

THE EFFECTS OF ANTHROPOGENIC
SENSORY POLLUTION ON ARTHROPOD DIVERSITY AND POLLINATOR
BEHAVIOR

Graduate Thesis

By

SIERRA DEE RODRIGUEZ

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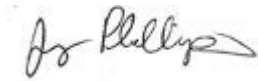
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SIERRA DEE RODRIGUEZ

Approved as to style and content by:



Jennifer, Phillips, Ph. D.
Assistant Professor
(Chair of Committee)



Jose Rodolfo, Valdez Barillas, Ph. D.
Associate Professor
(Committee Member)



Jenny, Hazlehurst, Ph. D.
Assistant Professor
(Committee Member)

ABSTRACT

The Effects of Anthropogenic

Sensory Pollution on Arthropod Diversity and Pollinator Behavior

(April 2023)

Sierra Dee Rodriguez, B.Sc., Texas A&M University – San Antonio

Graduate Thesis Chair: Dr. Jennifer N. Phillips

Pollinators provide a key ecological function in terrestrial ecosystems, yet in recent years, they have encountered unprecedented declines, likely due to anthropogenic change. Light and noise pollution, which can interfere with the visual and auditory systems of animals that regulate daily behaviors, are important factors to consider when communities are encroached by human development. While many researchers have looked at how vertebrate species behaviorally react to human caused habitat degradation and sensory pollution, little is known about how invertebrates, including arthropod pollinators, are affected, and whether there is a negative cascading effect on the plants that they pollinate. This research investigates threats to arthropod biodiversity and pollination services from light pollution and noise pollution with field observations and experiments. This research is unique and is an important first step to understanding why arthropods and arthropod pollinators are in decline and will inform land managers in important conservation action.

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I. RESULTS, TABLES, & FIGURES

Pitfall Trap Order Richness

Two models were competitive within 2 AICc for order Richness. First, a model that included both continuous variables, noise and light, and secondly, a model that uses categorical Treatment (Table 1A). The first model indicates a significant positive effect of both noise and light on order richness (Table 1B, Figure 1.). The second ranked model that includes treatment suggests that Light+Noise Treatment are associated with a significant increase in Total orders (Table 1C, Figure 1.)

Table 1A: Model selection results for order Richness where a model with Noise Level (LAeq) and Light Level (Lux) are the top model predictors.

Model	Intercept	LAeq	Lux	Treatment	df	logLik	AICc	delta wi	wi
4	9.34	0.4	0.42		5	-245.65	501.8	0.00	0.37
5	8.63	-	-	+	6	-245.37	503.5	1.66	0.16
3	9.34	-	0.36		4	-247.89	504.1	2.3	0.12
2	9.40	0.33	-		4	-248.13	504.6	2.8	0.09
7	8.79	-	0.26	+	7	-244.86	504.7	2.91	0.08
6					7	-245.05	505.1	3.29	0.07
1	9.40	-	-		3	-249.69	505.6	3.75	0.06
8	8.96	0.24	0.25	+	8	-244.57	506.5	4.64	0.04

Table 1B: Results of top model where Light level (Lux) and Noise level (LAeq) both positively affect order richness.

Random Effects

Groups	Name	Variance	SD
Section	(Intercept)	0.84	0.92
Residual		3.44	1.86

Number of Observations: 118 Groups: Section 6

Fixed Effects

	Estimate	SE	df	t	p	
(Intercept)	9.3952	0.41	5.7687	22.795	< 0.0001	***
Light Level (Lux)	0.4241	0.18	115.5238	2.307	0.0228	*
Noise Level (LAeq)	0.3984	0.19	116.2121	2.145	0.0340	*

Table 1C: Random Effects for Insect Order Richness ~ Treatment, the second ranked model within 2 AICc.

Groups	Name	Variance	SD
Section	(Intercept)	0.7638	0.8739
Residual		3.4401	1.8548

	Estimate	SE	df	t	p	
(Intercept)	8.63	0.49	14.21	17.55	< 0.0001	***
Light	0.88	0.48	112.07	1.83	0.07	
Light+Noise	1.43	0.48	112.07	2.15	0.004	*
Noise	0.77	0.48	112.04	1.60	0.11	

Tukey's T-Test, pairwise comparison, Linear Hypotheses:

Linear Hypotheses:	Estimate	SE	z	p	
Light vs. Control	0.88	0.48	1.83	0.26	
Light+Noise vs. Control	1.43	0.48	2.97	0.02	*
Noise vs. Control	0.77	0.48	1.60	0.38	
Light+Noise vs. Light	0.55	0.49	1.13	0.67	
Noise vs. Light	-0.12	0.48	-0.24	1.00	
Noise vs. Light+Noise	-0.67	0.48	-1.38	0.51	

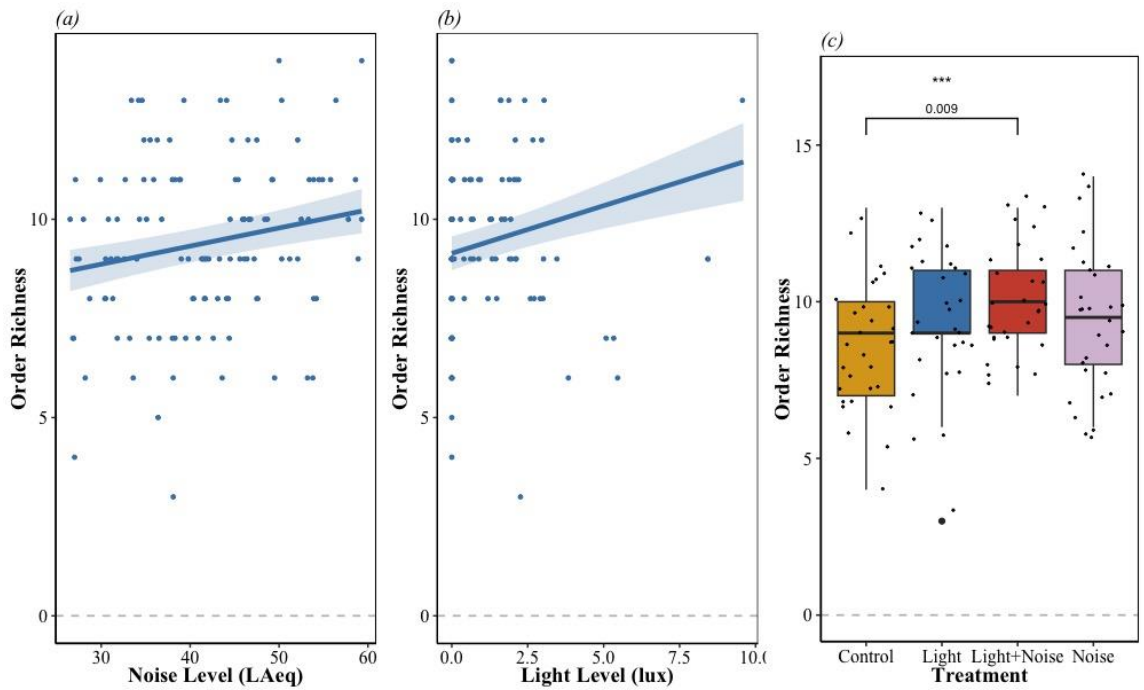


Figure 1. The first ranked model indicates a significant positive effect of both noise and light on order richness (a), (b). Order Richness is increased in Light+Noise Treatments across our four treatment types (c). Where we find significance between our top model predictors of Light+Noise and Control with a p-value of 0.009.

Pitfall Trap Arthropod Abundance

For pitfall trap arthropod abundance, the top model is the null model, and the next highest model was not competitive as it was greater than 2 AICc (2.08), and therefore it was not examined. We find no significant effect from any of our predictor variables on insect abundance.

Table 2A: Candidate Models for Abundance ~ Treatment + LAeq + Lux

Model	Intercept	LAeq	Lux	df	logLik	AICc	Δw_i
1	332.0			2	-976.87	0.00	0.48
3	332.0		14.61	3	-976.85	2.08	0.17
2	332.0	-13.00		3	-976.86	2.08	0.17

Pitfall Trap Evenness

Two models were within 2 AICc of the top ranked null model for pitfall trap evenness (Table 3A). First, a model that included continuous variable Noise (LAeq), and the second model included continuous variable Light (Lux). There was no significant effect from noise or light on evenness across treatment types. Therefore, we find no difference in evenness between our four treatment types.

Table 3A: Candidate Models for Evenness ~ Treatment + LAeq + Light Level. The null model is ranked first, followed by a model with Noise only.

Model	Intercept	LAeq	Lux	Treatment	df	logLik	AICc	Δw_i	w_i
1	1.27	-	-		2	-34.73	73.6	0	0.41
2	1.27	-0.03	-		3	-34.35	74.9	1.35	0.21
3	1.27	-	0.02		3	-34.52	75.3	1.69	0.17
4	1.27	-0.02	0.01		4	-34.24	76.8	3.28	0.08
5	1.30	-	-	+	5	-33.23	77	3.43	0.07
7	1.32	-	0.02	+	6	-33.03	78.8	5.25	0.03
6	1.31	0.01	-	+	6	-33.18	79.1	5.56	0.03
8	1.33	0.02	0.03	+	7	-32.95	80.9	7.36	0.01

Fixed Effects

	Estimate	SE	t	p	
(Intercept)	1.267	0.03	42.19	< 0.0001	***
Noise Level (LAeq)	-0.026	0.03	-0.86	0.39	

Fixed Effects

	Estimate	SE	t	p	
(Intercept)	1.267	0.03	42.13	< 0.0001	***
Light Level (Lux)	0.019	0.03	0.64	0.525	

Pitfall Trap β -diversity

We find support that treatment affects arthropod order composition (Table 4A).

Specifically, this pattern appears to be driven by differences in continuous noise level

(LAeq) (Table 4B), not light (Table 4C). We find using the multi-level pattern analysis

that there are three species of arthropods significantly associated with Control, Noise, and

Light treatment types (Table 4E).

Table 4A. PERMANOVA values for arthropod order composition (i.e. β -diversity) across four treatments.

	Df	SumsOfSqs	R2	F	p	
Treatment	3.00	0.49	0.05	1.90	0.01	***
Residual	114.00	9.73	0.95	-	-	
Total	117.00	10.21	1.00	-	-	

Table 4B. PERMANOVA values for arthropod order composition (i.e. β -diversity) across continuous noise levels (LAeq).

	Df	SumsOfSqs	R2	F	p	
Noise Level (LAeq)	1.00	0.44	5.31	0.04	0.001	***
Residual	116.00	9.77	-	0.96	-	
Total	117.00	10.21	-	1.00	-	

Table 4C. PERMANOVA values for arthropod order composition (i.e. β -diversity) across continuous light levels (lux).

	Df	SumsOfSqs	R2	F	p
Light Level (lux)	1	0.11	0.01	1.28	0.25
Residual	116	10.10	0.99	-	-
Total	117	10.21	1.00	-	-

Table 4D. NMDS Centroid table

Pitfall Centroids:	NMDS1	NMDS2	NMDS3	NMDS4
Control Treatment	-0.0685	-0.0433	-0.0575	0.0534
Light Treatment	-0.0694	0.0376	-0.0023	-0.0825
Light+Noise Treatment	0.1214	0.0221	0.0534	-0.0614
Noise Treatment	0.0182	-0.0143	0.0081	0.0857

Table 4E. Multi-level pattern analysis indicates the following arthropod three species are significantly associated with treatment types.

Family	Treatment	stat	p
Pseudoscorpiones	Noise	0.987	0.013 *
Thysanura	Light, Noise	0.912	0.028 *
Collembola	Control, Light, Noise	0.997	0.001 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Sticky Trap Abundance

For total number of arthropods across our four treatment types, we found significance with our top model predictors of Control and Light, and significance between Light and Noise where the p-values were both greater than 0.001. Light attracts significantly higher abundances of arthropods compared to control treatments. The relationship between Light alone and Noise alone is significant, where higher insect abundances are present in Light alone, compared to Noise alone where the significance of both relationships are

$p < 0.001$ (Table 5A, Figure 2). Conversely, the Noise treatment did not have a significant effect on insect abundances compared to Control treatment ($p = 0.956$).

Table 5A. Model parameters for sticky trap Abundance ~ Treatment.

	Estimate	SE	df	t	p	
(Intercept)	34.55	7.23	75	4.78	< 0.001	***
Light	40.35	10.22	75	3.95	< 0.001	***
Light+Noise	19.75	10.22	75	1.93	0.05	.
Noise	-5.68	11.04	75	-0.52	0.61	

Linear Hypotheses

	Estimate	SE	Z	p	
Light vs. Control	40.35	10.22	3.95	< 0.001	***
Light+Noise vs. Control	19.75	10.22	1.93	0.214	
Noise vs. Control	-5.68	11.04	-0.52	0.956	
Light+Noise vs. Light	-20.6	10.22	2.02	0.182	
Noise vs. Light	-46.03	11.04	-4.17	< 0.001	***

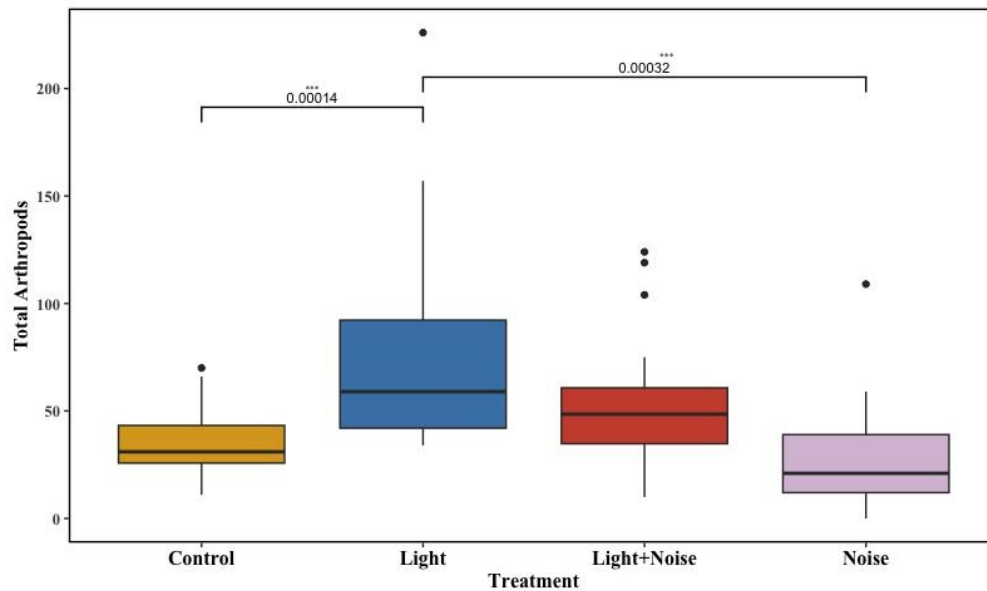


Figure 2. The Linear Hypothesis table and Figure 2. illustrate the relationships between light and control; and noise and light are significant where the p-value is < 0.001.

Pollinator Observation

For total pollinator visits, AICc model selection indicates that the null model is the top model, followed by three models within 2 Δ AICc (Table 6A). The second ranked model included treatment, temperature, and the number of flowers (Table 6B). The third ranked model included continuous noise variable LAF90 + Temperature + the number of flowers on the observation plant (Table 6A). The third ranked model was treatment alone (Table 6A). The third ranked model (LAF90 + Temp + No. FH) indicates a there is significance in the relationship between the number of total pollinators observed and the number of flowers available, where the p-value was 0.01 (Table 6B, Figure 3). The number of flower heads is significant in this model where the p-value is 0.01, the estimate = 0.006, SE = 76.62, df = 76.62, t = 2.61. Flower heads was the only significant fixed effect in this model. Additional post-hoc examination of a dependent variable, visits/flowerheads, did not alter any patterns, suggesting no effects of sensory pollutants on pollinator visitation rates as measured.

Table 6A. Total Pollinator Visits Model Selection

	K	AICc	ΔAICc	AICc w_i	Cum. w_i	LL
Null	4	275.05	0	0.27	0.27	-133.31
Treatment + Temp + No. FH	7	275.35	0.30	0.24	0.51	-130.04
LAF90 + Temp + No. FH	7	275.44	0.39	0.22	0.73	-130.09
Treatment	5	276.97	1.92	0.10	0.84	-133.16
LAF90	5	277.17	2.12	0.09	0.93	-133.26
Treatment + Temp	6	279.10	4.05	0.04	0.97	-133.08
LAF90 + Temp	6	279.27	4.23	0.03	1	-133.17

Table 6B. Model results for the third ranked model: Treatment + Temp + No. of Flower Heads Model.

Groups	Name	Variance	SD
Flower Type	(Intercept)	0.1105	0.3324
Color	(Intercept)	0.04918	0.2218
Residual	0.75549	0.8692	

	Estimate	SE	df	t	p	
(Intercept)	3.8437	1.1011	63.9847	3.491	< 0.0001	***
Noise Treatment	0.0906	0.1836	90.9062	0.493	0.62	
Temperature	-0.0004	0.0155	58.2168	-0.028	0.98	
No. of Flower Heads	0.0063	0.0024	76.6229	2.616	0.010	*

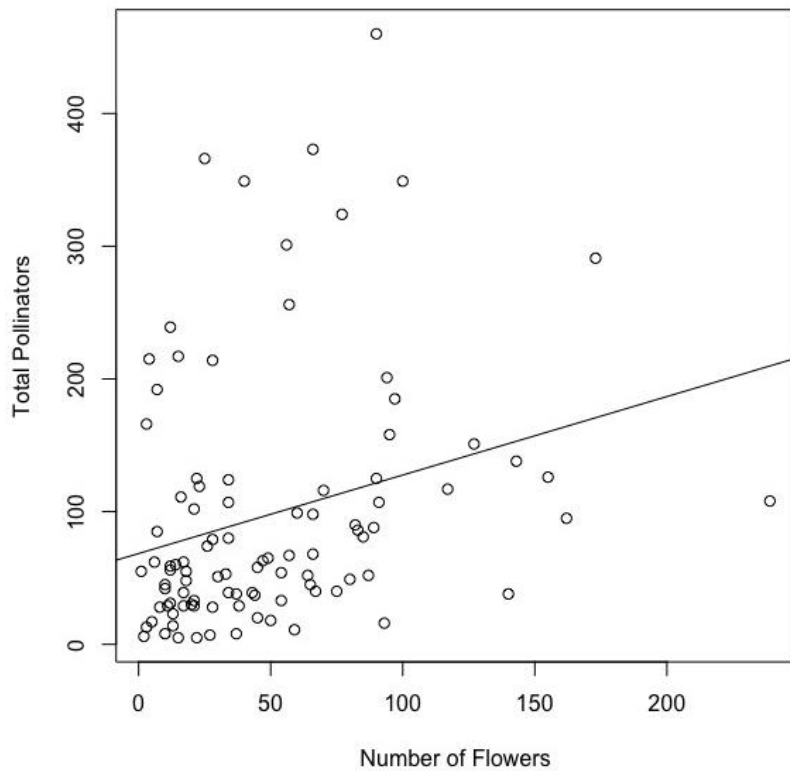


Figure 3. Table 6B. and Figure 3. illustrate that the number of total pollinators observed are significantly affected by the number of flowers available.

To test for differences in Coleopteran pollinator visits, we used the same GLMM models and model selection procedure described above but replaced the order with Coleoptera as the response variable and Treatment, noise level (LAF90), temperature, and shade remained predictor variables, with Flower Type and Section as random effects. The top model was continuous noise levels (LAF90), the null was the second ranked model, and treatment was third. These three models were competitive within 2 Δ AICc for Total Coleoptera Pollinator Visits. The top model suggests a weak negative effect on coleopterans but is insignificant at the 95% confidence interval level (Table 7A, Figure 4).

Table 7A. Model selection table for order Coleoptera

	K	AICc	ΔAICc	AICc w_i	Cum. w_i	LL
LAF90	5	372.19	0	0.34	0.34	-180.77
null	4	372.49	0.30	0.29	0.63	-182.03
Treatment	5	374.06	1.87	0.13	0.77	-181.70
LAF90 + Temp	6	374.28	2.08	0.12	0.89	-180.67
Treatment + Temp	6	376.11	3.92	0.05	0.94	-181.59
LAF90 + Temp + No. of FH	7	376.12	4.01	0.05	0.98	-180.47
Treatment + Temp + No. of FH	7	377.98	5.79	0.02	1	-181.36

AIC	BIC	logLik	deviance	df.resid
371.5	384	-180.8	361.5	92

Table 7B. Top-ranked model for Coleoptera visits ~ LAF90

Random effects

Groups	Name	Variance	SD
Flower Type	(Intercept)	0	0
Section	(Intercept)	0.01166	0.108
Residual		2.42206	1.556

Fixed Effects

	Estimate	SE	df	t	p
(Intercept)	3.4	0.760	95.54	4.46	< 0.001 ***
LAF90	-0	0.018	96.88	-1.64	0.105

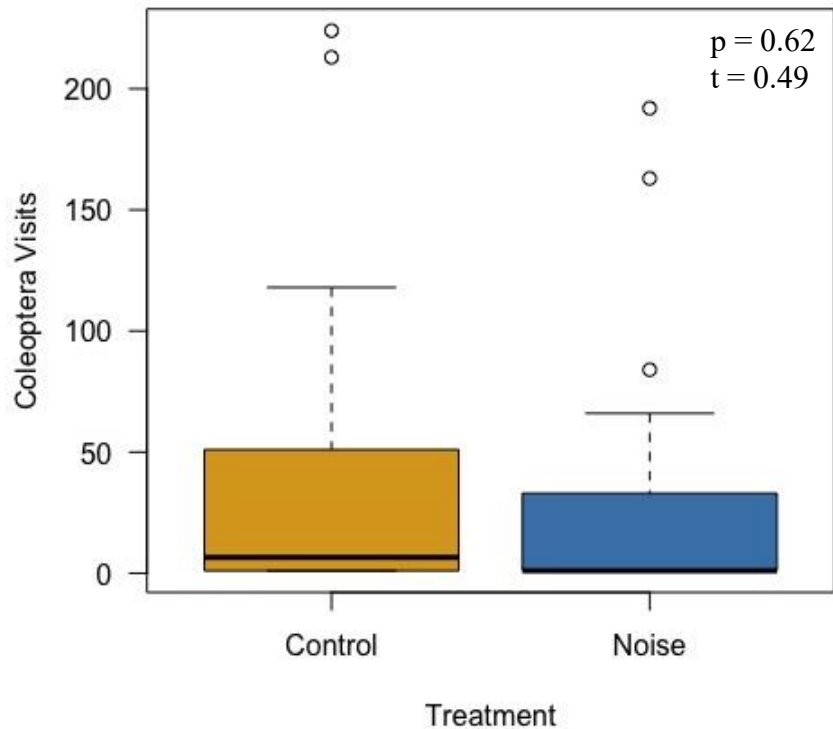


Figure 4. We found no significant difference between the treatment type and the total number of Coleoptera.

To test for differences in Dipteran pollinator visits, we used the same GLMM models and model selection procedure described above but replaced Diptera as the response variable. Two models were competitive within $2 \Delta AIC_c$, where the top model was Treatment + Temperature + the number of flowering heads on the observation plant. The second ranked model consisted of continuous noise levels (LAF90) + Temperature + No. of FH.

The top model indicates a significant negative effect of the number of flowering heads on Dipterans (Table 8A, Figure 5). Treatment is not significant in this model, but trending towards significance where $P < .06$.

Table 8A. Model selection table for order Diptera

	K	AICc	ΔAICc	AICc w_i	Cum.w_i	LL
null	4	275.05	0.00	0.27	0.27	-133.31
Treatment + Temp + No. of FH	7	275.35	0.30	0.24	0.51	-130.04
LAF90 + Temp + No. of FH	7	275.44	0.39	0.22	0.73	-130.09
Treatment	5	276.97	1.92	0.10	0.84	-133.16
LAF90	5	277.17	2.12	0.09	0.93	-133.26
Treatment + Temp	6	279.10	4.05	0.04	0.97	-133.08
LAF90 + Temp	6	279.27	4.23	0.03	1.00	-133.17

Table 8B. Treatment + Temperature + No. of Flowering Heads model for order Diptera

Random Effects

Groups	Name	Variance	SD
Flower Type	(Intercept)	0.01855	0.1362
Color	(Intercept)	0	0
Residual		1.23357	1.1107

Fixed Effects

Groups	Estimate	SE	df	t	p
(Intercept)	0.42	1.26	96.14	0.33	0.07
Noise Treatment	0.40	0.23	96.88	1.77	0.08
Temperature	0.02	0.02	95.19	1.01	0.31
No. of FH	0.01	0.002	38.11	5.01	< 0.001 ***

Table 8C. Noise Treatment model

Random Effects

Groups	Name	Variance	SD
Flower Type	(Intercept)	0.3241	0.5693
Color	(Intercept)	< 0.001	< 0.001
Residual		1.309	1.144

Fixed effects

	Estimate	SE	df	t	p	
(Intercept)	2.36	0.23	18.50	10.07	< 0.001	***
Noise Treatment	0.45	0.24	92.18	1.84	0.07	.

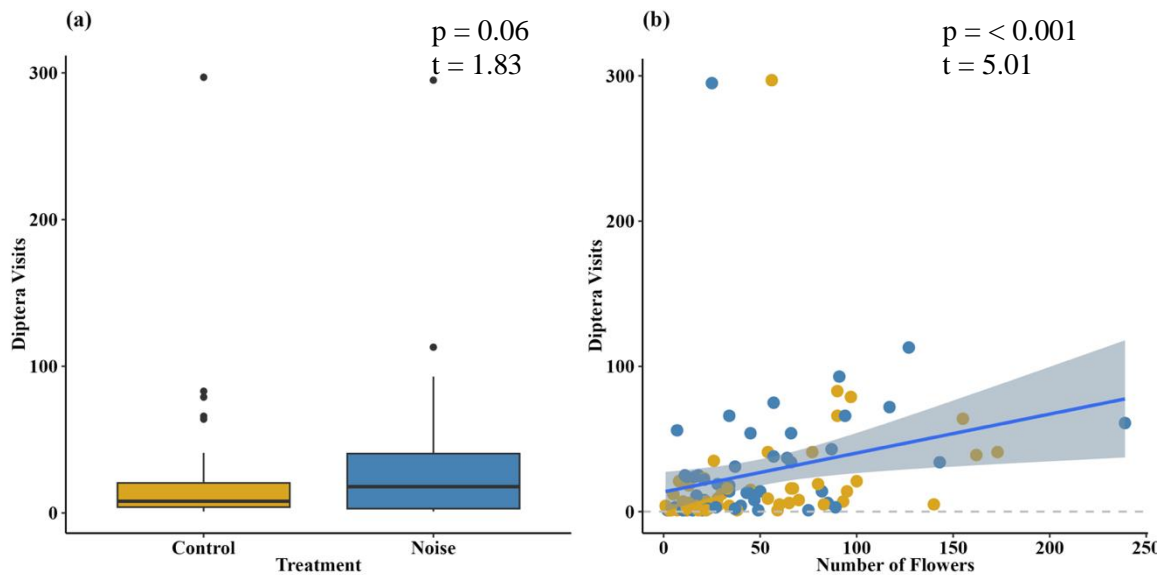


Figure 5: A) Treatment has a weak negative effect on visits by Dipteran pollinators, while the number of flower heads increases the number of dipteran visits (B).

To test for differences in pollinators from the taxonomic order Lepidoptera, we used the same GLMM models and model selection procedure described above but Lepidoptera pollinator visits as the response variable. The null model is the top model, and the second ranked model is treatment, but it is greater than 2 AICc therefore we did not examine it (Table 9).

Table 9. No models were ranked above the null model for order Lepidoptera.

	K	AICc	ΔAICc	AICc wi	Cum. wi	LL
null	4	310.42	0	0.470	0.47	-150.99
Treatment	5	312.54	2.12	0.16	0.63	-150.94
LAF90	5	312.64	2.22	0.16	0.79	-150.99
Treatment + Temp + No. of FH	7	314.67	4.25	0.06	0.84	-149.71
LAF90 + Temp + No. of FH	7	314.76	4.34	0.05	0.90	-149.75
Treatment + Temp	6	314.79	4.38	0.05	0.95	-150.93
LAF90 + Temp	6	314.89	4.47	0.05	1	-150.98

To test for differences in the number of pollinators from the taxonomic order Hymenoptera, we used the same GLMM models and model selection procedure described above but replaced the response variable with the total number of Hymenoptera visitors. Model selection indicates that the null model is the top model. Within 2 AICc were two models, a model that included Treatment and secondly, a model that included continuous noise variable LAF90. There was no significant effect from our predictor variables of Treatment alone or LAF90 alone (Table 10B, 10C; Figure 6).

Table 10A. Model selection for order Hymenoptera

	K	AICc	ΔAICc	AICc w_i	Cum. w_i	LL
null	4	298.82	0	0.37	0.37	-145.19
Treatment	5	299.73	0.91	0.23	0.60	-144.54
LAF90	5	300.65	1.83	0.15	0.75	-145.00
Treatment + Temp + No. of FH	7	301.88	3.06	0.08	0.83	-143.31
Treatment + Temp	6	301.92	3.09	0.08	0.91	-144.49
LAF90 + Temp	6	302.88	4.06	0.05	0.96	-144.97
LAF90 + Temp + No. of FH	7	303.09	4.27	0.04	1	-143.92

Table 10B. Treatment model for order Hymenoptera*Random effects*

Groups	Name	Variance	SD
Flower type	(Intercept)	0.84	0.91
Color	(Intercept)	0.11	0.34
Residual		0.85	0.92

Fixed effects

	Estimate	SE	df	t	p	
(Intercept)	2.35	0.31	19.59	7.66	< 0.001	***
Noise Treatment	0.23	0.20	81.80	1.17	0.246	

Table 10C. Noise (LAF90) model for order Hymenoptera*Random effects*

Groups	Name	Variance	SD
Flower Type	(Intercept)	0.90	0.95
Color	(Intercept)	0.10	0.31
Residual		0.83	0.91

Fixed effects

	Estimate	SE	df	t	p	
(Intercept)	2.124	0.57	84.16	3.73	< 0.0001	***
LAF90	0.008	0.01	88.23	0.65	0.519	

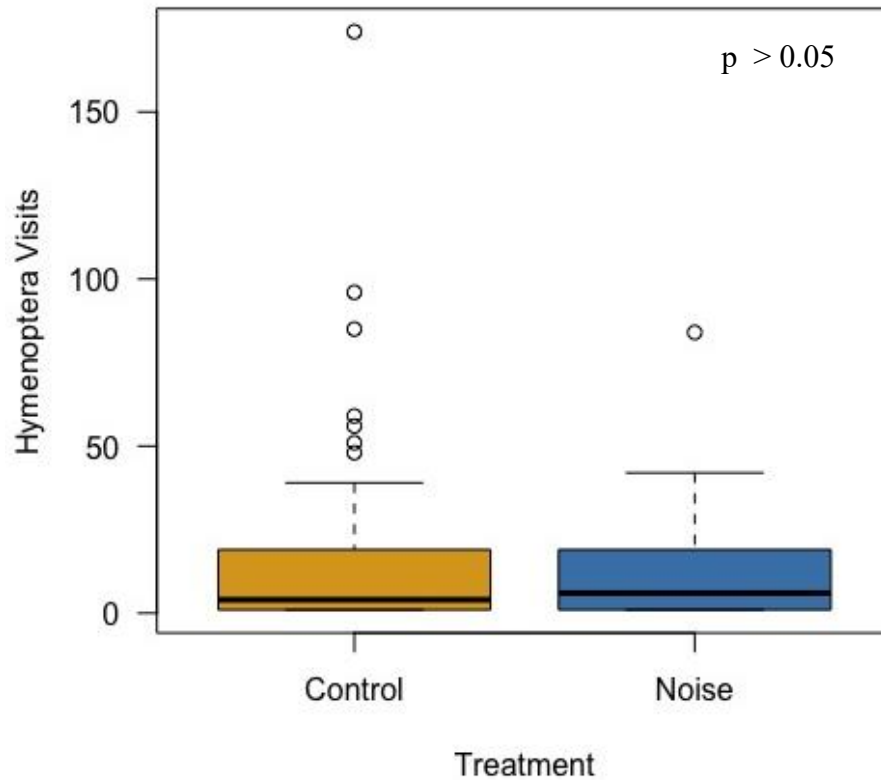


Figure 6. We found no significant difference between Total Hymenoptera across treatment types of control and noise.

Pollinator diversity

The top model for pollinator evenness was the null model. Two models were competitive within $2 \Delta AICc$ for evenness across treatment types of noise and control. The second ranked model consisted of the variable No. of FH. The third ranked model was continuous noise levels (LAF90). We found no significant difference between the No. of FH, and continuous noise levels (LAF90) and pollinator evenness (Table 11B, 11C).

Table 11A. Pollinator Evenness Model Selection Table

	K	AICc	ΔAICc	AICc w_i	Cum. w_i	LL
null	3	71.79	0	0.34	0.34	-32.77
No. of FH	4	72.61	0.83	0.29	0.57	-32.09
LAF90	4	73.76	1.97	0.13	0.70	-32.66
Treatment	4	73.96	2.18	0.12	0.82	-32.76
LAF90 + No. of FH	5	74.68	2.89	0.08	0.90	-32.01
Treatment + No. of FH	5	74.84	3.05	0.07	0.97	-32.09
LAF90 + Treatment + No. of FH	6	76.75	4.96	0.03	1	-31.91

Table 11B. The No. of FH (number of flower heads) model for pollinator evenness was not significant.

Random effects

Groups	Name	Variance	SD
Flower Type	(Intercept)	0	0
Residual		0.1135	0.3369

Fixed effects

	Estimate	SE	df	t	p
(Intercept)	0.6017	0.052	97	11.61	< 0.001
No. of FH	0.0009	0.0007	97	1.17	0.246

Table 11C. Continuous noise (LAF90) model for pollinator evenness was not significant.

Random Effects

Groups	Name	Variance	SD
Flower Type	(Intercept)	0	0
Residual		0.1148	0.3388

Fixed effects

	Estimate	SE	df	t	p
(Intercept)	0.72	0.17	97	4.37	< 0.001
LAF90	-0.002	0.003	97	-0.46	0.65

Pollinator Voucher Specimen β -diversity

To determine how our 2 treatment types of Noise and Control, influence pollinator β -diversity, we used the PERMANOVA `adonis2` function using the Kulczynski dissimilarity index with 999 permutations in R-Studio package `vegan`. Models included effects of Treatment, continuous Noise levels (LAF90), and number of flowering heads on the observation plant.

We found no significant difference of turnover between treatment types (Table 12A). We found a significant relationship between pollinator order and flower type (Table 12B), but not for continuous noise level (Table 12C). Voucher Specimen were categorized by taxonomic order, family levels and treatment (Table 13A). The Jaccard dissimilarity matrix table indicates Treatment type is significant (Table 13B).

We used a multi-level pattern analysis to assess voucher specimen Family composition (i.e. β -diversity). We find two taxonomic families are significantly associated with control treatment sites, Hymenoptera: Andrenidae and Diptera: Bombyliidae (Table 13C). We performed a species accumulation curve on our voucher specimen (Figure 7).

Table 12A. PERMANOVA table results for Treatment indicates no significant effect on order composition.

Permanova table 1	Df	SumOfSqs	R2	F	<i>p</i>
Treatment	1	0.2937	0.02	1.60	0.15
Residual	95	17.4062	0.98		
Total	96	17.6999	1.00		

Table 12B. PERMANOVA table results for Flower Type indicates a significant effect of flower species on order composition (i.e. β -diversity) values of arthropod pollinator.

Permanova table 2	Df	SumOfSqs	R2	F	<i>p</i>
Flower Type	18	4.19	0.24	1.34	0.039 *
Residual	78	13.51	0.76		
Total	96	17.70	1.00		

Table 12C. PERMANOVA table results for LAF90 indicates no significant effect on arthropod pollinator order composition.

Permanova table 3	Df	SumOfSqs	R2	F	<i>p</i>
LAF90	1	0.31	0.02	1.69	0.17
Residual	95	17.39	0.98		
Total	96	17.70	1.00		

Table 13A. Voucher Specimen table categorized by taxonomic order, family levels and treatment.

order	Family	Control	Noise
Lepidoptera	Lycaenidae	1	0
Lepidoptera	Nymphalidae	1	0
Hymenoptera	Megachilidae	8	5
Hymenoptera	Apidae	4	5
Hymenoptera	Andrenidae	12	0
Lepidoptera	Scythrididae	1	5
Hymenoptera	Halictidae	8	3
Diptera	Tachinidae	1	1
Diptera	Bombyliidae	4	0
Coleoptera	Cleridae	2	3
Hymenoptera	Scoliidae	1	0
Coleoptera	Burpestidae	2	7
Coleoptera	Cerambycidae	1	3
Hemiptera	Lygaeidae	1	0
Hymenoptera	Braconidae	2	3
Coleoptera	Mordellidae	3	1
Hymenoptera	Ichneumonidae	1	0
Coleoptera	Melyridae	1	0
Hemiptera	Miridae	0	1
Diptera	Syrphidae	0	2
Coleoptera	Lamproyidae	0	1
Hymenoptera	Sphecidae	0	1
Coleoptera	Meloidae	0	2
Lepidoptera	Hesperidae	0	1
Diptera	Rhagionidae	0	1
Hemiptera	Rhopalidae	0	1
Hymenoptera	Formicidae	0	2
N = 102	TOTAL	54	48

Table 13B. Jaccard dissimilarity matrix table indicates Treatment type is significant.

	Df	SumOfSqs	R2	F	p
Treatment	1	1.28	0.025	2.76	0.002 ***
Residual	110	51.01	0.98		
Total	111	52.29	1		

Table 13C. Multi-level pattern analysis indicates that two families are positively associated with Control sites.

Family	Treatment	stat	p
Andrenidae	Control	0.451	0.001 ***
Bombyliidae	Control	0.344	0.013 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

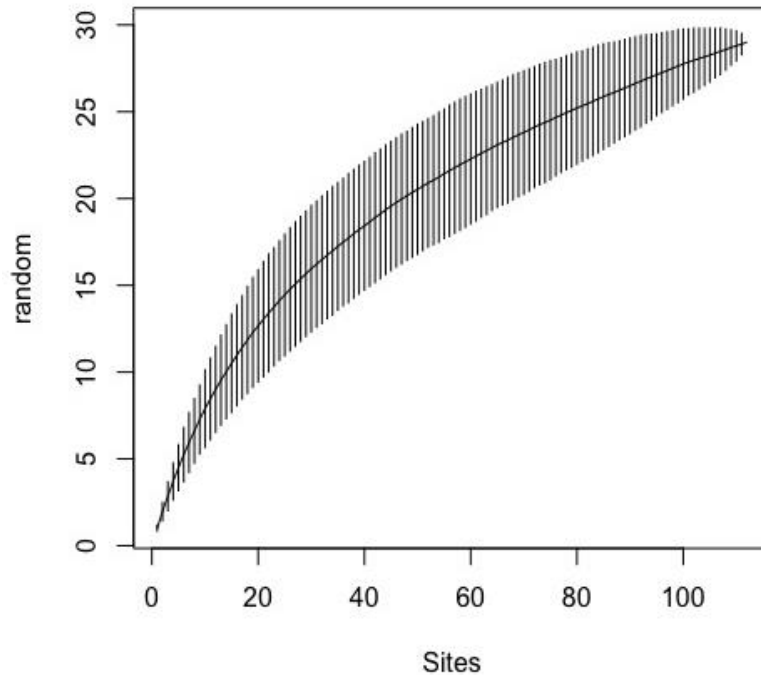


Figure 7. The species accumulation curve, of a population gives the expected number of observed species or distinct classes as a function of sampling effort. Our species accumulation curve appeared to plateau around 100 sampling locations, indicating that the number of species observed may have reached a maximum.

II. INTRODUCTION

Pollinator foraging behavior has played a significant role in influencing plant morphology, signaling, and community structure since angiosperms began to dominate the landscape over 400 million years ago (Ehrlich & Raven, 1964). Functioning and healthy terrestrial ecosystems depend on pollinators to perform important ecological tasks (Ollerton, 2017). Flowers differ in terms of their structure, color, odor, and nectar reward. This is largely attributed to the pollinators that visit these diverse flowers. This has been termed “pollinator syndrome” and continues to be refined as a framework for understanding the modes of floral diversity, compared to the function of pollination services (Dellinger, 2020). Pollination syndromes are often identified by a group of morphological characteristics that are thought to indicate convergent floral adaptations to specific kinds of animal pollination (Ollerton et al., 2011). Plant-pollinator relationships are one of the most ecologically important classes of species interactions. As without pollinators, approximately 86% of angiosperms (~ 352, 000 species) could not seed set and reproduce. And without plants to provide pollen and nectar rewards, hundreds of thousands of animal species would starve (Ollerton et al., 2011). Moreover, some plants and pollinators have tightly coevolved together and depend on one another for survival (Fleming & Holland, 1998; Wilson et al., 2021).

These symbioses are under increasing threat from anthropogenic disturbances (Francis et al., 2012; Knop et al., 2017; Macgregor & Scott-Brown, 2020). As human activity steadily increases, pollinating animals face pressures and are likely altering their natural behavior to contend with urbanization, habitat degradation, climate change, and pollution

(Bunkley et al., 2017; Jones & Leather, 2013; Owens et al., 2020). Anthropogenic noise and light are two common sources of sensory pollutants. Noise pollution is the propagation of elevated sound levels (noise) above 65 decibels (dB). There are many sources of noise pollution, but common types include, traffic noise, air traffic noise, construction, and large outdoor events. Artificial light at night, referred to as ALAN hereafter, is defined as excessive, intrusive, or prominent artificial light in the environment (Davies & Smyth, 2018; Dominoni et al., 2020; Sanders & Gaston, 2018). ALAN may disrupt the nocturnal and crepuscular pollinator's ability to regulate circadian rhythm, by masking, distracting, or misleading pollinators (Dominoni et al., 2020). Light may act as a sink, attracting pollinators to plants in lit areas, or by attracting pollinators to the light source (Owens et al., 2020). Alternatively, ALAN may act as a repellent, repelling nocturnal arthropods and pollinators away from the light source and suitable forage (Skutelsky, 1996). Insects and pollinators may also avoid illuminated areas due to perceived or associated predation events (Rydell, 2006; Skutelsky, 1996). Light pollution impacts the activity level of some nocturnal insects (Dreisig, 1980) and potentially pollinators. Those affected are likely reducing the temporal niche they operate within (Tierney et al., 2017). Light may also have cascading effects on the plants located in lit areas (Seymoure, 2018). Acoustic noise, ALAN, and chemicals are some of the common pollutants released into the environment by humans. These anthropogenic drivers may act additively, in conflict, or synergistically and could potentially have cascading effects on insects and the plants they pollinate (Deora et al., 2021; Owens et al., 2020; Phillips et al., 2021; Wilson et al., 2021).

Groups of arthropod pollinators likely use different mechanisms for assessing and responding to sensory stimuli. Visual and auditory cues aid in conspecific communication, predator detection, and flower location. Hymenoptera and Diptera rely on both visual and acoustic information (Morley et al., 2013). Chordotonal sensory organs are present in insects and crustaceans and are not found in any other class of animals (Kavlie & Albert, 2013). In 2013, Kavlie and Albert outlined that knowledge on the sensory pathways of chordotonal ears is still rudimentary and that simple model ears of insects would be a great opportunity to better understand these fundamental questions within sensory biology. These sensory organs have the potential to function as proprioceptors, which keep track of position and relative motion (Kavlie & Albert, 2013). They can also serve as exteroceptors, like the Johnston's organ found in antennae of mosquitos and honey bees, which detects vibrations in the air. For example, in honey bees, this sensory organ is sensitive to air vibrations up to 500 Hz (Kirchner, 1993; Towne, 1995). In the mosquito species *Culex pipiens*, this sensory system is sensitive to 85 to 470 Hz (Lapshin & Vorontsov, 2017). Both proprioceptors and exteroceptors have been linked to cold avoidance behavior and temperature entrainment of the circadian clock (Kavlie & Albert, 2013). Mechanosensory hair-like structures on insect's body can also serve as receptors for sound vibration (Boublil et al., 2021). Therefore, sensory pollution may mask the arthropods and arthropod pollinators' ability to perceive the environment or predators and may affect their circadian rhythm, overall foraging efficiency, and reproductive success.

Previous research has studied the effects of anthropogenic sensory pollution on vertebrate behavior and seedling recruitment (Francis et al., 2012; Phillips et al., 2021; Willems et

al., 2022) but little is known about how sensory pollution affects invertebrate behavior (Morley et al., 2013; Swaddle et al., 2015), and how, in turn, would affect the plants they interact with. Recent reports of declining insects (Goulson, 2019; Wagner et al., 2021) and pollinators (Potts et al., 2010) worldwide highlight the importance of new studies that focus on arthropods and pollinator behavior and the underlying mechanisms these animals use to contend with anthropogenic threats in urban landscapes. This research seeks to investigate this gap in knowledge.

Noise

Previous research indicates that noise disrupts predator-prey interactions. In our New Mexico study system, it has been shown that anthropogenic noise pollution from compressors changes terrestrial arthropod abundances (Bunkley et al., 2017).

Abundances for arthropods on compressor sites were significantly fewer for certain groups of animals like crickets and grasshoppers. As compressor noise levels increased, predatory arthropods such as velvet ants, jumping spiders and wolf spiders also decreased. A positive association between noise and abundance was found for one family, leafhoppers (Cicadellidae). Noise may be disrupting predatory arthropods, such as velvet ants and spiders, ability to perceive cues from the environment like the presence of prey but may act as a predator shield for other herbivorous families such as leafhoppers. Another laboratory experiment from the literature on the effect of sound pollution on soybeans, ladybugs, and aphid predation, found that lady bugs exposed to loud rock music were less effective predators. This resulted in a higher density of aphid populations, and lower overall biomass of soybean plants in comparison to the control groups (Barton et al., 2018).

One arthropod that has been somewhat well studied is the jumping spider family (Salticidae). Jumping spiders are an ideal model to study terrestrial arthropod behavior because they are a widespread, cosmopolitan species with acute vision. Jumping spiders also have sensory hair all over their bodies that aid in detection of acoustic signals (Denbaum, 2019). They have elaborate courtships displays which include visual and auditory elements. Behavioral studies on acoustic perception demonstrated jumping spiders respond to low 80 Hz tones by freezing, a known antipredator acoustic startle response. The spider's neural responses to 80-380 Hz persisted at distances greater than 3 meters (Shamble et al., 2016). Arthropods that lack tympanal organs (i.e., spiders) were previously thought to only able to perceive stimuli in near field ranges. Furthermore, mechanical stimulation of hairs on the patella of the spider revealed neural units corresponding with those during acoustic stimuli. This work supports the idea that hairs play a role in detection of acoustic cues and suggests that these auditory responses aid in predator detection and facilitate an acoustic startle response (Shamble et al., 2016).

Sound detection in invertebrates is especially poorly understood, but arthropod hearing in commercially vital species of crustaceans has been documented in the literature. Sound production in lobsters was first documented 60 years ago (Moulton, 1957). Since, several studies have looked at intraspecific communication as the potential use of sound in these crustaceans (Atema & Cobb, 1980; Atema & Voigt, 1995; Breithaupt, 2002).

Mechanistically, we know buzzing sounds are created by crustaceans by rapid contraction of internal muscles located at the base of the antennae (Mendelson, 1969). American lobsters (*Homarus americanus*) produce sound features, characterized by low (~ 100 Hz) frequencies (Fish, 1966; Jézéquel et al., 2018). Additionally, real or simulated feeding

sounds of king crabs (*Paralithodes camtschaticus*), increased movements (Tolstoganova, 2002). Like spiders, crustaceans lack the typical hearing organ or air-filled spaces used for sound pressure detection (Popper et al., 2001; Popper & Hawkins, 2018). However, crustaceans have a variety of external sensory receptors that have been shown to detect low frequency particle motion (Budelmann, 1992). Jézéquel et al. found in 2021 that American lobsters (*Homarus americanus*) can detect auditory acoustic stimuli between the threshold range of (80 – 120 Hz) (Jézéquel et al., 2021). American lobsters auditory range encompasses the frequency range of the buzzing produced, supporting the idea that sound production and detection is used for intraspecific communication (Jézéquel et al., 2021). Jézéquel's work highlights the role of external cuticular hairs in sensory detection in arthropods. This work supports the idea that hairs play a role in sensory detection in arthropods. This study implies that hearing is mechanistically possible for a variety of arthropods, both terrestrial (Albert & Göpfert, 2015; Shamble et al., 2016; Sutton et al., 2016; Towne, 1995) and aquatic (Jézéquel et al., 2021). Given the vital ecological and economic roles terrestrial and marine arthropods serve, this research draws attention to effects of anthropogenic noise (Jézéquel et al., 2021) and accentuates the idea that hair aids in sensory detection in some arthropods, which may be relevant to terrestrial arthropod hearing.

Arthropod herbivore reactions to change in noise has also been documented. Elevated heart rate is used as a measurement unit for stress in animals, including arthropods.

Monarch butterfly caterpillars (*Danaus plexippus*), exposed to simulated traffic noise during playback studies had higher heart rates than control animals, suggesting that caterpillars perceive noise as a stressor. Caterpillars exposed to chronic noise for 7 or 12

days both showed no elevated heart rate at the end of larval development, indicating that chronic noise exposure can lead to habituation to stressors. Habituation to stressors during larval development could have implications to adult behavioral response to anthropogenic stress (Davis et al., 2018). Broadly speaking, these results highlight that noise may affect some groups and life stages of animals more negatively than others. More research is needed to better understand the mechanisms specific taxonomic groups use to contend with sensory pollution.

Noise affecting pollinators is the least documented in the sensory ecology literature compared to work on vertebrates. A single study in the UK investigated the effects of multiple pollutants on pollinator communities near roadside verges and found no significant impacts from noise. They found a higher density of bees after treatments and suggested this increase in pollinator density may be due to site disturbance during equipment setup. Other studies have found that bees maintain a high species richness and sometimes increase in abundance where disturbance is more occasional and localized (Archer et al., 2013; Winfree et al., 2007). Previous work in the San Juan Basin in northwestern New Mexico has demonstrated that noise pollution alters ecological services such as pollination. Some services such as pollination increased, while seedling recruitment decreased in the presence of compressor noise. Black-chinned hummingbirds (*Archilochus alexandri*) visited artificial flowers in noise five times more than flowers in control sites (Francis et al., 2012). These findings suggest that noise may act as a predator shield for some species such as the Black-chinned hummingbird, and indirectly affect hummingbird pollinated plants found in the system, such as scarlet gilia (*Ipomopsis aggregata*). Phillips et al. (2021) found that plant communities were different between

long-term noise plots and control plots, where one hypothesized mechanism is a disruption in pollination services (Phillips et al., 2021). Whether this is the mechanism of environmental change remains to be tested and is one goal of this thesis.

Light

Artificial light at night (ALAN) is a novel evolutionary issue for animals to contend with. Though recent research has studied behavior in response to light pollution, it is still under researched in invertebrate groups. Light pollution misleads moths (Lepidoptera) and dung beetles (Coleoptera), as they misidentify light sources as celestial cues (Davies et al., 2013; Kyba et al., 2017; Owens et al., 2020). A study in the UK found that moth species that exhibit positive phototaxis and or are nocturnally active, have stronger negative population declines in comparison to species that do not show positive phototaxis, or are diurnal species (van Langevelde et al., 2018). Other studies have demonstrated that artificial light at night has a negative effect on nocturnal pollinators, where pollination visits were reduced by 60% in lit areas compared to control (dark) areas (Knop et al., 2017). Research using structural modeling on the combined effects of anthropogenic noise and light pollution on a bat pollinated tree, *C. pentandra*, found significant effects of ALAN on bat pollination, with decreased pollination visits as ALAN exposure increased. However, the trees reproductive success yielded a positive effect from light exposure. This study suggests that plants exposed to light may benefit by producing more photosynthates due to the extended photo period, and ability to sustain large quantities of fruit (Dzul-Cauich & Munguía-Rosas, 2022). These results further demonstrate that ALAN may potentially have cascading effects on plants and their pollinators. Light and noise may affect pollination systems synergistically or antagonistically.

Here, we propose to study the effects of sensory pollution on arthropod biodiversity and pollinator behavior. The objective of this thesis is to examine the effects of continuous natural gas noise exposure on abundance, species richness, beta diversity, and pollinator behavior. Specifically, we will address two main objectives: (1) Quantify invertebrate biodiversity using a full factorial light and noise experiment and (2) describe diurnal insect pollinator visitation rates between noise and control experimental plots and describe presence absence patterns of diversity using voucher specimens. To our knowledge, this research is the first of its kind to investigate arthropod diversity across both light and noise treatments, and the first to delve into arthropod pollinator behavior in noise, which can provide important insights to observed insect and pollinator declines worldwide.

III. RESEARCH QUESTION & HYPOTHESES

This thesis aims to answer the question “How does sensory pollution affect the abundance, diversity, and behavior of insects and insect pollinators?”

Hypothesis (1) we hypothesize that persistent noise negatively affects the diversity of insects by interfering with their ability to navigate or causing avoidance behaviors.

Prediction 1a. As noise increases, order Richness decreases.

Prediction 1b. As noise increases, arthropod abundance decreases (Bunkley et al., 2017).

Prediction 1c. As noise increases, arthropod evenness decreases.

Prediction 1d. As noise increases, species composition (beta diversity) changes.

Hypothesis (2): we hypothesize that artificial light at night (ALAN) increases both abundance and diversity of insects due to the innate attraction to lights.

Prediction 2a. As light increases, order Richness increases.

Prediction 2b. As light increases, arthropod abundance increases.

Prediction 2c. As light increases, arthropod evenness decreases.

Prediction 2d. As light increases, species composition (beta diversity) changes.

Hypothesis (3): We hypothesize that light and noise combined have antagonistic effects, where light attracts and noise repels pollinators, which in turn will affect the diversity of pollinators visiting.

Prediction 3a. As light and noise increases, order Richness increases.

Prediction 3b. As light and noise increases, insect abundance increases.

Prediction 3c. As light and noise increases, insect abundance decreases.

Prediction 3d. As light and noise increases, species composition (beta diversity) changes.

Hypothesis (4) we hypothesize that noise treatments will negatively affect pollinator movement and visitation rates by disrupting orientation flights to food sources.

Prediction 4a. As noise goes up, pollination visits decrease.

Prediction 4b. Sensitive pollinator species will be absent from noise plots.

IV. SIGNIFICANCE AND IMPLICATIONS

Future habitat restoration activities specific to the natural history and habitat needs of important pollinators could promote the sustainability of pollination services to these species, but it is impossible to know how effective those activities could be without first learning more about the pollinator communities in question. Given the current global

collapse of arthropod insect and pollinator populations, our research addresses this by prioritizing research on experimentally testing how sensory pollution affects insect diversity and pollinator behavior.

V. RESEARCH DESIGN

Study Location

The San Juan Basin, located in the northwest corner of New Mexico, is among the most productive oil and gas basins in the United States (Fassett, 2010). Our study area, Rattlesnake Canyon Habitat Management Area (RCHMA, henceforth ‘RCHMA’), is situated in northwestern New Mexico and managed by the Bureau of Land Management (BLM, henceforth ‘BLM’). The habitat is dominated by pinyon pine (*Pinus edulis*), Utah juniper (*Juniperus osteosperma*), and sagebrush (*Artemisia tridentata*), with BLM leasing oil and natural gas sites across the area, some of which produce constant noise from large compressors (Francis et al., 2009, 2011). Chronic noise pollution via resource extraction has been disturbing this region for approximately 70 years (Fassett, 2010). In previous studies, the RCHMA has been used as a long-term study system to investigate the effects of anthropogenic sensory pollution (Bunkley et al., 2017; Francis et al., 2009, 2011, 2012; LaGory et al., 2001; Phillips et al., 2021; Willems et al., 2022; Wilson et al., 2021). We aimed to use this unique opportunity to examine the effect Light, Noise and the combination of Light+Noise has on insect diversity. To achieve this, JNP conducted a full factorial experimental design with Control, Light alone, Noise alone, and Light+Noise treatments in 2018 and 2021, using 24 plots. Each plot had an approximately 250m radius around the central well pad. In 2022, we grouped the plots into two treatments, Noise and Control. Treatment and Control plots were at least 0.5km

apart to ensure different conditions. Areas of the four treatments were grouped into six distinct sections or “colors” to account for potential landscape level variation and latitude.

Methods

To test our hypotheses, we took multiple approaches, both experimental and observational. First, we investigate which arthropod orders and families occurred on and around natural gas well sites in a long-term study system in New Mexico to examine the effects of sensory pollutants on 1) arthropod diversity 2) arthropod abundance and 3) pollinator visitation rates.

Arthropod Diversity and Abundance across sensory pollution treatments

To investigate potential differences in richness, abundance, evenness, and beta diversity of arthropods across the four treatments, we utilized data collected from 120 pitfall traps that were evenly distributed across all treatments in 2018. Each site was equipped with 5 traps, with locations determined by the presence of light posts at lit sites and randomly distributed at Control and Noise plots. Pitfall traps were left out for 6 nights, sieved into clean jars and preserved in 90% ethyl alcohol. Specimens were sorted to taxonomic order using dichotomous keys in the laboratory. Evenness was calculated using Simpson’s inverse diversity index, where abundance was the number of individuals sorted to the order level.

In 2021, we repeated the 120-sample design using sticky traps to better capture flying insects unlikely to fall into pitfall traps and insects that do not preserve well in alcohol. The sticky traps were constructed by attaching 12x12 gridded cardboard to wooden

stakes five meters from light posts for Light or Light+Noise treatment, and randomly between 75-100 meters for Control and Noise treatments. Both sides of the cardboard were painted with Tanglefoot, a natural, chemical free liquid used to trap flying and walking insects (Phillips et al., 2019). We collected sticky traps after 7 nights and assessed insect abundance by counting each insect on both sides of the trap.

Pollinator visitation rates in noise

In May of 2022, our study system consisted of 12 noisy sites and 12 control sites as we did not erect light towers. This provided us with the opportunity to investigate the effects of chronic compressor noise on pollinator visitation in comparison to control plots. We began by locating flowering plants on each site and measuring the levels of artificial noise at each plant. Subsequently, we conducted 20-minute pollinator observations at the flowering plants by counting the number of pollinators on each flower every 60 seconds and categorizing them by insect order. Flowers available within the landscape were used, which resulted in variations in flower type and size, but we tried to select flowers that were ≤ 1 by 1 ft in size. After the 20-minute observation period, we collected a voucher pollinator specimen of each type of pollinator seen from the observation plant. Specimens were collected for a five-minute period to standardize the sampling effort. We used an aspirator for smaller specimens and a capture by hand technique using vials for collection, while larger Lepidoptera were collected using a butterfly net. Pollinators were only collected from the center of observation flowers. The most abundant insect groups encountered on flower reproductive structures were bees, wasps, ants (Hymenoptera), flies (Diptera), beetles (Coleoptera), moths, butterflies (Lepidoptera), and true bugs (Hemiptera). The total number of observations was 98 trials, where 50 were on Control

Plots and 48 were on Noise plots. Additionally, we documented the observation plants: flower type, the number of flowering heads on the plant, and recorded weather information at each observation. Insects captured in the field were put into kill jars for euthanasia, prepared, pinned, stretched, and appropriately labeled for storage. All voucher specimens were sorted by treatment type, pinned, and taxonomically classified to the furthest taxonomic level (Family) using taxonomic keys and iNaturalist. Insects were temporarily stored in insect boxes in foam with silica desiccant packages in each box during the field season. All specimens are stored in Cornell insect boxes in the Texas A&M University – San Antonio Entomological Collection.

We investigated diversity metrics at the order level, where there each pollinator belong to five common orders, Hymenoptera (bees, ants, wasps), Coleoptera (beetles), Diptera (flies), Lepidoptera (moths and butterflies) and lastly an “Other” column of pollinators that were not classified to the order level during observation. We collected 113 voucher specimen post pollinator observation. We later analyzed beta diversity on 102 voucher specimens taxonomically identified to the family level.

Noise and Light Measurements

For all experiments (pitfall, sticky traps, and observations), continuous levels of artificial light at night and noise levels were taken at each observation point or trap. To record the noise conditions, we took a 4-minute background noise recording at each focal plant using a Larson Davis 831 Type 1 Sound Level Meter (SLM; Larson Davis model 831, firmware 2.206, A-weighting, fast response, 0.0 dB gain, re: 20 μ Pa, with one minute in each cardinal direction. We collected light levels with a Konica-Minolta T-10A

Illuminance Meter at each pitfall or sticky trap at least 1 hour after sunset, held horizontally at the height of the trap.

The approach to use three different insect sampling methods pitfall traps, sticky traps and pollinator observations respectively, was dependent on funding for each field season. Data collected in years 2018, and 2021 were collected by JNP. JNP and SDR collected data in 2022.

Statistical Analyses

For clarity, we present our results in the following order: (1) pitfall trap order richness, (2) pitfall trap insect abundance, (3) pitfall trap evenness, (4) pitfall trap β -diversity, (5) sticky trap insect abundance, (6) pollination visits, and (7) pollinator evenness and (8) pollinator β -diversity.

All analyses were conducted in R (R Core Team, 2022). We used linear mixed effect models and AICc (Bates et al., 2015; Mazerolle, 2020; Arnold, 2010) to understand what sensory pollutants, if any, have an effect on arthropod diversity metrics (1) order richness, (2) pitfall arthropod abundance, (3) evenness), (6) pollination visits, and (7) pollinator evenness. We also examined whether broad scale treatments or microhabitat measures of light and noise were more predictive of patterns in diversity and pollinator visits. To calculate order evenness, we used the Inverse Simpson's diversity index in the vegan package in R-Studio (Oksanen, 2022). To understand what model best predicts diversity metrics (dependent variables 1-5), for pitfall and sticky traps across our 4 treatment types of Light, Noise, Light+Noise and Control treatments, we used the Lme4 package in R-Studio to explore candidate models with AICc (Arnold, 2010; Bates et al., 2015). Using function dredge in R package MuMIn (Barton, 2011) we examined the

global linear mixed-effects regression model with Treatment, continuous noise level (LAeq), and continuous light level (lux) as predictor variables. To account for possible spatial autocorrelation, the section each sample belonged to was specified as a random effect. We examined and present results for all top models within 2 AICc (Arnold, 2010). We log transformed dependent variables that did not fit the assumption of normality. If a categorical variable (i.e., treatment), is included in top ranked models, we used the `glht` function from R package `multcomp` to use post-hoc Tukey tests to look at the difference between treatments (Hothorn et al., 2008; Phillips et al., 2021).

We followed a similar process for variable (6) pollination visits, with additional fixed effects of number of flower heads, temperature, flower species and random effect of section, LAF90, or the A-weighted sound level 90% of the measured time, as an updated measure of noise pollution. We used variance inflation factors (VIFs) to evaluate collinearity and retained all variables with $VIF < 5$ (Allison, 2012). Using packages `AICcModavg` and `MuMIn`, we compared candidate models consisting of all potential subsets of variables in the global model with the `dredge` function (Barton, 2011; Mazerolle, 2020). We examined the global linear mixed-effects regression model with Total Visits, Total Coleoptera, Total Diptera, Total Lepidoptera, and Total Hymenoptera as the response variables and Treatment, continuous noise level (LAF90), the number of flower heads, temperature, and shade as predictor variables.

To determine how our 4 treatment types of Light, Noise, Light+Noise and Control, influence terrestrial arthropod order composition (β -diversity), we used the `PERMANOVA adonis2` function using the Kulczynski dissimilarity index with 999

permutations in R-Studio package *vegan* (Oksanen, 2022). We tested the individual effects of treatment, Light level (lux), and Noise level (LAeq). To identify taxonomic terrestrial arthropod orders significantly associated with treatment types, we performed a multi-pattern analysis using the R package "indicspecies" (De Cáceres, 2022). The analysis used the *IndVal.g* association function and a significance level of 0.05.

For pollinator voucher specimens, we quantified pairwise compositional dissimilarity between Noise and Control sites based on taxonomic family occurrences to understand beta-diversity between Noise and Control treatments. We used the Jaccard index with the "jaccard" package (Chung et al., 2022) in RStudio to examine non-metric analyses based on the presence/absence voucher specimen dataset. We used the PERMANOVA *adonis2* function in R-Studio package *vegan* (Oksanen, 2022) to measure multivariate ordination, and beta diversity results between groups. To identify taxonomic arthropod orders and family groups significantly associated with treatment types, we performed a multi-pattern analysis using the R package "indicspecies" (De Cáceres, 2022). The analysis used the *IndVal.g* association function and a significance level of 0.05. Next, a species accumulation curve was generated using the R package *vegan* to visualize the number of species that were observed as the number of sampling locations increased.

VI. DISCUSSION

Overall, we find evidence that sensory pollutants alter insect diversity, abundance, and behavior. The methodology used to survey insects appears to be important, and functional groups are likely affected differently.

Pitfall traps

Our pitfall results indicate that for order richness, continuous measures of noise and light both have a positive effect on richness (Table 1B, Figure 1.). At the broader treatment level, the trend persists, with the effects of Light+Noise increasing order Richness most significantly compared to pitfall traps on quiet and dark Control plots (Table 1C, Figure 1.). These results illustrate that artificial light at night and anthropogenic noise can alter ecological community richness at the order taxonomic for terrestrial arthropods. Based on our beta diversity analysis, we see that noise may be affecting some terrestrial arthropod orders differently. We find three orders (Collembola, Thysanura, Pseudoscorpiones) are significantly associated with treatment types (Table 4E). Noise seems to drive turnover between terrestrial species diversity across treatment types. For example, Bunkley et al(2017), found that predators (velvet ants, jumping spiders, wolf spiders, etc.) were decreased in noise and pests (leafhoppers) were increased (Bunkley et al., 2017). Additional work into the identifying functional roles of arthropod orders within the community may help elucidate possible mechanisms driving these patterns in response to sensory pollutants.

We found no significant effect across our four treatment types for insect abundance or evenness using pitfall trap methods, indicating that the overall number of insects caught by pitfall traps is consistent. This result did not match our original prediction, that light would innately increase both terrestrial arthropod abundance. Alternatively, nonflying, terrestrial arthropods may be innately attracted to light but fail to reach the light, and or the pitfall traps near the light. Functional groups of arthropods such as ground dwelling decomposers orders Collembola and Thysanura, and arthropod predators such as

Pseudoscorpiones may be more susceptible to pitfall trap collection methods in comparison to larger bodied arthropods, and arthropods with the ability to fly or jump. Additionally, ground dwelling arthropods such as Collembola, Thysanura and Pseudoscorpiones might be less susceptible to the effects of sensory pollutants due to natural buffers such as leaf litter and debris. Additional research should be conducted on ground dwelling arthropods to better understand these patterns.

Sticky Traps

Using a different methodology aimed at flying arthropods, our results suggest that Flying arthropods may be more susceptible to being drawn towards lit areas, resulting in higher insect abundances in the Light treatments. Additionally, the higher abundances of arthropods in the Light treatment could be attributed to the fact that flying arthropods can travel some distance to reach the light, whereas terrestrial insects likely are unable to, or at a much slower rate. Furthermore, the results provide evidence that Light treatment attracts significantly higher abundances of arthropods compared to both Control and Noise treatments. The significant difference observed in arthropod abundances between Light treatment and Noise treatment supports the hypothesis that ALAN increases arthropod abundances due to the innate attraction to lights. This result aligns with our a priori hypothesis that light increases insect abundance. Many studies have highlighted the effects of light pollution but to our knowledge this is the first study to analyze the effects of both light and noise simultaneously on flying arthropod abundance.

Pollinator Observations

We find no significant trend between pollinator visitation rates in control versus noisy plots, but we did find a weak negative association at the order level between Coleopterans (Beetles) and a positive association for Dipterans (Flies). Pollinating beetles were less abundant and flies more abundant in noisy environments. However, no significant trends were observed among other orders examined, such as Hymenoptera, and Lepidoptera. We found no significant difference of turnover between treatment types; therefore β -diversity is not significantly affected at the pollinator order level by treatment type. This is contradicting to a previous pollinator diversity study, where they find detrimental effects to pollinator functional groups from traffic related pollution (Noise and NO₂) (Fisher et al., 2022). Furthermore, as one intuit, we found a significant relationship between pollinator order and the number of flower heads on the observation plant. Other studies have examined the effects of plant traits and environmental factors on pollinator visitation rates and found that floral display (i.e. the number of open flowers on a plant, on any given day) consistently explained among-plant visitation rates across all regions in the study, but visitation rate was not significantly affected by any other biological or environmental variables (Sanchez - Lafuente et al., 2005). We suggest future studies standardize the amount of flower heads, and flowering plants while conducting a robust, full sampling in order to fully understand how diversity of pollinators may vary across continuous noise levels. Additionally, increasing the sample size and extending the sampling period may further elucidate these patterns.

Pollinator Voucher Specimen Diversity

Our multi-level pattern analysis revealed two families Andrenidae (miner bees) and Bombyliidae (bee flies) are both positively associated with control plots (Table 12C). These two species both appear to be avoiding noisy plots.

Persistent noise may be driving certain species out of noisy areas, and noise may be one of the factors that changes community composition. Additionally, these changes in the acoustic environment might have cascading effects on the plants these animals pollinate (Francis et al., 2009, 2012; Phillips et al., 2021). The anthropogenically altered soundscape may be affecting the relationships between the pollinators and the animals that predate or parasitize these pollinator families. Some parasitoids rely on acoustic eavesdropping and noise can alter their ability to locate hosts (Phillips et al., 2019). Over time noise could be one of the factors that changes community composition. Community turnover and vegetation are likely affected by pollination for specific plant pollinator relationships. These relationships could be one of the influences driving changes in plant community diversity in this habitat. Preliminary data suggests further research is needed to investigate why some families are affected by noise, and to investigate the mechanisms and potential cascading ecological effects.

Host Parasite Interactions – Andrenidae and Bombyliidae

Our multi-level pattern analysis revealed Andrenidae and Bombyliidae arthropod pollinators are both significantly associated with control treatments. This finding is interesting and presents a new area for future research. We find evidence from the literature that Bombyliid flies and Andrenid bees are linked, where flies from the family

Bombyliidae have been documented as parasites of andrenid bees (Drake, 2013; Yeates & Greathead, 1997). Furthermore, we find documentation from the literature citing bombyliids to also be hyperparasites, where some bombyliids will parasitize, parasitoids of Andrenid bees (Drake, 2013; Paxton & Pohl, 1999). Focusing on the effects of noise pollution in an already “noisy” relationship between andrenid bees and bombyliid flies, would be a great next step for this research. Though we find evidence that andrenids and bombyliids are significantly associated with control treatments, whether bombyliids are indeed following their hosts to control treatment sites remains to be tested and would be a great future direction for this research.

Additionally, these results highlight the effects of sensory pollutants in rural areas; understanding these patterns in rural areas away from confounding urban areas can allow us to better understand the specific effects of light and noise.

Cascading effects

Depending on their role in the ecosystem, some arthropods might benefit from sensory pollutants, such as aphids, and leafhoppers like Bunkley found in 2017 (Bunkley et al., 2017). There could also be indirect effects that can cascade throughout the community, affecting some animals such as predators (Francis et al., 2012) and insectivores, more detrimentally than others. From the plant perspective, rates of herbivory may be increased because of sensory pollutants, where pest arthropod populations are unchecked by predators. This may lead to overall differences between plant communities between noisy and quiet areas (Phillips et al., 2021). In light, we see an increase in predatory arthropods such as ants (Formicidae). These changes in order richness and beta diversity,

could have cascading effects on arthropod and arthropod pollinator communities in sensory disturbed areas.

Arthropod Perception

Within the incredibly diverse group of Arthropoda, we find documentation of sensory abilities in the literature. At the taxonomic order level, we know approximate hearing thresholds based on insect taxonomic order (Morley et al., 2013). We know that at the order level, Hymenopterans can hear in the range of (0.2 - 0.3 kHz), while Dipterans, Lepidopteran, and Hemipterans, can hear in the (0 – 50 kHz) range and Coleopterans within the (20-20 kHz) range (Morley et al., 2013; Schaub et al., 2008; Towne, 1995). These hearing ranges are within the spectrum of noise found in our study sites (Francis et al., 2011). We also know that pollinating orders such as Hymenoptera and Diptera rely upon both visual and acoustic information (Morley et al., 2013) for foraging (Barragán-Fonseca et al., 2020), navigation (Warrant et al., 2004), landmark orientation (Warrant et al., 2004), and host parasite interactions (Phillips et al., 2019). Furthermore, the sensory organ known as the Johnston's organ is present in both families, Andrenidae and Bombyliidae. Both families are positively associated with control treatment types, and these results suggest noise sensitivity in these families. The fruit fly *Drosophila melanogaster* contains the largest chordotonal organs found in insects. This organ appears to be particularly prominent in the order Diptera – flies and mosquitoes (Kavlie & Albert, 2013). This could be a possible mechanism behind why we find some fly families are sensitive to noise. Additionally, Shamble's finding in 2016 and Jézéquel's finding in 2021 regarding the importance of hair in sensory detection underscores the need for further research on the role of hair in sensory perception in arthropods that lack

tympanal organs. Future research exploring the role of hair in noise sensitive pollinator families such as Andrenidae and Bombyliidae should be conducted, given that some bees in this family are more hairy or robust than others, and both have the Johnston “hearing” organ.

We measure sensory pollutants such as light in (Lux) as perceived by the human eye and noise in decibels (dB) as perceived by human ears. “Umwelt” is a German term used to describe what an animal can sense and perceive and within the animal kingdom there are likely limits to sensory abilities, unique to the animal’s overall umwelt and its occupied niche. Yet we measure sensory disturbances from light and noise in terms of human perception. At the taxonomic order level, we have broad thresholds for some important insect orders (Morley et al., 2013) and commercial crustaceans (Jézéquel et al., 2021) but little is known about other arthropod groups and their respective hearing threshold capabilities and mechanisms they may utilize to detect sensory pollutants. Research that teases apart these sensory thresholds for light, noise and the combination of Light+Noise for arthropod families or even at the genus level, will contribute greatly by informing the scientific community, and improving conservation efforts for these specific taxa. Once the baseline thresholds for hearing abilities in small, overlooked taxa such as arthropods is created, technology to measure and assess sensory perception in accordance with their capabilities can be improved upon. Research that adds to this growing body of knowledge on sensory perception in non-human animals will aid innovators to improve the technology used to quantify continuous measures of noise and light.

Sensory Pollution Traps

As Bunkley demonstrated in 2017 noise can increase pest like arthropods such as Leafhoppers (Hemiptera: Cicadellidae) (Bunkley et al., 2017). We have demonstrated with our study that arthropod abundance and richness can be affected by sensory pollutants, positively for certain arthropods and negatively for others. Recent research finds evidence of receptivity to vibroacoustic stimuli in the invasive Spotted Lanternfly (*Lycorma delicatula*), where *L.delicatula* were attracted to broadcasts of 60-Hz vibroacoustic stimuli (Rohde et al., 2022). Other arthropod pests such as mosquitoes rely on hearing of females for courtship and mating (Loh et al., 2023). Using a trap with specific playback frequencies might be a cost effective, method for controlling mosquitoes and associated outbreaks. Understanding functional groups of taxa and their hearing thresholds may be a useful integrated pest management (IPM) technique for trapping pest like arthropods, such as the invasive spotted lanternfly (Hemiptera: Fulgoridae), other invasive Hemipterans such as the Red-streaked Leafhopper (Hemiptera: Cicadellidae), and disease transmitting mosquitoes (Diptera: Culicidae).

Interaction of Light+Noise

The effects of light and noise are still poorly understood for arthropods. Our study is novel, as it is the first of its kind to perform a full factorial experiment to examine the singular effects of Light and Noise, and the combination Light+Noise. This experimental design allows us to better understand the individual effects and the interaction of combined sensory pollutants, at the broad treatment level and at the microhabitat level using continuous Noise and Light measurements. We found that continuous noise levels (LZeq) and continuous light levels (Lux) had significant positive effect of on order

richness for our pitfall trap method. We also find a significant relationship between order Richness and Light+Noise Treatments across our four treatment types. We find that terrestrial arthropod order richness is increased in the treatment type of Light+Noise combined. Broadly speaking, these findings are interesting as it appears the combination of light and noise pollutants seem to have a negating effect, where order richness levels in the combination of Light+Noise seem to be similar to order richness measures for control treatment types. Looking at the microhabitat level and the continuous noise and light readings individually, we see that as noise and light levels increase, order richness increases. These results further support the idea that noise and light, and the combination of the two might be affecting some arthropods more detrimentally than others, at the functional level (decomposers, ground dwellers, terrestrial arthropods, flying arthropods, arthropod pollinators), order level, family level and potentially species level.

VII. CONCLUSION

Overall, sensory pollution seems to have some effects on arthropod diversity. We find that Light increases diversity metrics and abundance. For pollinators, it seems Coleopterans (beetles) may be negatively influenced, while Dipterans (flies) may be positively influenced in Noise. For beta diversity, we find three terrestrial arthropod orders, Collembola, Thysanura, and Pseudoscorpiones, are significantly associated with treatment sites. For our pollinator voucher specimen, we find two families are significantly associated with control treatment plots, Andrenidae and Bombyliidae, respectively. Dipterans could be using noise as a predator shield, or they could be following Andrenid bees to control sites. Additional repetitions and a deeper dive into

species specific patterns, and their functional roles in the ecosystem, will help elucidate how noise and light disrupts.

VIII. REFERENCES

- Alaasam, V. J., Kernbach, M. E., Miller, C. R., & Ferguson, S. M. (2021). The Diversity of Photosensitivity and its Implications for Light Pollution. *Integrative and Comparative Biology*, 61(3), 1170–1181. <https://doi.org/10.1093/ICB/ICAB156>
- Albert, J. T., & Göpfert, M. C. (2015). Hearing in *Drosophila*. *Current Opinion in Neurobiology*, 34, 79–85. <https://doi.org/10.1016/J.CONB.2015.02.001>
- Allison, P. (2012). When can you safely ignore multicollinearity. *Statistical Horizons*, 5.
- Archer, C. R., Pirk, C. W. W., Carvalheiro, L. G., & Nicolson, S. W. (2013). Economic and ecological implications of geographic bias in pollinator ecology in the light of pollinator declines. <https://doi.org/10.1111/j.1600-0706.2013.00949.x>
- Arnold, T. W. (2010). Uninformative Parameters and Model Selection Using Akaike's Information Criterion. *The Journal of Wildlife Management*, 74(6), 1175–1178. <https://doi.org/10.1111/J.1937-2817.2010.TB01236.X>
- Atema, J., & Cobb, J. S. (1980). *Social behavior*. In: *The Biology and Management of Lobsters: Vol. 1* (J. S. Cobb & B. Phillips, Eds.). New York: Academic Press.
- Atema, J., & Voigt, R. (1995). *Behavior and Sensory Biology In: Biology of the Lobster, Homarus americanus* (J. Factor, Ed.). Academic Press.
- Barber, J. R., Crooks, K. R., & Fristrup, K. M. (2010). The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology & Evolution*, 25(3), 180–189. <https://doi.org/10.1016/J.TREE.2009.08.002>
- Barragán-Fonseca, K. Y., van Loon, J. J. A., Dicke, M., & Lucas-Barbosa, D. (2020). Use of visual and olfactory cues of flowers of two brassicaceous species by insect pollinators. *Ecological Entomology*, 45(1), 45–55. <https://doi.org/10.1111/EEN.12775>
- Barton, B. T., Hodge, M. E., Speights, C. J., Autrey, A. M., Lashley, M. A., & Klink, V. P. (2018). Testing the AC/DC hypothesis: Rock and roll is noise pollution and weakens a trophic cascade. *Ecology and Evolution*, 8(15), 7649–7656. <https://doi.org/10.1002/ECE3.4273>
- Barton, K. (2011). *MuMIn: multi-model inference*. Rpackage version 1.0. 0.

- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using **lme4**. *Journal of Statistical Software*, 67(1). <https://doi.org/10.18637/jss.v067.i01>
- Boublil, B. L., Diebold, C. A., & Moss, C. F. (2021). Mechanosensory Hairs and Hair-like Structures in the Animal Kingdom: Specializations and Shared Functions Serve to Inspire Technology Applications. *Sensors (Basel, Switzerland)*, 21(19). <https://doi.org/10.3390/S21196375>
- Breithaupt, T. (2002). Sound Perception in Aquatic Crustaceans. In *The Crustacean Nervous System* (pp. 548–558). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-04843-6_41
- Budelmann, B. U. (1992). Hearing in Crustacea. In *The Evolutionary Biology of Hearing* (pp. 131–139). Springer New York. https://doi.org/10.1007/978-1-4612-2784-7_9
- Bunkley, J. P., McClure, C. J. W., Kawahara, A. Y., Francis, C. D., & Barber, J. R. (2017). Anthropogenic noise changes arthropod abundances. *Ecology and Evolution*, 7(9), 2977–2985. <https://doi.org/10.1002/ECE3.2698>
- Chung, N. C., Miasojedow, B., Startek, M., & Gambin, A. (2022). *Test Similarity Between Binary Data using Jaccard/Tanimoto Coefficients*.
- Davies, T. W., Bennie, J., Inger, R., de Ibarra, N. H., & Gaston, K. J. (2013). Artificial light pollution: Are shifting spectral signatures changing the balance of species interactions? *Global Change Biology*, 19(5), 1417–1423. <https://doi.org/10.1111/gcb.12166>
- Davies, T. W., & Smyth, T. (2018). Why artificial light at night should be a focus for global change research in the 21st century. *Global Change Biology*, 24(3), 872–882. <https://doi.org/10.1111/GCB.13927>
- Davis, A. K., Schroeder, H., Yeager, I., & Pearce, J. (2018). Effects of simulated highway noise on heart rates of larval monarch butterflies, *danaus plexippus*: Implications for roadside habitat suitability. *Biology Letters*, 14(5). <https://doi.org/10.1098/RSBL.2018.0018>
- De Cáceres, M. (2022). *Indicator Species Analysis using 'indicspecies'*.
- Dellinger, A. S. (2020). Pollination syndromes in the 21st century: where do we stand and where may we go? *New Phytologist*, 228(4), 1193–1213. <https://doi.org/10.1111/NPH.16793>

- Denbaum, P. (2019). *Visual reactions to auditory stimulus by the jumping spider Phidippus princeps (Araneae, Salticidae)*. Uppsala Universitet. <https://www.diva-portal.org/smash/get/diva2:1320879/FULLTEXT01.pdf>
- Deora, T., Ahmed, M. A., Brunton, B. W., & Daniel, T. L. (2021). Learning to feed in the dark: How light level influences feeding in the hawkmoth *Manduca sexta*. *Biology Letters*, 17(9). <https://doi.org/10.1098/RSBL.2021.0320>
- Dominoni, D. M., Halfwerk, W., Baird, E., Buxton, R. T., Fernández-Juricic, E., Fristrup, K. M., McKenna, M. F., Mennitt, D. J., Perkin, E. K., Seymoure, B. M., Stoner, D. C., Tennessen, J. B., Toth, C. A., Tyrrell, L. P., Wilson, A., Francis, C. D., Carter, N. H., & Barber, J. R. (2020). Why conservation biology can benefit from sensory ecology. *Nature Ecology & Evolution*. <https://doi.org/10.1038/s41559-020-1135-4>
- Drake, M. C. (2013). Emergence Pattern Of *Bombylius Major* (Diptera:Bombyliidae) And Its Parasitism Rate On *Andrenacineraria* (Hymenoptera: Andrenidae) At A Devon Bank. *British Journal of Entomology & Natural History*, 26, 199–209.
- Dreisig, H. (1980). The importance of illumination level in the daily onset of flight activity in nocturnal moths. *Physiological Entomology*, 5(4), 327–342. <https://doi.org/10.1111/j.1365-3032.1980.tb00243.x>
- Dzul-Cauich, H. F., & Munguía-Rosas, M. A. (2022). Negative effects of light pollution on pollinator visits are outweighed by positive effects on the reproductive success of a bat-pollinated tree. *The Science of Nature*, 109(12), 3. <https://doi.org/10.1007/s00114-021-01783-5>
- Ehrlich, P. R., & Raven, P. H. (1964). Butterflies and Plants: A Study In Coevolution. *Evolution*, 18, 586–608. <https://doi.org/10.1111/j.1558-5646.1964.tb01674.x>
- Fassett, J. E. (2010). The San Juan Basin, a complex giant gas field, New Mexico and Colorado. . *Search and Discovery*, Article #10254.
- Fish, J. F. (1966). Sound Production in the American Lobster, *Homarus Americanus* H. Milne Edwards (Decapoda Reptantia). *Crustaceana*, 11(1), 105–106. <https://doi.org/10.1163/156854066X00504>
- Fisher, J. C., Rankin, E., Irvine, K. N., Goddard, M. A., Davies, Z. G., & Dallimer, M. (2022). Can biodiverse streetscapes mitigate the effects of noise and air pollution on human wellbeing? *Environmental Research*, 212. <https://doi.org/10.1016/J.ENVRES.2022.113154>

- Fleming, T. H., & Holland, J. N. (1998). The evolution of obligate pollination mutualisms: senita cactus and senita moth. *Oecologia*, *114*, 368–375.
- Francis, C. D., & Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: an urgent conservation priority. *Ecology and the Environment*, *11*(6), 305–313.
- Francis, C. D., Kleist, N. J., Ortega, C. P., & Cruz, A. (2012). Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1739), 2727–2735. <https://doi.org/10.1098/RSPB.2012.0230>
- Francis, C. D., Ortega, C. P., & Cruz, A. (2009). Noise Pollution Changes Avian Communities and Species Interactions. *Current Biology*, *19*(16), 1415–1419. <https://doi.org/10.1016/J.CUB.2009.06.052>
- Francis, C. D., Paritsis, J., Ortega, C. P., & Cruz, A. (2011). Landscape patterns of avian habitat use and nest success are affected by chronic gas well compressor noise. *Landscape Ecology*, *26*(9), 1269–1280. <https://doi.org/10.1007/s10980-011-9609-z>
- Glossary of Acoustic Terminology. (2012). *EIAR-NIS, Appendix*.
- Goulson, D. (2019). The insect apocalypse, and why it matters. *Current Biology*, *29*(19), R967–R971. <https://doi.org/10.1016/J.CUB.2019.06.069>
- Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous Inference in General Parametric Models. *Biometrical Journal*, *50*(3), 346–363.
- Jézéquel, Y., Bonnel, J., Coston-Guarini, J., Guarini, J., & Chauvaud, L. (2018). Sound characterization of the European lobster *Homarus gammarus* in tanks. *Aquatic Biology*, *27*, 13–23. <https://doi.org/10.3354/ab00692>
- Jezequel, Y., Jones, I. T., Bonnel, J., Chauvaud, L., Atema, J., & Mooney, T. A. (2021). Sound detection by the American lobster (*Homarus americanus*). *Journal of Experimental Biology*, *224*(6). <https://doi.org/10.1242/jeb.240747>
- Jones, E. L., & Leather, S. R. (2013). Invertebrates in urban areas: A review. [Http://Www.Eje.Cz/Doi/10.14411/Eje.2012.060.Html](http://www.Eje.Cz/Doi/10.14411/Eje.2012.060.Html), *109*(4), 463–478. <https://doi.org/10.14411/EJE.2012.060>
- Kavlie, R. G., & Albert, J. T. (2013). Chordotonal organs. *Current Biology*, *23*(9). <https://doi.org/10.1016/j.cub.2013.03.048>
- Kirchner, W. H. (1993). Acoustical communication in honeybees. *Apidologie*, *24*(3), 297–307. <https://doi.org/10.1051/apido:19930309>

- Knop, E., Zoller, L., Ryser, R., Cerpe, C., Horler, M., & Fontaine, C. (2017). Artificial light at night as a new threat to pollination. *Nature, Letter*, 548.
- Kyba, C. C. M., Kuester, T., De Miguel, A. S., Baugh, K., Jechow, A., Hölker, F., Bennie, J., Elvidge, C. D., Gaston, K. J., & Guanter, L. (2017). Artificially lit surface of Earth at night increasing in radiance and extent. *Science Advances*, 3(11).
https://doi.org/10.1126/SCIADV.1701528/SUPPL_FILE/1701528_SM.PDF
- LaGory, K. E., Chang, Y.-S., Chun, K. C., Reeves, T., Liebich, R., & Smith, K. (2001). *A Study of the Effects of Gas Well Compressor Noise on Breeding Bird Populations of the Rattlesnake Canyon Habitat Management Area, San Juan County, New Mexico*.
- Lapshin, D. N., & Vorontsov, D. D. (2017). Frequency organization of the Johnston's organ in male mosquitoes (Diptera, Culicidae). *The Journal of Experimental Biology*, 220(Pt 21), 3927–3938.
<https://doi.org/10.1242/JEB.152017>
- Loh, Y. M., Su, M. P., Ellis, D. A., & Andrés, M. (2023). The auditory efferent system in mosquitoes. *Frontiers in Cell and Developmental Biology*, 11.
<https://doi.org/10.3389/FCELL.2023.1123738>
- Macgregor, C. J., & Scott-Brown, A. S. (2020). Nocturnal pollination: an overlooked ecosystem service vulnerable to environmental change. *Emerging Topics in Life Sciences*, 4(1), 19–32. <https://doi.org/10.1042/ETLS20190134>
- Mazerolle, M. J. (2020). *AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c)*.
- Mendelson, M. (1969). Electrical and Mechanical Characteristics of a Very Fast Lobster Muscle. *Journal of Cell Biology*, 42(2), 548–563.
<https://doi.org/10.1083/jcb.42.2.548>
- Morley, E. L., Jones, G., & Radford, A. N. (2013). The importance of invertebrates when considering the impacts of anthropogenic noise. *Proceedings of the Royal Society B: Biological Sciences*, 281(1776).
<https://doi.org/10.1098/RSPB.2013.2683>
- Moulton, J. M. (1957). Sound Production In The Spiny Lobster *Panulirus argus* (Latreille). *The Biological Bulletin*, 113(2), 286–295.
<https://doi.org/10.2307/1539086>
- Oksanen, J. (2022). *vegan: community ecology package*. .
<https://rdr.io/rforge/vegan/>

- Ollerton, J. (2017). Pollinator Diversity: Distribution, Ecological Function, and Conservation. *Https://Doi.Org/10.1146/Annurev-Ecolsys-110316-022919*, 48, 353–376. <https://doi.org/10.1146/ANNUREV-ECOLSYS-110316-022919>
- Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos*, 120(3), 321–326. <https://doi.org/10.1111/J.1600-0706.2010.18644.X>
- Owens, A. C. S., Cochard, P., Durrant, J., Farnworth, B., Perkin, E. K., & Seymoure, B. (2020). Light pollution is a driver of insect declines. *Biological Conservation*, 241, 108259. <https://doi.org/10.1016/J.BIOCON.2019.108259>
- Paxton, R., & Pohl, H. (1999). The Tawny Mining Bee, *Andrena Fulva* (Muller) (Hymenoptera, Andreninae), At A South Wales Field Site And Its Associated Organisms: Hymenoptera, Diptera, Nematoda And Strepsiptera. *British Journal of Entomology & Natural History*.
- Phillips, J. N., Francis, C. D., Ruef, S. K., Garvin, C. M., & Le, M.-L. T. (2019). *Background noise disrupts host-parasitoid interactions*. <https://doi.org/10.1098/rsos.190867>
- Phillips, J. N., Termondt, S. E., & Francis, C. D. (2021). Long-term noise pollution affects seedling recruitment and community composition, with negative effects persisting after removal. *Proceedings of the Royal Society B: Biological Sciences*, 288(1948). <https://doi.org/10.1098/RSPB.2020.2906>
- Popper, A. N., & Hawkins, A. D. (2018). The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America*, 143(1), 470–488. <https://doi.org/10.1121/1.5021594>
- Popper, A. N., Salmon, M., & Horch, K. W. (2001). Acoustic detection and communication by decapod crustaceans. *Journal of Comparative Physiology A: Sensory, Neural, and Behavioral Physiology*, 187(2), 83–89. <https://doi.org/10.1007/s003590100184>
- Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O., & Kunin, W. E. (2010). Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution*, 25, 345–353. <https://doi.org/10.1016/j.tree.2010.01.007>
- R Core Team. (2022). *R: A Language and Environment for Statistical Computing* (4.2.2).
- Rohde, B. B., Cooperband, M. F., Canlas, I., & Mankin, R. W. (2022). Evidence of Receptivity to Vibroacoustic Stimuli in the Spotted Lanternfly *Lycorma*

- delicatula* (Hemiptera: Fulgoridae). *Journal of Economic Entomology*, 115(6), 2116–2120. <https://doi.org/10.1093/jee/toac167>
- Rydell, J. (2006). Bats and their insect prey at streetlights. . *Ecological Consequences of Artificial Night Lighting*.
- Sanchez - Lafuente, A., Guitian, J., Medrano, M., Herrera, C., Rey, P., Luisa, M., & Cerda, X. (2005). Plant Traits, Environmental Factors, and Pollinator Visitation in Winter-flowering *Helleborus foetidus* (Ranunculaceae). *Annals of Botany*, 96, 845–852. <https://doi.org/10.1093/aob/mci236>
- Sanders, D., & Gaston, K. J. (2018). How ecological communities respond to artificial light at night. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, 329(8–9), 394–400. <https://doi.org/10.1002/JEZ.2157>
- Schaub, A., Ostwald, J., & Siemers, B. M. (2008). Foraging bats avoid noise. *The Journal of Experimental Biology*. <https://doi.org/10.1242/jeb.037283>
- Seymoure, B. (2018). Enlightening Butterfly Conservation Efforts: The Importance of Natural Lighting for Butterfly Behavioral Ecology and Conservation. *Insects*, 9(1). <https://doi.org/10.3390/insects9010022>
- Shamble, P. S., Menda, G., Golden, J. R., Nitzany, E. I., Walden, K., Beatus, T., Elias, D. O., Cohen, I., Miles, R. N., & Hoy, R. R. (2016). Airborne Acoustic Perception by a Jumping Spider. *Current Biology*, 26(21), 2913–2920. <https://doi.org/10.1016/J.CUB.2016.08.041>
- Skutelsky, O. (1996). Predation risk and state-dependent foraging in scorpions: effects of moonlight on foraging in the scorpion *Buthus occitanus*. *Animal Behaviour*, 52(1), 49–57. <https://doi.org/10.1006/ANBE.1996.0151>
- Sutton, G. P., Clarke, D., Morley, E. L., & Robert, D. (2016). Mechanosensory hairs in bumblebees (*Bombus terrestris*) detect weak electric fields. *Proceedings of the National Academy of Sciences of the United States of America*, 113(26), 7261–7265. https://doi.org/10.1073/PNAS.1601624113/SUPPL_FILE/PNAS.1601624113.SM01.WMV
- Swaddle, J. P., Francis, C. D., Barber, J. R., Cooper, C. B., Kyba, C. C. M., Dominoni, D. M., Shannon, G., Aschehoug, E., Goodwin, S. E., Kawahara, A. Y., Luther, D., Spoelstra, K., Voss, M., & Longcore, T. (2015). A framework to assess evolutionary responses to anthropogenic light and sound. In *Trends in Ecology and Evolution* (Vol. 30, Issue 9, pp. 550–560). Elsevier Ltd. <https://doi.org/10.1016/j.tree.2015.06.009>

- Tierney, S. M., Friedrich, M., Humphreys, W. F., Jones, T. M., Warrant, E. J., & Wcislo, W. T. (2017). Consequences of evolutionary transitions in changing photic environments. *Austral Entomology*, 56(1), 23–46. <https://doi.org/10.1111/AEN.12264>
- Tolstoganova, L. K. (2002). Acoustical behavior in king crab (*Paralithodes camtschaticus*). *Crabs in Cold Water Regions: Biology, Management, and Economics*, 247–254. <https://doi.org/10.4027/ccwr/bme.2002.19>
- Towne, W. F. (1995). Frequency Discrimination in the Hearing of Honey Bees (Hymenoptera: Apidae). *Journal of Insect Behavior*, 8(2).
- van Langevelde, F., Braamburg-Annegarn, M., Huigens, M. E., Groendijk, R., Poitevin, O., van Deijk, J. R., Ellis, W. N., van Grunsven, R. H. A., de Vos, R., Vos, R. A., Franzén, M., & WallisDeVries, M. F. (2018). Declines in moth populations stress the need for conserving dark nights. *Global Change Biology*, 24(3), 925–932. <https://doi.org/10.1111/GCB.14008>
- Wagner, D. L., Grames, E. M., Forister, M. L., Berenbaum, M. R., & Stopak, D. (2021). Insect decline in the Anthropocene: Death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America*, 118(2), e2023989118. <https://doi.org/10.1073/PNAS.2023989118/ASSET/5453ADFD-580A-44EF-BFA0387FE6FF8B76/ASSETS/IMAGES/LARGE/PNAS.2023989118FIG05.JPG>
- Warrant, E. J., Kelber, A., Gislén, A., Greiner, B., Ribi, W., & Wcislo, W. T. (2004). Nocturnal vision and landmark orientation in a tropical halictid bee. *Current Biology*, 14(15), 1309–1318. <https://doi.org/10.1016/J.CUB.2004.07.057>
- Willems, J. S., Phillips, J. N., & Francis, C. D. (2022). Artificial light at night and anthropogenic noise alter the foraging activity and structure of vertebrate communities. *Science of the Total Environment*, 805. <https://doi.org/10.1016/J.SCITOTENV.2021.150223>
- Wilson, A., Seymoure, B., Jaeger, S., Milstead, B., Payne, H., Peria, L., Vosbigian, R., & Francis, C. (2021). Direct and Ambient Light Pollution Alters Recruitment for a Diurnal Plant-Pollinator System. *Integrative and Comparative Biology*.
- Winfree, R., Griswold, T., & Kremen, C. (2007). Effect of human disturbance on bee communities in a forested ecosystem. *Conservation Biology: The Journal of the Society for Conservation Biology*, 21(1), 213–223. <https://doi.org/10.1111/J.1523-1739.2006.00574.X>

Yeates, D. K., & Greathead, D. (1997). The evolutionary pattern of host use in the Bombyliidae (Diptera): a diverse family of parasitoid flies. *Biological Journal of the Linnean Society*, 60(2), 149–185. <https://doi.org/10.1111/J.1095-8312.1997.TB01490.X>

IX. SUPPLEMENTAL MATERIAL

Glossary:

Noise pollution – the propagation of elevated sound levels (noise) with ranging impacts on humans or other living organisms.

Acute Noise – short bursts or exposure to noise (ex: cars intermittently passing on a road)

Chronic Noise – continuous noise (ex: oil compressor on 365 days a year)

Frequency (Hz and kHz): for a periodic signal, the maximum number of times per second that a segment of the signal is duplicated. For a sinusoidal signal, the number of cycles (the number of pressure peaks) in one second (Hz). Frequency equals the speed of sound (340 ms⁻¹) divided by wavelength (Barber et al., 2010).

dB – dB is a scale used to measure sound levels, where sound pressure levels are unweighted. Also referred to as dB (Z).

dBA – dBA is a scale where levels are "A" weighted according to the weighting curves to approximate the way the human ear hears.

L_{eq} – Time-averaged values, such as equivalent continuous sound level (L_{eq}), can be extremely informative to describe sounds that are chronic or frequent; measured using Larson Davis Sound Meter (Francis & Barber, 2013). If A-weighted, called LA_{eq}. If unweighted, called LZ_{eq}.

LAF90 – refers to those A-weighted noise levels in the lower 90 percentile of the sampling interval; it is the level which is exceeded for 90% of the measurement period. It will therefore exclude intermittent features of traffic and is used to estimate a background level ('Glossary of Acoustic Terminology', 2012).

Particle Velocity – the second distinct component to a sound wave undetectable to humans but detectable by many invertebrates using flagellar mechanosensory structures such as hair or antennae (Morley et al., 2013).

Light pollution – Excessive, intrusive, or prominent artificial light in the environment (Alaasam et al., 2021).

Artificial light at night (ALAN) – Artificial light at night; light manufactured and emitted into the nighttime environment by humans. The cause of light pollution (Alaasam et al., 2021).

Skyglow – Cumulative brightness of the night sky as a result of either light pollution or natural light sources (Alaasam et al., 2021).

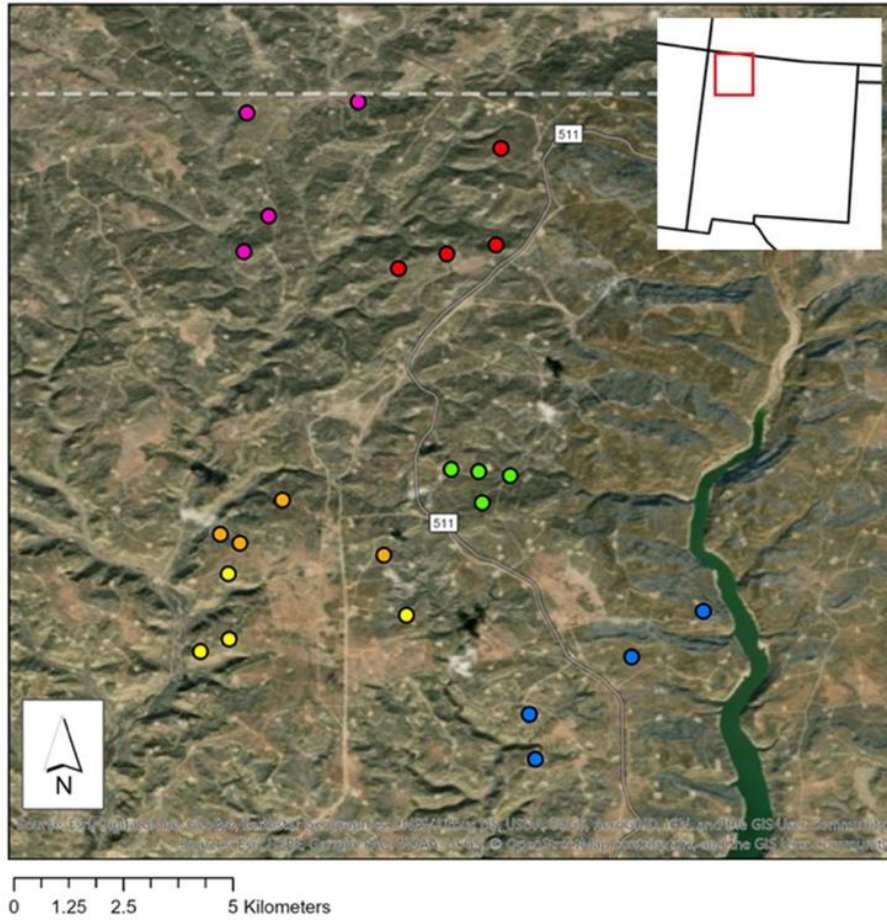
Lux – A measure of illuminance, equal to one lumen/m², and used as a measure of light intensity relative to distance from the light source (Alaasam et al., 2021).

Illuminance – Total luminous flux per unit area, i.e., the amount of light hitting a given area (Alaasam et al., 2021).

Table 1: Frequency hearing ranges by insect order.

Insect order	Frequency (kHz)
Hymenoptera*	0.2 - 0.3
Diptera*	0 - 50
Lepidoptera	0 - 50
Hemiptera	0 - 25
Coleoptera	20 – 50

Table 1: Approximate hearing ranges of insect orders. Asterisk indicates insect orders sensitive to particle velocity (Morley et al., 2013; Schaub et al., 2008; Towne, 1995).



Map courtesy of Joshua S. Willems. We conducted six repetitions of the four treatments across the landscape. The color clusters are to account for spatial autocorrelation of latitude.

SIERRA DEE RODRIGUEZ

VITA

srodriguez1@tamusa.edu ; sierrarodriguez@tamu.edu

Education

Master of Science in Biology (M.S.)
Texas A&M University – San Antonio
Graduation Date: May 20th, 2023
Advisor: Dr. Jennifer N. Phillips
Contact: jphillips@tamusa.edu

Bachelor of Science in Biology (B.S.)
Texas A&M University – San Antonio
Graduation Date: August 14th, 2021

Peer Reviewed Publications

* Indicates co authorship

<https://orcid.org/0000-0002-3272-1211>

Wincheski, Riley J; Jones, Ian T; **Rodriguez, Sierra Dee***; Jesus-Soto, Michael; Fletcher, Skylar; Pretends-Eagle, Troy; Grice, James W; Abramson, Charles I. “Training Honey Bees (*Apis mellifera*) to Push a Cap: Shaping, Observational Learning, and Memory.” *International Journal of Comparative Psychology*.
Accepted: April 18, 2023

Rodriguez, Sierra Dee; Wincheski, Riley J; Jones, Ian T; Jesus-Soto, Michael; Fletcher, Skylar; Pretends-Eagle, Troy; Grice, James W; Abramson, Charles I. “Some Phenomena of the Cap Pushing Response in Honey Bees (*Apis mellifera* spp.)” *Journal of Comparative Psychology*.
Accepted: January 31, 2023

Pretends-Eagle, Troy; **Rodriguez, Sierra Dee***; Jesus-Soto, Michael; Fletcher, Skylar; Jones, Ian T; Grice, James W; Abramson, Charles I. “An observation of a potentially novel defensive behavior against pesticides: Ants (*Messor oertzeni* Forel 1910) build a defensive wall against ant traps in the field (Preliminary note).” *Bulletin of Insectology*.
Accepted: October 11, 2021.

In Prep

Rodriguez, Sierra Dee; Navarro, Leonardo; Francis, Clinton D; Phillips, Jennifer N. Combined effects of light and noise on insect diversity and pollination services. Target journal: *Biological Conservation*.

Graduate Funding & Awards

1. Texas A&M University – San Antonio Student Research Symposium 2023
– 1st Place Graduate Student Oral Presentation
2. Charlotte Magnum Program Housing Support (SICB) 2023
3. Animal Behavior Society Diversity Travel Award 2022
4. Texas Ecological Laboratory Research Grant 2022
5. Texas A&M University – San Antonio College of Arts and Sciences (CoAS)
Graduate Research Grant 2022
6. Texas A&M – San Antonio Graduate Assistantship Program in Teaching 2021-2023

Graduate Presentations

1. Texas A&M University – San Antonio Student Research Symposium (SRS) April 2023 Oral Presentation: “The Effects of Sensory Pollution on Arthropod Diversity and Pollinator Behavior”
2. Master of Science in Biology: Public Thesis Defense April 19th, 2023
“The Effects of Sensory Pollution on Arthropod Diversity and Pollinator Behavior.”
3. Society for Integrative and Comparative Biology (SICB) January 2023 Austin, Texas Oral presentation: “The Effects of Sensory Pollution on Insect Diversity and Pollinator Behavior.” Session Chair for “Sensory Ecology, Communication, Cognition” session.
4. Animal Behavior Society (ABS) Conference in San Jose, Costa Rica. July 2022 – Poster.

Research Experience

2021-2023 Research Assistant, Dr. Jennifer N. Phillips Lab, Texas A&M University - San Antonio. Contact: jphillips@tamusa.edu

2021 Volunteer for Amphibian Surveys (SAAN) at the San Antonio Missions, a National Park Service site with Dr. Marvin Lutnesky, Texas A&M University - San Antonio. Contact: mlutnesky@tamusa.edu

2019 National Science Foundation (NSF - REU) Undergraduate Student Researcher in Lesbos, Greece for 8 weeks. Advisor: Dr. Charles I. Abramson, Oklahoma State University Laboratory of Comparative Psychology and Behavioral Biology. Contact: charles.abramson@okstate.edu

Teaching Experience

Teaching assistant for from 2021 – 2023 at Texas A&M University — San Antonio
Supervisor: Marie Tipps, tmtipps@tamusa.edu

- Fall 2021: 4 General Biology II (BIOL 1307) lab sections
- Spring 2022: 2 General Biology II (BIOL 1307) lab sections
- Fall 2022: 2 Cell Biology (BIOL 2431) lab sections
- Spring 2023: 2 General Biology II (BIOL 1307) lab sections

Professional Memberships

Animal Behavior Society (ABS)

Society for Integrative and Comparative Biology (SICB)

Undergraduate Research Funding

1. National Science Foundation Research Experience for Undergraduates (REU)
Grant Award #1560389 research stipend (\$4,400)
2. National Science Foundation Louis Stokes Alliance for Minority Participation
Grant
(CIMA-LSAMP) Award #1712626 research stipend (\$3,500)

Undergraduate Awards and Acknowledgments

1. The Charlotte Mangum Student Support Travel Award — The Society for Integrative and Comparative Biology (SICB) National Conference in Austin, Texas January 2020.

2. St. Philips College Travel Award — Emerging Leaders National (ERN) Conference 2020
3. S.A.C.U.C.C.A — San Antonio Colleges and Universities Career Centers Association Student Achievement Award Scholarship – March 2019
4. USAA McKinley Alamo Colleges REU Workshop Scholarship – December 2019
5. T-STEM Challenge Scholarship Fall 2019 & Spring 2019
6. St. Philip’s College Student Engagement Grant – Fall & Spring 2018, Spring 2019.

Undergraduate Poster Presentations

1. The Emerging Researchers National (ERN) Conference 2020 – Washington, D.C.
2. Society for Integrative and Comparative Biology (SICB) Conference 2020 – Austin, TX.
3. CIMA – LSAMP Undergraduate Research Symposium 2019 – San Antonio, TX.
4. University of Central Oklahoma REU Poster Symposium 2019 – Edmond, OK.
5. St. Philip’s College Undergraduate Research Symposium 2018, 2019 – San Antonio, TX.
6. Alamo Colleges Women Breaking Through Conference Panelist 2019 – San Antonio, TX.

Media

1. Texas A&M University – San Antonio ¡*Adelante!* magazine article about my research:
https://issuu.com/tamusanantonio/docs/18905_txa_m_tamsa_adelante_s23_final