding buzzes decreased significantly with more fallow land at the 20 km scale.

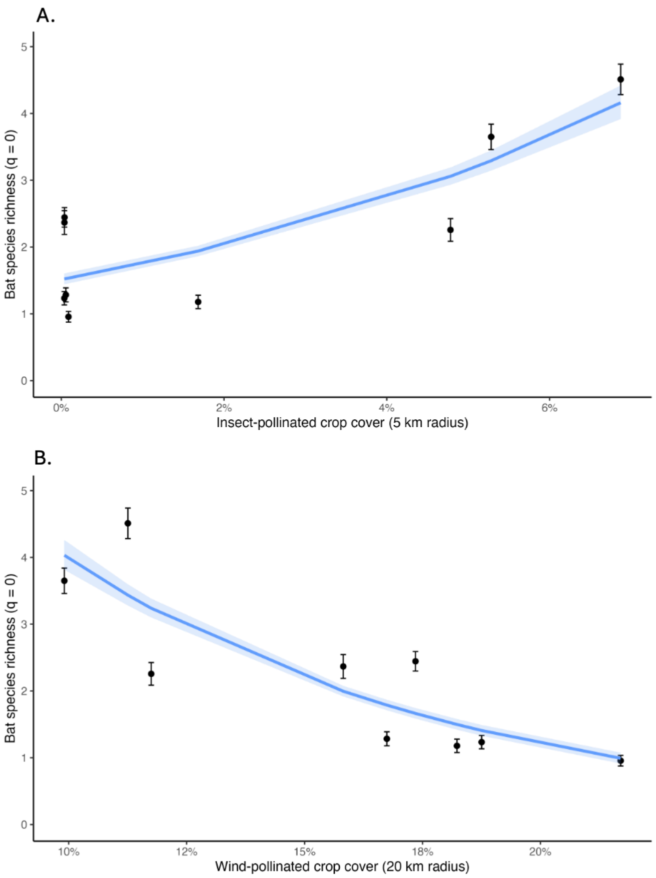

Figure 6. (A) The relationship between total species richness and insect-pollinated crop cover in a 5 km radius. (B) The relationship between bat species richness and wind-pollinated crop cover in a 20 km radius. Raw data is plotted with mean and standard error bars, while blue lines represent GLMM model fit and 95% CI.

Effects of CRP Land:

The proportion of total CRP land in the surrounding landscape showed consistent negative relationships with total bat detections (β = -0.6, 95% CI [-1.02, -0.18], p = 0.005; Figure 7 and Table S4), total bat feeding buzzes, and on the chances of detecting several species including Canyon bat (*Parastrellus hesperus*), Long-legged myotis (*Myotis volans*), and Western small-footed myotis (*Myotis ciliolabrum*). These negative relationships held at multiple spatial scales, and when analyzing individual CRP practices separately. The CRP practices with the strongest negative relationships with bat diversity and activity were CP1 (permanent non-native grasses), CP2 (permanent native grasses), and CP38E/CP38E-4D (wildlife enhancements). For example, the chance of detecting *C. townsendii* was negatively correlated with greater proportion of CRP CP2 cover in a 5 km radius.

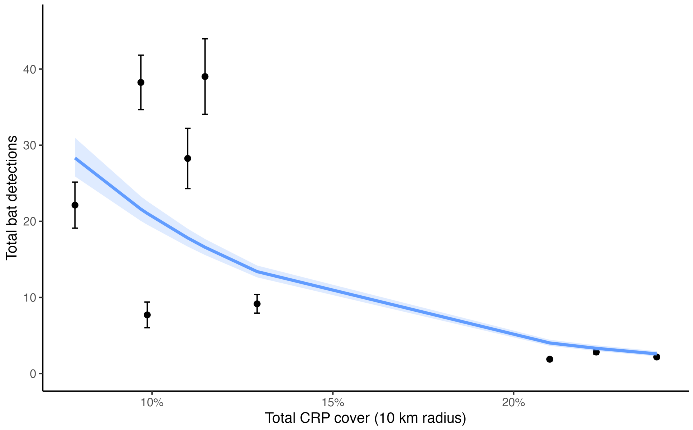

Figure 7. The relationship between total bat detections and total CRP land cover in a 10 km radius. Raw data is plotted with mean and standard error bars, while the blue line represents GLMM model fit and 95% CI.

Effects of Protected Areas and Natural Habitat:

Protected areas (GAP status 1-3) showed no significant relationships with total bat detections, Shannon diversity, or feeding buzzers, but it showed positive relationships with the chances of detecting several species, including Long-eared myotis (*Myotis evotis*), *C. townsendii* and *E. maculatum.* Detections of several species (Canyon bat (*Parastrellus hesperus*), Yuma myotis (*Myotis yumanensis*), and Little brown bat (*Myotis lucifugus*) increased significantly with more natural area at the 20 km scale.

In contrast to the neutral impact of protected land, land with no known protected status (GAP status 4) had consistent positive relationships with community-level bat metrics. Bat Shannon diversity increased significantly with more GAP status 4 land cover at 5 km, 10 km (β = 0.52, 95% CI [0.3, 0.75], p = < 0.001; Figure 8 and Table S5), and 20 km scales, while species richness also increased significantly with more GAP status 4 land cover at 10 km scales. Also at 5-20 km scales, the chance of detecting several species increased significantly with more GAP status 4 land, including Big brown bat (*Eptesicus fuscus*), Pallid bat (*Antrozous pallidus*), Silver-haired bat (*Lasionycteris noctivagans*), and Western small-footed myotis (*Myotis ciliolabrum*).

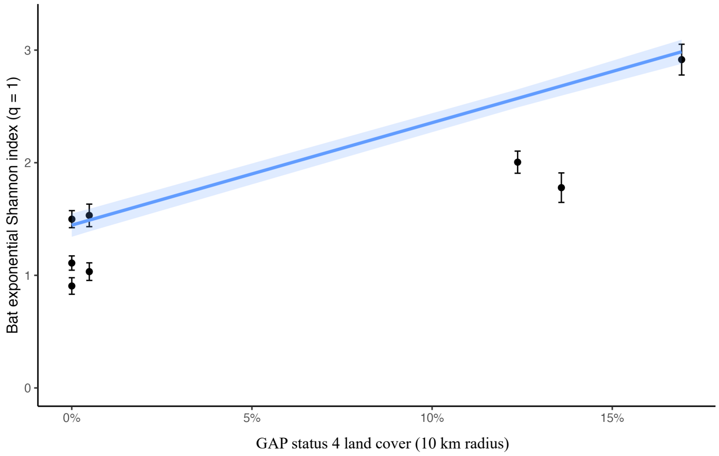

Figure 8. The relationship between bat Shannon diversity and GAP status 4 land cover in a 10 km radius. Raw data is plotted with mean and standard error bars, while the blue line represents GLMM model fit and 95% CI.

Effects of Developed Land:

Detections for several bat species (Silver-haired bat (*Lasionycteris noctivagans*) and Hoary bat (*Lasiurus cinereus*) increased significantly with more developed land at 5-10 km scales, while they decreased significantly for Spotted bat (*Euderma maculatum*).

Effects of Water Features:

Out of the three water feature categories (polygon for lakes and ponds, linear for rivers and streams, and point for springs and seeps), point water features (springs and seeps) had the strongest positive effect on bat responses. Total bat detections (β = 0.49, 95% CI [0.07, 0.91], p = 0.021; Figure 9 and Table S4), bat Shannon diversity, total bat feeding buzzes, the proportion of calls with feeding buzzes, and the chance of detecting several species (e.g., Big brown bat (*Eptesicus fuscus*) and Little brown bat (*Myotis lucifugus*)) all increased significantly with more springs and seeps in the surrounding landscape (2-10 km scales). Detections of Western small-footed myotis (*Myotis ciliolabrum*) increased significantly with more linear water features (streams, rivers).

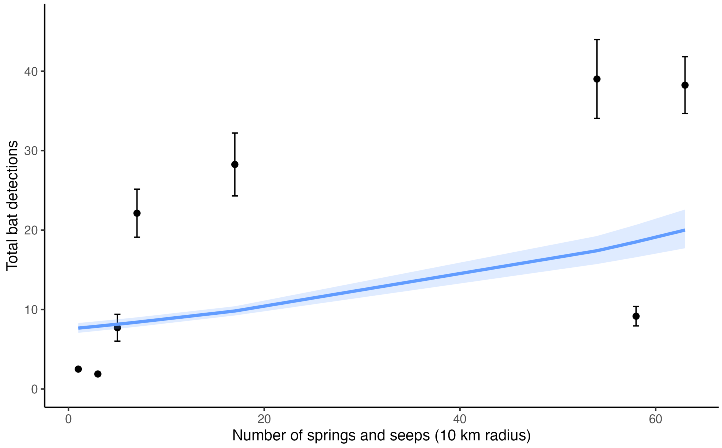

Figure 9. The relationship between total bat detections and the number of springs and seeps in a 10 km radius. Raw data is plotted with mean and standard error bars, while the blue line represents GLMM model fit and 95% CI.

Effects of Nocturnal Flying Insects:

In general, insect abundance had less of an effect on bat activity and diversity than climate and landscape factors. However, while the model had low explanatory power, (marginal R2 = 0.02), total bat feeding buzzes increased significantly with higher insect abundance (β = 0.36, 95% CI [0.1, 0.62], p = 0.006; Figure 10 and Table S6). Additionally, when analyzed at hourly time scales throughout the night, we found that bat detections and feeding buzzes generally followed the same temporal trends as insect abundance, with greater correlation from sunset to just before sunrise, after which insect abundance spiked without a corresponding spike in bat activity (Figure 11).

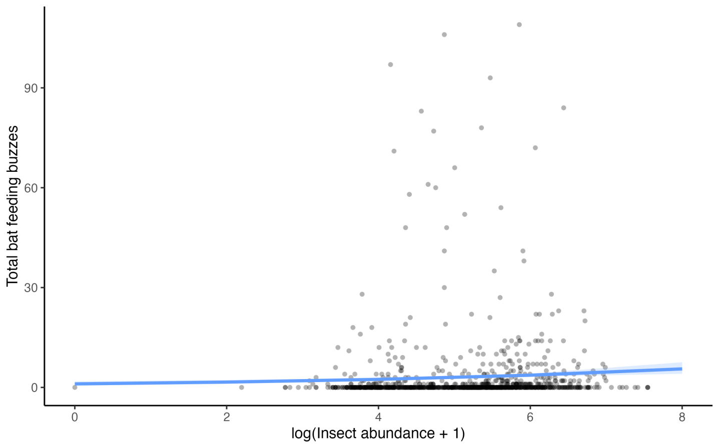

Figure 10. The relationship between total bat detections and insect abundance. Gray points represent raw data, while the blue line represents GLMM model fit and 95% CI.

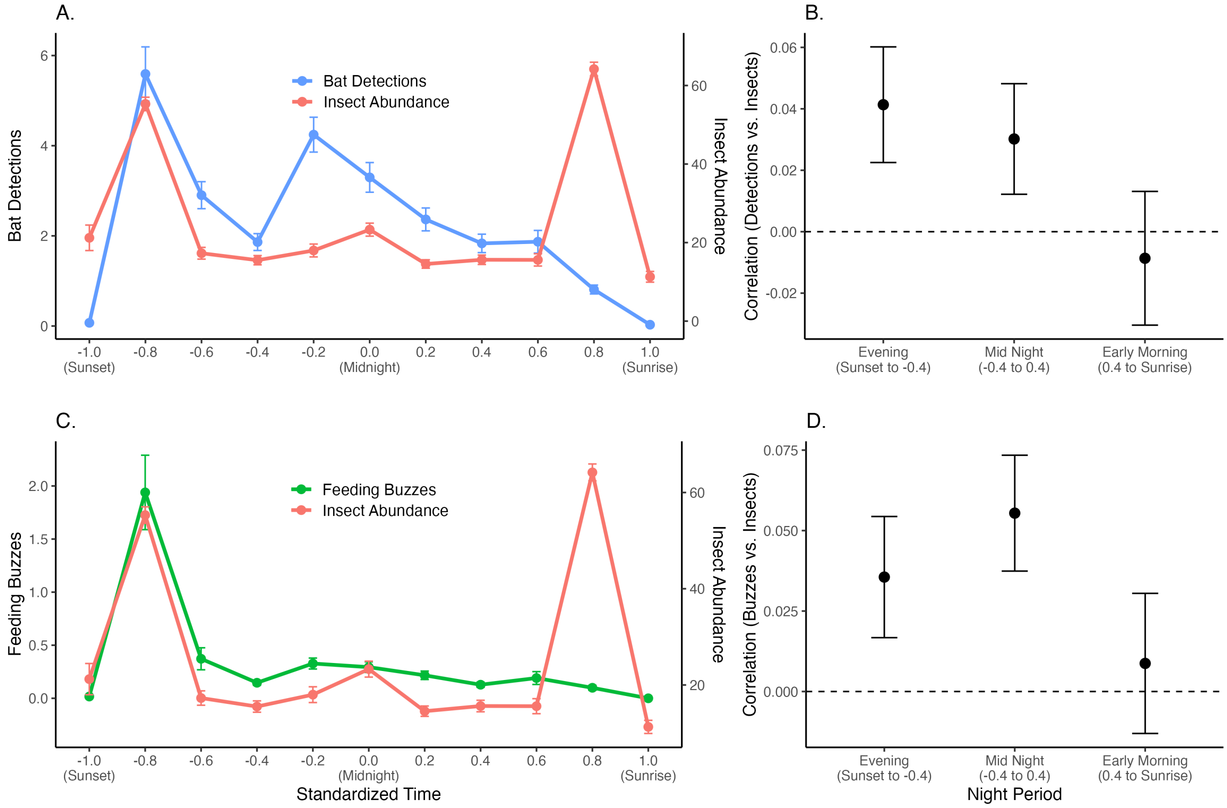

Figure 11. (A) Bat detections and insect abundance at standardized intervals between sunset and sunrise, summarized across all sampling nights with mean and standard error bars displayed. (B) The correlation between bat detections and insect abundance during different time intervals, summarized across all sampling nights with mean and standard error bars displayed. (C) Bat feeding buzzes and insect abundance at standardized intervals between sunset and sunrise, summarized across all sampling nights with mean and standard error bars displayed. (D) The correlation between bat feeding buzzes and insect abundance during different time intervals, summarized across all sampling nights with mean and standard error bars displayed.

Townsend's Big-eared Bat:

We detected *C. townsendii* a total of 19 times across six sites and all three regions, in August and September 2024, and April and May 2025 (Figure 12). The species was most common in, and significantly associated with the Northern region of Douglas County. Although the models were data-deficient, we found evidence that the chances of detecting *C. towsendii* increased significantly with warmer minimum temperatures during the preceding four months, more GAP status 2 protected area at the 20 km scale (β = 0.63, 95% CI [0.14, 1.12], p = 0.011; Figure 13A and Table S7), and higher crop diversity at the 10 km scale (β = 0.62, 95% CI [0.14, 1.11], p = 0.0011; Figure 13B and Table S8). In contrast, the chances of detecting *C. townsendii* decreased with more CRP CP2 land (permanent native grasses) at the 5 km scale.

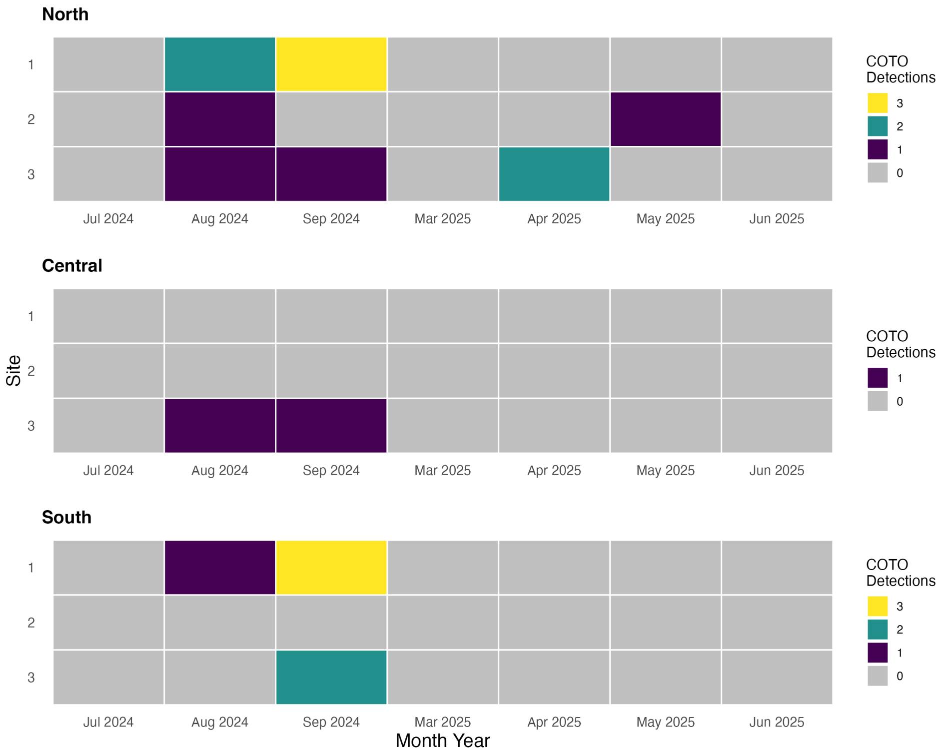

Figure 12. Monthly detections for *C. townsendii* at each of the three sites in the North, Central, and South regions of Douglas County. Cells are colored by the number of detections.

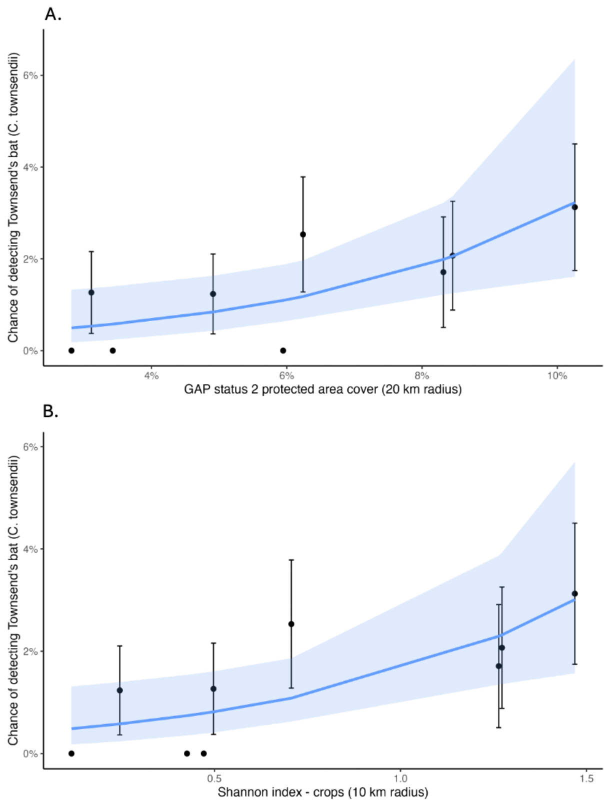

Figure 13. (A) The relationship between the chance of detecting *C. townsendii* and GAP status 2 protected area cover in a 20 km radius. (B) The relationship between the chance of detecting *C. townsendii* and the Shannon diversity of crops in a 10 km radius. Raw data is plotted with mean and standard error bars, while blue lines represent GLMM model fit and 95% CI.

Discussion:

Key Findings:

Several of the strongest relationships observed in this study corroborate known predictors of bat diversity and activity. Warmer nighttime and long-term minimum temperatures were consistently the strongest predictors of bat activity, diversity, and feeding behavior, reinforcing the importance of climate in structuring bat communities. The positive effects of springs and seeps on bat diversity and activity highlight the critical importance of water resources for bats, especially in arid shrubsteppe ecosystems. Even these small water features likely serve multiple functions for bats—providing drinking water, supporting increased insect abundance and diversity, supporting trees for roosting, and creating thermal refugia during extreme weather events. Our results highlight that protected areas in agricultural regions should encompass such water features in order to better support bats.

We found that having more protected land (GAP status 1-3) in the landscape increased the chances of detecting several species. Although the models were data-deficient due to a low number of detections, it is interesting to note that the two rarest (and vulnerable) species, *C. townsendii* and *E. maculatum*, responded more positively to protected areas (GAP status 2 and 3, respectively) than other more common species, perhaps indicating that these species are especially in need of protected habitat.

However, at the community level, we found that bats responded more positively to land with no known protected status (GAP status 4, which may include private land and agriculture). This counterintuitive finding may be due to the fact that the protected land in this region is largely managed for endangered species like the Pygmy rabbit (*Sylvilagus idahoensis*) and the Greater sage-grouse (*Centrocercus urophasianus*), and not specifically for bats. As discussed below, bats may also prefer and be drawn to areas with diverse insect-pollinated agriculture in this region, perhaps due to increased densities of insect prey. Furthermore, it is important to note that GAP status does not measure *effectiveness* of management to protect biodiversity. Indeed, GAP status 4 land, while not necessarily managed for biodiversity, may nevertheless encompass large swathes of habitat that are suitable for bat foraging. It is also important to note that many of the GAP status 4 lands in this region may encompass water features, and thus this effect may be more of an indication of bats' response to water than to protected land.

Our finding that CRP lands consistently showed negative associations with bat diversity may have several explanations. First, it is important to note that the sites with the highest proportion of CRP land in surrounding landscape were the three sites in the Central region of Douglas County (Figure S1A), which also consistently showed the lowest bat diversity and activity (Figure S3). This may be explained by other factors besides CRP land, including the fact that these sites also had lower proportions of protected land surrounding them (Figure S1B). Nevertheless, it is surprising that these negative effects were consistent across multiple CRP practices and spatial scales, with the strongest associations observed for CP1 and CP2 (non-native and native grass plantings) and CP38E (wildlife enhancement) practices. Overall, these results points to the need for additional studies to determine what unmeasured factors may be contributing to this effect. For example, CRP contracts have varying ages and durations, and younger contracts may represent recently restored land that has not yet yielded biodiversity benefits. It may also be the case that the types of habitats restored by the CRP in this region are not preferred by bats, or that they do not encompass features like water sources that bats require. However, it is also possible that current CRP implementation may create simplified habitats that do not adequately support the insect communities required by specialist predators, including many moth-specialist bats like *C. townsendii*.

The contrast between CRP effects and the positive impacts of insect-pollinated crops reveals an important ecological distinction: well-managed, diversified agricultural systems with many flowering crops may provide more valuable foraging habitat for bats even than certain types of habitat restoration. This may in part be due to these diversified crop systems attracting and supporting large numbers of insect prey, including nocturnal pollinators like moths, and pest species. Indeed, although overall insect abundance showed only modest effects on bat responses, feeding buzzes increased significantly with higher insect abundance, and nightly temporal patterns in bat activity generally mirrored insect abundance. Our results thus emphasize bats' key pest control services in agricultural regions, and stress the importance of protecting and restoring habitat that supports populations of insect prey. This may be especially important for the conservation of threatened, moth-specialist species like *C. townsendii*. Our finding that bat diversity and activity is negatively associated with more wind-pollinated crops at large spatial scales also suggests that simplified agricultural systems—common for cereal grain monocultures—may not adequately support bats, perhaps in part due to heavy chemical input that suppresses populations of insect prey.

Our detection of *C. townsendii* across multiple sites and regions, while limited in total numbers, provides valuable updated distribution information for this candidate species. The species' positive association with GAP status 2 protected areas and high crop diversity, combined with negative responses to CRP grasslands, may suggest that Townsend's bat benefits from intermediate levels of human management that maintain habitat complexity and diverse prey communities, including landscape-scale approaches that encourage agricultural diversity rather than monoculture systems. The strong regional association with northern Douglas County indicates this area should be prioritized for targeted conservation efforts.

Methodological Advances and Limitations:

Our validation of camera trap-based insect monitoring and acoustic bat surveys coupled with post-processing using machine learning demonstrates the effectiveness of these non-invasive techniques for large-scale wildlife monitoring. The temporal resolution achieved through continuous monitoring revealed important diel and seasonal patterns that would be missed by traditional survey approaches, providing a foundation for long-term monitoring programs essential for adaptive management.

Although the camera trap-based insect monitoring was generally successful, one limitation is its inability to distinguish between insect groups or species. This may partially explain the low predictive power of our detected insect abundance for bat diversity and activity. Bats likely track the densities of their preferred insect prey, which varies by species, and which this methodology cannot identify. Future efforts should focus on using automated monitoring techniques (e.g., moth light traps) that can identify insect groups and species. Furthermore, there were several obstacles encountered in the field that led to gaps in the monitoring data. For instance, we discovered that birds likely enjoyed resting and defecating on the cameras, obscuring the lenses in several instances. This could be avoided by attaching bird deterrents to the cameras. One of the cameras also suffered a complete failure during the 2025 monitoring, resulting in a loss of data from one of the sites.

Additionally, while acoustic monitoring offers a powerful tool for broad-scale bat surveys, detection biases for low-intensity callers like *C. townsendii* remain a limitation. The two-year monitoring period, while intensive, represents a snapshot that does not capture longer-term population trends or responses to extreme climate events. Expanding monitoring to additional regions within the Columbia Plateau would help determine the broader applicability of our findings.

Future Research Priorities:

Future research should focus on: (1) detailed vegetation and insect community assessments within protected and CRP lands to understand mechanisms underlying bat responses; (2) experimental manipulation of CRP management practices to identify modifications that better serve multiple conservation objectives; (3) expanded monitoring, including roost identification and landscape habitat suitability modeling for *C. townsendii* and other SGCN species in the Colombia Plateau; (3) coupling bat acoustic monitoring with automated insect monitoring approaches that are able to assess insect diversity, rather than just total abundance.

Conclusions:

This study provides a comprehensive assessment of how bat diversity and activity are affected by climate, land use, and insect abundance in the Columbia Plateau, advancing evidence-based bat conservation in one of North America's most important agricultural regions. We successfully documented all 14 expected bat species, including all SGCN expected in the region, and the candidate species *C. towsendii*, demonstrating that these agricultural landscape support significant bat diversity. Temperature emerged as the primary driver of bat activity, with consistent positive effects across species and temporal scales. Agricultural practices showed contrasting effects: diverse, insect-pollinated crops enhanced bat diversity and activity while current CRP practices and wind-pollinated monocultures showed negative associations. Protected areas and natural water sources, particularly springs and seeps, provided critical habitat components for supporting diverse bat assemblages, especially for *C. townsendii* and other SGCN.

At the culmination of this study, we have successfully achieved our three major objectives: (1) We comprehensively evaluated the effects of climate, insect abundance and agroecological land use on bat diversity and activity across Douglas County. (2) We provided updated distribution, population density, and habitat association data for *C. townsendii* and other SGCN species, providing WDFW with current information on population status across Douglas County's threatened shrubsteppe habitats. And (3) We successfully validated low-cost, scalable camera trap and acoustic monitoring techniques suitable for future assessments of insect and bat communities.

Conservation Implications:

Our results indicate that effective bat conservation in agricultural landscapes requires integrated, evidence-based approaches that balance agricultural productivity with maintaining habitat quality. The current structure of major conservation programs may require modification to better serve insectivorous wildlife communities. Our results suggest that conservation strategies for rare and vulnerable species like *C. townsendii* should emphasize protected area expansion, including protecting critical habitat features such as water sources, alongside diversified crop systems. Furthermore, given the strong temperature-activity relationships we detected, climate adaptation should be integrated into conservation planning. Maintaining habitat connectivity and resource availability will be essential for allowing bat populations to respond to shifting environmental conditions.

Management Recommendations:

Based on our findings, we recommend that WDFW and other management agencies consider the following tiered management priorities:

Short term goals:

- Reassess current CRP and protected land management practices for their value to bat communities, and incorporate habitat features that better support bats and their insect prey
- Prioritize protection of springs, seeps, and other water sources in conservation planning
- Focus *C. townsendii* conservation efforts in northern Douglas County

Medium-term goals:

- Develop incentive programs for agricultural practices that support insect-pollinated crop diversity, especially within 5 km of key bat habitat patches
- Expand protected area in key bat habitat areas for rare and vulnerable species
- Establish long-term bat and insect monitoring protocols using validated passive techniques

Long-term Goals:

- Develop landscape-scale conservation frameworks that optimize both agricultural production and wildlife habitat
- Build partnerships with agricultural stakeholders to implement bat-friendly farming practices
- Integrate climate change projections into bat habitat conservation planning

Attachments:

Supplementary Materials:

- **Cosma_WDFW25_supplements.docx:** Supplemental table and figures
- **Cosma_WDFW25_modelSummaryNight_2025.csv**: All GLMM model summaries at nightly resolution
- **Cosma_WDFW25_modelSummaryWeek_2025.csv:** All GLMM model summaries at weekly resolution.

Datasets:

- **Cosma_WDFW25_allBatData.csv:** Complete dataset of all bat detections throughout the study period, by monitoring location and date, with species classification data from SonoBat software.

Acknowledgments:

We would like to thank the Washington Department of Fish and Wildlife for funding this study; Abigail Tobin (WDFW) for scientific input on bat biology and monitoring; and Ted Weller (USFS) for scientific input on bat biology and monitoring, and assistance with manual vetting.

Other Comments:

As requested by WDFW, we are working with Ted Weller (USFS) to confirm each bat species presence per site and month by manually vetting a subset of the recordings. Following completion of manual vetting, we will submit final, vetted species by month by site datasets to WDFW, and submit the data in a standardized format to BatAMP (https://batamp.databasin.org/).

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